COVER CROPPING IN THE SGMA ERA

A comprehensive overview of water impacts, policy implications, and recommendations for California's water managers

2024

A report prepared by a multi-disciplinary author committee as an outcome of the Soil-Water Interface Expert Convening Series

Cover Photo: Two adjacent plots in an almond orchard after an intense winter storm. On the right, cover crops have helped capture more of the precipitation in the ground; on the left, water pools on the bare ground. Courtesy of Donny Hicks, 2023.

This 2024 report is the product of a convening process (2022-2023) jointly developed by the California Association of Resource Conservation Districts (CARCD), California Department of Food and Agriculture (CDFA), Natural Resources Conservation Service of California (NRCS-CA), and University of California Agriculture and Natural Resources (UC ANR) and assembled by Sustainable Conservation. It was collaboratively developed by members of the Report Author Committee (see full list of contributors below), and led by Sustainable Conservation. With a goal of articulating the learnings from the convenings and carrying forward the conversations, insights, and remaining questions, the contents represent the invaluable contributions of all attendees of the Soil-Water Interface Expert Convenings: Cover Crops Impact on Water Budgets (see Appendix A for more information and a full list of convening participants).

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BACKGROUND

Increasing variability in precipitation, coupled with the rapidly growing demand for irrigation water, is causing a sharp decline in aquifer levels, threatening agricultural productivity, reducing access to clean drinking water, and causing adverse environmental externalities. The Sustainable Groundwater Management Act (SGMA) was designed to address these declines, but the management actions of locally established Groundwater Sustainability Agencies (GSAs) may have unintended consequences for sustainable agricultural practices, such as the adoption of cover crops.

Cover crops are non-income generating crops that are used to protect and improve the soil between regular annual crop production or between rows of perennial tree/vine crops. The benefits of cover cropping include improved pollinator habitat, infiltration, water storage, carbon capture, and soil health, as well as decreased runoff and erosion – all vital factors in California's new "normal" agricultural context. These potential benefits are especially salient in the San Joaquin Valley (SJV), where SGMA implementation is the most restrictive.

To understand the potential of cover cropping under SGMA, a collaborative initiative including more than 100 multidisciplinary experts came together to answer the following questions: 1) what are the impacts of cover crops on water cycles (both benefits and use), 2) how does SGMA management account for cover cropping and is it effective, and 3) how can we ensure that this practice remains available to growers where and when it makes sense? This report synthesizes the learnings from that initiative, a policy analysis, interviews with GSA staff and consultants, and the expertise contributed by its 30+ authors.

FINDINGS: COVER CROPS AND WATER IN CALIFORNIA

Examining the research literature about cover crops' impact on water-related processes, research in California and Mediterranean climates was prioritized. The key findings are that:

- The water impacts of cover cropping are variable and they depend on many factors: climate, context, management, and more.
- Cover crop evapotranspiration (ET) can be negligible compared to bare ground in perennial and annual systems – *wintertime, rain-fed cover cropping does not necessarily significantly increase water losses compared to bare ground in the winter months.*
- The most consistent water-related benefits of cover cropping demonstrated in the *California-based* research literature are increased infiltration of water into the soil (often ≥40%) and the reduction of runoff (often ≥40%).

FINDINGS: GSA MANAGEMENT AND COVER CROPPING

In order to understand the impacts of GSA management on cover cropping, an analysis of plans, rules and regulations, and methodologies was necessary. Investigating 9 GSAs in the SJV, where plans were most fully developed and include allocation plans, the following were uncovered:

- GSAs are responsible for managing a large workload and considerable complexity. Minimal guidance in a policy based on local control is resulting in varying approaches and degrees of rigor in consequential water management processes.
- Cover crops may be unintentionally disincentivized because GSA approaches tend to account for cover crops' water use but not their water related benefits.
- Some common assumptions in GSA approaches are not reflective of the best available science and preclude the ability to account for the benefits of certain land management decisions. These are that:
    - Evaporation from bare ground is negligible.
    - Runoff is negligible.
    - The percentage of precipitation that percolates into groundwater is fixed.
- Requirements for bare ground exist in some GSA incentive programs. These requirements are unlikely to meet estimated water savings and are likely to create negative local impacts to air quality, water quality, and human health.
- Some GSA methodologies for incorporating precipitation are likely to result in unintended consequences for cover crop implementation, basin water management, and water use decisions.
- Relative to what is known about the margins of error of satellite ET estimates for common crops, little is known for winter cover crops. In particular, it is not well documented how factors such as increased cloud cover and bare ground could impact the accuracy of ET estimates for cover cropped parcels compared to non-cover cropped parcels.
- GSA methodologies for converting satellite ET data (total consumptive use) or flowmeter data (applied water) into consumptive use of groundwater (CUgw) estimates are variable and not always rigorous.
- An "illusion of precision" may lead GSAs to be less open to enabling multi-benefit practices.
- Current GSA approaches could negatively impact the success of other policies, programs, and efforts in California.

RECOMMENDATIONS

To support SGMA implementation and create a sustainable water future for California, we have created a list of recommendations to address the findings in our analysis. Fundamental to these recommendations is the need to ensure effective adaptive management.

Research: Develop and implement a coordinated effort to increase understanding of net water impacts of cover crops.

- Support, document, and analyze grower experiences implementing cover crops, collecting both quantitative and qualitative data and incentivizing this collection.
- Develop, fund, and implement a coordinated research program that addresses the most important gaps in knowledge.

Cover Crop-Specific Needs: Address gaps to enable effective integration of cover crops into GSA plans, allocation approaches, and incentive programs.

- Develop and distribute guidance on the characteristics of water-efficient cover cropping, for growers and GSAs who want to implement cover crop-specific programs.
- Develop a spatial dataset of cover crop adoption and update annually.
- Investigate current approaches to "natural lands" within GSAs and identify strategies that may be applicable to the practice of wintertime cover cropping.

GSA Guidance: Provide guidance and support to GSAs on consequential elements of allocations and consumptive use.

- Develop and distribute guidance documents on best practices and methodologies for converting satellite ET and flow meter data into estimates of consumptive use of groundwater.
- Develop and distribute guidance documents on best practices and methodologies for incorporating precipitation into groundwater allocations and consumptive use assessments.
- Provide guidance and technical assistance to GSAs in commonly lacking areas of expertise relevant to ensuring sustainable groundwater management, such as atmospheric science, ecology, and soil science.
- Develop and distribute guidance documents on calculating and incorporating estimates of the margin of error more explicitly into management in ways that increase knowledge about its magnitude and enable the implementation of multibenefit practices.

Data: Improve the quantity, spatial distribution, quality, and use of data necessary to develop approaches and to assess performance.

- Evaluate and invest in the most cost-effective ways to improve distribution and quality of key ET data inputs (e.g., supporting CIMIS, a new Eddy Covariance tower network).
- Identify and spotlight available high-resolution datasets central to GSA management.

Funding: Provide short-term and long-term funding to ensure successful and high-quality implementation of allocation approaches and consumptive use estimates.

- Provide shorter-term funding to support new, one-off initiatives such as the development of guidance documents or research agendas.
- Provide longer-term funding to support ongoing needs such as technical support for GSAs, and the provision of key ET data inputs.
- Identify solutions to ensure GSAs can raise the funding needed to meet the mandates of SGMA.

Aerial photos of orchards with and without cover crops. Courtesy of Andrew Gal, UC Davis.

VISION

To clarify the desired impact of our recommendations and their necessity, a detailed comparison of the current and ideal future states of GSAs and their approaches are included in the table below. The recommendations above aim to support this vision.

		CURRENT STATE *Based on analyzed GSAs*	**FUTURE STATE** *Vision for Effective Management*
OVERARCHING	***Cover Crop Penalties & Incentives***	Within their management approaches, GSAs do not directly penalize cover crops (e.g. with a fine) nor do they incentivize them. However, most current approaches are likely to indirectly disincentivize cover crop use through assumptions and approaches that capture water use but not water benefits.	GSA management systems more accurately account for cover crop water use, their water benefits, and (because they now effectively incorporate precipitation, runoff and infiltration), have the operating space to incentivize this multi-benefit practice if they so choose.
OVERARCHING	***GSA Guidance and Expertise***	GSAs and their consultants have received limited guidance and may lack multi-disciplinary expertise to support the development of the many complex processes necessary to meet their mandates. This has contributed to a wide range not only in approaches, but in the rigor and effectiveness of these approaches.	"Local control" with high-quality outcomes across the state is enabled by the availability of (1) guidance documents for vital processes – including allocations and consumptive use estimates, and (2) multi-disciplinary technical experts who can assist GSAs and their consultants in refining their approaches and methodologies.
OVERARCHING	***Managing to Margins of Error***	GSAs must make many assumptions about complex subbasin-wide processes. They do not publish margins of error resulting from these assumptions nor discuss implications or approaches for operating within it.	GSAs incorporate estimates of the margin of error more explicitly into management, ideally in ways that allow for increasing knowledge about its magnitude and create the space for the implementation of multi-benefit practices.
SPECIFIC	***Fallowing Credit***	Bare ground is sometimes a requirement to receive water credits, increasing the likelihood of negative air, soil, and water quality impacts alongside uncertain water quantity benefits	There are no bare ground requirements. Water-efficient cover cropping is allowed, and incentivized when appropriate, resulting in multiple co-benefits and positive or *de minimis* negative impacts to water budget.
SPECIFIC	***Infiltration and Runoff***	Broad assumptions about infiltration and runoff are common and often don't account for localized factors that can influence the magnitude of impacts, especially in extreme weather years.	GSA assumptions and approaches incorporate a more robust accounting for infiltration and runoff, including methods – such as effective precipitation – that allow for adjustments based on localized factors.
SPECIFIC	***Precipitation***	Precipitation is a central component of allocation and consumptive use schemes and is incorporated inconsistently. Among these approaches, some use assumptions which are especially ill-suited to California's future precipitation regimes.	GSAs have incorporated precipitation in ways that accurately account for the variability over time, while ensuring that growers can plan ahead and are not unfairly penalized in precipitation years that fall well outside of the "average."
SPECIFIC	***Consumptive Use Methodologies***	GSA methodologies for converting satellite ET (e.g. total consumptive use) data or flowmeter (e.g. total water applied) data into consumptive use of groundwater (CUgw) estimates are hard to obtain, variable, and not always rigorous.	GSA methodologies for converting satellite ET data and/or flowmeter data into CUgw estimates is easily accessible, robust, and based on best available science.
SPECIFIC	***Cover Crop Definitions***	There are no clear parameters to define what constitutes water-efficient cover cropping, increasing the perceived risk of developing cover crop-specific approaches or incentives.	Parameters for "water-efficient" cover cropping – including species and management practices – are available and based on best available science. GSAs provide clear parameters that fit their specific context (cropping, climatic, etc.) in any cover crop-specific approaches.

1 Introduction

1.1. CALIFORNIA WATER LANDSCAPE

Overview

In California's semi-arid, Mediterranean climate, the success of large-scale agriculture has long been tied to effective irrigation and active water management. The development of federal and state water projects, specifically the Central Valley Water Project and State Water Project, have enabled California to become the most productive agricultural state in the nation, producing approximately one-third of the nation's vegetables, three-quarters of its fruits and nuts (USDA ERS, 2023), and one-fifth of all dairy products (Matthews & Sumner, 2018). But growing agricultural operations alongside uncertain surface water supply and increasingly variable precipitation have led to high levels of groundwater extractions to keep up with irrigation demand. These extractions are contributing to rapidly declining aquifers, land subsidence, and coinciding deterioration in community drinking water quality, especially in regions with little to no surface water access.

To address these issues, the Sustainable Groundwater Management Act (SGMA), the preeminent regulatory scheme for managing groundwater water supply in California, mandates the avoidance of six undesirable results of groundwater overdraft – including chronic lowering of groundwater levels. But managing water use in the context of large agricultural systems developed without regulated water extraction is a challenge, and the local entities charged with implementing SGMA, Groundwater Sustainability Agencies (GSAs), face many hurdles in addressing aquifer overdraft. As GSAs implement Groundwater Sustainability Plans (GSPs) to ensure sustainable extraction of groundwater, there is increasing concern around the impact of these local regulations on the adoption of sustainable agriculture practices. This is particularly true where aquifer overdraft, and therefore GSA management intervention, is greatest: the San Joaquin Valley (SJV).

Physical Environment: Present and Future

Mediterranean climates found in California – characterized by dry, hot summers, and relatively mild winters with variable levels of precipitation – allow for up to three growing seasons. This seasonal variability means that agriculture in the region is highly dependent on irrigation during the dry spring and summer months. In a "normal" year, approximately 40% of irrigation water comes from groundwater sources, but as climate change increases the frequency and severity of droughts, that figure is often greater than 60% (SWRCB, 2022). With over 400 different commodity crops grown in the state, the diversity of cropping systems and historic climatic conditions already create substantial challenges for water management.

These difficulties are compounded by climate change, the impacts of which are already being experienced in California (OEHHA, 2022). The variability of overall winter precipitation in CA is projected to increase by ~54% with climate change (Zhou et al., 2020). Weather patterns that induce prolonged droughts have become more common in California (Swain et al., 2016) and an increase in extreme dry-to-wet precipitation events is projected with climate change (Swain et al., 2018). With increasing intensification of precipitation extremes, the increased risk of events that could produce large-scale catastrophic flooding is also expected (Gershunov et al. 2019; Huang and Swain, 2022). Although extreme precipitation years are becoming more frequent with climate change, the long-term average precipitation has been relatively stable (Mount et al., 2023). The variance around the average is increasing, with significant implications for California water users.

As the above weather-related changes continue to be realized, restriction of surface water supply and deliveries during droughts will further increase water pressures on growers. Given these significant ongoing pressures and the expected shifts in climate, there is an urgent need to increase agriculture's resilience and minimize the agronomic impacts of climate change (Patak et al., 2018) while reducing agriculture's impact on water resources.

Community Impacts

Agricultural demand and climate change, among other things, have fueled groundwater overdraft with significant impacts for California's groundwater dependent communities. The lowering of groundwater levels has resulted in water quality degradation and failures of domestic water supplies, with disproportionate burdens on marginalized communities (Sunding and Roland-Holst 2020; Bruno et al., 2022).The SJV agricultural region experiences the highest rates of drinking water contamination in the state, and over 1 million people across the state lack access to safe and affordable drinking water (California State Auditor, 2022) due to the combined impacts of pollutant leaching from irrigated agriculture and other local sources (i.e. dairy farms and septic tanks, Harter et al., 2017) and groundwater overdraft.

As land is fallowed due to water scarcity or as part of proactive public measures including incentive and grant programs, there is a significant risk of environmental impacts, including worsening air quality from windblown dust (Ayres et al., 2022). These impacts compound environmental injustices and health disparities already experienced by communities located in agricultural regions. Moreover, fallowing of farmland is expected to be accompanied by significant economic repercussions due to job losses if regional investments are not made (Fernandez-Bou et al., 2023).

The Regulatory Environment

Prior to SGMA, California was the last western state without a comprehensive groundwater regulatory framework. Today, California's water-focused regulations are some of the most restrictive in the nation (H. Burke et al., 2022) for both water use (e.g., SGMA) and water quality protection (Irrigated Lands Regulatory Program, CV SALTS, etc.). Under SGMA, Groundwater Sustainability Agencies (GSAs) have been formed in every medium- and high-priority subbasin, with the mandate to reach groundwater "sustainability" – the point where yearly water usage is in balance with average aquifer in-flows and undesirable results are avoided – within 20 years of the approval of a Groundwater Sustainability Plan (GSP).

In the context of SGMA, "subbasins" or "basins", usually refer to the geographical area of a GSA. They generally overlap with hydrological subbasins, or even just a portion of a subbasin, rather than precisely aligning with the hydrological bounds of a basin or subbasin. For consistency, the term subbasin is used in this report when referring to the geographical area of a GSA.

SGMA establishes a broad framework for GSAs to manage groundwater, giving them flexibility about how to achieve sustainability. In terms of informing specific implementation, the state released guidance that defines Best Management Practices (BMPs) for a very limited number of processes. The lack of more specific implementation requirements, as well as the delayed release of existing guidance, has meant that a wide variety of methods has been devised by the different GSAs, with varying levels of effectiveness, unintended consequences, and opportunities to incentivize different sustainability practices. For example, a recent report found that 60% of agricultural wells, 63% of domestic groundwater wells, and 91% of groundwater-dependent ecosystems in California's regulated basins were not protected from losing access to water under initial local planning for SGMA (Chappelle et al., 2023).

As the California Department of Water Resources (DWR) continues the review and approval process of GSPs, there is an opportunity to more clearly articulate how and when practices like cover cropping can help meet the goals of SGMA, and to ensure they can be adopted where suitable.

1.2. COVER CROPS

Cover crops are non-cash crops cultivated to protect and improve the soil between seasons of regular annual crop production or between trees in orchards and vines in vineyards (Fageria et al., 2005). When cover crops are not planted, the common practice in California is to manage the soil surface so that there is no vegetative growth — leaving only "bare ground". This is common both in between rows of perennial crops (e.g. orchards, vines) and during fallow periods — when normally productive land is not cultivated with a cash crop.

Cover crops have many widely accepted benefits to agricultural sustainability and the health of the environment and communities, such as improved soil health and reduced erosion. The specific benefits of cover crops can vary dramatically according to the local environment, management choices, and the goals of the grower (e.g., pollinator habitat, weed suppression, water infiltration, carbon sequestration). Under SGMA, in locations such as California's arid San Joaquin Valley, cover crops should be implemented in specific contexts to maximize their potential benefits and minimize water use. Therefore, for the purposes of this report, cover crops generally refer to non-cash crops that are:

- Winter-season annuals (native or non-native), managed resident vegetation, or cool season perennial permanent cover crops that are dormant in the summer season.
- Unirrigated (rainfed or utilizing residual soil moisture) or minimally irrigated to establish and maintain cover crop growth in years with low/erratic precipitation
- Terminated before spring temperatures and water use increase.

There are still uncertainties around the net impacts of cover cropping on on-farm consumptive water use, and the best management practices. However, the known benefits of the practice support the potential for widespread implementation in California. As we continue to resolve these questions, it will be possible to implement cover crops for their multiple benefits even in water-scarce environments, accurately accounting for the balance of their water benefits and net impacts to water budgets.

History of Use

The use of cover crops in Mediterranean climates can be traced back thousands of years (Groff, 2015; Pieters, 1927). In California, cover crops were utilized from the early 1900's, often in orchard and vineyard systems, where they were recognized to improve soil fertility, reduce erosion, and improve water infiltration (Ingels and Klonsky, 1998). Their popularity began to abate around 1950, as commercial pesticides and fertilizers became more readily available and more intensive farming methods were adopted (Ingels et al., 1994).

Over the last decade, there has been renewed interest in cover cropping as the practice is increasingly recognized for its multiple benefits to agriculture and the environment, with nationwide adoption increasing by 50% — from 10.3 to 15.4 million acres — between 2012 and 2017 (Wallander et al., 2021). A majority of this new acreage occurred in the Midwest and coincided with increasing incentives; in the USDA's EQIP program alone, financial support for cover cropping increased from less than $10 Million in 2005 to over $150 Million in 2018 (Wallander et al., 2021). However, cover crop adoption rates in California remain low relative to other parts of the country, with only a 2.9% increase in cover cropped acreage between 2012 and 2017, and a total of about 5% of agricultural land in cover crop management in the state (USDA 2019; LaRose & Meyers 2019, Wallander et al., 2021).

Potential Water, Soil, and Environmental Benefits

In examining the benefits of cover cropping, it is worth noting that the practice is not monolithic – there is no single set of species, management practices, or outcomes denoted by the term. Therefore, the specific management goals being addressed, and the subsequent management decisions being made, are key in determining the impact of a cover crop in the local environment. For instance, a management goal of increasing pollinator habitat will dictate the use of different species, different management choices (e.g., timing of termination – in this case after orchard or vine flowering), and lead to different environmental and agronomic outcomes (e.g., pollinator populations, water use, pest management, etc.). While cover cropping is a multi-benefit practice, maintaining clarity about the management goals is a necessity. Cover cropping benefits also depend on site-specific conditions such as weather and climate, soil type, and management practices.

While these benefits are broadly observed in studies of cover cropping, key questions remain around the ways to maximize these benefits in the specific climates and cropping systems of California.

When appropriately implemented in advantageous environments, cover cropping may:

- increase water infiltration
- reduce water runoff
- reduce wind and water erosion
- capture fog and form dew
- increase soil moisture and water storage capacity
- increase water use efficiency
- reduce nitrate leaching
- enhance soil structure and aggregation
- reduce soil temperatures
- reduce soil compaction
- reduce surface sealing and crusting
- build soil organic matter
- increase soil fertility
- support pest management
- provide pollinator habitat
- increase soil and on-farm biodiversity

Human Health Benefits

Cover crops are known to provide human health benefits indirectly due to their potential to improve air and water quality (Blanco-Canqui et al 2015). Cover cropping during the winter fallow period may reduce dust and particulate matter (e.g., PM 2.5 and 10) as fields are less prone to wind erosion when protected by plant canopies and their residues. Cover crops reduce runoff of sediment and associated fertilizers, pesticides, and organic matter, which means that nearby surface water systems and water bodies are better protected. Cover crops can incorporate excess nutrients, like nitrogen, into their biomass, thereby reducing nitrate leaching below the rootzone and into groundwater, thus reducing risk of degrading water quality for local communities. In some cases, cover crop management reduces grower reliance on synthetic fertilizers, pesticides, and herbicides, leading to lower chemical residues on crops and reducing potential health risks for producers, workers, and communities alike.

Uncertainties Around Water Impacts

In semi-arid agricultural regions challenged by water scarcity, such as the Central Valley, the uncertainty around cover crop water use has important implications for the broader adoption of this soil health practice. The net impacts of cover cropping on water demand remain uncertain due to the complex array of cropping systems and on-farm conditions seen here, as well as a lack of long-term studies that measure water balance over the life of the whole cropping system (including during and between crops). There is significant evidence that cover cropping can positively impact groundwater resources through an array of impacts on water capture and storage. The largest uncertainty is how the total water budget is affected, that is, whether more water is lost by cover crop transpiration than is saved through increases in infiltration, soil water storage, reductions in evaporation, and other positive water-related implications. The actual balance of this equation depends on specific management practices, weather conditions, soil type, species of cover crop, timing of establishment and termination, and more.

1.3. COVER CROP – WATER INTERACTIONS IN CALIFORNIA

California growers face a wide array of pressures, such as changing climate regimes, groundwater pumping regulations, and broader regulatory requirements to ensure human and environmental health in the state. Cover cropping has the potential to help address multiple facets of these converging pressures, and state agencies such as the California Department of Food and Agriculture (CDFA) and the California State Office of the Natural Resources Conservation Service (NRCS) are investing heavily in programs aimed at expanding adoption of the practice. Unfortunately, overall adoption remains low. One key barrier to increasing the adoption of cover cropping in the San Joaquin Valley is the uncertainty around its net water implications. The implementation of GSA regulation of groundwater use is potentially a large disincentive if there isn’t clarity around the net water balance of the practice. Cover crops can have water benefits (quantity and quality) and they use water to grow, but our knowledge around the net balance is still developing and this balance is site-, context-, and management-dependent.

Growers, researchers, crop and irrigation advisors, agencies, and communities have expressed concern that the water supply pressures associated with SGMA implementation will curtail adoption of cover crops in California. And this concern may not be unfounded. For example, while the percent of cover cropped acres compared to total acres funded by NRCS's EQIP remained relatively flat at 0.1-0.2% from 2017-2022 (NRCS, 2022), preliminary data from CDFA's Healthy Soils Program show a decline from 41% to only 7% over the same time period (M. Wolff, personal communication, November 17, 2023). With no underlying year-to-year biases in awardee selection processes, these declines suggest stagnation in cover crop adoption rates relative to other practices, possibly due to water use concerns.

To overcome this challenge, it is crucial to enhance our understanding of the effects of cover crops on water dynamics and to identify the conditions under which cover cropping can be most beneficial while minimizing water consumption. This will enable us to identify opportunities where cover cropping can achieve its potential as a multi-benefit practice to drive greater resilience in California agriculture.

1.4. CONVENING TO ADDRESS THIS NEED

This report is the culmination of an interdisciplinary, multi-stakeholder expert convening process aimed at generating practical insights for water planners, managers, and users around the water-related impacts of cover cropping and the implications of current water management within SGMA. The goals of this report are to collate research and on-the-ground perspectives, bring together multidisciplinary expertise, and fill key information gaps identified prior to and during the convening process. Specifically, the report provides:

1. A synthesis of available and emerging research of cover crop impacts to the water cycle with emphasis on California and other Mediterranean and semi-arid geographies,
2. An analysis of the impacts of SGMA and GSA management on cover crop implementation, and
3. Recommendations for water planners and managers to ensure the viability of cover cropping as a multi-benefit management tool.

The report is intended to be a resource for water agencies including the DWR and the SWRCB, irrigation and water districts, and local GSAs, whose implementation of SGMA has the potential to have unintended and detrimental effects on cover crop implementation. This document will also form the basis of forthcoming guidance for growers and technical assistance providers around implementing cover crops in water scarce conditions.

Convening Series

From October 2021 to May 2023, a collaborative effort involving the CDFA, California Association of Resource Conservation Districts (CARCD), Natural Resources Conservation Service (NRCS), University of California Agriculture and Natural Resources (UC ANR), and Sustainable Conservation led to the organization of three sequential expert convenings titled "Soil-Water

Interface Expert Convenings: Cover Crops Impact on Water Budgets." These events brought together a diverse group of stakeholders, including university, state, and federal government scientists; university extensionists; local technical assistance providers; conservation organizations; industry representatives; growers; state agencies; and others (refer to Appendix A for a comprehensive participant list). The convening series was designed as an action-oriented forum to build collective knowledge across sectors, share emerging research and observations, and formulate evidence-based recommendations. A key outcome of this series was the joint development of this report by an interdisciplinary team of over 30 experts.

Aerial photos of orchards with and without cover crops. Courtesy of Andrew Gal, UC Davis.

2 State of Knowledge: Cover Crops and Net Water Impacts

2.1. HOW COVER CROPS AFFECT PARCEL-LEVEL WATER BUDGET COMPONENTS

Cover crop net impacts to water budgets depend on interactions between biotic and abiotic factors (climate, soil type, etc.) and agricultural management practices. With many interlinked systems at play, articulating specific outcomes or interactions can be difficult. In order to frame the potential water impacts of cover cropping more effectively in the context of the parcel-scale water budget, they are arranged into three groups: processes that affect (1) water flowing out of the parcel (parcel outflows), (2) water flowing into the parcel (parcel inflows), (3) the storage of water within the parcel (especially in ways that may reduce irrigation applications and replenish aquifers), and (4) surface and ground water quality. Here, "parcel" refers to the surface and subsurface water systems of a specific land area.

This section – and the vast majority of research on cover crop-water relations – is based on field-scale processes, while SGMA related goals generally focus on the broader subbasin scale. Therefore, in the context of SGMA mandates, these flows are relevant in terms of their eventual effect on the subbasin or in their impact on groundwater use of individual water-users that is captured by GSAs. The findings collated below demonstrate the potential impacts of cover crops on field-level water processes that may affect growers' use of water under limited allocations and, with increased adoption, also affect the basin-level water budgets. Understanding these impacts is vital to informing the adoption and management of cover crops as they relate to water use and benefits, and a critical first step to understanding the magnitude of impact at a broader scale more relevant to water planners and managers.

The following sections document the current state of relevant science on cover crop effects on each process. To simplify and clarify these research observations, summaries have been provided for each of the following sections, synthesizing the key information documented in the scientific literature. These summaries should not be taken as a guarantee of similar results, but rather an indicator of the potential impacts of cover crops on water processes.

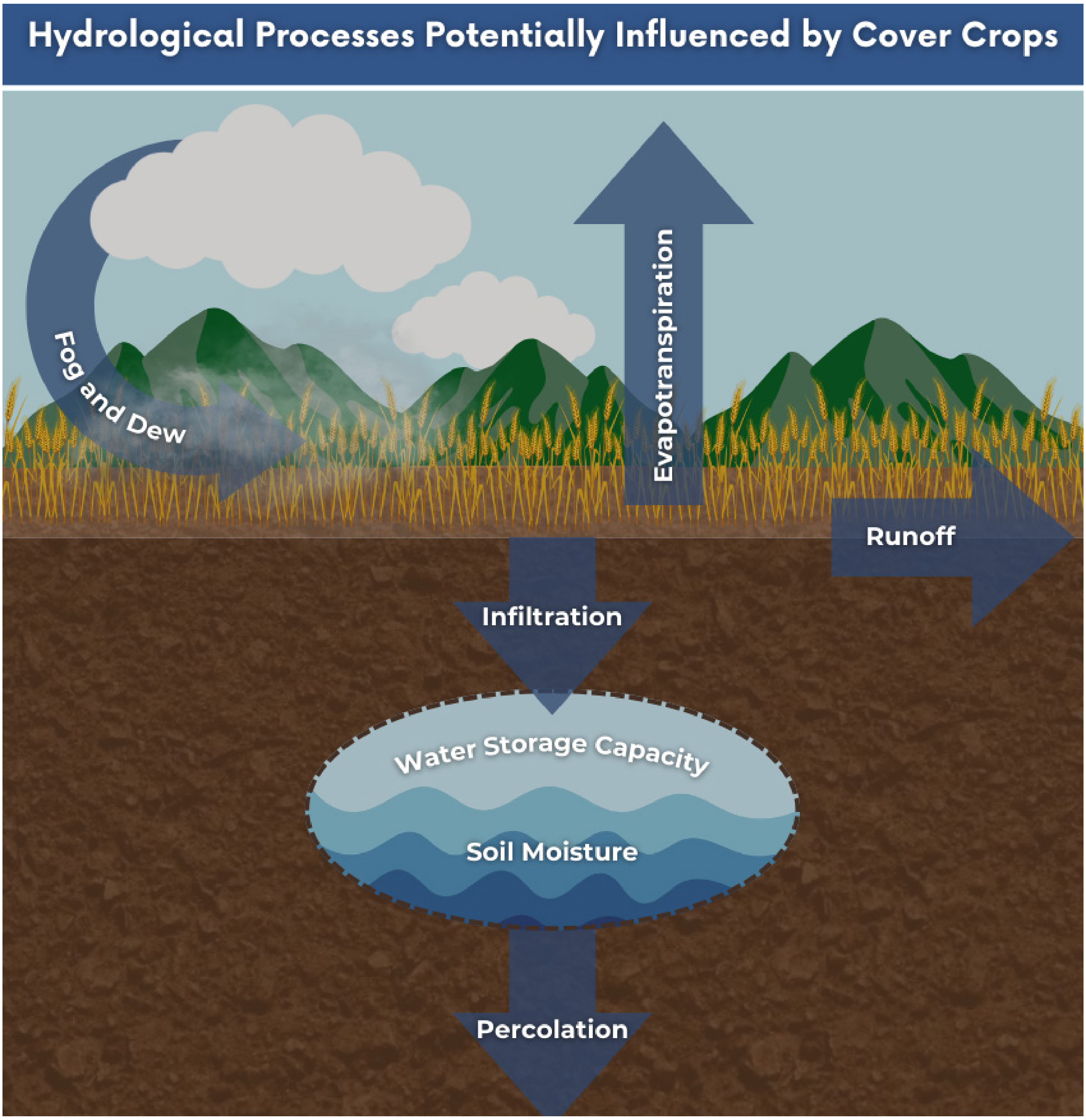

Figure 1: Hydrological processes that may be influenced by cover crops. This illustration depicts the major flows of water occurring on a parcel that cover cropping has the potential to impact. Research exploring the relationship for each in California and Mediterranean climates is presented below.

PARCEL-LEVEL OUTFLOWS

Outflows are processes by which water leaves a given parcel including water lost through evaporation, transpiration, the more commonly measured combined metric of evapotranspiration (ET), and runoff.

Evaporation

Evaporation is the loss of water to the atmosphere from soil and other surfaces. Evaporative demand, a measure of "atmospheric thirst," is the amount of water that the atmosphere can absorb from the land surface depending on conditions of temperature, wind speed, humidity, and solar radiation. Evaporative demand is a strong determinant of evaporation rates, alongside soil moisture and surface conditions. The evaporation of wintertime precipitation from bare ground represents a significant loss of water from California's agricultural lands (Burt et al., 2002). Cover cropping, an alternative to winter bare ground management, and post-termination biomass residues mulching the soil surface may reduce soil surface evaporation through multiple effects on surface conditions including soil shading, altering surface temperature, heat transfer, and radiation dynamics (Horton et al., 1996; Bodner et al. 2007; Klocke et al. 2009; Mitchell et al., 2012b; Kaye and Quemada 2017).

In California's San Joaquin Valley, cover crops have been shown to substantially reduce soil temperatures and the diurnal temperature range compared to bareground in tomato-cotton cropping systems (Mitchell et al., 2012a; 2015), with significant implications for reduced evaporation. Thus, the impact on evaporation may depend on the amount of soil moisture, cover crop residue retention, as well as the rainfall regime and distribution. Generally speaking, bare ground evaporates a significant amount of water, while cover crops and their residues may reduce evaporation rates.

Transpiration

Transpiration is the loss of water from the soil to the atmosphere through plants, and thus cover crop transpiration is a source of on-farm water loss. It is influenced by factors including soil characteristics (e.g. soil texture), weather, microclimate, soil moisture, and evaporative demand (temperature, relative humidity, windspeed, and solar radiation). Further, transpiration rates vary by species differences in stomatal regulation (Bertolino et al., 2019), rooting depth, canopy height, length of vegetative cycle, and leaf area index (i.e. ratio of leaf canopy area to ground area). Additionally, factors specific to cover crops such as the degree of perennial cropping system canopy cover may impact transpiration rates. Generally, research has found that increasing amounts of cover crop biomass correspond to increasing transpiration (Berriel et al., 2020), thus the timing of cover crop termination significantly impacts overall contributions to parcel transpiration.

In the cover cropping systems referred to in this paper, the generally lower evaporative demand of wintertime, and termination timed ahead of increasing spring temperatures generally limit transpiration to amounts that are significantly less than that of cash crops. In wet years, cover crop transpiration needs may be entirely met by precipitation. In dry years with appropriate management, relatively small amounts of applied water may be required to grow a winter cover crop — anecdotally, around 2 inches. Due to the range of factors and the more often studied framing that includes evaporation (evapotranspiration), more explicit estimates are not common for transpiration alone.

Evapotranspiration

Evapotranspiration (ET) represents the sum of water transpired from plants and evaporated from the land surface and is a primary measure through which crop water use is assessed by GSAs under SGMA. In California's water scarce regions, cover crops are generally grown during the winter months (October to May), a period of high seasonal precipitation and low atmospheric water demand. While cover crops increase on-farm transpiration, they also decrease soil water evaporation.

These opposing effects on evaporation and transpiration may explain why some studies have found negligible effects of cover cropping on field-based ET measurements (DeVincentis et al., 2022). For example, in California's Central Valley, Islam et al. (2006) found that winter cover cropping in a tomato-cotton rotation increased wintertime on-farm ET by 1.2 inches (cover cropped fallow ET: 5.4 inches; bareground fallow ET: 4.3 inches), as computed using a hydrologic modeling approach. More recent research using a residual energy balance (REB) method and surface renewal (SR) technique to determine ET, supported this finding and reported negligible differences between cumulative winter ET between cover cropped and bareground fallow in processing tomato fields in the Sacramento Valley (0.12 inches; Davis, CA) and San Joaquin Valley (0.71 inches; Five Points, CA)(DeVincentis et al. 2022). Overall, these values amount to less than a single irrigation event and are a low fraction (~4%) of annual crop water budgets. At one site in Mediterranean southern France, Tribouillois et al. (2018), showed that, compared to bare soil, cover crops planted in the winter fallow period of a maize- and wheat-based rotation increased ET by a maximum of 1.15 inches per year among several climate change scenarios, but did so without reducing water resources for cash crops.

Emerging and on-going research suggests that these same trends persist year-round (see Appendix B for further descriptions). Preliminary results from a multi-year and multi-orchard study in the San Joaquin Valley found no increase in wintertime ET between mature almond orchards with cover cropped vs. bare soil management (Flynn, Suvočarev, and others, unpublished research). Summer comparisons from these same sites show similar or slightly lower ET for cover cropped sites. Further, like all plants, total cover crop ET can depend on the amount and timing of precipitation. Data collected during an above average precipitation winter from Sacramento Valley paired adjacent young pistachio orchards (5 years old), with and without cover crops, show increased (15-20%) springtime ET with winter cover cropping (terminated in April) compared to bare ground orchards (Roby, Kisekka, and others, unpublished research). Research from this same site shows similar, and even slightly lower ET in cover cropped orchards, long after cover crop termination.

Some factors appear to have consistent effects on the ET of cover crops, including water availability (precipitation or irrigation), weather conditions, and cover crop species and biomass. Cover crop contributions to overall field or farm ET may also depend on the cropping context, for example, whether cover crops are grown as a non-irrigated replacement for bareground fallow in annual crops or in alleyways of perennial woody crops. Differences may also vary by the age of a perennial woody crop and how much shading the canopy provides if cover crop is grown past leaf out. This is an area where more research is needed.

When managed appropriately, wintertime cover crop water use is likely to be significantly less than that of irrigated cash crops because of seasonal differences in evaporative demand (winter vs. summer growing seasons) and canopy structure (e.g. short vegetation in the shade of tree canopies).

ET Summary

The overall amounts of ET resulting from cover cropped fields can be highly variable. Bare ground, the alternative to cover cropping, can lose significant amounts of water to evaporation. In California, cover crop ET in perennial and annual systems has the potential to be negligible compared to bare ground if managed for reduced water use. For example, in California's Central Valley, Islam et al. (2006) found that winter cover cropping in the fallow months of a tomato-cotton rotation (November through March) increased actual evapotranspiration by ~1.2 inches. More recent research reported the difference in seasonal cumulative ET between winter cover cropped and bare ground fields was negligible in both the Sacramento (~0.12 in., Davis, CA) and San Joaquin Valleys (~0.71 in., Five Points, CA) (DeVincentis et al. 2022).

As we gather more data, it will be possible to refine our understanding of the contexts in which cover crop ET will be likely minimized. The above examples suggest that the impact of cover crops on ET is similar or less than the effect of other factors (weather, soil, timing of establishment and termination, irrigation management, etc.) which suggests that they can be managed in a way to maximize benefits and minimize water costs.

Runoff

Runoff, the lateral flow of water across the soil surface, is one mechanism by which water can be lost from a parcel. Several key factors may increase runoff including slope gradient and precipitation amount and intensity. Additionally, the condition of the soil and vegetative surface, and therefore whether a site is cover cropped, may have a prominent role in determining wintertime runoff. During intense storms, cover crop vegetation reduces and dissipates the impacting energy of rain droplets on soil particles and forms a physical barrier slowing the velocity of overland water flows. Surprisingly this holds true across a range of field slopes in California agriculture.

For example, rainfall runoff was reduced by 40-75% in non-sloped fall-planted cover cropped tomato beds compared to the conventional, fallow-bed system in the Sacramento Valley (0.2% slope; Miyao and Robbins, 2000). Cumulative event runoff was significantly reduced in cover crop treatments compared to the winter fallow of mild-sloping tomato/safflower/corn/bean rotation beds in Yolo County (Joyce et al., 2002). In this same study, the differences between treatments are greatest when initial soil water contents are high. Cover crops also reduced runoff from winter storm events in a Yolo County tomato-oat production system, with total discharge reduced by 44% (1-1.5% slope; Smukler et al., 2012). On the higher end, runoff reductions of up to 87% were correlated with area of cover crop coverage on sloped hillside vineyards in Napa, California (5-15% slope; Battany and Grismer, 2000). Cover crops also reduced runoff by 60% in Mediterranean potato production (5-7% slope; Eshel et al., 2015) and by up to 80% relative to bare ground in a nearly level (2-3% slope) Mediterranean vineyard (Celette et al., 2008). Meanwhile, introducing cover crops to vineyards and olive groves in Europe reduced runoff when soil permeability was sufficiently high (Gómez et al., 2011).

Runoff Summary

For California, evidence indicates that cover crops can reduce runoff by at least 40% even in laser-leveled agricultural fields, depending on localized conditions and precipitation (Miyao and Robbins, 2000; Joyce et al., 2002; Smukler et al., 2012). Even greater reductions (upwards of 80%) are observed as slope gradients increase (Battany and Grismer, 2000). The reduction in runoff is especially important in light of the increasing intensity of precipitation events in California and the spectrum of slopes and topographies where crops are grown.

PARCEL-LEVEL INFLOWS

Inflows are processes by which water enters a parcel or basin, and include water from precipitation and surface water, and its subsequent infiltration.

Infiltration

Infiltration, the passage of water from the surface into the soil profile, is key for the capture and storage of rainwater and the efficient utilization of irrigation water. The rate of infiltration determines the proportion of water entering the soil, or lost via runoff and evaporation from surface ponding. Cover crops have been shown to significantly increase rates of water infiltration into soils via several mechanisms. Cover crops protect the soil surface from the dispersive forces of wind and water that otherwise result in increased runoff due to lowered soil surface strength and increased soil crusting. Likewise, the growth and subsequent decay of roots increases soil macropores and porosity. Over many years of continued implementation, plant biomass and exudates can increase soil organic matter (Peng et al., 2023), often resulting in changes to soil structure with positive impacts on infiltration rates. Cover crop benefits to infiltration rates are particularly important for maximizing water capture during intense rainfall events, when water is more likely to runoff soil surfaces. Additionally, cover crops may ensure more even infiltration across a parcel, avoiding the zones of ponding and runoff leading to increased variability in soil moisture.

In California, studies have noted such improvements to infiltration rates with the use of cover crops. Cover crops were observed to increase infiltration rates of water in a Central Valley almond orchard by a range of 37% - 147% after 5 years of implementation (Folorunso et al., 1992). In California's Southern San Joaquin Valley (Five Points), the impact was even greater; 15 years of consecutive use of cover crops in a tomato-cotton rotation resulted in a rate of water infiltration by 2.8 times compared to bare ground (Mitchell et al., 2017). Similarly, a study in Davis, CA found that infiltration rates were, on average, 2 times higher in a winter cover cropped tomato-corn-wheat-bean rotation than bare fallow soils in a 10-year trial (Colla et al., 2000). Cover crops also enhanced the ability of soils to transport water downward within the soil profile, resulting from increases in saturated hydraulic conductivity in a Mediterranean apricot orchard (Demir et al., 2019). One global meta-analysis observed that cover crops increased mean infiltration by over 76% and saturated hydraulic conductivity by 106% relative to non-cover cropped sites (Hao et al., 2023).

Infiltration Summary

Cover crops have been observed to substantially increase water infiltration into soils and these improvements occurred across a range of contexts and field slopes. For example, infiltration rates of cover cropped fields were 2.2 and 2.8 times higher than bare ground in the Sacramento and Southern San Joaquin Valleys, respectively (Colla et al., 2000; Mitchell et al., 2017). Given the available data, we conservatively estimate that cover crops increase infiltration by at least 40%. In California's climate future of increasing precipitation variability and intensity, improved infiltration becomes even more important: moving intercepted water belowground for future use can reduce runoff and topsoil erosion.

Fog and Dew Capture

Fog, water droplets suspended in the air, and dew, water droplets condensed on cooled surfaces, represent potentially significant water inputs in water scarce environments (Kaseke et al., 2017). Potential benefits to plants include the capture and subsequent drip of water droplets to the soil surface increasing soil moisture, decreasing transpiration rates, and increasing water use efficiency (Baguskas et al., 2018). Ground cover conditions, including the presence of cover crops, may influence the frequency and magnitude of fog and dew capture. One possible mechanism for the hypothesized increase in dewfall with cover cropping is that cover crops can lower minimum nighttime temperatures close to the soil (0.90 - 2.20˚F in citrus orchards; O'Connell and Snyder, 1999), thereby increasing relative humidity. This same phenomenon has been implicated for cover crops increasing frost risks in orchard systems, though such dynamics are thought to be shifting with climate change.

Although numerous growers and researchers attest that cover crops increase water captured from dew and fog resulting in increased soil moisture, the process is not well documented in California's agricultural regions. Even more importantly, the source of this water (i.e., whether it represents a significant external input or recycling of water within the system), its eventual fate (evaporation or capture by plants or soil), and future trends with climate change are not well understood.

The relative importance of fog and dew will likely vary by agricultural region. The occurrence of winter fog across the Central Valley, though highly variable, has significantly decreased over time through the 32 year span of 1981-2014 (Baldocchi and Waller, 2014). By contrast, California's coastal regions experience significant fog (Baguskas et al., 2018). In either case, when fog occurs, the potential sums of water are not insignificant.

Studies in geographies similar to California's Central Valley found dew contributions to be 0.65 - 2.70 inches per year (Aguirre-Gutierrez et al., 2019). A total of 0.51 inches of water accumulated as dew between February and June (or 12% of precipitation during the same period) in a dry valley shrubland in Spain (Moro et al., 2007). In contrast, other research suggests that in Mediterranean environments, dew's primary impact may be to increase crop water use efficiency rather than provide an additional source of water (Ben-Asher et al., 2010). Thus, there is potential for cover crops to improve dew formation and increase water availability, but more research is needed to understand its contributions to on-farm water dynamics.

Fog and Dew Capture Summary

Growers and researchers have experienced comparatively high levels of dew and fog capture in cover crops. These experiences led to an examination of these processes as a potential precipitative input impacted by cover cropping. While this review found no experimental data cataloging increased fog capture or dewfall water volumes in California, past research showed that even in the San Joaquin Valley, dewfall occurred on nearly a quarter of days (Scherm and Van Bruggen, 1993), though its occurrence has decreased significantly over time (Baldocchi and Waller, 2014). In similarly dry climates (e.g., Jalisco, Mexico), 0.65 - 2.7 inches of dew accumulated per year (Aguirre-Gutierrez et al., 2019). There is thus potential for cover cropping to increase the amount of water deposited through these processes, but more research is needed to understand their contributions to on-farm water dynamics. Specifically, the remaining questions concern the impact of cover cropping on dew and fog capture in California and whether any increase in capture represents a measurable input into the system relevant to water management.

STORAGE

Storage refers to water held within the soil of a given parcel or potentially drained to groundwater. Cover crop impacts on water storage-related processes are difficult to measure, but have the potential to offset crop water demand and thus reduce the amount of applied water (surface and groundwater) required by growers. As more water is stored in the soil from precipitation, it is possible that, especially with winter precipitation, the irrigation needs for cash crops could be reduced or delayed. At the very least, it is likely that a larger percentage of water will be productively transpired by cash or cover crops, rather than evaporated directly from soil surfaces or percolated out of the root zone.

Soil Water Holding Capacity

Soil water holding capacity refers to the maximum amount of water that can be held in a given soil. Cover cropping elicits soil changes that are beneficial to both infiltration and soil water holding capacity, such as increasing organic matter content, porosity, pore size distribution, soil aggregation, and aggregate stability (e.g. Araya et al., 2022; Koudahe et al., 2022). A global meta-analysis of 27 studies showed that continuous “living cover” can increase soil porosity by 8% and water held at field capacity by 9%, suggesting better ability to hold water in place where it falls (Basche & DeLonge, 2017).

Plant available water holding capacity (AWHC) is thought to vary with the commonly measured soil metric soil organic carbon (SOC) such that increases in SOC correspond to increases in AWHC (Bagnall et al., 2022). Notably, cover crops in Mediterranean climates have been thought to enhance organic matter in orchards with fine textured (Demir et al, 2019; Zumkeller et al., 2022) and loam soil (Ramos et al., 2010), while observations vary for coarse soil textures (Ball et al., 2020; Zumkeller et al., 2022). Global and national meta-analyses suggest a 8-15% net increase in total soil organic carbon attributed to cover crops (Hao et al., 2023; Jian et al., 2020; Peng et al., 2023). However, the extent to which cover crops may enhance such properties may depend upon cover crop species and mixture selection, the duration of practice implementation, the total amount of biomass produced, and environmental conditions (Blanco-Canqui et al., 2011; Blanco-Canqui & Jasa, 2019; Darapuneni et al., 2021). At the same time, studies have noted the overestimation of cover crop contributions to SOC stocks (Chaplot and Smith, 2023). Moreover, increases in soil organic carbon with cover crops may be limited to the upper soil layers, as was observed in a wheat-tomato rotation located in California's Sacramento Valley (30 cm, Tautges et al., 2019).

Uncertainties still exist on aspects such as the time extent of practicing winter cover cropping that is necessary for enhancing soil hydraulic parameters, such as soil water holding capacity, and the soil depths at which such enhancements occur.

Soil Water Holding Capacity Summary

Cover crops have the potential to increase soil water holding capacity — the total amount of water that can be stored in the soil — by improving the relevant soil characteristics of porosity, aggregation, and aggregate stability or by improving soil organic carbon, which is highly correlated with plant available water holding capacity (Bagnall et al., 2021). However, research in California is limited and tends to yield less impressive improvements than in wetter climates. Important questions remain regarding the magnitude of benefit in California and the timescales over which benefits can be achieved.

Soil Moisture

Soil moisture is the amount of water in the soil at a particular time. Cover crops can impact soil water in two distinct ways: directly drawing water out of the soil profile through transpiration, and indirectly by increasing soil water holding capacity and infiltration. Therefore, the impact of cover crops on this variable will be optimized under conditions with more, and more intense, precipitation and lower cover crop transpiration.

In one of the first investigations of cover crop impacts to soil water storage in California, Mitchell et al. (2015), showed that cover crops reduced net soil water relative to fallowed land by ~2 inches at a San Joaquin Valley site during periods of prolonged drought. But recent results from a 20-year trial in the San Joaquin Valley (Five Points) strengthen the evidence that winter cover crops can support soil health in drought-prone regions without negative impacts on soil moisture (Gomes et al., 2023). In certain situations, cover crops might reduce the soil moisture during their growth period, but increase moisture after termination due to the mulching effect of residue, allowing cash crops access to more overall water despite the water use (Paye et al., 2022a; Rodriguez-Ramos, 2022). A study in irrigated semi-arid Texas cotton production supports this finding that cover crops reduced soil moisture immediately prior to spring cotton planting, but after termination of the cover crop, season-wide average soil moisture was greater (J. Burke et al., 2022). More research is needed to understand what factors (such as soils, climate, and management) have the largest effect on soil water storage with cover crops, and if increased soil water storage leads to a reduction of applied water.

Soil Moisture Summary

Cover crops have the potential to increase overall soil water storage, even in cases where soil moisture is depleted leading up to termination. Mitchell et al. (2015) found that in the San Joaquin Valley during a prolonged drought period, cover cropping reduced soil water storage by between 0.25 - 2.10 inches as compared to bare ground. However, at the same location (Five Points), Gomes et al. (2023) found the reduction in soil moisture to be negligible. Post-termination mulching by cover crops is likely to increase this benefit. More research is needed to understand what factors (such as soils, climate, and management) have the largest effect on soil water storage with cover crops, and if increased soil water storage leads to a reduction of applied water.

Percolation

Percolation, sometimes called drainage, is the movement of water from the root zone into the underlying deeper soil layers. Percolation generally begins as a field's root zone exceeds its water-holding capacity, at which point any additional water added to the system either percolates or runs off, with water movement dictated by soil porosity, structure, and water content (Acevedo et al., 2022). Beyond the root zone, tracing the movement of water becomes increasingly difficult, and the pathways to aquifers depend upon the deep soil and rock layers beneath. As cover crops do not influence this deeper movement, it is difficult to draw connections between cover cropping and water movement into aquifers beyond their ability to increase the volume of water entering the soil profile and the soil water holding capacity.

While we are unaware of California-specific research linking cover crops to deep percolation, a meta-analysis of 28 temperate region studies found that cover cropping reduced percolation by an average of 1.06 inches compared to bare-fallow (Meyer et al., 2019). However the range spanned from reducing percolation by 4.33 inches to increasing percolation by 1.57 inches with no clear drivers of the variation. This is likely due to the fact that cover cropping increases the capture of water into the soil (infiltration), uses some of this water, and could also increase soil water holding capacity (less likely in California). These processes are opposing in terms of their effects on percolation. Therefore the primary impact of cover crops on percolation depends upon the balance of impacts to infiltration and water storage, cover crop water use, and the amount of water available. Future research on cover crop water benefits for percolation should focus on the impacts to infiltration and management for reduced cover crop water use.

Percolation Summary

Studies examining the effect of cover crops on percolation, the movement of water below the root zone into deeper soils, are limited. More research examining cover crop impacts on percolation in California's agricultural context may be helpful, especially for areas where there is hydrologic connectivity between soils and aquifers. That being said, the processes around infiltration and soil water holding capacity as well as cover crop water use are key in percolation outcomes related to cover cropping and thus more relevant to water management.

WATER QUALITY

There are numerous benefits provided by cover cropping that can support SGMA's requirements to avoid "undesirable results," especially around water quality. For the purposes of this section, we examine cover crop impacts on both ground- and surface-water quality.

Nutrient Scavenging For Water Quality

Winter cover crops have the potential to reduce nitrate leaching to groundwater during periods of fallowing or cash crop dormancy. High amounts of residual nitrogen can remain in the soil after the growing season as nitrogen fertilizer use efficiencies, defined as the ratio of nutrients removed to nutrients applied, hover around 50% for many cropping systems (Tomich et al., 2016). This residual nitrogen is susceptible to leaching below the rootzone and to groundwater in the winter when fields are fallow and California typically receives the majority of its rainfall.

Non-leguminous cover crops planted in the fall can immobilize nitrate during the winter when the highest risk for leaching occurs (Brennan et al., 2017; Gabriel et al., 2014; Abdalla et al., 2019; Thapa et al., 2018). In California vegetable production systems, Wyland (1996) found that having a non-leguminous cover crop reduced nitrate leaching by 65-70% compared to bare ground fallow. In a meta-analysis of Mediterranean agroecosystems, non-leguminous cover crops decreased nitrate leaching by 53% compared to bare-fallow (Shackelford et al., 2019).

Because the uptake of nitrate is tied to plant maturation and biomass accrual, the duration of cover crop growing period influences the efficacy of nitrate scavenging. Heinrich et al. (2014) found that early termination (after 8-9 weeks of growth) is less consistently effective at nitrate scavenging compared to full-season cover cropping. Growing a winter cover crop to "full term", (i.e. 3 months, with a C:N ratio of >20) as has been recommended in regulatory frameworks in California's Central Coast, may help maximize nitrogen scavenging benefits. However, more research is needed on the effect of planting and termination timing, and termination method (i.e. mowing, incorporation, etc.) on nitrogen dynamics and long-term fate of nitrate in California's diverse soils.

Water Quality Benefits Summary

The implementation of cover crops has significant potential impacts on water quality — an important consideration for management under SGMA. The two levers by which cover crops most directly affect water quality are through nutrient scavenging and erosion control. Nutrient scavenging is most important in relation to the fallow period of farmed fields or when high N residues remain in fields, when appropriately selected cover crops can help reduce nitrate leaching by more than 50% in California (Wyland et al., 1996) and other Mediterranean climates (Shackelford et al., 2019). More research is needed to optimize termination timing for nitrate scavenging with water use outcomes. Moreover, erosion prevention may help maintain surface water quality by reducing the amount of sediment and residual agricultural chemicals that enter surface waters. In California, winter cover crops provide a protective soil cover during the wintertime, when topsoils are most prone to erosion by both wind and water (Ayres et al., 2022). Further research is required to clarify the magnitude of these benefits in California's Central Valley.

Erosion Control

Erosion is the transport of soils by water and wind, with significant implications for surface water and air quality. Eroded soil may contain nutrients and other pollutants, which can further deteriorate local systems. Cover crops have long been described as a crop grown to prevent soil erosion (Pieters and McKee, 1938). Generally speaking, cover crops physically shield the soil surface, hold soils in place with their roots, slow water velocities, and support soil aggregate formation, which acts to greatly reduce erosion and associated soil and agricultural chemical losses by both wind and water (Frye et al., 1985; Langdale et al., 1991). Their utility in erosion control in North American cropping systems has been well documented (Sarrantonio and Gallandt, 2003) across a range of crops and climates (Mutchler and McDowell, 1990; Holderbaum et al., 1990; Decker et al., 1994; Dabney, 1998; Delgado et al., 1999).

In California, winter cover crops provide a protective soil cover between periods of regular crop production (i.e. late fall through early spring) when topsoils are most susceptible to erosion by both wind and water (Ayres et al., 2022). However, their effectiveness in erosion reduction depends on the timing of cover cropping, the amount of residue left behind, and the coupling of other practices (e.g. reduced tillage). An analysis of 8,000 runoff-plot years from 21 states, primarily in the Eastern US and the Great Plains, concluded that cover crops, seeded before cash crop harvest and terminated the following spring, were an effective erosion control during both winter months and the subsequent cash crop cycles in corn and cotton rotations (Langdale et al. 1991).

MANAGEMENT FACTORS THAT CONTROL COVER CROP – WATER INTERACTIONS

Cover crop management strategies — species selection, timing of establishment and termination, seeding densities, germination strategies, the duration of practice implementation, and whether the residues are left on the surface or incorporated into the soil — significantly impact the magnitude of the previously discussed water use and water benefits. While much research remains to be done on how the impact of cover crop management varies with soil, climate, and other cropping system characteristics (Bodner et al., 2007; DeVincentis et al., 2022), there are several ways that growers can manage for maximal water benefits.

Cover Crop Species

Cover crop species selection depends on grower goals (e.g., increasing pollinator habitat, decreasing pest populations, soil health, etc.), but has important implications for water use and water benefits. Common California cover crop species differ in their water efficiencies and temperature and moisture tolerances (Bullard, 2019; Smither-Kopperl and Borum., 2015). Species differences in root structure (tap root vs fine roots) may determine impacts to infiltration, erosion control, drought tolerance, and access to water (Williams and Weil, 2004; De Baets, et al., 2011; Zhao et al., 2017). Non-legumes are more effective nitrogen scavengers, an important consideration for growers wanting to reduce their risk of leaching nitrates to groundwater (Meisinger et al., 1991).

It is common practice for growers to plant mixtures of species as a winter cover crop to meet multiple objectives, and while research on single species is reported above, it has been observed that the water use of mixtures is similar to that of single species (Nielsen et al., 2015). While more research is needed to characterize cover crop species-specific water demand, growers can minimize their water use by planting drought tolerant varieties and species that are adapted to the region.

Establishment

A successful winter cover crop requires adequate moisture and suitable soil temperatures at planting time, which typically occur in the fall (September through November) in California (Ingels, 1998; Grant et al., 2006; Wauters et al., 2022). Cover crop establishment is generally not considered to require significant water — less than 2 inches is enough to germinate a cover crop (Smither-Kopperl, 2016). However, the method of cover crop planting and timing of winter precipitation will determine if and how supplemental irrigation is used for establishment and growth (Brennan and Boyd, 2012; Mitchell et al., 2015; Mitchell et al., 2022). A strategy employed by orchard growers includes planting a cover crop prior to dormant season water applications including post-harvest irrigation, before the onset of winter rains, prior to fall and winter water applications aimed at leaching salts; or prior to recharge activities (Wauters et al., 2022; Grant et al., 2006). In some cases, irrigating a cover crop is often not possible due to lack of available water and the types of more efficient targeted irrigation systems (drip, micro-sprinklers, etc.) that may not reach orchard alley ways.

Termination Timing

The timing of the termination is one of the most critical factors in determining net water impacts of cover crops. Cover crop termination dates have a significant impact on soil water balance and ET — an early spring termination date can significantly reduce water use compared to a late spring termination date, when temperatures become warmer and evapotranspiration rates are higher. For example, Islam and others (2006) estimated that water loss through ET could be reduced by upwards of 31% if cover crops were terminated one month prior to senescence. However, cover crops can use minimal water over the season if terminated promptly before depleting soil moisture, because bare soil also loses water over the winter (Smither–Kopperl and Borum, 2016; De Vincentis 2022). A study from a semiarid Mediterranean site in Spain found that for annual rotations, early cover crop termination can preserve soil moisture from precipitation while later termination date may lead to more soil water depletion (Alonso-Ayuso et al., 2014). In New Mexico, up to 80% of wintertime cover crop water use occurred in the spring (late March - April), highlighting the importance of early termination, especially in dry years (Paye et al., 2022a; 2022b). However, by optimizing cover crop termination — terminating late enough to achieve desired benefits (i.e., pollination, nitrate scavenging, etc.) but early enough to reduce water use and competition with the cash crop for water – the trade-off between cover crop benefits and water use can be minimized (e.g. Kaye and Quemada, 2017).

Residue Retention

Methods for terminating cover crops include mechanical (tillage, mowing, crimping), chemical (herbicide), and biological (livestock grazing). Each of these termination methods, as well as residue management strategies — whether residues are incorporated into soils or left on the surface, can have different impacts on water balance. There can be significant differences in water dynamics when cover crop residues are left on the surface as mulch or if they are integrated into soils (Mitchell et al., 2022).

Management Impacts on Water Summary

Cover crop management strategies play a pivotal role in their impact on water budgets. Species selection is pivotal and must be tailored to management goals. Choices around the seeding and irrigation of cover crops are also pivotal, especially in regards to the timing of planting and the integration with existing irrigation systems. Finally, timing and method of termination, and the fate of residues, can have large impacts on cover crop water use, with late termination significantly increasing water use. Ultimately, these findings point to the need for refined grower guidance (similar to Wauters et al., 2022), especially to meet water use management targets for cropping systems in the Central Valley.

Stacked Management Practices

One burgeoning area of interest is the potential to combine cover cropping with other soil health promoting agricultural practices (e.g. reduced tillage, compost application, grazing). This can increase cover crops' potential water cycle benefits or support complementary or synergistic practices that yield multiple benefits.

Compost application, the process of incorporating decomposed organic matter into soils to improve soil physical, chemical, and biological parameters, is often combined with cover cropping, and the following studies highlight its impacts on water. A long-term study from a Sacramento Valley maize-tomato rotation demonstrated that a long term (19 years) practice of cover cropping, in combination with compost addition, led to greater microbial biomass and aggregate stability and increased infiltration rates compared to conventionally managed plots (Tautges et al., 2019). While cover cropping alone led to increases in surface SOM, losses were documented at depth in this same study. A meta-analysis of Mediterranean cropping systems found compost (applied both alone and in conjunction with cover crops) produced the largest increases in SOC of any other practice examined (e.g. slurry application, cover crop, no-till, conventional) (Aguilera et al., 2013).

Adoption of reduced tillage with cover crops has been shown to further improve infiltration rates, soil aggregation, and increase soil water-holding capacity (Mitchell et al., 2017; Li et al., 2019). In a 20-year trial, reduced tillage intensity combined with cover crops led to significantly greater soil moisture content compared to cover cropping with standard tillage, while both treatments had greater soil moisture than standard tillage without cover crops (Gomes et al., 2023). High residue preservation coupled with no tillage could reduce evaporation relative to bare soil by as much as 4 inches during the summer season (Mitchell et al., 2012b).

Grazing is a third practice often stacked with cover cropping with benefits for soil organic matter and fertility, and cover crop biomass control. In a dryland grazing system in Colorado, grazing did not affect the water use of cover cropping, nor did the inclusion of animals increase soil bulk density through soil compaction (Kelly et al., 2021). Inclusion of grazing also does not impact the reduction of runoff that can come with planting cover crops (Mubvumba et al., 2023). Grazing cover crops can have variable impacts on soil water content (Peterson et al., 2019; Brewer et al., 2023).

Stacked Management Practices Summary

The implementation of cover cropping is often combined with other soil health oriented agricultural practices such as compost application, reduced tillage, and livestock integration/grazing. In combination, these practices can actually increase the net water benefits of cover cropping. For example, cover cropping alongside reduced tillage increases total soil moisture (Gomes et al., 2023) and alongside compost can actually generate the largest increase in soil organic carbon (Aguilera et al., 2013). Even when these combinations do not directly boost the water impacts of cover cropping, they can act in complementary ways that increase total benefit. While livestock grazing in combination with cover crops can impact soil moisture dynamics, well-managed grazing is unlikely to negatively impact the other water-related benefits of cover cropping.

NET WATER IMPACTS AND RELEVANT ONGOING RESEARCH

There is currently relatively little published research dealing directly with the topic of the net impacts of cover crops on water usage, especially in California. One of the few studies that has so far probed this question in California finds that winter cover crops may break even in terms of their net water impacts (DeVincentis et al., 2022). An exploratory model simulation found similar results for dryland winter wheat relative to a bare fallow (Peterson et al., 2022). With the water supply pressures brought about by the implementation of SGMA, prolonged drought conditions, and the information needs of growers, among other stressors, this is an area of active and ongoing research. There are several ongoing studies attempting to address this question directly, in addition to answering research questions aimed at individual water budget components. In fact, there are at least 12 such research projects being undertaken in California, which are detailed in a table in Appendix B and described in the following paragraphs.

Ongoing Research from the Convening Community

There are many important research initiatives being led by convening participants and the broader network of researchers which are currently underway. The total funding for these projects is more than $6 million, with a majority of project funds coming from public sources, including state (CDFA) and federal (USDA) agencies. Several projects are sponsored through private funds which come primarily from crop commodity boards for rice, almond, and pistachio.

A majority (two-thirds) of the projects are being conducted in perennial crop systems in the San Joaquin Valley, with over half of the funds specifically directed at cover cropping in almond orchards in that region. Although these projects likely represent a subset of the California-based research being conducted on how cover crops impact water budgets, these trends in their scope and financing provide a useful description of the current research environment. Compared to federal or state budgets for similar branches of research (e.g. the $15 Billion California climate package), and taking into account the importance of this topic, $6 million is a relatively small aggregate sum.

Emerging Findings

While detailed results from these projects are not yet available, preliminary findings (see Appendix B) support the idea that cover crops may represent a net positive (or at least an insignificant net negative) to the water balance of a parcel under a certain range of conditions (Suvocarev and others, in prep). Other studies have found that in winters with greater than average precipitation, ET may be on the order of 15-20% greater than bare ground (Roby and others, in progress). In the San Joaquin Valley, cover crop type (and associated properties) are likely to determine the soil-plant-water dynamics and are therefore an important area of future research to determine the optimal species for certain contexts. In almond orchards in the San Joaquin Valley, it is likely that management which combines cover crops and grazing does not increase ET compared to bare soil orchards and can significantly increase infiltration, especially during winter precipitation events (Suvocarev and others, in preparation). In pistachio orchards in both the San Joaquin and Sacramento Valleys, winter cover cropping in an above average precipitation year increased spring ET, net carbon assimilation by trees, and albedo for the shortwave radiation (both PAR and NIR components) relative to orchards with clean-cultivated ground (Zaccaria and others, in preparation). If these impacts result in increased nut yield and in better nut quality (larger nuts), cover crops may increase an orchard's physical and economic water productivity. A cover crop treatment in a table grape vineyard in lower San Joaquin Valley (Parlier, CA) enhanced vine-row soil moisture through summer months when serving as a mulch (Fernando et al., 2024).

Notable Upcoming Work

In addition to these in-progress efforts, there are projects on the horizon whose results will be particularly meaningful in the context of SGMA compliance. One project led by UC Davis scientists will appraise uncertainties and errors of actual ET estimated with satellite remote sensing methods for micro-irrigated orchards and vineyards grown with cover crops versus clean-cultivated floors (Zaccaria and others, in progress). Another study being conducted by researchers at the Public Policy Institute of California will estimate net water balances for water limited annual cropping systems in the San Joaquin Valley (Peterson and others, in progress). The work will focus on small grains (e.g. wheat, triticale, barley).

Table 1.

		← Confidence Level Based on Availability of Research → Low		High
Water Budget	Inflow	Increased Fog and Dew Capture		Increased Infiltration
	Storage	Increased Percolation	Increased Soil Moisture and Water Storage	
	Outflow		Increased Evapotranspiration (ET)	Decreased Runoff
Water Quality Benefits			Increased Nutrient Scavenging	Decreased Erosion
Management factors determining net water impacts of cover crops			Species Selection	Termination Timing
			Seeding Rate	
			Stacked Practices	

Table 1: Confidence in potential cover crop impacts to water budgets. Based on available, contextually relevant information, we have higher confidence that cover crops increase infiltration, decrease runoff and erosion and that water use is affected by termination timing. Factors such as the impacts on ET (and the drivers of those impacts) are less understood. Our recommendations aim to capture these influences, and create the space for these practices while the other potential benefits are better understood.

2.2. KEY SCIENCE TAKEAWAYS

Disentangling the net-water impacts of cover crops is difficult because processes are nuanced, context-dependent, and an area of active research. Winter cover cropping can be implemented in many different ways and specific water impacts may depend on species, how the cover crop is managed, the cash crop system, and environmental conditions.

There is a significant need for water-related gaps to be filled, specifically quantifying the net impact of cover crops on water budgets (the balance of water use and water-related benefits) in a diversity of California's cropping systems and environmental contexts. Moreover, there is a need to identify the management practices that are most likely to achieve cover crop water benefits while minimizing their water use.

However, based on current available research, we conservatively estimate that the water benefits likely to be realized for California growers include increased infiltration (often ≥40%) and reduced runoff (often ≥40%) relative to bare ground management. In years with increased precipitation, this benefit is likely to be greater. Although research is still ongoing around Central Valley cover crop water use, existing research suggests winter cover crop water use can be negligible compared to bare ground. This is, in part, due to the high rates of evaporation from bare ground management. Early results from additional studies suggest that winter cover crop ET is highly dependent on precipitation and the impact of cover crops on overall ET is thought to be much less than other factors (weather, climate, soil type, management).

Given the current available information, it is clear that cover crops are more likely to have net positive water impacts during years with significant and intense precipitation; in fields where soils demonstrate poor infiltration, are prone to compaction or crusting, and where fields are sloped; and when cover crops are managed for reduced water use.

3 Policy Analysis

3.1. INTRODUCTION

The following section highlights the ways in which water management under SGMA interacts with the practice of cover cropping. While GSA water management necessarily assesses cover crop water use, the methods of doing so may have implications for the future viability of the practice in the San Joaquin Valley. Here we present an analysis of specific GSA approaches to identify relevant trends and themes emerging from their implementation of demand management and their relevance to cover cropping. It is important to note that GSAs face a huge array of challenges to work through and an extremely diverse set of circumstances, resources, and capacities to meet these needs.

3.2. METHODOLOGY

In early 2023, we conducted a review of SGMA mandates, requirements, and guidance documents, shedding light on the structure of GSAs, the scope of guidance provided, and the management problems they must address. We then conducted an analysis of GSA approaches to water budgets, allocations, and consumptive use, along with explicit mention of cover crops in policies or regulations. Our analysis included nine GSAs selected using the following criteria: located in the San Joaquin Valley, availability of a completed GSP, existence of a groundwater allocation plan (final or draft), and ease of access to information about their approaches and methodologies. For each GSA, the relevant sections of the GSP and readily accessible rules and regulations were reviewed. Interviews with GSA representatives were conducted to further clarify approaches and methodologies. Additionally, we interviewed consulting firms involved in the development of GSPs to understand how broadly representative our findings were.

The findings presented here are not necessarily representative across all GSPs, but rather include trends common among this small subset of San Joaquin Valley GSAs and those in the consultants' experiences. In fact, many GSAs have yet to implement allocation planning (and in some parts of the state, they may not have to). The sample set was used to understand current approaches and glean insights that can inform future implementation as more GSAs begin developing and implementing groundwater allocations.

3.3. SUMMARY OF GSA MANAGEMENT PROCESSES

Disentangling the intricacies of the implementation of SGMA and its intersections with cover cropping first requires a detailed examination of how GSAs are implementing this legislation. GSAs are mandated to regulate the management of the water supply of their respective subbasin such that by 2040 (or 2042 for basins that are not critically overdrafted), groundwater extraction does not exceed its replenishment. To do so, they must develop a water budget, which includes a quantification of sustainable yield and overdraft. They then identify management actions they will take to address the overdraft and achieve sustainable yield. Those actions typically fall under "supply augmentation" (bringing more water into the subbasin) or "demand management" (reducing the amount of water pumped from the subbasin) (Wardle et al., 2021). While supply augmentation alone may be sufficient for some subbasins and GSAs, demand management is often needed for subbasins with high levels of groundwater overdraft. Demand management includes allocating the sustainable yield among water users and then assessing grower water use relative to that allocation. This review and assessment focuses primarily on demand management. Given that a key aspect of SGMA is local control, approaches to demand management vary across GSAs.

To guide the development of GSPs, the DWR has released a set of guidance documents and BMPs covering monitoring, modeling, water budgets, sustainable management criteria, as well as an annotated example GSP outline. These documents adhere to SGMA's guiding principle of local control, and as such they do not mandate specific methods for calculating or managing water allocations and water use. They explicitly do not require or set forth specific rules and regulations for groundwater pumping (Friberg et al., 2023). Rather, they clarify the legal mandates created by the act, such as the requirement to identify undesirable conditions, and provide frameworks for approaching these mandates.
In the absence of more specific guidance, GSAs are employing a variety of approaches but tend to follow a few similar paths to address the requirements set forth in SGMA.

Water Budgets

Water budgets are models of the water entering and leaving a GSA subbasin (inflows and outflows, respectively), as well as water stored in the basin, split by water source type and water use sector. Constructing a subbasin water budget is a prerequisite to defining sustainable yield, allocations, and consumptive use. Water budgets represent not only current, but historical and projected water flows. To ensure the ability to accurately calculate sustainable yield, GSAs determine the magnitude of water budget inflows and outflows at the subbasin scale. It's important to note that while some elements of the water budget — such as infiltration and runoff — may be considered inflows or outflows at the parcel scale (as defined in section 2.1.), they are not always considered as such at the subbasin scale.

Sustainable Yield

The sustainable yield is the amount of groundwater that may be extracted and allocated within the GSA boundary for beneficial use without causing undesirable results (e.g., lowering groundwater levels, degrading quality, etc.). According to DWR, the sustainable yield should be estimated "over a base period representative of long-term conditions in the basin and including any temporary surplus" (DWR, 2017). This "base period" can vary dramatically between GSAs and the specific range of years selected directly impacts the calculations of overdraft and sustainable yield (Hanak et al., 2020).

Groundwater Allocations

In order to move toward operation within sustainable yield, GSAs in the most critically overdrafted basins have begun establishing groundwater allocation plans. A groundwater allocation is the amount of groundwater an individual water user may consume in a given water year. Groundwater allocations are the division of the sustainable yield and subsequent assignment of portions to the individual landowners, growers, and other water users in the GSA boundary. GSAs take different approaches to allocating sustainable yield, each with their own advantages and disadvantages (see Babbitt et al., 2018). Some examples of methods include allocations based on number of acres, number of irrigated acres, or a fraction of historic pumping. Acre-based methods were used among the GSAs examined here. Many GSAs with high levels of groundwater overdraft also establish transitional allocations, which ratchet down over time, creating a period of adjustment prior to reaching the allocation necessary to achieve sustainable yield.

Consumptive Use of Groundwater

GSAs with allocations must estimate actual groundwater consumed by a water user against their groundwater allocation — this is the consumptive use of groundwater (CUgw). In other words, the consumptive use of groundwater (CUgw) is the estimate of how much groundwater a water user removes from the basin during a given time period. It is important to note that, due to the nature of available information, GSA capacity, and practicality concerns, this quantity is estimated annually based on a (limited) set of data inputs and assumptions. The following sections explore some of the data sources, assumptions, considerations, and processes that have important implications for cover cropping during the consumptive use stage of management.

Common Tools Used to Estimate Consumptive Use of Groundwater

There are two primary tools used by GSAs that provide the data needed to estimate water users' CUgw: satellite-based ET and flowmeters. Here, it is important to note that these two tools quantify two distinct metrics of water use, and neither tool directly measures CUgw.

The vast majority of GSAs have elected to use satellite-based estimates of ET as their primary data input to determine CUgw. Satellite-based ET tools estimate total consumptive use (CUTotal) of water, or all water lost from the land surface to the atmosphere. In the agricultural context, CUTotal refers to water from all sources, including groundwater, any applied surface water, and precipitation. Thus, GSAs must calculate CUgw based on CUTotal, as discussed in the following section. As precipitation increases, subsequent evaporation and transpiration of water increases as well due to the increased water availability. Therefore, satellite-based ET estimates are directly impacted by the amount of precipitation.

There are a variety of satellite-based ET tools used by GSAs, including LandIQ, OpenET, and IrriWatch, among others. LandIQ is currently the most commonly used satellite-based ET tool in the San Joaquin Valley for GSAs that have, or are in the process of developing, groundwater allocations. These tools vary in terms of their functioning, open vs. closed source, and preference among different communities. Reports around the accuracy for OpenET are available (Volk et al., 2024, Melton et al., 2022), and a white paper is forthcoming for LandIQ.

The widespread GSA preference for The widespread GSA preference for satellite-based ET tools is due to the relatively lower cost, ease of use, and streamlined data access across the entire management area. A third party provides GSAs with consumptive water use data, without requiring action on the part of the grower. Some of the commonly cited reservations around satellite-based ET estimates include variable accuracy (or margin of error) and, in some cases, 'black box' methodology. Proponents of satellite-based methods for water accounting acknowledge the margins of error, but propose that the inaccuracy or bias in the satellite-based ET data is similar in many cases to the margins of error for meters or other tools for understanding water use (Volk et al., 2024), should be relatively consistent across water users within the GSA (unlike flowmeters), and may be improved with ground truthing and calibration.

Flowmeters are installed in pipes to measure the volume of water flowing through the pipe. They can be used to measure how much water is applied to the land, including groundwater usage. There are many proponents of using flowmeter data to assess the CUgw, as there is an assumption that it is a more direct measurement. However, there are still margins of error in converting applied groundwater as measured by flow meters to CUgw, as discussed in the following section. Additionally, the monitoring and maintenance requirements and costs of this method, to both GSAs and growers, introduce other uncertainty and barriers to its widespread adoption under SGMA. These include upfront investments for installation, time and labor for recording, reporting, and maintenance, and more. Flowmeters are also known for the challenges they present in obtaining consistent measurements over a long period of time, including meter down time and user error.

While GSAs generally utilize satellite-based ET estimates as the primary input for determining consumptive use, many also incorporate flowmeter-based "dispute resolution" policies. These policies allow growers to challenge the CUgw assessments of satellite-based ET estimates, and usually require that growers supply flow meter data, calibration records, and irrigation schematics. The GSA may then convert this information into an alternative estimate for CUgw which, if lower, will be applied instead.

The California Irrigation Management Information System (CIMIS) administers approximately 150 weather stations across the state, collecting a range of readings. While different tools use different data inputs, one important source of data for many is the system of CIMIS stations and its weather and Potential ET (ETo) data. This is especially true outside of the southern San Joaquin Valley: LandIQ is more prevalent in the southern SJV and uses its own proprietary stations. CIMIS weather data is used in various GSA models and methodologies, but even more important are the CIMIS-generated ETo data. CIMIS ETo is the consumptive water use calculated for "well-watered and well-maintained" standard 12-cm tall grass surface located at each station. The ETo values are calculated with the standardized Penman-Monteith equation (ASCE-ESRI, 2005) from measurements of weather parameters (solar radiation, temperature, etc.). The ETo values can then be used to interpolate satellite-based ET estimates in between satellite overpasses. This enables satellite-based ET estimates to be made over time, rather than limited to momentary satellite passes.

However, anecdotally, these ETo measurements are not always reliable, as CIMIS stations are unequally distributed and not all stations meet the "well-watered and well-maintained" grass requirement.

Crop coefficients are ratios for individual crop species which are used to calculate ET for that crop by comparing it to the ET measured for a reference crop. Although developing specific cover crop coefficients is sometimes discussed as a necessary step to improving water use estimates of cover crops, crop coefficients are not a key part of current SGMA management approaches. They can be used in cases where growers use flowmeter data rather than satellite-based ET estimates (where these coefficients may be used to support the calculations). LandIQ does not use crop coefficients (although they do back-calculate them), and OpenET has an ensemble of models generating ET values and of these models only one of the six uses crop coefficients. It is possible that crop coefficients are more central in other ET tools, but those have not been examined here. While cover crop coefficients may not be a key input for the satellite ET tools, they could help growers and their advisors better understand and manage cover crop water use.

Converting Tool Data into Estimates of Consumptive Use of Groundwater

As noted above, the tools commonly used by GSAs don't directly generate CUgw data. Flowmeters measure applied groundwater, some of which may run off or percolate beneath the root zone. Satellite-based ET tools estimate total consumptive use (CUtotal), or the consumptive use of groundwater and other water sources. In other words, both of these data sources must undergo a series of calculations to be converted from their respective measures into CUgw.

Satellite ET measures the consumptive use of water from all sources: groundwater, surface water, and precipitation (i.e. CUtotal = CUgw + CUsw + CUprecip). Therefore, it is necessary to calculate the proportion of ET estimates attributable to CUgw. There are many simplifications and assumptions required to do so and it is from these that important implications for cover cropping arise.

As CUgw = CUtotal - CUsw - CUprecip, and CUtotal is measured by satellite ET, the values for both consumptive use of surface water and precipitation must be calculated to obtain the value of the consumptive use of groundwater. While surface water and precipitation amounts are generally available and relatively reliable, converting these amounts into the consumptive use of surface water and precipitation is much more complex. GSAs must make decisions about the proportion of surface water and precipitation they believe will be evaporated or transpired, will runoff to other areas, and will infiltrate and percolate below the root zone where it will no longer be picked up as ET. These are dynamics that are particularly impacted by the presence of cover crops.

Flowmeters measure applied groundwater, but do not measure exactly how much of the groundwater applied is consumptively used by crops versus how much evaporates or percolates back into groundwater. Therefore, these readings also act as a primary data input rather than the "final output" in assessing allocations. Applied water readings must be converted to CUgw by calculating the portion of the applied groundwater that is evapotranspired versus how much runs off or percolates back through the root zone into the groundwater supply. One method of doing this is by using a consumptive use fraction (CUF), which is the percent of total applied water that is actually consumed (i.e. expected to leave the basin through ET). Actually measuring the CUF is complicated, so it is usually approximated based on the type of irrigation system used (for instance: ~0.65 for gravity irrigation and ~0.80 for pressurized irrigation systems). This means that the use of flowmeters for calculating CUgw also rests on a series of calculations involving several rather large assumptions about the movement of water.

Whichever tool is used, the data generated needs to be converted into CUgw. These conversions include complex assumptions and methodologies, such as the consumptive use of precipitation or the fraction of applied water which doesn't runoff or percolate back into groundwater supplies. Therefore, the rigor of these assumptions and methodologies is directly tied to the accuracy of the resulting estimate of consumptive use of groundwater.

Converting Tool Data Into Consumptive Use Of Groundwater (Cugw)

For the purposes of this report, “consumptive use” refers to the amount of water from all sources that is used and ultimately leaves the subbasin. The consumptive use of groundwater (CUgw) is the portion of consumptive use coming from groundwater sources. CUgw is what GSAs deduct from groundwater allocations in a given year to assess their water use against their allocation. Neither satellite-based ET tools nor flow meters directly measure CUgw. Below are basic illustrative examples of how tool data can be converted to CUgw.

Satellite-based ET tools measure total consumptive use (CUtotal). To arrive at CUgw, GSAs can model, estimate, or make assumptions about the proportion of CUtotal that comes from other sources like precipitation and surface water.

$$\overbrace{CU_{Total}}^{\text{tool data}} = \boxed{\mathbf{CU_{GW}}} + CU_{SW} + CU_{Precip}$$

$$\boxed{\mathbf{CU_{GW}}} = \overbrace{CU_{Total}}^{\text{tool data}} - \overbrace{CU_{SW}}^{\text{assumption}} - \overbrace{CU_{Precip}}^{\text{assumption}}$$

Flow meters measure applied groundwater (AWgw). To arrive at CUgw, GSAs can make assumptions or estimates about how much of the AWgw runs off or percolates. This is often done in the form of a Consumptive Use Fraction (CUF), or an estimated percent of total AWgw that is available for plant use.

$$\overbrace{AW_{GW}}^{\text{tool data}} = \boxed{\mathbf{CU_{GW}}} + Runoff_{GW} + Perc_{GW}$$

$$\boxed{\mathbf{CU_{GW}}} = \overbrace{AW_{GW}}^{\text{tool data}} - \overbrace{Runoff_{GW}}^{\text{assumption}} - \overbrace{Perc_{GW}}^{\text{assumption}}$$

$$\boxed{\mathbf{CU_{GW}}} = \overbrace{AW_{GW}}^{\text{tool data}} * \overbrace{CUF}^{\text{assumption}}$$

Figure 2: Converting Tool Data into CUgw - a review of the basic components of CUgw and areas where assumptions are made to represent complex, context-dependent processes.

The Incorporation of Precipitation

Precipitation is a critical process in the movement of water within a basin. GSAs must incorporate precipitation into many of their management processes, from water budgets to consumptive use, but the approaches to doing so are varied and consequential. Additionally, the approaches can be difficult to evaluate, as the underlying methodologies and assumptions often are not easily accessible in public documents.

Precipitation must first be incorporated in the water budget, as it is a key inflow into a basin. GSAs use historical annual precipitation totals to calculate an average annual precipitation, establishing how much water to expect from this inflow. However, there is variation among GSAs in the historical period used in calculations and how future projected changes in climate are accounted for. In California's variable climate, the range of years selected can have a large impact on the final historical average annual precipitation value (Hanak et al., 2020). Another area where variation arises is in how GSAs incorporate this process into their water budgets; for instance, determining the proportion of precipitation that remains in the basin instead of running off or leaving as ET. GSAs typically use a relatively simple assumption such as a fixed percentage of precipitation broadly or sometimes more locally based on soil type. How they incorporate precipitation into their water budgets is important, because these budgets are the foundation for the calculation of sustainable yield and allocations. The following examines different approaches for addressing precipitation in allocations.

In addition to their water budgets, most GSAs also incorporate precipitation into their allocation and consumptive use approaches. This is particularly prevalent with GSAs that are using satellite-based ET estimates, as these estimates are capturing ET from all sources, including precipitation. In these allocation plans, there are some key decision points that drive the variation between GSAs: 1) what "base" precipitation they will use for their allocation, 2) what fraction of that "base" precipitation goes into the allocation, 3) how that fraction is incorporated into the allocation, 4) how that allocation will be drawn down in a given year, and 5) if and how an allocation with an average "base" precipitation will be adjusted to actual precipitation. A brief explanation of each decision point is described here, followed by examples in Table 2.

1. What "base" precipitation a GSA will use in the allocation

There are two main approaches here: use the actual precipitation data, or use a historical average. This decision has important implications for subsequent decisions on how to account for and incorporate precipitation in a given year, as discussed below.

2. What fraction of the "base" precipitation goes into the allocation

Not all of the water that falls on a parcel will necessarily evaporate or transpire off that same parcel — it could run off to another parcel or percolate below the root zone. Determining this adjustment is an area where many assumptions and simplifications are made. GSAs often assume a fixed percentage, despite the fact that the amount of precipitation likely to leave a parcel through ET is based on many factors (e.g. soil surface condition, surface cover, precipitation intensity, soil health, soil type, and more). This is an area where the diverse characteristics of precipitation, land surfaces, and land management that influence the fate of precipitation are not taken into account.

3. How that fraction of the base precipitation is incorporated into the allocation

Some GSAs incorporate precipitation as part of the total allocation and others include it as a separate "bucket" (category) of the allocation, along with other "buckets," such as transitional allocations. Other GSAs do not include precipitation in their allocation but address it in the decision point that follows.

4. How the allocation will be drawn down in a given year to reflect consumptive use

GSAs that have included precipitation within one overall allocation commonly draw down the allocation using total consumptive use (CUtotal), or the satellite-based ET estimate. GSAs that have established separate "buckets" commonly identify a priority order of those buckets and draw down the buckets in that order. GSAs that have not included precipitation in their allocations can decide to subtract out the CUprecip from the CUtotal generated by satellite-based ET estimates and use this modified CU estimate to draw down the allocation. This process can be complicated by the fact that data is not available until after precipitation has fallen (usually at least a month later).

5. If and how an allocation process using average precipitation will be adjusted to incorporate actual precipitation

GSAs using average "base" precipitation to set the allocation can decide not to adjust the allocations based on actual precipitation. GSAs that decide to adjust the allocations have several options, depending on the decisions made above. One option is to incorporate the actual precipitation as the data comes in or at year's end, adjusting the allocation up or down with a "credit" to reflect the difference between the average precipitation and the actual amount that fell. Another approach, in those allocations using different allocation "buckets," is to stop drawing down any additional CUprecip once the precipitation "bucket" is empty. GSAs adjusting based on actual precipitation face the same challenges related to delayed timing of precipitation data.

Table 2. Example Approaches for Incorporating Precipitation into Allocations

Decision Point	Example 1 (a, b)	Example 2 (a, b)	Example 3
1. What "base" precipitation will be used for their allocation?	Average annual precipitation.	Average annual precipitation.	Actual precipitation.
2. What fraction of "base" precipitation goes into the allocation?	Fixed percentage is applied across all parcels.	Fixed percentage is applied across all parcels.	None
3. How is the fraction incorporated into the allocation?	Precipitation is embedded within total allocation.	Precipitation has its own allocation "bucket," separate from groundwater allocation "bucket."	Precipitation is not included in allocation. Allocation is for groundwater only.
4. How is the allocation drawn down in a given year?	CUtotal is applied against total allocation.	CUtotal is applied against the "buckets" in a specific order, precipitation "bucket" first.	CUprecip is removed from CUtotal and only CUgw is applied against the groundwater allocation.
5. What adjustments are made to account for the difference between average and actual precipitation?	(a) None ----------------------------------- (b) Use a "credit" to increase or decrease allocation, based on actual precipitation.	(a) None. Begin drawing down groundwater "bucket" once precipitation "bucket" is empty. ----------------------------------- (b) Once the precipitation "bucket" is empty, do not draw down groundwater "bucket" for any additional CUprecip.	Not applicable (average not used for the allocation).

Table 2: Example Approaches for Incorporating Precipitation into Allocations — some decision points which are often addressed in incorporating precipitation into allocations and some examples of how they have been addressed. These decisions can have large management implications, as discussed in the following section.

GSAs are responsible for managing a large workload and considerable complexity. Minimal guidance in a policy based on local control is resulting in varying approaches and degrees of rigor in consequential water management processes.

Local control is a fundamental tenet of SGMA and gives GSAs the ability to determine their own approaches, as long as they meet baseline requirements. GSAs have been tasked with an enormous amount of work, some of it incredibly complex and requiring both deep and broad expertise to be done well. To date, only limited guidance and best management practices have been provided to GSAs. This lack of guidance relative to the task at hand has resulted in a wide array of approaches and a wide array of rigor within those approaches, especially for aspects that are more controversial with water users – such as allocations and consumptive use. This finding – although not entirely unexpected – has broad ramifications and underpins many of the findings and recommendations in this report.

One way that GSAs are navigating the uncertainty and meeting the many SGMA requirements within the stipulated timelines is by using consultants. There are many clear benefits to this approach, including added capacity, more expansive expertise, and possible efficiencies and increased rigor with consultants working across multiple GSAs. However, these benefits are not always fully realized, due in part to the lack of guidance. For example, facing varying demands from GSA clients, consultants working across GSAs were limited in their ability to develop highly rigorous, replicable approaches. Also, some GSAs do not have a full understanding of the models, methodologies, or assumptions that their consultants used. Finally, many of the consultants used by GSAs are hydrogeologists and engineers. This expertise is critical to basin sustainability, but so are other areas of expertise – such as soil science, ecology, and atmospheric science (e.g., micrometeorology, biometeorology) – which were largely absent from GSA processes. Guidance on best practices could create space for more rigorous approaches, could improve GSA internal understanding of underlying methodologies, and could help incorporate elements that better capture full hydrologic cycle functioning, including the benefits of cover cropping in the context of that water cycle.

Mandates are inconsistent with local control, and exhaustive guidance may go against the spirit of local control. However, some guidance and best practices targeted in specific areas – such as those mentioned in this report – could help improve the rigor and outcomes of the approaches taken by GSAs at the local level.

Cover crops may be unintentionally disincentivized because GSA approaches tend to account for cover crops' water use but not their water-related benefits.

There were no explicit policies stating that the adoption of cover cropping would be penalized in the estimate of consumptive use of groundwater in any of our assessed GSAs. However, their approaches tend to include estimates of cover crop water use but not their water-related benefits, which could disincentivize the practice. The lack of inclusion of water related benefits stems partly from a lack of necessary data, partly from a lack of capacity (time, resources, and/or expertise), and partly from assumptions made in how GSAs create their water budgets and sustainable yield, track the consumptive use of groundwater, and account for precipitation, among others. However, approaches that can capture both the water impacts and the water benefits of cover crops – and other practices – are vital for managing California's groundwater, especially in the face of increasingly extreme weather events.

Some common assumptions in GSA approaches are not reflective of the best available science and preclude the ability to account for the benefits of certain land management decisions.

At the level of the water budget, and therefore also sustainable yield, GSAs are required to make assumptions to simplify processes that enable management. However, some of the assumptions made by certain GSAs have the potential to be problematic for the implementation of cover cropping, or even the accuracy of the budget more generally. This section will identify and discuss these interrelated assumptions based on SGMA regulations and subset of GSAs examined.

Assumption: Evaporation from bare ground is negligible

Some GSAs are assuming that bare ground evaporation is negligible. This can be seen in how certain GSAs entirely discount the satellite ET readings of bare ground or require bare ground for fallowing credit. This assumption makes sense at a cursory glance — i.e., that without plants transpiring, water from precipitation remains in the ground or returns to groundwater. However, assuming bare ground has no – or minimal – loss to evaporation contradicts scientific findings (see Evaporation section) and is likely to bias farmers toward bareground management, a practice with known environmental and human health consequences (see Key Takeaway #5).

Assumption: Runoff is negligible

GSAs focus on the sub basin or basin level, and in our analysis they often assume, procedurally, that runoff does not occur or is minimal (i.e. although there might be field-level runoff, that water ultimately remains within the basin). This assumption simplifies water budget and allocation calculations, but it could result in increasing error, especially with California's variable precipitation regime. With the incidence of extreme precipitation on the rise, the magnitude of runoff is likely to increase, with more water flowing off growers' parcels into surface water systems and out of the subbasin. This has implications for cover cropping as well. The reduction of runoff is one of the most well supported water-related benefits of the practice (see runoff 2.1.a.). With assumptions of minimal or no runoff in their water budgets, GSAs close the door to accounting for this benefit, which will only become more important in time as California faces more extreme flooding events.

Assumption: The percentage of precipitation that percolates into groundwater is fixed

In developing water budgets and assessing consumptive use, GSAs using satellite-based ET estimates usually account for differences in the amount of precipitation that falls versus the amount that leaves a parcel through ET. As many GSAs assume that runoff is negligible, any variation in this amount is determined by how much water is assumed to percolate below the rootzone. GSAs often use a fixed percentage across their management area to estimate this process. Even when there are differences in how they account for particular areas, they are often assuming those differences are fixed based on soil type. In doing so, GSAs have not accounted for other factors known to influence how much precipitation is captured in the soil profile, how much runs off, and how much percolates deeply. These processes are determined by factors such as vegetative cover, soil surface properties (e.g. crusting or compaction), soil structure, landscape slope, and the intensity or size of precipitation events. This limits the possibility of accounting for variation in infiltration and runoff, key benefits of cover crops and – more broadly – factors that are becoming increasingly important in California's climate future of more extreme floods and droughts.

Requirements for bare ground exist in some GSA incentive programs. These requirements are unlikely to meet estimated water savings and are likely to create negative local impacts to air quality, water quality, and human health.

One area where the use of cover crops was explicitly disallowed was in certain crediting programs, which require growers to maintain bare ground in annual cropping systems to receive credit for the water-use savings of fallowing. This requirement is not present in all crediting programs, but it is worth mentioning as bare ground can evaporate significant amounts of water, contrary to the requirement's underlying assumption that bare ground evaporation is negligible. This requirement, therefore, is unlikely to achieve all of the estimated water savings it assumes. Bare ground requirements can also aggravate the unintended side effects of fallowing, especially air and water quality degradation that impacts human health, and could impede the outcomes of other policy and regulatory efforts. Bare ground requirements may also incur significant costs to growers due to the need to maintain bare ground through chemical or mechanical means.

Some GSA methodologies for incorporating precipitation are likely to result in unintended consequences for cover crop implementation, basin water management, and water use decisions.

Precipitation is a very complicated process to effectively incorporate into water supply management, especially for GSAs using satellite-based ET estimates for calculating the consumptive use of groundwater. There is a wide variety in how different GSAs approach the process and these approaches can yield vastly different outcomes with respect to their alignment with current science, management goals, and effective user experience. It's important to note that some of these outcomes may be due in part to relative lack of expertise in certain areas – such as soil science, ecology, and atmospheric science – and to accelerated timelines for developing allocation and consumptive use approaches in response to extreme drought conditions prior to 2022-2023.

How GSAs approach precipitation can have profound impacts on their ability to accurately account for water processes, for cover cropping and beyond. These approaches relate to the incorporation of precipitation into allocations, how the relevant processes of infiltration and runoff are included in this incorporation, and the multiplying effect of climate change on vulnerabilities in certain approaches. These three topics are discussed in more detail in the sub-sections below.

Impacts of Approaches to Precipitation

While decisions around precipitation in water budgets are important, the most variable and consequential approaches to precipitation arise as GSAs develop and account for allocations. When doing so, GSAs must make several important decisions (outlined in section 3.3.). These decisions – individually and as a whole – are consequential to developing allocation approaches that accurately account for water, enable growers to manage adaptively, and create the space to incentivize sustainable agriculture practices. The following are some examples to illustrate the implications of some of the common methods utilized by GSAs.

In cases where GSAs use historical average precipitation for their allocation approaches, the difference between actual precipitation and that average becomes hugely important – and the greater the difference, the more challenging it is to effectively manage. For instance, in a winter with much greater than average precipitation, ET will inevitably increase, whether or not crops need the water. Increased ET in extremely wet years could draw down substantial amounts of a grower's allocation if adjustments to actual precipitation aren't made. In areas with relatively small groundwater allocations, this scenario could result in a grower no longer having allocated water available when they need to irrigate their crops, despite not having pumped groundwater. Some GSAs are addressing this issue by creating a separate precipitation allocation "bucket" and not allowing excessive precipitation to draw down the groundwater allocation "bucket." In other words, once the precipitation allocation "bucket" is empty, any additional ET assumed to be due to precipitation is not charged to the grower. Others are addressing it by increasing or decreasing allocations using a precipitation credit, based on actual precipitation.

Approaches that respond to this variability are especially important given that the difference between a given year's precipitation and the historical average can be large in California and is expected to be larger in the future. If GSAs do not adjust precipitation to account for actual rainfall, growers could be forced to exceed their allocation in extremely wet years in order to cultivate their crops, due to the mismatch in timing when the precipitation is falling and when their crops need water. And in dry years, growers would likely use up their full allocation to compensate for the lack of precipitation. If a GSA's approach results in growers exceeding their allocations in wet years and using their full allocation in dry years, the actual inflows and outflows will likely not match the GSA's planned inflows and outflows. Without adjustments, this mismatch will impede the GSA from meeting its management goals over time.

In cases where GSAs incorporate actual precipitation in allocation approaches, other challenges can arise depending on how they choose to do so. Some GSAs do not allot growers any additional allocation until the actual precipitation data is available, which can be a month or more after the precipitation event. This can lead to billing cycles where the total ET from fields (ET from applied water and precipitation) exceeds a grower's allocation, leading to penalties and fines that can only be rectified at a future billing cycle or at year's end, depending on when the GSA can integrate the precipitation data. These approaches run counter to best practices for weather-adaptive irrigation management, which is to adjust timing and amount of irrigation based on precipitation in real time (past and forecast).

Infiltration and Runoff

The incorporation of precipitation into allocations necessitates an accounting of the fate of that water, i.e. the percentage that leaves the basin through ET and runoff, as well as the remainder – the proportion percolating into the ground and remaining in the basin. Many factors influence the fate of that water, such as intensity or amount of precipitation, existing soil moisture, local ground cover, and soil conditions. While most GSAs do not currently incorporate these influencing factors, they all do make assumptions – whether explicit or implicit – about runoff, infiltration, and percolation rates. GSAs, therefore, could adjust those assumptions based on best available science and local conditions.

There are limited examples of this type of adjustment being done through the use of soil type to adjust the specific yield, e.g. creating a soil-specific yield, in water budgets. A similar approach could be taken to incorporate other factors influencing water flows in both water budgets and allocations. For example, a GSA could use a conservative 40% reduction in runoff (see section 2.1.a.) to adjust assumed runoff rates for parcels using cover crops in allocations. Or, they could adjust assumed infiltration rates based on conservative 40% increase in infiltration (see section 2.1.b.). Without doing so, they could disincentivize practices that evapotranspire but improve infiltration and runoff. In doing so, they would better account for actual flows of water and encourage practices that help improve these beneficial flows.

California's Climate Future

Effective management decisions for incorporating precipitation and accounting for infiltration and runoff are important now, but when viewed through the lens of the future of California's precipitation regimes, they become even more vital. It is most likely that this future features increasing variability (drier and wetter years) with the intensity of precipitation increasing due to atmospheric rivers (Gershunov et al., 2019). Under these conditions, the difference between actual precipitation and average will become more pronounced, increasing the importance of GSA approaches to incorporating actual precipitation. And with more frequent and intense atmospheric rivers, the risk of increased runoff is likely to be much greater than in the past, particularly on land with poor infiltration. Without adjustments based on land conditions that influence these factors, the margin of error between the average assumed infiltration and runoff and the actual infiltration and runoff will continue to grow along with the increasing intensity of rain events.

Approaches to incorporating precipitation are quite consequential in determining the extent to which the water benefits of practices such as cover cropping are captured, effective water-use decisions are incentivized, and basin management strategies are likely to meet their intended goals. Currently, there are many permutations to these approaches found across the analyzed GSAs, and some are more effective than others in motivating the changes needed to achieve management goals.

Relative to what is known about the margins of error of satellite ET estimates for common crops, little is known for winter cover crops. In particular, it is not well documented how factors such as increased cloud cover and bare ground could impact the accuracy of ET estimates for cover cropped parcels compared to non-cover cropped parcels.

As discussed previously, a commonly cited concern of satellite-based ET data is the margin of error, and one common response to this concern is that the margin of error applies equally to all parcels and is not, therefore, a significant issue in the context of water allocations and consumptive use estimates. However, there are at least a few examples where satellite-based ET data sources and methodologies may create greater margins of error for certain parcels compared to others, including those with cover crops.

For example, cloud cover increases during wintertime, reducing the likelihood that a given satellite pass (which might normally occur every eight days) will have clear lines of sight. As a result, there are fewer directly-estimated ET data points in wintertime and a greater reliance on gap-filling techniques including interpolation using data from in-situ sites, such as ETo from CIMIS stations. More frequent use of interpolation vs. direct estimate in turn may impact the margin of error. Parcels growing winter, rain-fed cover crops could, therefore, experience a greater margin of error compared to parcels without winter cover crops. Another challenge that has been suggested for some satellite-based ET data is the greater potential for error for bare – or near bare – ground. Since bare ground is often the "control" comparison for cover crops and there is a greater expanse of bare ground in the winter, having accurate estimates for both is important.

A better understanding of the magnitude and the implications of these – and possibly other – scenarios that could generate greater margins of error for some parcels compared to others is important to improve implementation of allocations and consumptive use that rely on satellite ET-based data.

GSA methodologies for converting satellite ET data (total consumptive use) or flowmeter data (applied water) into consumptive use of groundwater (CUgw) estimates are variable and not always rigorous.

Most conversations concerning cover crops under SGMA focus on these different data sources and, especially in the case of satellite ET estimates, their accuracy – or margin of error. These are important discussions, and they should continue. That said, neither of these tools directly measures consumptive use of groundwater (CUgw), so the methodology and assumptions GSAs use to convert tool data into CUgw is equally important in the accuracy of assessing groundwater use. An important finding of this report is that these consequential methodologies are rarely discussed, that GSA approaches are highly variable, and that some approaches use very simplistic assumptions. The conversion of these data sources into CUgw influence not only GSAs' ability to account for the water benefits of cover crops, but also their ability to effectively manage water.

To convert satellite ET-based total consumptive use (CUtotal) data into CUgw, precipitation is a very important factor (see following section). "Effective precipitation" is the amount of precipitation that is available to be consumptively used (as compared to how much runs off or percolates below the root zone). Most GSAs use a simplistic assumption that a fixed and high percentage of precipitation goes to total CU (as accounted by satellite-based ET estimates), i.e. is available for plant use.

To convert flow meter applied groundwater (AWgw) data into CUgw, similar assumptions need to be made about how much of that applied groundwater is available to be used (as compared to how much runs off or percolates below the root zone). A common approach is applying a consumptive use fraction (CUF) to the AWgw to arrive at CUgw. This CUF is typically a set percentage based on irrigation system type.

Both of the common GSA approaches mentioned above ignore many of the factors that influence how much water runs off or percolates down versus how much is actually available for plant use. These factors include the amount and intensity of precipitation, soil surface conditions, soil saturation, soil structure, atmospheric water demand, slope, and others.
It is extremely complicated – if not impossible – to fully account for all of these aspects across all acres in a GSA with current science and technology. However, there are feasible options currently available to calculate effective precipitation and CUF that are more robust than the approaches many GSAs are taking.

GSAs are grappling with feasible options for converting data into CUgw and are open to insights about how to improve. Guidance would enable GSAs to more rigorously account for water movement and encourage landowners to take direct action to capture and store precipitation in their operations.

An “illusion of precision” may lead GSAs to be less open to enabling multi-benefit practices.

The management of groundwater supply entails complex interacting systems, with myriad uncertainties. In fulfilling their mandates, GSAs are forced to simplify these multifaceted dynamics and work with some level of uncertainty. If exacting precision was required for the rates of every single system flow (e.g., the exact volume of water, usually in acre feet (AF), passing from each parcel into groundwater), GSAs would be forced to commit all their resources to continually refining this knowledge. Instead, they operate within windows of uncertainty and are forced to generalize for the purposes of sparing limited resources and achieving progress in their politically nuanced contexts. They do this by using various assumptions, estimates, and models.

Despite this complexity and uncertainty, GSAs must drive behavior change that results in basin-level changes towards sustainable yield, including changes in groundwater pumping. Therefore, in almost every GSA, we see groundwater allocations being assessed in very precise terms of tenths or hundredths of AF, despite this “precision” arising from the simple division of generalized basin-level estimates. This allows growers to be charged very precisely, and may therefore instigate necessary changes in behavior, but it over represents the level of certainty under which GSAs are operating. We term this mismatch the “illusion of precision” and note its near-universal presence in GSA management. A lack of recognition of this “illusion of precision” means that GSAs may be uncomfortable considering multi-benefit practices – such as cover crops – that have some uncertainty regarding water use, even though the levels of uncertainty around these practices may be similar to, or less than, the uncertainty of other assumptions being made.

Current GSA approaches could negatively impact the success of other policies, programs, and efforts in California.

As mentioned above, GSA approaches tend to include estimates of plant water use but not water related benefits, which could disincentivize not only cover crops but any non-cash crop vegetative cover. Aside from providing water quantity related benefits, vegetative cover can provide other benefits important for the health of our communities and watersheds, including improved water quality, improved air quality, reduced soil erosion, habitat and species protection, among others. Disincentivizing non-cash crop vegetative cover would negatively impact a range of policies and programs in California that rely on vegetative cover to provide these multiple benefits, such as the AB 32 Scoping Plan, the California Water Plan, the Climate Adaptation Strategy, the Natural and Working Lands Climate Smart Strategy, 30x30, the Healthy Soils Program, and the Multibenefit Land Repurposing Program, to name a few.

VISION

To clarify the desired impact of our recommendations and their necessity, a detailed comparison of the current and ideal future states of GSAs and their approaches are included in the table below. The recommendations above aim to support this vision.

		CURRENT STATE *Based on analyzed GSAs*	FUTURE STATE *Vision for Effective Management*
OVERARCHING	***Cover Crop Penalties & Incentives***	Within their management approaches, GSAs do not directly penalize cover crops (e.g. with a fine) nor do they incentivize them. However, most current approaches are likely to indirectly disincentivize cover crop use through assumptions and approaches that capture water use but not water benefits.	GSA management systems more accurately account for cover crop water use, their water benefits, and (because they now effectively incorporate precipitation, runoff and infiltration), have the operating space to incentivize this multi-benefit practice if they so choose.
	GSA Guidance and Expertise	GSAs and their consultants have received limited guidance and may lack multi-disciplinary expertise to support the development of the many complex processes necessary to meet their mandates. This has contributed to a wide range not only in approaches, but in the rigor and effectiveness of these approaches.	"Local control" with high-quality outcomes across the state is enabled by the availability of (1) guidance documents for vital processes – including allocations and consumptive use estimates, and (2) multi-disciplinary technical experts who can assist GSAs and their consultants in refining their approaches and methodologies.
	Managing to Margins of Error	GSAs must make many assumptions about complex subbasin-wide processes. They do not publish margins of error resulting from these assumptions nor discuss implications or approaches for operating within it.	GSAs incorporate estimates of the margin of error more explicitly into management, ideally in ways that allow for increasing knowledge about its magnitude and create the space for the implementation of multi-benefit practices.
SPECIFIC	***Fallowing Credit***	Bare ground is sometimes a requirement to receive water credits, increasing the likelihood of negative air, soil, and water quality impacts alongside uncertain water quantity benefits	There are no bare ground requirements. Water-efficient cover cropping is allowed, and incentivized when appropriate, resulting in multiple co-benefits and positive or *de minimis* negative impacts to water budget.
	Infiltration and Runoff	Broad assumptions about infiltration and runoff are common and often don't account for localized factors that can influence the magnitude of impacts, especially in extreme weather years.	GSA assumptions and approaches incorporate a more robust accounting for infiltration and runoff, including methods – such as effective precipitation – that allow for adjustments based on localized factors.
	Precipitation	Precipitation is a central component of allocation and consumptive use schemes and is incorporated inconsistently. Among these approaches, some use assumptions which are especially ill-suited to California's future precipitation regimes.	GSAs have incorporated precipitation in ways that accurately account for the variability over time, while ensuring that growers can plan ahead and are not unfairly penalized in precipitation years that fall well outside of the "average."
	Consumptive Use Methodologies	GSA methodologies for converting satellite ET (e.g. total consumptive use) data or flowmeter (e.g. total water applied) data into consumptive use of groundwater (CUgw) estimates are hard to obtain, variable, and not always rigorous.	GSA methodologies for converting satellite ET data and/or flowmeter data into CUgw estimates is easily accessible, robust, and based on best available science.
	Cover Crop Definitions	There are no clear parameters to define what constitutes water-efficient cover cropping, increasing the perceived risk of developing cover crop-specific approaches or incentives.	Parameters for "water-efficient" cover cropping – including species and management practices – are available and based on best available science. GSAs provide clear parameters that fit their specific context (cropping, climatic, etc.) in any cover crop-specific approaches.

4 Recommendations

INTRODUCTION

This section contains both technical and non-technical recommendations. Certain authors and their affiliated organizations abstained from contributing to non-technical recommendations, as noted in the "Authorship" section on page 3 of this report.

Cover cropping is a multi-benefit agricultural practice with proven benefits to agriculture, communities, and ecosystems. The practice can improve soil health, boost biodiversity, support pollinators, aid in pest and weed control, and curtail erosion, along with a wide range of water-specific benefits. Even in the Mediterranean climates of California, studies have demonstrated consistent improvements to infiltration (often ≥ 40%) and reductions in runoff (often ≥ 40%). In the state's changing climate, marked by more intense and variable precipitation, these water benefits are increasingly essential for sustainable water management.

At the same time, cover crops — like any other vegetation — use water. In the SJV, wintertime cover cropped acres have been found to increase ET relative to bare ground by varying amounts. Existing research does indicate that winter cover crops' water use compared to bare ground can be negligible on the parcel scale, with recorded increases in ET as low as 0.12 inches (see discussion in Section 2.1.a.), but additional efforts are needed to clarify the conditions necessary to maximize water benefits while minimizing water use in additional cropping contexts.

Understanding the Potential Net Impact of Cover Crops on San Joaquin Valley Water Budgets

While this is an area of active and on-going research, results from published studies from the San Joaquin Valley (SJV) can provide some initial insight into this question. The net impact of cover crops on water budgets depends upon both their water use and water benefits.

Based on our current understanding of the literature, ~1.2 inches (0.1 AF/acre) over and above water loss from bare ground management may be a conservative estimate for wintertime, rain-fed cover cropping (Islam et al., 2006, see section 2.1.a. for discussion). Using this conservative estimate, the adoption of cover crops on 30% of SJV irrigated agriculture acreage (1.59 million cover cropped acres) would result in ~159,000 AF of additional water use, or 1.1% of total average annual SJV agricultural water use (see Appendix D for calculations and data sources). This water would come predominantly from wintertime precipitation.

However, the water use above does not account for the water capture benefits of cover crops and is thus not the net impact. For comparison, many growers have noted that cover crops allow them to delay the start of their irrigation. In March, almond orchards with double-line drip irrigation in the SJV use approximately 2.25 inches of water (Haviland et al., 2020); avoiding irrigation for this month could thus potentially save more water than the aforementioned conservative estimate of ~1.2 inches of additional water use from winter cover crops. Additionally, with conservative estimates of 40% reduction in runoff and 40% increase in infiltration (see section 2.1.a. and 2.1.b.), wintertime cover crops on 1.59 million acres would also play a large role in basin-wide water capture and storage during CA's increasingly extreme precipitation events.

Further research and a more comprehensive accounting of both water use and water benefits are needed to arrive at more accurate estimates of net water impact.

While there remains some uncertainty regarding the net water impact of cover crops, GSAs face uncertainty and margins of error across much of their work to manage groundwater sustainability. Considering cover cropping's broad benefits and relatively minor potential impact on water budgets, the practice should not be unnecessarily disincentivized under SGMA before that certainty is obtained. However, some of the methodologies and approaches being used by GSAs are likely to do just that and could even limit GSAs' ability to account for and manage basin-wide water dynamics more generally.

GSA management structures and methodologies will need refinement beyond GSP approval; adaptive management will be key, as will integrating data, shared learning, and innovation. The recommendations below highlight actions that can be taken to help GSAs refine their approaches, using best available science and on-the-ground experiences to ensure their success in achieving locally led sustainable groundwater management.

RESEARCH

Develop and implement a coordinated effort to increase understanding of net water impacts of cover crops.

Many institutions and individuals are actively pursuing research that is directly relevant to cover crops, but current efforts are not adequately funded or coordinated to specifically address the most important knowledge gaps. Additionally, growers are implementing cover cropping and generating data, but this information is generally not collected and analyzed along with research findings.

- ***Support, document, and analyze grower experiences implementing cover crops in the San Joaquin Valley through the collection of quantitative and qualitative data.***

  The on-the-ground experiences of the many growers and technical assistance providers that implement cover cropping may not be formalized in published scientific literature but are nonetheless vital sources of knowledge and data for the practice of cover cropping in water-scarce environments. The expanded knowledge gained from different grower and technical assistance provider experiences could be used to increase understanding and to develop Best Management Practices (BMPs) for specific grower contexts.

  » Collect and platform existing grower knowledge and data about cover crop water use, benefits, and management strategies. Similar work has been conducted by the UC Sustainable Agriculture Research and Education Program (see SAREP, 2021) for Sacramento Valley and wine country growers. With additional funding support, the geographic scope of this resource could be expanded to the San Joaquin Valley, with an emphasis on water data.

  » For existing research funding programs, incentivize the collection of high-quality data to fill remaining research gaps. Where granting programs to incentivize cover crop implementation (e.g. HSP, SWEEP, EQIP) are able to do so, request (and fund) recipients to gather information directly addressing key knowledge gaps for cover cropping.

- ***Develop, fund, and implement a coordinated research program that addresses the most important gaps in knowledge on cover crops' net water impacts.***

  Formal research into cover cropping and water impacts is underway, but there is a lack of overarching resources and coordination to drive efficient investment in the most vital knowledge gaps. Sufficient funding and a collaborative effort to develop such a coordinated research program could build off the key areas identified in the convening and collaborative writing processes (see appendix C for more information).

COVER CROP-SPECIFIC NEEDS

Address gaps that need to be filled to enable effective integration of cover crops into GSA plans, allocation approaches, and incentive programs.

Currently, there is no guidance around water-efficient cover cropping, spatially explicit information about where it's being practiced, or clear methodologies for incorporating the practice into GSA management. Investment in the following is vital to drive the ability of GSAs to incorporate the practice into management, but adjusting structural barriers (addressed in later recommendations) will also be necessary to more accurately assess the net water impacts of the practice.

- ***Develop and distribute guidance on the characteristics of water-efficient cover cropping, for growers and GSAs who want to implement cover crop-specific programs.***

  A generalized state-wide framework should be developed to guide state initiatives and serve as a model for local adaptations. Support establishing parameters rather than strict definitions for water-efficient cover cropping, acknowledging the practice's diversity and varying management goals. Clearly articulated parameters, such as species, seeding densities, canopy density, and typical planting and termination times, are essential for any potential credits or incentives associated with cover crop use. Incorporate a mechanism for updating these parameters based on new research and grower experiences. Such definitions will ensure clarity for growers and managers in the implementation, accounting, and potential crediting of cover crops.

- ***Develop and maintain a spatial dataset of cover crop adoption.***

  Based upon the definition of cover crops agreed to by the state, such a dataset would be useful for GSAs in disbursing incremental precipitation credits and potential discounts, as well as for tracking of broader state goals and more accurate modeling of long term SGMA outcomes. Given the existing datasets and available information (e.g., LandIQ-provided crop dataset, ILRP INMPs, etc.), this could be a relatively resource-light development. Ideally, such a dataset would be updated annually.

- ***Investigate current approaches to "natural lands" within GSAs and identify strategies that may be applicable to the practice of wintertime cover cropping.***

  GSAs currently account for the water balance of natural lands within their water budgets. Natural lands use water but correspond to a wide range of benefits. The specific approaches GSAs are taking to integrate natural lands were outside of the scope of this analysis, but could provide valuable lessons for the effort to balance the water use, water benefits, and broader benefits of the practice of wintertime cover cropping. This could be a targeted effort to categorize these approaches, assess what strategies may be applicable to wintertime, rain-fed cover cropping, and detail specific ways to apply these strategies to the assessment of cover crops and other multi-benefit non-cash crop vegetative cover.

GSA GUIDANCE

Provide guidance and support to GSAs on consequential elements of allocations and consumptive use.

In the spirit of local control, there has been limited guidance provided to GSAs to develop their plans and subsequent rules and regulations. As a result, there are varying approaches and degrees of rigor in consequential aspects of demand management, such as converting tool data into CUgw estimates, incorporating precipitation in management, and addressing margins of error. Investing in guidance and support with examples of best practice methodological frameworks and approaches would create pathways for GSAs to consider adopting those that make the most sense in their contexts. This guidance and support could help reduce potentially biased accounting of cover crop water use (i.e., without accounting for their water-related benefits), and could also improve GSAs' ability to successfully manage water in California's climate future.

- ***Develop and distribute guidance documents on best practice methodologies for converting satellite ET and flow meter data into estimates of CUgw.***

  For GSAs with allocations, accurately tracking consumptive use is one of the most central, and difficult, management challenges. While data quality with satellite ET and flow meters remains an important concern, one of the most under-appreciated challenges is the methodology in using this data to back into the variable of concern: consumed groundwater. The variation in GSA approaches, the use of scientifically unsupported assumptions, and the lack of general discussion about this stage of the process mean that guidance here would have an outsized impact on GSAs' ability to achieve accurate water accounting to meet SGMA mandates.

- ***Develop and distribute guidance documents on best practices and methodologies for incorporating precipitation into groundwater allocations and consumptive use assessments.***

  Effectively incorporating precipitation into water budgets, allocation plans, and accounting is exceptionally difficult for GSAs. This is apparent in the variation in approaches and levels of success in developing management plans that are not vulnerable to unintended outcomes in years of extreme precipitation. Best practice examples could be developed on different approaches to addressing precipitation in a range of options for establishing allocations and drawing them down in a given year. Such guidance would prove a valuable resource for incorporating precipitation in ways that meet management goals over time without creating unintended consequences for water users.

- ***Provide guidance and technical assistance to GSAs in commonly lacking areas of expertise relevant to ensuring sustainable groundwater management, such as atmospheric science, ecology, and soil science.***

  The foundational tenet of local control has allowed GSAs to respond to the local agricultural, community, environmental, and political conditions of their subbasin. At the same time, it has forced each GSA to develop monumental plans, rules and regulations, and processes in a relatively short time period, often with limited capacity and a lack of expertise across all relevant areas of the water cycle that impact groundwater. The state-supported development of guidance and technical support for GSAs in specific areas of expertise could help address these burdens and ensure that GSAs are availed of the necessary capacity to fulfill their mandates, especially in more niche, yet vital, areas of water cycle knowledge.

- ***Develop and distribute guidance documents on calculating and incorporating estimates of the margin of error more explicitly into management in ways that increase knowledge about its magnitude and enable the implementation of multibenefit practices.***

  Guidance that provides frameworks for assessing margin of error and examples of how to operate within it would help ensure that GSAs have the tools to "play it safe," while also providing a cushion to enable management decisions aimed at sustainability. Enabling these management decisions is especially important for multibenefit practices that have a potentially negligible impact on total water outflows or a potential benefit to water inflows, both of which are likely to be the case for winter cover cropping in some areas.

DATA

Improve the quantity, spatial distribution, quality, and use of data necessary to develop approaches, implement management processes, and assess performance.

GSAs are dependent on high-quality and easily-accessible data to accurately account for water movement within their subbasins. GSAs rely on external providers for varying qualities and resolutions of data. Improving the quality, distribution, and use of data will only have positive downstream benefits on outcomes, including GSAs' ability to accurately model and account for water processes.

- ***Evaluate and invest in the most cost-effective ways to improve distribution and quality of key ET data inputs.***

  High quality and reliable ET data is a need across both GSAs and across multiple facets of individual GSA implementation, from water budgets to consumptive use. In our work, two of the most discussed options for ensuring better ET data have been increasing funding for the CIMIS network and developing a new network of eddy covariance towers. Both options would increase the availability of vital, on-the-ground readings of ET that can be used in many ways, including to calibrate and validate satellite ET data. Before any funding decisions are made, it is important to evaluate the all-in costs (including the costs for the land and water required for CIMIS) as well as the quality and utility of the data generated.

» CIMIS stations form a cornerstone for the ability to estimate ET, model local weather conditions, and more, but there are issues with reliability and coverage. While these issues may have been less consequential in the past, the situation has changed now that CIMIS data is more widely used for SGMA implementation. These stations now represent a valuable resource in California's water management and policy, for both cover crops, and various cropping systems more broadly.
» A network of full path eddy covariance towers, on the other hand, would require large upfront investment to install them across a range of Central Valley cropping systems. However, such a network would place direct measures of ET across the landscape, a key for validating and refining satellite-based measures. "Full path" towers allow for an estimate of the tower's individual accuracy, further supporting their utility.

- ***Identify and spotlight available high-resolution datasets central to GSA management.***

Without any guidance, GSAs have used a range of different data products and resolutions in the development and implementation of their GSPs. Data products for precipitation and evapotranspiration are quickly becoming more accessible at higher resolutions (e.g. 30x30 meter) and other potentially useful data products are steadily coming online. A curated list of available data products that are spatially explicit and high resolution (in space and time) would ensure that GSAs are aware of these useful datasets and can integrate them to increase their ability to accurately model and account for water processes.

FUNDING

Provide short-term and long-term funding to ensure successful and high-quality implementation of allocation approaches and consumptive use estimates.

GSAs must account for and manage many complex and dynamic processes to ensure successful outcomes related to allocation and consumptive use. GSAs currently have varying levels of capacity and resources to do so. Additional, reliable funding from a variety of sources is needed to provide the guidance, support, research, and data to support GSAs in implementing effective demand management programs.

- ***Provide shorter-term funding to support new, one-off initiatives such as the development of guidance documents or research agendas.***

  Some of the recommendations above are discrete and/or time-bound efforts that would require shorter-term funding. Proposition 68, passed by voters in 2018, allocated $470 million for groundwater sustainability and has been one key source of funding for SGMA implementation. SGMA has continued to be supported by the Administration and the Legislature through supplementary budget allocations in the years since. There is bipartisan recognition of the need for ongoing investment to ensure that California meets its groundwater sustainability goals. As the Legislature considers future water bond proposals, elected officials may wish to consider targeted allocations in groundwater sustainability funding that address some of the recommendations above that are more short-term in nature. Bond funds, which are one-time allocations of funds best suited for project-based needs, may be instrumental in helping to establish the databases, new guidance documents, and research identified in this report. Funding should focus on multi-benefit efforts, such as cover cropping, that might not normally be prioritized by GSAs, but that help ensure successful outcomes for both SGMA and broader state goals.

- ***Provide longer-term funding to support ongoing needs, such as technical support for GSAs and the provision of key ET data inputs.***

  Some of the recommendations above require a longer-term source of funding to support SGMA implementation activities over time and ensure a level of programmatic stability that greatly enhances the odds of successful implementation. Initiatives such as the establishment of technical advisory positions by the state to assist GSAs, expansion and ongoing support of CIMIS, and other state-level support functions that will continue for the foreseeable future would be well-served by a dedicated source of funding. Such funding could also help create the operating space to address multi-benefit practices like cover cropping, which might not otherwise be a priority for GSAs. We recommend that the Legislature, together with all groundwater stakeholders, explore potential solutions that establish ongoing funds to assist growers in adopting sustainable management practices that will benefit agriculture, communities, and the environment.

- ***Identify solutions to ensure GSAs can raise the funding needed to meet the mandates of SGMA.***

  SGMA establishes the ability of GSAs to set fees to support their necessary work in carrying out the Act. However, GSAs still face structural limitations on their ability to raise the necessary funds to administer their programs: specifically, the need to successfully pass Proposition 218-mandated votes to levy fee structures which include "property-related fees" (e.g. groundwater allocations based on acreage). This has proven to be an obstacle to obtaining the necessary funding to support the adoption of sophisticated water budgeting, accounting, and measurement practices. These practices are crucial not only to implement the recommendations in this report but also to truly understand the water available in groundwater basins and the true impacts of all practices on that supply. The Legislature may wish to consider informational hearings on these structural limitations, solicit the input of GSAs, growers, community members, and environmental experts on potential solutions to address the issue.

5 Conclusion

The practice of cover cropping has many benefits that are vital to California's sustainable agricultural future – including benefits to water, soil, the environment, and human health. Cover cropping can improve infiltration and water cycling, increase biodiversity and soil health, and protect air and water quality for local communities, among others. Current patterns in the implementation of SGMA may create unintended barriers to realizing those benefits.

The most prevalent example is that GSA systems often account for the direct water use of cover crops but not their water-related benefits, including runoff and infiltration. The net impacts of cover crops on water budgets are highly context-dependent and research is active, but there are clear cases demonstrating that even in California's San Joaquin and Sacramento Valleys, it is possible to implement them with negligible impacts on water use.

The findings and recommendations provided above aim to:

- support a more accurate understanding and accounting of cover crops' net water impact,
- remove barriers to their use for multiple benefits in contexts where it makes sense, and
- ensure that GSA are more effectively and accurately accounting for and managing water flows in their subbasins in California's changing climate.

The water-related benefits of cover crops, such as their ability to slow down and capture more water during precipitation events, are only becoming more important as California faces more extreme weather events. Our understanding of the conditions under which they have the lowest net water use (and even potential water savings) is rapidly increasing. As we reduce barriers to the implementation of cover crops, this management tool can be utilized to its true potential: as one of many in a toolkit supporting the health and sustainability of California's agriculture, environment, and communities in a rapidly changing future.

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7 Appendices

APPENDIX A - SOIL-WATER INTERFACE EXPERT CONVENINGS: ADDITIONAL INFORMATION

The three convenings were designed to achieve the following:

1. October 2022: Establish what we know and don't know about cover crop impacts on water use and impacts to water budgets and strategies to reduce cover crop water use under water scarce conditions.
2. November 2022: Expand our collective understanding through a series of panel discussions on key topics: evapotranspiration (ET) as a method used to assess consumptive water use under SGMA; the roles of ET platforms (e.g. LandIQ, OpenET, Irriwatch, CIMIS) in providing data to GSAs; and GSA mandates under SGMA and information needs as it relates to cover crops.
3. May 2023: Understand how GSA approaches to water budgets, allocations, and consumptive use calculations, and developing a framework for understanding how policies and regulations may impact cover crop adoption in the San Joaquin Valley.

The report is based on learnings and insights from the in-person meetings, surveys, and a synthesis of the most relevant published and emerging research. The paper is compiled by Sustainable Conservation staff and a group of about 30 expert volunteers, who elected to participate after attending the convening process. Over the course of the convenings, there were a total of 98 unique participants from 48 different organizations. These organizations range from agency to industry, see figure below. A full list of attendees is presented on the following pages.

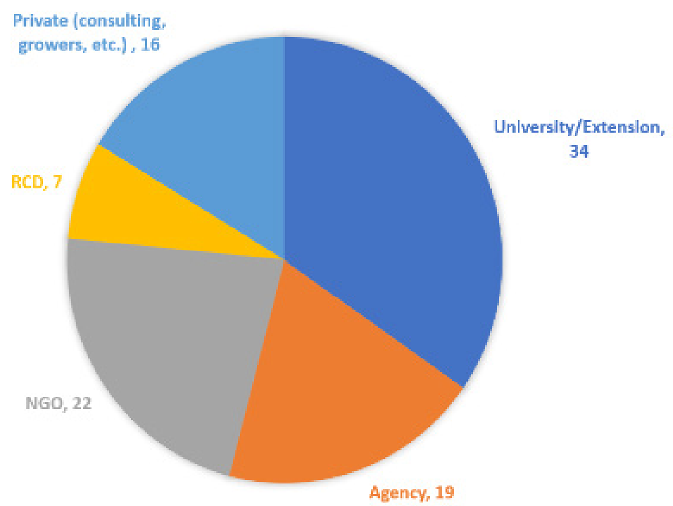

Figure A: Number of unique convening participants per organizational type.

FULL LIST OF CONVENING ATTENDEES

PARTICIPANT	AFFILIATION	SECTOR
Clair Akin	UC ANR	University/Extension
Reyn Akiona	Valley Eco	Private
Matt Angell	RCD Madera Chowchilla	RCD
Emily Ayala	Community Alliance with Family Farmers	NGO
Ann Baier	NCAT	NGO
Priscilla Baker	USDA - NRCS	Agency
Nicolas Bambach	UC Davis	University/Extension
Ravneet Behla	CDFA	Agency
Sharon Benes	CSU Fresno	University/Extension
Caddie Bergren	UC ANR	University/Extension
Ashley Boren	Sustainable Conservation	NGO
Jeff Borum	RCD East Stanislaus	RCD
Sonia Brodt	UC ANR	University/Extension
Ellen Bruno	UC Berkeley	University/Extension
Rosie Burroughs	CSU Chico, Center for Regenerative Agriculture and Resilient Systems	University/Extension
Ward Burroughs	Burroughs Family Farm	Private
Andrew Carroll	EcoThrive Farm Management	Private
Sarah Castle	Sustainable Conservation	NGO

PARTICIPANT	AFFILIATION	SECTOR
Jessica Chiartas	UC Davis	University/Extension
Rory Crowley	ROCS	Private
Ruth Dahlquist-Willard	UC ANR	Private
Jeff Davids	Davids Engineering	University/Extension
Charlotte Decock	Cal Poly	University/Extension
Charles Delgado	Sustainable Conservation	NGO
Alyssa DeVincentis	UC Davis	University/Extension
Rex Dufour	National Center for Appropriate Technology	NGO
Annie Edwards	NRCS/PMC	Agency
Vicky Espinoza	The Nature Conservancy	NGO
Maria Fernanda Ridoutt Orozco	Community Alliance with Family Farmers	NGO
Ryan Flaherty	Sustainable Conservation	NGO
Margot Flynn	UC Davis	University/Extension
Amelie Gaudin	UC Davis	University/Extension
Elliot Grant	Sustainable Conservation	NGO
Robyn Grimm	Environmental Defense Fund	NGO
Margaret Gullette Lloyd	UC ANR	University/Extension
Lauren Hale	USDA - ARS	Agency
Donny Hicks	Olam Food Ingredients	Private
Brian Hockett	RCD Northwest Kern	RCD
Glenda Humiston	UC ANR	University/Extension

PARTICIPANT	AFFILIATION	SECTOR
Douglas Iten	Great Valley Seed Company	Private
Virginia Jameson	CDFA	Agency
Tom Johnson	Kamprath Seeds	Private
Zahangir Kabir	USDA	Agency
Jessie Kanter	UC ANR	University/Extension
Modibo Keita	Sustainable Conservation	NGO
Joel Kimmelshue	Land IQ	Private
Isaya Kisekka	UC Davis	University/Extension
Richard Kreps	Ultra Gro, CCA	Private
Anna Larson	CalCAN	NGO
Sarah Light	UC ANR	University/Extension
Cayle Little	CA Department of Water Resources	Agency
Karen Lowell	USDA - NRCS	Agency
Paul Lum	American Farmland Trust	NGO
Karl Lund	UC ANR	University/Extension
Khaled M. Bali	UC ANR	University/Extension
Stetcyn Maldonado	Project Apis m	NGO
Joseph McIntyre	10 Circles	Private
Josué Medellín-Azuara	UC Merced	University/Extension
Forrest Melton	NASA, CSU Monterey Bay	Agency
Hudson Minshew	USDA - NRCS	Agency

PARTICIPANT	AFFILIATION	SECTOR
Jeff Mitchell	UC Davis	University/Extension
Jorge Andres Morande	UC Merced	University/Extension
Daniel Mountjoy	Sustainable Conservation	NGO
Kelley Moyers	UC Merced	University/Extension
Mallika Nocco	University of Wisconsin - Madison	University/Extension
Toby O'Geen	UC Davis	University/Extension
Felix Ogunmokun	UC Davis	University/Extension
Tapan Pathak	UC ANR	University/Extension
Caitlin Peterson	Public Policy Institute of California	NGO
Wendy Rash	USDA - NRCS	Agency
Matt Reiter	Point Blue Conservation Science	NGO
Matthew Roby	USDA ARS	Agency
Amy Rocha	USDA - NRCS	Agency
Rogell Rogers	Sustainable Conservation	NGO
Tony Rolfes	USDA - NRCS	Agency
Jesse Roseman	The Almond Board of California	Private
Silas Rossow	Cal Ag Solutions	Private
Allegra Roth	UC Berkeley	University/Extension
Rob Roy	USDA - NRCS	Agency
Sebastian Saa	The Almond Board of California	Private
Sam Sandoval Solis	UC Davis	University/Extension

PARTICIPANT	AFFILIATION	SECTOR
Amy Siliznoff	RCD Madera Chowchilla	RCD
Johnnie Siliznoff	NRCS	Agency
Emily Smet	CARCD	RCD
Margaret Smither-Kopperl	USDA - NRCS	Agency
Kosana Suvočarev	UC Davis	University/Extension
Billy Synk	Pollinator Partnership	NGO
Sara Tiffany	Community Alliance with Family Farmers	NGO
Cam Treddenick	CARCD	RCD
Kayla Ungar	CDFA	Agency
Emily Waring	UC Merced	University/Extension
Hannah Waterhouse	UC Santa Cruz	University/Extension
Vivian Wauters	UC Davis	University/Extension
Sam Williams	Sustainable Conservation	NGO
Michael Wolff	CDFA	Agency
Chad Wood	Wood Ranches	Private
Jennifer Wood	CARCD	RCD
Daniele Zaccaria	UC Davis	University/Extension

APPENDIX B - ONGOING RESEARCH

The following table provides a summary of relevant ongoing research efforts that collaborators were aware of and specific details about these individual efforts.

Example On-going Cover Crop - Water Research Projects										
Topic	**Region**	**Crop System**	**Crop Type**	**Expected Publication**	**Point of Contact**	**Funding Source**	**Outflow**	**Inflow**	**Storage**	**Other Benefits**
ET	Sacramento Valley	Rice	Annual	2025	Kosana Survocarev	Rice Research Board	X			
ET + Infiltration	San Joaquin Valley	Almond	Perennial	2024	Kosana Survocarev	General Mills, Project Apis M.	X	X		
ET + Soil moisture	Sacramento Valley	Pistachio	Perennial	2025	Matthew Roby, Isaya Kisekka	USDA NIFA, USDA ARS SAWS Unit	X		X	
ET + Soil moisture	San Joaquin Valley	Almond	Perennial	2025	Mallika Nocco	USDA NRCS Conservation Innovation Grant	X		X	X
ET	San Joaquin Valley	Pistachio	Perennial	2025 + 2026	Daniele Zaccaria	California Pistachio Research Board	X			
ET estimates from remote sensing	San Joaquin Valley	Almond, Pistachio, Wine grapes	Perennial		Daniele Zaccaria	CDFA Specialty Crop Block Grant	X			

Example On-going Cover Crop - Water Research Projects - Continued										
Topic	**Region**	**Crop System**	**Crop Type**	**Expected Publication**	**Point of Contact**	**Funding Source**	**Outflow**	**Inflow**	**Storage**	**Other Benefits**
Soil moisture	Sacramento Valley		Annual	2025	Sarah Light	CDFA Healthy Soils Program			X	
Water balance	San Joaquin Valley	Winter small grains: Wheat, Triticale, barley	Annual	2025	Caity Peterson	USDA NIFA-AFRI grant	X	X	X	
Ag MAR	San Joaquin Valley	Southeast asian vegetable	Annual	2025	Ruth Dahlquist-Willard	CDFA Specialty Crop Block Grant		X		
Soil microbiology	San Joaquin Valley	Table grapes	Perennial	2024	Lauren Hale	USDA-ARS, CDFA, and an NRCS dynamic soil properties program			X	X

Table A: Details of individual ongoing research efforts relevant to the impacts of cover cropping on water budgets and within SGMA management systems.

APPENDIX C - DEVELOPING A RESEARCH AGENDA

Assessing the Water Impact of Cover Crops on California Production Agriculture Water Budgets

This example research agenda outlines strategic research areas surrounding cover crops and the accurate accounting of their water use and benefits under the Sustainable Groundwater Management Act (SGMA) framework. The following examples represent key gaps in our understanding of cover crop water dynamics, the accuracy of GSA measurement paradigms, and the management factors which are most central to growers' ability to implement this sustainable agricultural practice. The content below should be seen as a starting point in the collaborative development of a strategic, multi-party research agenda, not as a completed product. The areas identified below are the result of the convening and collaborative writing processes. Further engagement across relevant institutions will be necessary to fully develop, refine, and actualize a research agenda of this scale.

EXAMPLE RESEARCH THEMES

1. Document and analyze grower experiences of cover crop implementation in the San Joaquin Valley through the collection of quantitative and qualitative data.

Objective: Collect and platform existing grower knowledge and data about cover crop water use, benefits, and management strategies (e.g. Expert Grower Database: Cover Cropping Practices in Orchards and Vineyards developed by UC SAREP [SAREP, 2021]).

Methodology: Through grower interviews, surveys, and outreach, collect information regarding cover crop cultural practices, management, water use, and outcomes for major cropping systems of the San Joaquin Valley. Develop a searchable database and synthesize information to inform best management practices for optimizing cover crop benefits while minimizing water use.

2. Quantifying Net Water Budget Impact of Cover Crops

Objective: Determine the net water budget impact of cover crops for a range of cropping and environmental contexts.

Methodology: 1) Conduct coordinated multi-year, replicated field experiments to measure water inflows and outflows in paired cover-cropped and bare ground managed fields across different crop species/mixes, soil types, and weather conditions to quantify the range of potential net water impacts. 2) Compare on-the-ground ET measurements to satellite ET estimates for the same parcels to understand cover crop-specific biases.

3. Understand the magnitude of difference between ET of winter cover crop and bare ground sites using satellite-derived ET estimates of Evapotranspiration (ET)

Objective: Compare ET from cover crop vs. bare ground management using satellite-based tools, to understand the magnitude of differences in ET between these management practices, accounting for soil type, cover crop species, precipitation patterns, topography, and management actions.

Methodology: Utilize satellite ET data coupled with collection of ground-truthed and grower supplied data to compare broad patterns of water usage in parcels with winter cover crops versus bare ground management.

APPENDIX D - UNDERSTANDING THE POTENTIAL NET IMPACT OF COVER CROPS ON SAN JOAQUIN VALLEY WATER BUDGETS

The calculations presented here illustrate water use associated with a 30% increase in cover crop adoption on San Joaquin Valley (SJV) irrigated agricultural acreage, which was selected because it represents a two- to six-fold increase in cover crop adoption for various SJV cropping systems. Besides the assumptions around 1.2 additional inches of water use by cover crops, all data is from Hanak et al. (2019).

How much additional water would cover crops add to SJV irrigated agricultural water use, if cover crops were implemented on 30% of acres?

In the SJV, there are ~5,300,000 acres of irrigated agriculture (Hanak et al., 2019). Assuming a 0.1 AF/acre increase in water use with winter cover crops, adoption of cover crops across 30% of all SJV irrigated agricultural acreage would contribute to an additional 159,000 AF of water use.

As a percentage of current SJV irrigated agricultural water use?

In the SJV, the total water use across all irrigated agriculture has been estimated to be ~14,400,000 AF/year (Hanak et al., 2019). Following the previous calculation, 159,000 AF represents 1.1% of total SJV agricultural water use.

Summary Table

	30% of Acres
Number of acres	1,590,000 acres
Volume of water use	159,000 AF/year
% of SJV ag water use	1.1%