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Review

Irrigation Decision Support Systems (IDSS) for California's Water–Nutrient–Energy Nexus

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Abstract: California has unsustainable use of agricultural water and energy, as well as problems of severe drought, nitrate pollution and groundwater salinity. As the leading producer and exporter of agricultural produce in the United States, 5.6 percent of California's energy is currently used for pumping groundwater. These problems and new regulatory policies (e.g., Sustainable Groundwater Management Act, Irrigated Lands Regulatory Program) pressure growers to schedule, account and maintain records of water, energy and nutrients needed for crop and soil management. Growers require varying levels of decision support to integrate different irrigation strategies into farm operations. Decision support can come from the public or private sector, where there are many tradeoffs between cost, underlying science, user friendliness and overall challenges in farm integration. Thus, effective irrigation management requires clear definitions, decision support and guidelines for how to incorporate and evaluate the water–nutrient–energy nexus benefits of different practices and combinations of practices under shifting water governance. The California Energy Commission-sponsored Energy Product Evaluation Hub (Cal-EPE Hub) project has a mission of providing science-based evaluation of energy-saving technologies as a direct result of improved water management for irrigation in agriculture, including current and future irrigation decision support systems in California. This project incorporates end-user perceptions into evaluations of existing decision support tools in partnership with government, agricultural and private stakeholders. In this article, we review the policy context and science underlying the available irrigation decision support systems (IDSS), discuss the benefits/tradeoffs and report on their efficacy and ease of use for the most prevalent cropping systems in California. Finally, we identify research and knowledge-to-action gaps for incorporating irrigation decision support systems into new incentives and requirements for reporting water and energy consumption as well as salinity and nitrogen management in the state of California.

Keywords: food–water–energy nexus; nitrate leaching; precision agriculture; water productivity; irrigation management; soil moisture

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1. Introduction

Agricultural production in California includes the cultivation of approximately 400 crops accounting for one-third of vegetable and two-thirds of fruit and nut production in the United States [1]. According to California Agricultural Production Statistics (2019), this agricultural abundance makes California a leading US state accounting for over 13% of the country's total value in agricultural production. Some of California's leading crops include almonds, grapes, strawberries, pistachios, lettuce, walnuts and processing tomatoes [1]. In order to produce these crops for export across the country and other parts of the world, great amounts of water, fertilizer and energy are used. In California, agricultural water use represents one-fifth of the electricity consumed for water use and four percent of total electricity consumption annually [2]. Approximately 75–80% of the total water pumped is used to irrigate three million hectares throughout the state [3,4]. The majority of the water and energy consumption is during the summer growing season (June to August), relying on groundwater that uses between 496 to 1750 Megajoules per Megaliter of water [5]. Declines in aquifer levels, increased land subsidence and loss of storage strain growers for energy efficiency improvements in drought years. The amplified demand for water and energy during drought also lowers stream flows and lake levels, which impact the production of hydroelectric power. In addition, the water table is lowered continually during these periods, as growers pump groundwater from deeper wells demanding more power. The California drought assessment of 2014 reported a loss of 8.1 million ML of surface water with a simultaneous increase of 6.3 million ML in groundwater pumped for an additional cost of USD 454 million [6]. Flood and furrow irrigation still account for approximately 40 percent of the total irrigated area in California, despite the advances and investments in irrigation systems. The adoption of the drip and micro-sprinkler irrigation significantly increased in acreage between 1991 (0.52 million hectares) and 2010 (16 million hectares) [7]. Figure 1 identifies the hydrologic regions across the state of California and the distribution of major crops, irrigation methods and levels of salinity in irrigation water.

California's increasing severity of droughts not only depletes groundwater but also increases the carbon footprint and greenhouse gas emissions from increased burning of fossil fuels to generate the power for pumping groundwater. After facing several severe drought years, state leaders implemented incentives, regulations and policies to manage groundwater that require record keeping and reporting of water use, nitrogen (N) leaching and energy consumption. Simple and scalable irrigation decision support systems are needed to facilitate base information for growers to manage and maximize irrigation water, energy and N use efficiency. On-farm water management using irrigation decision support systems coordinates the development and management of water, land and related resources aimed toward equitable economic welfare and sustainable water use for future generations [8,9]. Irrigation decision support systems (IDSS) are integrated solutions combining and interpreting real-time meteorological, soil moisture and/or crop water stress data using telemetric services to help growers make irrigation decisions. Most of the first IDSS developed in California ranged from spreadsheets to stand-alone software. With recent improvements in public weather-station networks, sensor technology, satellite and aerial imaging, wireless communications and cloud computing, web and smartphone applications automating a range of complex calculations involved in evapotranspiration-based irrigation scheduling, crop and soil nitrogen status IDDS have been developed.

The California Energy Product Evaluation Hub (or Hub) was proposed by the California Energy Commission to fill an information gap between energy sector manufacturers and large commercial and institutional customers. The purpose of the Hub is to accelerate the adoption of beneficial technologies by informing customers purchasing distributed energy resource products through procurement processes. The objectives of the Hub are to evaluate the selected distributed energy resource products (e.g., IDSS) in a rigorous and transparent manner and widely disseminate the evaluation results to large commercial and institutional customers. The evaluations will allow comparisons of similar technologies, as well as comparisons to existing government and industry standards. The evaluations, and the data behind them, will be distributed through the Hub's public web platform. The Hub is a cooperative effort among the University of California, Davis, Lawrence Berkeley National Laboratory, Energy Solutions and the Center for the Built Environment of the University of California, Berkeley.

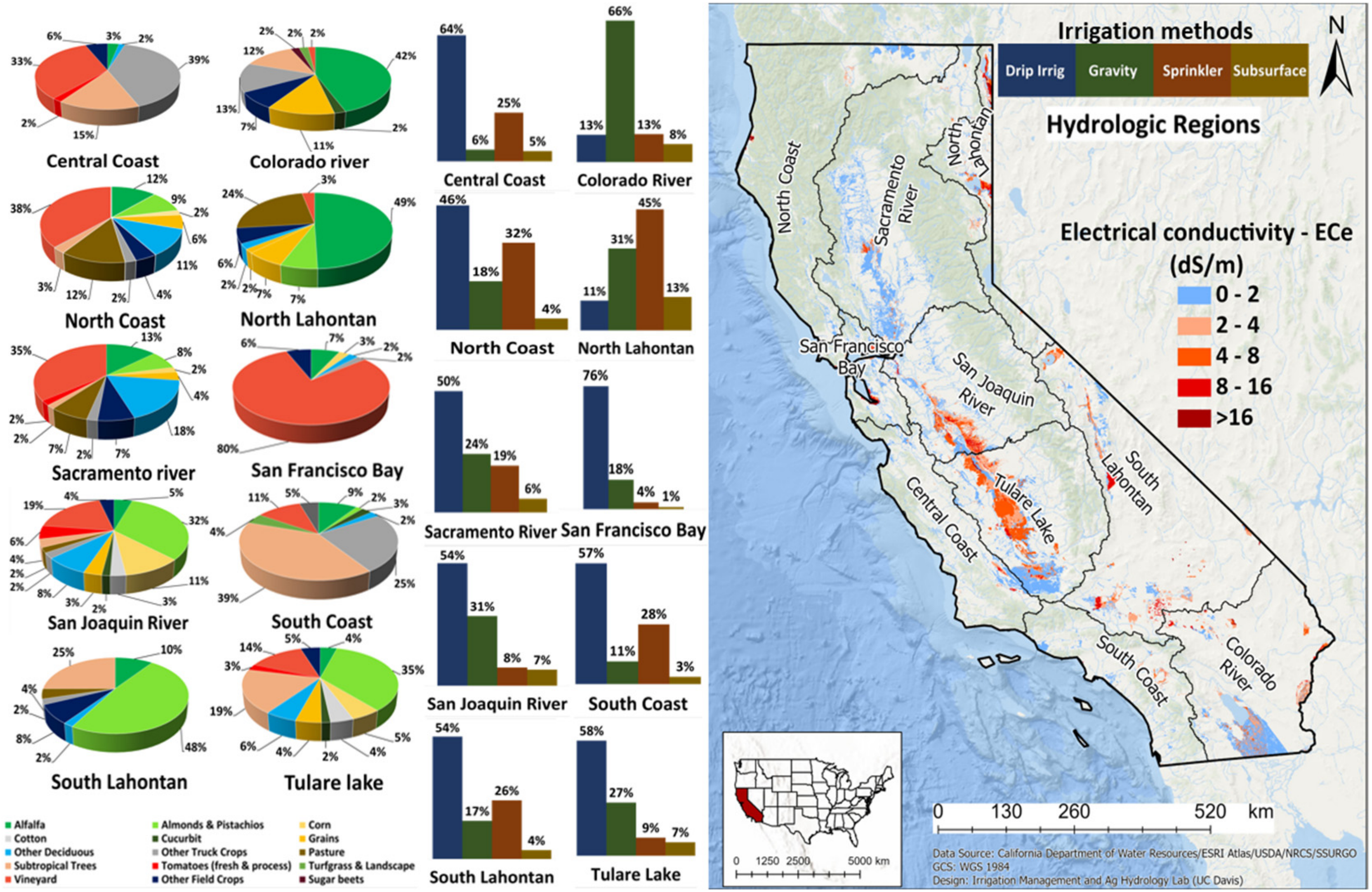

Figure 1. Distribution of irrigation methods, major crops and irrigation water salinity levels in hydrologic regions of California.

The overall goal of this narrative review is to identify, compile and assess the available IDSS in California and how they may serve multiple water, energy and nutrient management goals. Here, we discuss the different water budget components and measurements used in crop canopy, soil moisture, aerial reflectance and satellite-based IDSS. We also consider diverse California cropping and irrigation systems and how different IDSS are integrated into existing crop irrigation management as part of the ongoing research of the California Energy Product Evaluation Hub. Finally, we identify knowledge gaps in IDSS research and current available tools for integrating energy, nitrogen leaching and soil salinity management.

2. Objective and Review Methodology

We identified all active IDSS in California through a comprehensive search of all IDSS on the search engines and in consultation with a California IDSS product advisory group. The IDSS product advisory group consisted of growers, certified crop advisors, cooperative extension advisors, the California Department of Agriculture, California Agricultural Irrigation Association and additional government, industry and trade organizations. The advisory group helped define the IDSS needs for the California cropping system. This information was used to identify the commercially or freely available technologies and exclude the IDSS that have not yet been made available for widespread use.

Section 3 defines California's water management context and the need for IDSS under increasing drought, regulation and risk management. Section 4 provides a broad overview of soil–plant–atmosphere approaches for IDSS. Section 5 describes the commercially available IDSS based on soil tension, canopy temperature, stem water potential and remote-sensing techniques. Section 6 describes the science, policy and role of IDSS for integrated irrigation and energy management in agricultural systems. Section 7 describes the science, policy and role of IDSS for integrated irrigation and nitrogen (N) management to control the environmental problems or groundwater contamination due to excessive N fertilizer uses. Section 8 describes the science, policy and role of IDSS for integrated irrigation and salinity management. Sections 9 and 10 focus on IDSS as a holistic effort for water, nutrient and salinity management and consider the innovation, validation and adoption strategies.

3. Context for IDSS in California Agriculture

3.1. Water Scarcity

Overdrawn aquifers, decline in snowpack, frequent droughts and rising evaporative demand are increasing water scarcity in California. These water resource concerns have led to decreasing water availability for irrigation, increasing regulation (e.g., reduced allocations), increasing energy consumption, difficulty in water/fertilization co-management and increasing water and energy prices. Because the annual evaporative demand exceeds precipitation in the majority of California, irrigation is generally considered compulsory. While most of the precipitation falls in the winter, key economic crops have high water demands during the spring–summer–fall season. Additionally, there is a spatial disconnect between precipitation and agricultural water demand in California. Most of the surface water used for agriculture comes from precipitation in the northern part of the state, while the Central Valley and southern parts of the state have the greatest demand for agricultural water. These discrepancies in space and time have led to complex water conveyance, storage and transfer systems that are important for understanding the potential benefits of IDSS for California growers [10].

Although California spans a wide range of climates, much of the state, including some of the most productive farmland, occupies semi-arid regions of the Central and Imperial Valleys, which are characterized by a Mediterranean climate with hot, dry summers and mild, wet winters. Statewide, the average water use is roughly 50% environmental, 40% agricultural and 10% urban [11]. By necessity, California has adopted management strategies to deal with water shortages, such as reusing water, long-distance water conveyance and desalination technologies to complement local ground and surface water [12]. Unfortunately, water supply diversification strategies can also lead to increased energy use and, consequently, to increased greenhouse gas emissions [13]. California's water system is estimated to emit 10% of the state's greenhouse gas emissions [14]. Water–energy nexus approaches recognize the close connection between water and energy and the importance of considering all aspects of these complex systems [15,16]. As irrigation makes up a large portion of the water supply system in the state, it is under critical consideration by both government agencies and agricultural end users. Policy makers face the difficult task of balancing the needs of diverse stakeholders, protecting the environment and providing reliable, sustainable water supplies to agricultural, industrial and residential customers [16]. At the same time, California growers face more frequent and severe drought events, warmer temperatures and variable rainfall associated with climate change [17], leading to increasing dependence on irrigation [18].

Growers also face increasing competition for irrigation water and growing concerns about the environmental impacts of irrigation. Growers pay for water, energy and infrastructure to irrigate crops. California growers pay between USD 12/106 ML^{-1} water in direct costs and USD 17/151 ML^{-1} water in energy costs [19–21]. While growers are willing to adopt new technologies to reduce risks during periods of water shortage, the information provided by extension services and other educational sources plays an important role in new irrigation technology adoption [22].

3.2. Regulations

California growers identify the key barriers to water and energy conservation efforts as (1) cost, (2) a lack of return on investment (3) and uncertainty about the future of available water. Cost alone is not enough to increase IDSS adoption or agricultural water conservation [23]. In semi-arid regions, regulating surface water without regulating groundwater (or vice versa) increases pressure on the unregulated water source instead of increasing the use of IDSS [24]. However, approaches that involve cooperation across institutional ecosystems as well as multi-actor governance and participation to jointly regulate groundwater and surface water quantity, nutrient/pollutant transport and energy usage may increase IDSS adoption [23,25].

For the past century, California has been a demonstrative example where the regulation and governance of surface water quantity and quality have placed tremendous stress on groundwater supply and energy required to pump groundwater in years with limited surface water allocation. However, the legislation and policies adapted in 2014–2016 are attempting to jointly regulate groundwater and surface water quantity, quality and cooperation across institutions. In 2014, California passed the Sustainable Groundwater Management Act (SGMA), in which two state agencies (Department of Water Resources and State Water Resources Control Board) mandate and oversee communities self-organizing into groundwater sustainability agencies [26]. Each agency created groundwater sustainability plans to achieve sustainability goals by 2040–2042. Similarly, in 2014, the California Irrigated Lands Regulatory Program was expanded to regulate nitrates in discharge to both surface and groundwater from irrigated agricultural lands [27]. California's 2020 heat wave and widespread agricultural power outages have spurred agricultural trade organizations to consider the need for IDSS to accommodate off-peak energy usage and regulations imposed by utility companies [28]. However, there are not yet any direct statewide regulations on the energy used for groundwater pumping in California.

3.3. Loss and Risk Management

3.3.1. Infrastructure Failures

IDSS could help growers plan for water usage throughout the growing season when adjustments may be required to accommodate irrigation interruptions to avoid yield losses at critical moments. For example, in the 2018 Census on Irrigation and Water Management, 1792 CA growers (29,538 ha) reported yield losses because of irrigation interruptions related to groundwater/surface water shortages, equipment failure, energy shortages, high salinity, loss of water rights or increase in water costs [29]. Having a formal IDSS in place does not prevent water, energy or infrastructure disruptions but instead could assist in identifying equipment failures and providing the projected data and calculations needed for difficult decisions—how best to prioritize the available water across the farm to the crops that will have the highest potential for short- and long-term revenue.

3.3.2. Disease-Based Losses and Water

Growers using intuitive, informal irrigation practices may err on the side of applying 'extra' water to ensure that crop water requirements are met. Additionally, some IDSS may also err on the side of overprediction of evapotranspiration and crop water requirements to match grower management practices. Although this logic may decrease the risk of underwatering or water stress, it can increase water logging, nitrate leaching, anoxia, denitrification, salinity, soil erosion and runoff, in addition to the wasted energy and water costs [30]. In California perennial crops, overirrigation or irrigating too soon can impact root development—especially of shallow, fine roots—which can lead to long-term yield losses, especially if the root zone oxygen concentration drops below 10% [31]. In both annual and perennial crops, overirrigation that increases soil and/or canopy moisture can often increase the survival, growth, infection and dispersal of pathogens, which ultimately leads to disease-based yield losses [32]. However, it is important to note that not supplying enough water to meet crop needs can also trigger many belowground diseases [32]. For a comprehensive review of irrigation–disease interactions, please see Swett (2020) [32]. Although IDSS could integrate crop-specific co-management of water and diseases in the future, to the best of our knowledge, no IDSS currently have this function for California cropping systems.

4. Soil–Plant–Atmosphere Approaches and Data for IDSS in California

4.1. Precipitation

Precipitation is an important component of the hydrologic cycle considered for all water budgets. In California, real-time rainfall data can be acquired from different sources, such as the Department of Water Resources California Irrigation Management Information System (CIMIS), National Oceanic and Atmospheric Administration's California Nevada River Forecast Center (CNRFC) and United States Climate Data. For annual water budgeting, monthly precipitation data are often used. Several researchers have observed decreases in precipitation and increases in autumn temperatures since the 1980s [33,34]. In 2018, the delayed start of precipitation months resulted in the most destructive wildfires of California, burning about 766,439 hectares of land area [34,35]. This has not only disturbed water budget planning and estimation, but it has also impacted the contamination of groundwater and other available sources of irrigation by changing the pH due to debris and ash [36].

4.2. Evapotranspiration

Evapotranspiration depends on weather conditions, crop type, canopy density/development, stomatal conductance and regulation, irrigation system and management, soil management and soil type. In California, the estimates of reference evapotranspiration (ET_o) come from the 153 active CIMIS stations that are sited, maintained and equipped by the California Department of Water Resources to measure shortwave solar radiation (pyranometer), soil temperature (thermistor), air temperature (HMP35), relative humidity (HMP35), wind direction (wind vane), wind speed (anemometer) and precipitation (tipping bucket rain gauge). The state is divided into 18 ET_o climatic zones based on long-term monthly CIMIS averages. Additionally, a spatial CIMIS data product combines the network of available stations for ground measurement and satellite data in order to simulate the ET_o of the whole state. CIMIS estimates hourly ET_o for cool-season grass with a height of 0.10–0.15 m using the CIMIS Penman equation, which is modified from the Penman equation [37], with an approach for estimating net radiation from shortwave solar radiation, temperature and relative humidity measurements developed and validated using 71 net radiometers across California [38]. The CIMIS Penman equation also uses different weights for wind speed in the hourly estimation of ET_o depending on whether it is day or night time and a unique cloud factor obtained from each CIMIS station [39].

In addition to the CIMIS network, the National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) satellites have been used to predict incoming solar radiation as the main source energy for evapotranspiration. Satellite-based ET_o maps are calculated on a two-kilometer grid, which is an important contribution of data for decision making, given that the distance between the CIMIS stations can be tens of kilometers. These freely available estimates of ET_o can be paired with crop-specific coefficients (K_c) to estimate crop evapotranspiration (ET_c) during the growing season. It is important to note that evapotranspiration offers decision support as to how much water has been used by the crop based on meteorological data or will be used by the crop based on meteorological forecasting [40,41].

4.3. Irrigation Scheduling Resources

The quantity and timing of water application to irrigate a crop is a critical part of planning a growing season. Crop management activities are mainly dependent on the moisture present in the soil and root matrix. Scheduling depends on the combination of evaporative demand from the atmosphere, spatial and temporal heterogeneity in soil properties and changes in crop canopy during a growing season. California IDSS currently schedule irrigation by measuring, remotely sensing and/or modeling some combination of three different categories: (1) evapotranspiration, (2) allowable depletion of soil moisture and (3) canopy characteristics [42]. In this work, we discuss California IDSS and state specific data sources that can be used to ascertain data from these categories and represent these tools and sensors in Figure 2. These categories are used in IDSS throughout the world, and we recommend Gu et al. (2020) for an in-depth general review [43].

4.3.1. In Situ Calculation of Crop Coefficient Values

Crop coefficient (K_c) values can be obtained for the entire growing season from historical evapotranspiration databases for specialty crops (almonds, walnuts, pistachios, processing tomatoes, etc.) developed by the University of California under the drought management program. There are available databases maintained by the University of California Agriculture and Natural Resources (https://www.sacvalleyorchards.com/et-reports/ (accessed on 20 August 2021)) Westlands Water Districts (https://wwd.ca.gov/water-management/irrigation-guide/ (accessed on 20 August 2021)) that provide regional estimates of ET_o and ET_c for growers. Significant efforts have been made to measure actual evapotranspiration to derive the K_c values specific to California crops and management. Direct measurements using lysimetry, eddy covariance and surface renewal have estimated K_c values for almond, pistachio, walnut, processing tomato, wine grapes, lettuce, rice, corn, wheat, and alfalfa (Table 1) [44–68]. It is important to note that the K_c values derived from actual evapotranspiration studies have several assumptions and site-specific limitations for widespread adoption and water use projections. Attention should be given as to whether water stress had occurred during the actual evapotranspiration measurement periods as well as the uncertainty of actual evapotranspiration estimates by a methodological approach. The use of crop coefficients for irrigation of perennial crops is often more challenging than for annual crops. This is because there can be significant variability as a consequence of the crop density, crop load, row orientation, variety, irrigation system, pruning, floor management, soil type, salinity/sodicity and plant vigor between the two types.

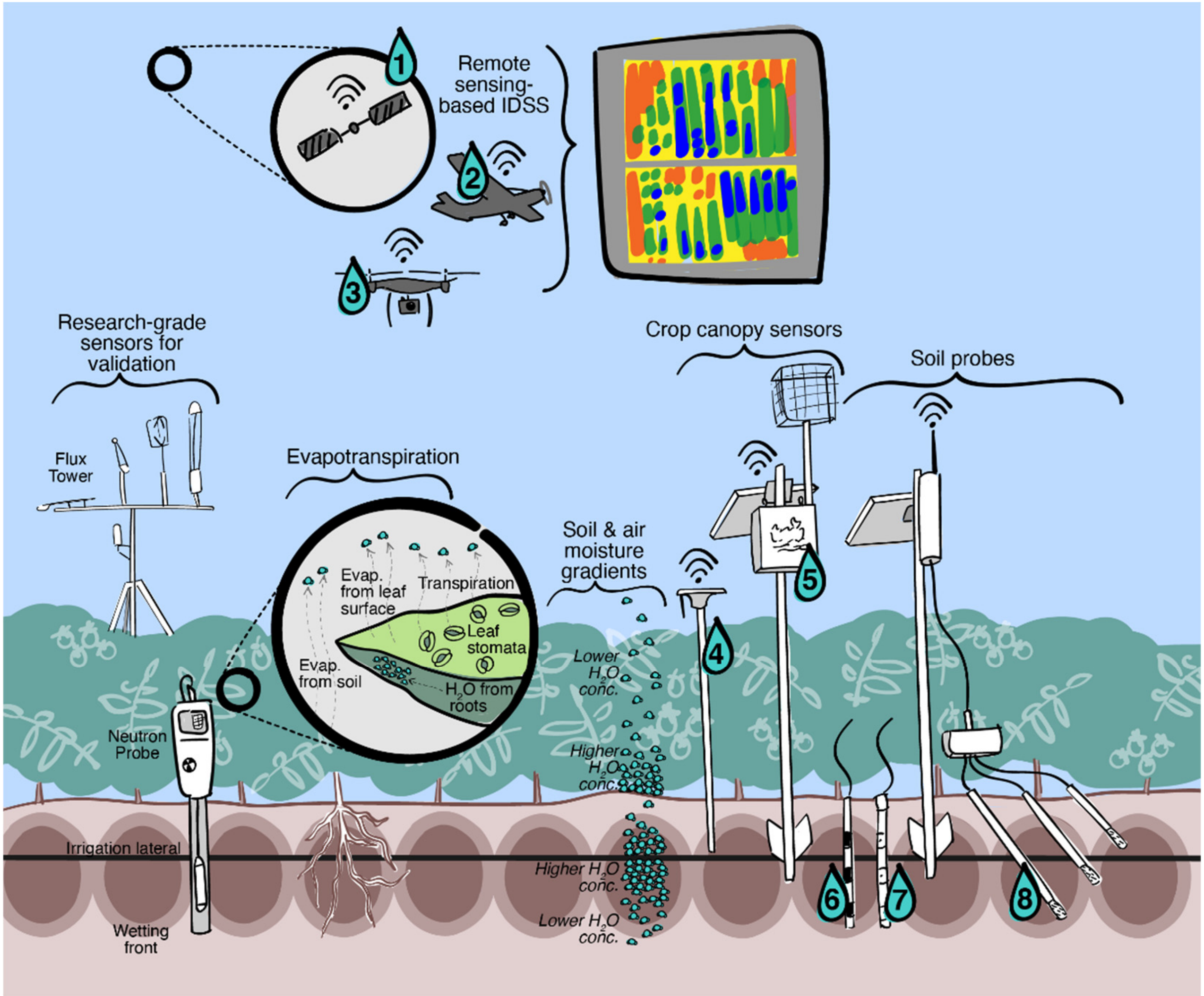

Figure 2. Conceptual illustration of integration and application of imagery (IDSS 1 is satellite imagery, 2 is aerial reflectance, and 3 is drone imagery using multispectral/thermal cameras), canopy (IDSS 4 and 5 based on crop evapotranspiration and other canopy-based parameters) and soil-based IDSS (IDSS 6 and 7 based on volumetric water content and 8 based on soil water potential) in a processing tomato field. Eddy covariance tower and neutron moisture probes are useful to estimate a complete water balance for validation of these available IDSS measurements. Artwork by Dr. Bonnie McGill.

Some California crops, such as processing tomato, wine grapes and olives for oil, can benefit from some degree of water stress in order to decrease the vegetative growth and/or improve the quality of the final product (e.g., sauce, wine, olive oil). Growing these crops can either benefit from constant water stress monitoring or development of K_c values that are multiplied by stress coefficients (K_s) after long-term data collection combined with fruit analysis and careful considerations with experienced growers and processors. The measurement of evapotranspiration values reveals much information about the irrigation needs; however, IDSS should also factor distribution uniformity, soil type, irrigation system efficiency, crop density, floor (interrow perennial cover crop) management, perennial stand density and variety when interpreting the published K_c values across California.

Table 1. Crop coefficient and seasonal water requirement ranges of major crops of California. Crop coefficient periods have been approximated for each crop, see notes column for more details.

Crop	Crop Coefficient * Initial	Developing	Late	Notes	Water Requirement (cm per Season)	References
Almonds	0.20–0.78	0.80–1.09	0.40–1.17	Mature trees; intial (hull, shell, integuments), developing (hardening, embryo growth), late (maturity, ripening, hull split).	104–112	[48–52]
Pistachios	0.07–0.79	0.82–1.19	0.35–1.19	Mature trees; initial (bloom, leafout, shell expansion), developing (shell hardening, nut fill), late (nut fill, shell split, hull split, harvest, post harvest).	76–127	[51,53–55]
Walnuts	0.12–0.93	1.00–1.10	0.28–0.97	Mature trees; initial (bloom, leafout, flowering, growth of hull), developing (shell and kernal development), and late (hull split).	104–112	[56,57]
Tomatoes	0.20–0.45	1.00–1.20	0.30–0.90	Processing and fresh market tomatoes; initial (planting, prebloom, bloom), developing (bloom, early fruit set, late fruit set), late (late fruit set, first color, red fruit, preharvest).	53–76	[51,56,58]
Grapes	0.30–0.37	0.62–0.85	0.45–0.75	Table, wine and rasin grapes; initial (shoot development, flowering), developing (berry formation, verasion), and late (berry ripening, harvest, senescence).	25–76	[51,59,60]
Lettuce	0.17–0.61	0.83–1.02	0.45–0.98	Lettuce grown year-round; initial (emergence to 40% canopy cover), developing (40% canopy cover to 80% canopy cover), and late (80% canopy cover to harvest).	30–61	[51,56,61,62]
Rice	0.95–1.05	1.20–1.25	0.60–0.95	For both paddy and non-paddy grown rice, initial (vegetative phase), developing (reproductive phase), and late (maturation phase).	61–122	[51,56,63]
Corn	0.18–0.26	1.06–1.17	0.30–0.55	Field and sweet corn; initial (vegetative stage), developing (reproductive stage), and end (maturity).	56–76	[56,64]
Wheat	0.26–0.70	1.09–1.15	0.25–0.41	Winter wheat; initial (tillering), developing (stem exension and heading), late (ripening, harvest).	46–53	[51,65,66]
Alfalfa	0.30–0.40	0.95–1.30	0.50–1.30	Initial (planting to 10% cover), developing (10% cover to senescence), and late (senescence to maturity).	51–117	[56,67,68]

* Periods of initial, developing, and late for crop coefficients have been approximated for each crop, see notes column for more details.

4.3.2. Scheduling with Allowable Depletion

The allowable depletion of soil moisture approach requires some knowledge or *a priori* assumption of the effective crop rooting depth, soil textural and hydrological properties and estimates of either soil volumetric water content or soil water potential. These parameters are used to estimate the plant available water content (AWC) as the difference between field capacity and permanent wilting point. The allowable depletion is established as a threshold based on a fraction of AWC or specific soil water potential at which water stress will occur without irrigation. The allowable depletion can differ by soil texture, crop type, as well as phenological stage. In California, the allowable depletion can range from 25% AWC in onions to 90% AWC in ripening wheat but generally runs in the 45–50% AWC range [69–71]. Allowable depletion, whether measured or modeled, offers decision support regarding how much to irrigate (e.g., refill the soil profile), as well as when to initiate irrigation. It is important to note that allowable depletion is not a direct assessment of plant water stress but rather assumes plant water stress based on empirical relationships between plant physiological stress (e.g., stem water potential, canopy temperature, reduced transpiration) and soil volumetric water content or soil water potential.

Soil cohesion and adhesion to water molecules determines the soil water potential (suction or negative pressure). Plants take up water when water potential is between the field capacity (-0.33 bar) and permanent wilting point (-15 bar). Therefore, irrigation scheduling is performed by maintaining the soil moisture within this range of soil water potential. The most commonly used methods for soil moisture or water potential monitoring in California are tensiometers, electrical resistance block (watermark sensors) or capacitance-based sensors [72]. Recent developments in telemetric operations allow manufacturers to combine the soil moisture sensors with web or mobile applications as remote systems. Additionally, the user friendliness of remote telemetry and real-time moisture data in the field are now integrated with automated irrigation systems. Some of the common telemetric operators for soil moisture sensors in California are Wildeye, Farm(X), Hortau, Irriwatch and AquaSpy.

4.3.3. Scheduling with Crop Canopy Characteristics

Recent advancements in the capture and interpretation of remotely sensed vegetative indices (e.g., normalized difference vegetation index or NDVI) allow growers to empirically derive real-time values of crop coefficients throughout the growing season [73–75]. Remote sensing tools, such as directly or remotely piloted aerial vehicles or satellite imagery, aid in the use of algorithms to combine remotely sensed vegetative indices and soil reflectance maps [76–79]. This combination helps growers manage irrigation in orchard cropping systems where NDVI and other index values for individual trees can be calculated. In California, these services are widely provided by Ceres Imaging Inc. to specialty crop growers. Additionally, CropManage uses satellite-based estimates of phenology for irrigation scheduling [80–82].

5. IDSS for Crop Water Management in California

The use of IDSS has increased in California in the last decade, especially for efficient water application preparation for the SGMA regulatory standards. The most common IDSS in California integrate two major components: (1) data input/analysis and (2) user interface. The data input/analytical techniques acquire data based on soil, crop and/or weather parameters, and the user interface is based on telemetry that simplifies the acquired data using statistical interpretation, photogrammetry and/or simulation modeling. The ease of understanding or user friendliness of the acquired information depends on the use of graphics, color notations and approach to simplify the complex data [83]. The IDSS commonly used in cultivating specialty crops in California can be classified into three types (Table 2): (1) soil-based IDSS, (2) canopy-based IDSS and (3) remote-sensing IDSS. Irrigation strategies, such as deficit irrigation, subsurface drip irrigation, overhead linear move sprinkler irrigation, deep root irrigation, pressure-compensated drip irrigation, automated surface irrigation, and tail recovery systems may enhance water use efficiency for high-value crops in California [84].

5.1. Soil-Based IDSS

In IDSS, soil moisture is generally reported in inches of water per foot of soil or as a percentage of weight or volume [2,85], while soil water potential is usually reported in bars or kPa. The California IDSS based on soil moisture usually also estimate or infer soil hydrologic properties (e.g., texture, AWC) to contextualize the recommendations. Therefore, the soil sensors used as IDSS can be divided into two types.

Type 1—IDSS based on volumetric moisture content. These soil moisture sensors include time domain reflectometry, capacitance and frequency domain reflectometry sensors [80,86].
Type 2—IDSS based on soil water potential. These sensors include tensiometers and granular matrix sensors [87,88].

Table 2. List of commonly available IDSS for agricultural crops.

IDSS Type	Name of Device	Key Parameter (s)	Telemetry	Service Provider or Integration Partners
Soil-based	Sentek Drill and Drop Probes (Stepney, Australia)	Volumetric Moisture Content Soil temperature Soil salinity	IrriMax	Wildeye (Fresno, CA, USA) Wiseconn (Fresno, CA, USA)
	AquaCheck Sub-Surface probes (Perry, IA, USA)	Volumetric Moisture Content		Farm(X) (Mountain View, CA, USA)
	Hortau 1k sensors (Québec, QC, Canada)	Soil water potential	Irrolis 3	Hortau (Québec, Canada)
	Irrometer tensiometer (Riverside, CA, USA)	Soil water potential	IRROcloud	Irrometer (Riverside, CA, USA), Agri-Valley irrigation (Merced, CA, USA), Bennett and Bennett (Selma, CA, USA), Bi-County Irrigation (Yuba City, CA, USA), Wildeye (Fresno, CA, USA), Crouzet Irrigation Supply (Porterville, CA, USA), Hydratec, Inc. (Windham, NH), Reedley Irrigation (Reedly CA, USA)
	Watermark Sensor (Riverside, CA, USA)	Soil water potential	IRROcloud	
Canopy-based	Arable Mark 2 (San Francisco, CA, USA)	Crop Evapotranspiration Canopy temperature Precipitation Growing degree days Leaf wetness NDVI	Arable Open and Arable Mobile	Arable (San Francisco, CA, USA) Netafim (Tel Aviv-Yafo, Israel) (integrated data from Arable through NetBeat)
	Tule sensors (Davis, CA, USA)	Actual Evapotranspiration	Tule Web or mobile application	Tule Technologies (Davis, CA, USA)
Imagery-based	Ceres Imaging (Oakland, CA, USA)	Thermal imagery Water stress maps Color infrared maps Colorized NDVI	Ceres imaging web and mobile application	Ceres Imaging (Oakland, CA, USA) John Deere (Moline, IL, USA) ** Climate Field View (San Francisco, CA, USA) **
	Irriwatch (Maurik, The Netherlands)	Soil moisture and actual evapotranspiration using daily satellite imaging using SEBAL model	Irriwatch Portal web and mobile application	Vinduino Crop Optimization Technology (Temecula, CA, USA) **
	CIMIS *	Reference Evapotranspiration	153 CIMIS Stations through web and mobile applications	University of California, Davis WATERIGHT **
	CropManage *	Evapotranspiration using satellite imagery	CropManage Web Application	University of California Agriculture and Natural Resources (UCANR)
	Open ET *	Evapotranspiration and consumptive water use using satellite imagery	OpenET Web application	NASA, DRI, EDF, Google Earth Engine

* Available for free through web or mobile application. ** Integration partners.

Soil sensors are generally provided by IDSS vendors in combination with their telemetric services to access the data through cloud-based data storage applications. The selection of these sensors is based on evaluating water and energy savings, installation and maintenance, ease of use and suitability for specialty crops and soil type, data interpretation and additional services. Vendors have the capability of making recommendations to growers by integrating and installing in situ weather stations. However, the CIMIS weather stations are widely spread throughout the state and provide reliable and validated information on the required weather parameters for water budgeting. Some commonly used soil moisture sensors can be combined with telemetric services provided either by the sensor company or by a separate IDSS vendor.

Soil moisture probes are widely used to determine the real-time volumetric moisture content allowing user-friendly or site-specific calibrations. Measurements can be taken at the desirable depths throughout the soil profile. These sensors also provide additional information on soil temperature and salinity. These sensors, based on design, can also measure soil water potential up to −10 bars. The sensors are provided to growers as leased assets, and real-time irrigation recommendations are made through telemetry services. Examples include tensiometers that are designed to measure soil water potential in heavy (0–1 bar) and light soils (0–0.3 bar). Watermark sensors are based on electrical resistance in soils and are widely useful for measuring soil matric potential up to 2 bars.

5.2. Canopy-Based IDSS

The metabolic processes in a plant system are driven by its water content. Plant water status can be estimated by monitoring physiological and metabolic processes, such as stem or leaf water potential, relative moisture content, stomatal conductance, canopy temperature and xylem cavitation [2,73,89–92]. The most commonly measured water stress parameters in California are canopy temperature, canopy cover and stem water potential [2]. These plant water status indicators are most useful for irrigation timing and can be used to inform when irrigation is required, when crops are not receiving enough irrigation, when there are problems with irrigation systems (e.g., distribution uniformity), as a proxy for soil salinity stress and for applying controlled stress to improve crop quality or health. Plant water status indicators are less useful for understanding how much irrigation is needed, as they do not provide information about soil moisture or evaporative demand. Plant-based IDSS are generally combined with meteorological parameters and/or evapotranspiration data.

5.2.1. Canopy Cover

Radiation interception and evapotranspiration depend on the canopy cover and surface area of a crop. Canopy cover serves as an important parameter for several remote-sensing techniques used as IDSS. As crop canopies change throughout the growing season in terms of their size, area and reflectance properties, so do the values of the crop coefficient (K_c). The spectral reflectance of vegetation or crop canopy can help growers understand the variability in the field by assessing the plant vigor and chlorophyll content [93,94]. A key component of canopy-based IDSS is the crop and growth stage-specific K_c value. The K_c values are usually determined from field studies measuring actual evapotranspiration and ET_o [95,96] but can also be assessed using measurements of leaf area index, light interception and percent canopy cover. Some of the commonly used IDSS based on evapotranspiration and canopy parameters include Arable Mark 2 sensors and Tule sensors. These sensors are leased by the respective vendors, and the irrigation recommendations based on canopy parameters are informed through web/mobile applications. Arable Mark 2 sensors are often combined with the soil moisture probes to apply the soil and canopy parameters to complete the water budget equation for irrigation decisions.

5.2.2. Canopy Temperature

Canopy temperature indirectly measures water deficit when it increases above the surrounding ambient temperature [97]. In general, the variability in canopy temperature is also a result of solar radiation and air temperature. Different indices are used for irrigation scheduling using canopy temperatures. Some examples include the Crop Water Stress Index, Stress Degree Days, Stomatal Conductance Index, Degrees Above Canopy Threshold and Time Temperature Threshold (TTT) [98–101]. In California, the Crop Water Stress Index and Degrees Above Canopy Threshold have been evaluated for wine grapes, corn, pistachios and wheat growers using infrared thermal radiometry [102,103]. The Crop Water Stress Index is calculated by determining the canopy temperature minus the air temperature relative to a well-watered and non-transpiring reference crop [103]. Contrary to the Crop Water Stress Index, the Degrees Above Canopy Threshold only requires a single canopy temperature measurement for quantifying water stress [103,104]. For point-based measurements, canopy temperature can be acquired using an infrared thermal radiometer [103]. At larger spatial scales, thermal and spectral imagery IDSS (e.g., Ceres Imaging) using remote-sensing tools can be used for determining indices based on canopy temperature.

5.2.3. Stem Water Potential

Stem water potential is an indicator of how hard a plant is pumping to move water from the soil (−15 to 0 bars) through the xylem (−2 to −60 bars) to the atmosphere (−200 to −800 bars) [105]. In California, stem water potential is most commonly used and recommended for high-value perennial crops, such as grapes, almonds, walnuts and prunes [106,107]. Stem water potential is most often measured by a pressure chamber, which applies pressure to a sample leaf until the water is pushed out of the stem [90,106,108]. There are growing numbers of sensors available for measuring the stem water potential. These sensors can function as micro-chips or micro-tensiometers or dendrometers for installation in woody vines or trunks [108]. In order to be useful, stem water potential measurements need to be contextualized in relation to the environmental demand, as they are sensitive to temperature and vapor pressure deficit [105]. Local tools are available for growers to correct stem water potential readings in reference to the evaporative demand and compare the readings to baseline values when water is not limited. The use of stem water potential measurements is high in wine grapes, as growers are interested in maintaining specific levels of stress after veraison in order to maintain the quality (M. Cooper, personal communication). Larger California vineyards have 'pressure bomb teams' to constantly test stem water potential throughout the vineyards during the key time periods. Although there are disease management benefits to maintaining stress at hull split, nut growers have still been slow to adopt the pressure chambers to measure stem water potential, with adoption rates of under 20% among almond growers [109].

5.3. Remote-Sensing IDSS

Remote and proximal sensing tools can be used either independently or in conjunction with ground measurements to estimate actual evapotranspiration, ET_c, allowable depletion and plant water status. Remote sensing can use several modes of data collection, including satellite, aerial imaging and scanning towers. Remotely sensed measurements of evapotranspiration typically use thermal imaging as an indicator of canopy radiometric temperature, where higher temperatures indicate relatively lower rates of evapotranspiration (relatively higher partitioning to sensible heat flux), and relatively lower temperatures indicate higher rates of evapotranspiration (relatively higher partitioning to latent heat flux). Remotely sensed vegetation indices from multispectral data, such as NDVI, can be used as analogs for the leaf area index, canopy cover and height, which are also required for evapotranspiration mapping algorithms. All remotely sensed evapotranspiration models solve for sensible heat flux, soil heat flux and net radiation, which leaves the latent heat flux or the energy equivalent of evapotranspiration as the remainder of the energy budget. Some of the energy balance models commonly used in evapotranspiration estimation include Two-Source Energy Balance (TSEB), Surface Energy Balance Algorithm for Land (SEBAL), Surface Energy Balance System (SEBS), Mapping EvapoTRanspiration using Internalized Calibration (METRIC) and High-Resolution Mapping of EvapoTranspiration (HRMET) [77,110–115].

These types of evapotranspiration maps and crop stress indices have been integrated into several IDSS that serve California, such as Ceres Imaging (Oakland, CA, USA), Irriwatch (Maurik, The Netherlands) and Open ET (a satellite-based water data resource launched by National Aeronautics and Space Administration (NASA) and United States Geological Services (USGS)). However, one potential concern or drawback is that detectable differences in evapotranspiration based on canopy radiometric temperature may be revealed too late for irrigation intervention, in that crops exhibiting this level of water stress have already suffered some yield loss from decreased photosynthesis [116]. This limitation of thermal imaging has led to new areas of development for IDSS that may involve combining a variety of spectral bands, solar-induced fluorescence and thermal imagery to provide additional information relating water status to yields [117,118].

Proximal sensing of soil apparent electrical conductivity can be a useful tool to develop high-resolution maps of AWC and other important soil physical and hydrological properties [119]. These soil maps can be used in conjunction with maps of evapotranspiration or stem water potential measurements to assess plant water status [77,78]. In many areas outside of California, commercial IDSS have been developed to assign management zones based on soil properties, especially in regions where center pivot irrigation systems dominate and can be retrofitted or designed with variable rate application technology. New opportunities for precision irrigation exist in California micro-irrigation systems using variable frequency drives to irrigate based on the management zones. However, there are not yet commercially available IDSS in California that rely primarily on soil apparent electrical conductivity mapping to delineate zone-based irrigation management.

6. IDSS for Energy Management in California

6.1. General Considerations

The California agricultural sector consumes 75% of total water use in California compared to 24% and 1% for municipal and industrial sectors, respectively [4]. During the most recent megadrought between 2012 and 2016, the groundwater contribution to total water use nearly doubled from 30–40% to 60%, with most of this being used for agricultural irrigation [120,121]. Agricultural groundwater consumption is directly linked with the energy required to pump groundwater from the aquifers. In California, 8% of total energy use is for agriculture, and 70% of the agricultural energy used is for groundwater pumping [122]. Agricultural water and energy demand surge in dry years and the summer months—especially in the afternoons during peak daily energy demand for water to cool both crops and humans [123]. Additionally, 60% of daily water-related energy demand is due to pumping irrigation water in California from surface and groundwater sources [124].

Most surface irrigation systems have an irrigation efficiency of 67.5–70%, while the traditional sprinkler system ranges between 70 and 82.5%. Drip and micro-sprinkler systems have the highest irrigation efficiency compared to sprinkler or surface systems, ranging between 87.5 and 90% [125]. Pressurized surface and subsurface drip or micro-sprinkler irrigation systems improve irrigation efficiency but require more energy than surface flood or gravity irrigation [121,126]. Because there has been a nearly commensurate conversion in half of California's irrigated lands from surface flood or gravity systems to pressurized systems since 1972 [127], California's irrigation infrastructure has unfortunately increased its overall energy consumption while increasing its overall water use efficiency.

6.2. Science

There are opportunities for coupled energy and water conservation in agriculture through improving irrigation system efficiency, application efficiency, as well as crop water use efficiency. Agricultural pumping of irrigation water uses approximately 10 TWh of electricity per year [128], and at least 1 TWh or 10% of this usage could be conserved through improved control of water with better water metering and improved distribution uniformity [4]. Additionally, pumping reductions through science-based irrigation scheduling efforts on farm- or district-wide scales may also reduce energy consumption [123]. Additional energy savings may be available through increasing the pump efficiency to 55–65% and using variable frequency drives to facilitate changes in pump speeds when system pressure demands are not peaking [129]. Moreover, on-farm solar generation and solar or hybrid solar pumps can also curb peak energy demands that coincide with peak water demands [123].

Finally, either front loading pumping to on-farm water storage structures in advance of peak energy demand [123,130] or applying a larger magnitude of irrigation a week in advance of a predicted heat wave could mitigate peak energy usage during heat waves [126]. However, scheduling larger irrigation events in advance of a heat wave would have to ensure that soil properties facilitated storage rather than drainage of excess water. Similarly, deficit irrigation has been suggested for energy conservation; however, this would need to ensure that there either would not be a significant yield loss or that the yield losses would be low enough to justify an overall profit based on reduced energy and irrigation costs. Finally, there is an opportunity for collective and community-based action from irrigation districts and newly formed groundwater sustainability agencies to use and develop district-wide tools for common pool energy users to pump and store water in advance of peak times, as well as prioritize and optimize groundwater pumping based on the crop stage and need during droughts and heat waves [131].

6.3. Policy

The above coupled energy and water management measures require supportive policies and governance for success, in which California has made some promising progress. In response to the groundwater-pumping-related energy use and high greenhouse gas emissions during the megadrought of 2012–2016, California enacted the State Water Efficiency and Enhancement Program (SWEEP) in 2014, which is the first and largest program of its kind in the United States to date. The SWEEP program involves a competitive application process for growers to receive grants to make improvements that will reduce water and energy consumption, greenhouse gases, as well as improve drought resilience and air quality. Agricultural operations can receive grants for three project categories: (1) pump and motor enhancements, which include installing variable frequency drives and replacing or improving the efficiency of motors or pumps; (2) irrigation system enhancements for systems with pumps, which include system pressure reduction measures, soil moisture sensors, automating irrigation systems and IDSS; (3) fuel conversion and renewable energy, which include changing fuel types to low-carbon fuel, as well as the installation of on-site renewable energy sources to offset fuel use [132].

Applicants must quantify the baseline information about current energy, infrastructure efficiency and water use. Approximately one-third of applicants have been awarded SWEEP at a maximum of USD 100,000 for 18 months [133]. The awardees must use baseline water and energy data, as well as the SWEEP Irrigation Water Savings Assessment Tool and California Air Resources Board Greenhouse Gas Calculator tool, to quantify the projected water and energy savings. The SWEEP program has invested USD 80 million in over 800 projects for an annual water saving of 88,496 Megaliters and GHG reduction of 80,077 MTCO2e [134]. The program's challenges include the need for a stable, continuous funding source and increased accessibility for small and socially disadvantaged growers [133]. Specifically, although a third of projects have been located in disadvantaged communities, only 10% of the funds have gone to socially disadvantaged growers and ranchers [133,134]. Although the SWEEP program has incentivized and improved the irrigation system infrastructure and design for energy optimization, there is still a need and large opportunity for IDSS and training related to coupled water and energy management in California [133].

6.4. Decision Support for Irrigation and Energy Management

Although there has been an identifiable need for co-management of irrigation and energy, there is currently only one decision support tool deployed for this purpose in California. The California Energy Commission funded the research and development of AgMonitor [135]. AgMonitor integrates irrigation schedules based on the crop coefficient approach and monthly aerial imagery with flow metering and all on-farm energy sources and sinks. This IDSS provides information on irrigation magnitude and timing events that will also optimize energy conservation across a farm and has been validated in key Californian crops, such as processing tomato, almond, pistachio and alfalfa. Although commercially available IDSS are limited in this area, there are currently research-level IDSS in development to optimize irrigation applications with photovoltaic power production [136,137].

7. IDSS for Nitrogen (N) Management in California

7.1. General Considerations

California's intensive irrigated agricultural production has led to the use of large amounts of nitrogen (N) fertilizers. In contrast, N over-application has been associated with water pollution and various human health concerns [138]. More than 50 years of tradeoffs between the use of N fertilizer and the health of the environment have been documented in California [139,140]. Over the past years, the volume of inorganic N fertilizer used in the state has expanded dramatically. The annual sales between 1980 and 2001 have exceeded 600,000 tons of N [141].

A significant increase in the N fertilizer application rate was observed in the Sacramento Valley, San Joaquin Basin and Tulare Basin of the Central Valley for the period 2002–2012 compared to 1991–2001 [142,143]. Nitrogen loading in the Sacramento Valley, San Joaquin Basin and Tulare Basin saw a significant increase in 2002–2012 compared to 1991–2001 [138]. More than 740,000 tons of N fertilizer was loaded on roughly 2.7 million hectares of irrigated farmland in California. The excess N fertilizer leaches to groundwater and affects the quality of drinking water [144]. Improper management of N fertilization in California has contributed to the unsustainability of agricultural production and has threatened the health of Central Valley communities whose drinking water relies on groundwater resources.

7.2. Science

Crop N needs have been investigated to provide growers with tools to determine proper fertilizer applications. Numerous quantitative and complex decision-making tools have been consistently used to achieve improved nutrient management and irrigation. Online spreadsheet models and IDSS that process large amounts of information have been implemented by the University of California to help growers determine the appropriate amounts of N fertilizers to apply (Table 3) [82]. Early season leaf sampling in tree crops was developed to estimate N status in tree tissues and make adjustments in fertilizer timing and amount. Brown et al. [145] developed online spreadsheet models for managing N in almonds and developed the four Rs of N management (right rate, right time, right place, right source). The right rate consists of applying N in appropriate proportion to tree demand. The right time is the N application with the accurate timing with tree uptake, which starts at 70% leaf out and stops soon after harvest. The right place encompasses variable rate irrigation and N application to address in-orchard soil and yield variability as well as N application to the tree's active root zone or foliage. The right source refers to using the type of fertilizer that optimizes other nutrients and suits the crop and the environment [146]. The Soil Nitrate Quick Test (SNQT), developed for vegetables, provides an estimate of the soil mineral N status capable of offsetting a fraction of the total N required by a crop. Hartz et al. [147] developed N requirements for processing tomatoes in the Central Valley. Nitrogen application guidelines were later modelized to help growers optimize N application in processing tomato production [148] and across several key California crops [149].

Table 3. Principal decision support systems (DSS) for assisting with nitrate and salinity management of vegetable and tree crops in California.

IDSS Name	Operation Mode	Software Available	Reference
N management			
CropManage	Web-tool-based	https://cropmanage.ucanr.edu/ (accessed on 20 August 2021)	[82]
FARMS	Web-tool-based	https://ciswma.lawr.ucdavis.edu/ (accessed on 20 August 2021)	[81]
N budget calculator	Web-tool-based	http://fruitsandnuts.ucdavis.edu/N_Budget_Calculator/ (accessed on 20 August 2021)	[126]
Salinity management			
WARMF	Computer-based	-	[82]
SJRRTM	Web-tool-based	https://www.restoresjr.net/restoration-flows/water-quality/ (accessed on 20 August 2021)	[81]

7.3. Policy

To respond to California's nitrate issues, the State Water Board has evaluated the existing policies to determine if existing water regulations are sufficient and have improved the wastewater regulations to protect groundwater quality (www.cvsalinity.org (accessed on 20 August 2021)). The dischargers, such as growers, food processors, municipalities and ranchers, have to comply with new regulations (e.g., Salt and Nitrate Management Plan). Californian growers are under rising regulatory pressure to improve N use efficiency in agricultural production to decrease nitrate leaching. Therefore, they need the tools to accurately estimate crop N needs and availability to confidently adjust the N application rates. The federal and state agencies responsible for protecting air and water quality have been assessing the causes, consequences and costs of California's agriculture-wide N use. This concern explains the various regulatory initiatives, such as the Central Valley Regional Water Quality Control Board's Irrigated Lands Regulatory Program, the Central Coast Regional Water Quality Control Board's renewal process for the Irrigated Agricultural Lands Waiver, the Climate Action Reserve's N Fertilizer Reduction Protocol and the Central Valley Regional Water Quality Control Board's General Order for Dairy Waste Dischargers and the Central Valley Salinity Alternatives for Long-term Sustainability (CV-SALTS) program [150].

CV-SALTS is a collaborative program tasked to develop environmentally and economically sustainable management plans for nitrates and salts in the Central Valley. The Executive Committee encompasses diverse stakeholder groups, such as agricultural groups, cities, industry, regulatory agencies and community and environmental justice representatives. The Salt and Nitrate Management Plan (SNMP) developed by CV-SALTS is built on a range of existing water quality management policies. It proposes additional policies, mechanisms and tools to provide the Central Valley Water Board with the appropriate means for addressing the long-term loading of salt and nitrates in the different regions of the Central Valley. CV-SALTS is also tasked with developing an all-inclusive regulatory program with adequate strategies to address the management of salts and nitrates sustainably [151].

7.4. Decision Support for Irrigation and N Management

Numerous IDSS for irrigation + N have been developed by extension services, universities and other institutions involved in water management for states or regions [152]. Some IDDS that help manage N in CA include CropManage, Food, Agriculture, Resource Management System (FARMs) and the N Budget Calculator.

CropManage can help growers and farm managers determine watering and fertilizer N schedules on a field-by-field basis. All the required components to determine crop water needs, such as ET_o and weather data (from CIMIS), estimated K_c, as well as adequate irrigation scheduling based on soil properties, are available without the need for in-field sensors. CropManage is publicly available at: https://cropmanage.ucanr.edu/ (accessed on 21 August 2021). The software automates all steps required to calculate crop water requirements, including N recommendations, based on soil crop N uptake models, nitrate quick test values and credits for nitrate in irrigation water and preceding crop residues. CropManage also helps growers track irrigation and fertilizer schedules on multiple fields and allows data sharing among users from the same farming operations. The web-based application record-keeping capability allows growers to review water and N applications on each field and maintain data required to comply with water quality regulations. CropManage can be integrated with other web applications and data sources to improve the accuracy of irrigation and fertilizer models [82].

FARMs is a user-friendly geospatial web-based application that simplifies the use of the decision support system for agrotechnology transfer (DSSAT) model by automating processes such as weather, climate and soil input. FARMs was developed using DSSAT-CSM and open-source GIS software. FARMs allows adaptive management to perform in-season yield predictions using both weather and climatic data to evaluate the potential impacts of management decisions on end-of-season yield. FARMs uses NASA POWER weather data integrated through an API [153]. FARMs simulates nitrogen cycling of the cropping systems and quantifies crop N stress based on nitrogen uptake versus available nitrogen and is expressed as a range between 0 (no stress) to 1 (maximum stress). FARMs also simulates the probability of nitrate leaching from a given irrigation and N management strategy.

The N Calculator is a predictive model that helps growers by advising on the timing and the appropriate amount of N fertilizer to meet yield-based demand [145]. The N Calculator has many functions, including calculating fertilization rates based on the newest UC N management research, applying the four Rs of nutrient management (right source, right rate, right timing and right location), enabling efficient fertilizer use, calculating N supplies from non-fertilizer sources, such as cover crops groundwater and compost, and cloning the N budget from one orchard to another within and between years.

For example, using this tool for almonds requires entering a yield estimate for pre- and post-bloom and adding early season tissue-sampling results. The N Calculator helps to meet much of the nutrients management required from the Irrigated Lands Regulatory Program. The Irrigated Lands Regulatory Program requires keeping an Irrigation and N Management Plan (INMP) worksheet onsite and submitting a summary report to one's coalition in post-harvest time.

8. IDSS for Salinity Management in California

8.1. General Considerations

About 40% of global irrigated land is located in arid/semi-arid zones, and this irrigation is often associated with salinization [154]. With the development of intensive irrigation practices, the Central Valley of California has become one of the world's most productive farming regions. The continuously increasing levels of crop production are threatened due to the deteriorating irrigation water quality. Clay layers impeding percolation to deeper groundwater regions have led to salt accumulation in drainage water in many Central Valley regions. One of the primary sources of salts is the water supply imported from the Sacramento–San Joaquin River Delta. About 250 tons of salt a day are imported into the San Joaquin Valley through the state and federal water project canals [155]. The soils of the Central Valley's western regions are sedimentary and alluvial from the origin and formed in an uplifted seabed. The native salts have mineralized and leached to the shallow water tables over time due to irrigation and flooding [156]. In the predominantly clay and silty clay soil textures, as plants extract water from the soil and transpire, the salt concentration level of the drainage water is likely to increase. As a result, salts are likely to concentrate in the root zone and accumulate in shallow water tables through leaching [157]. Excessive salt concentrations affect a plant's osmotic balance and trigger a reduction in plant water uptake and stomata closing, which causes transpiration inhibition to occur [158]. The increasing soil salinity slowly and steadily contaminates water supplies and reduces crop production.

Various factors, such as drought, climate change, water shortages and land-use changes, could exacerbate the salinity conditions.

More than 1.8 million hectares of irrigated cropland in Central Valley (primarily in the San Joaquin Valley) are affected either through saline irrigation water or saline soils, and tens of thousands of hectares of productive agricultural land are at risk (Figure 1) [159]. Salt accumulation has triggered more than 99957 hectares to be taken out of agricultural production, and another 0.6 million hectares are considered damaged by salinity [155]. Current management activities address only 15% of the annual salt load [150]. The direct annual costs from increasing salinity will range from USD 1 billion to USD 1.5 billion, and total annual income impacts to the State of California are predicted to range between USD 1.7 billion and USD 3 billion by 2030 [160]. The income reduction in the Central Valley will range between USD 1.2 billion and USD 2.2 billion [160]. In 2014, salinity reduced California's agricultural revenues by USD 3.7 billion, amounting to 8.0 million tons of crop production lost [161].

8.2. Science

The U.S. Salinity Laboratory (1954) classified five cases of agricultural soil salinity: non-saline (0–2 dS m^{-1}), slightly saline (2–4 dS m^{-1}), moderately saline (4–8 dS m^{-1}), strongly saline (8–16 dS m^{-1}) and extremely saline (>16 dS m^{-1}) [162]. Although this salinity system is the most commonly used, many other classification systems of salt-affected soils exist and are available in the literature [163]. The presence of salt in soil water may affect plant growth either through salt-specific or osmotic effects. The salt-specific or ion-excess effect of salinity occurs when excessive salt amounts enter the crop, accumulate and damage the transpiring leaves' cells and trigger plant growth reductions. The osmotic or water deficit effect of salinity occurs when salt in the soil solution decreases the plant's water uptake ability and leads to a decrease in the crop growth rate [164]. Salinity stress affects all the major plant processes, such as germination, growth, water uptake and yield [165].

Salinity can be classified as natural or primary salinity and second-hand salinity or human-induced salinity. Primary salinity comes from salts accumulation over long periods of time via natural soil or groundwater processes. Two natural processes contribute to primary salinity. The first is the weathering process that breaks down rocks and releases various types of soluble salts, including chlorides (of sodium, calcium and magnesium), sulfates and carbonates. The passive results from oceanic salt that the wind carries inland are deposited in the soil by rainfall. Passive salinity occurs due to human activities, leading to the modification of the soil's hydrologic balance [165].

8.3. Policy

The increase in salts concentration in the California Central Valley due to many factors, including intensive irrigation, has led to crises and political decisions toward remediation. High concentrations of selenium were found in fish in Kesterson National Wildlife Refuge, and vast numbers of deformed and dead waterfowl were discovered at the refuge [166]. In 2006, the Central Valley Regional Water Quality Control Board's Salt and Boron Total Maximum Daily Load for the San Joaquin River was approved, and a salinity control plan entitled 'Actions to Address the Salinity and Boron Total Maximum Daily Load Issues for the Lower San Joaquin River' was adopted in response to the Salinity and Boron Total Maximum Daily Loads [156]. Solutions for addressing salinity in the Central Valley water require considering innovative salt management strategies for both the short term and the long term to reach salt balance and restoration of the impacted areas. In 2015, the State Water Resources Control Board adopted Resolution No. 2015–0010 to approve Basin Plan amendments and to include the Salinity Variance Program, which applies to surface water under the Clean Water Act (CWA). The Salinity Variance Program follows water quality standards that include the following constituents: electrical conductivity, total dissolved solids, chloride, sulfate and sodium [155]. Recognizing the challenges of managing salinity in surface and ground waters, the Salt and Nitrate Management Plan

(SNMP) was implemented as part of the Central Valley Salinity Alternatives for Long-Term Sustainability (CV-SALTS).

The long-term salinity management strategies recommended by the SNMP are divided into three different phases, as described below.

(i) Phase I focuses on developing a prioritization and optimization study for salinity management by using an interim salinity approach.
(ii) Phase II is related to environmental permits, obtaining funding, engineering and design.
(iii) Phase III consists of the implementation of physical projects to manage salt in the long term.

The interim salinity permitting approach is recommended by the SNMP to be set in place for 15 years. The interim salinity approach requires dischargers to participate in the prioritization and optimization study. However, the dischargers opting out of participating in the prioritization and optimization study would not be eligible for obtaining a variance under the Salinity Variance Program (https://www.cvsalinity.org (accessed on 29 August 2021)).

8.4. Decision Support for Irrigation and Salinity

Although there are not currently any California IDSS that also factor salinity management, there are several decision tools available to manage salinity in California. One of the water quality regulation tools used throughout the U.S. is the EPA-supported Total Maximum Daily Load (TMDL). The TMDL is a controlling tool for allocating responsibility for contamination in impaired waterbodies by assessing the assimilative capacity of the waterbody for the contaminant, determining the mass loading from non-point and point sources, which contribute to the pollution, and developing downstream water quality strategies reducing the excess of the pollutants in the waterbody. The implementation of the TMDL tool in the Central Valley of California has led to the development of decision support system tools, such as the Watershed Management Risk Management Framework (WARMF) and the San Joaquin River Real-Time Management (SJRRTM).

The Watershed Management Risk Management Framework (WARMF) model is a decision support system designed to guide stakeholders towards a comprehensive watershed management plan. The tool helps specifically to facilitate TMDL implementation at the watershed level. The embedded model uses a mass balance approach for an extensive suite of potential San Joaquin River pollutants, such as total dissolved solids (measured as EC), suspended solids, phosphates and nitrates. Models are also used to simulate agricultural and wetland drainage return flows and estimate the salts buildups from shallow groundwater. Components such as simulation models, graphical software and GIS software are incorporated into a graphical user interface (GUI) to easily visualize the model flow and salinity information. The WARMF model contains hydrologic routing that is capable of calculating flow and water quality at roughly one-mile intervals [156,167].

The SJRRTM is a web-based salinity DSS that combines WARMF and assimilative salt capacity forecasts information to increase stakeholder awareness of the unique opportunities and measures to improve water quality resource management in the San Joaquin River Basin. The decision support system was implemented using OpenNRM, an open-source software that systematically allows users to perform tasks such as creating, modifying and managing data and web content. One of the specific features of the SJRTM web portal has been the integration of WARMF model-generated flow with real-time SJR tributary flow and EC data with salt load assimilative capacity predictions [156].

In addition to decision support systems, various models are widely used for salinity management studies in the Central Valley. Models such as Westside Agricultural Drainage Economics (WADE) [168] and the Agricultural Production Salinity Irrigation Drainage Economics (APSIDE) [169] are examples of policy models used in the Central Valley. The APSIDE model has the specificity of simulating the agricultural production and projected income in response to irrigation water quality and drainage policy constraints [169].

9. IDSS for Irrigation System Management

Under increasing water deficit or drought conditions, distribution uniformity plays a critical factor in managing the available water efficiently while simultaneously improving and maintaining the yield and quality of specialty crops [170,171]. Distribution uniformity can be defined as the even distribution or spread of applied irrigation to avoid over- or under-watering at specific locations across the field. Non-uniform distribution can not only reduce the yield, but it affects the drainage, increases soil erosion risk through runoff, increases nitrate leaching and reduces the available nitrate content in the soil [172,173]. Under California's arid conditions, a reduced use of water and energy in the agricultural sector is largely dependent on efficient DU. Although it is impossible to attain 100% distribution uniformity, the goal is to maximize the uniform and efficient distribution of the applied irrigation water.

Application use efficiency is the ratio of the amount of water lost through evapotranspiration to the amount of water applied for crop production [174]. The joint initiative of the California Department of Food and Agriculture and Department of Water Resources has a goal of decreasing 1200–1220 ML of agricultural water use per year through on-farm efficiency improvements. The majority of California's crops are now cultivated using micro-irrigation systems, such as sprinkler, drip and subsurface drip irrigation. The distribution uniformity for drip and subsurface drip irrigation systems is determined by taking the ratio of average flow of the lowest quarter of emitters to all emitters sampled [130,175].

Decision support tools offer the potential for site-specific irrigation management, which optimizes distribution uniformity by delineating the fields into management zones [176,177]. The UCANR's Bilingual Emission Uniformity Calculator uses a bilingual (English and Spanish) interface with an Excel spreadsheet model to help growers calculate distribution uniformity based on emitter discharge measurements [178]. Using wireless sensor networks (soil and crop canopy-based), irrigation automation and telemetric control through mobile or cloud-based applications allows the growers to efficiently increase the distribution uniformity based on real-time data. Growers can use automation equipment to avoid over- or under-watering with remote access [179,180]. In California, many nut growers in the state are using an alternative method of determining transpiration uniformity rather than using distribution uniformity [181]. Transpiration uniformity describes the uniform loss of water from the field, in contrast to DU, which defines the spread across the field. Because transpiration is an indicator of plant metabolism, it can also be affected by nutrients, pests or soil heterogeneity, which would not be related to the uniformity of an application. Remote-sensing IDSS are useful in evaluating the distribution uniformity based on thermal and NDVI maps generated using multispectral imagery. In California, Ceres Imaging is widely used by orchard and vegetable growers to identify the water stress due to uneven distribution uniformity based on colorized NDVI and thermal maps, as shown in Figure 3. The identification of stressed areas at an early stage in a crop field allows growers to quickly identify, diagnose and correct irrigation system problems to avoid yield losses at the harvest stage.

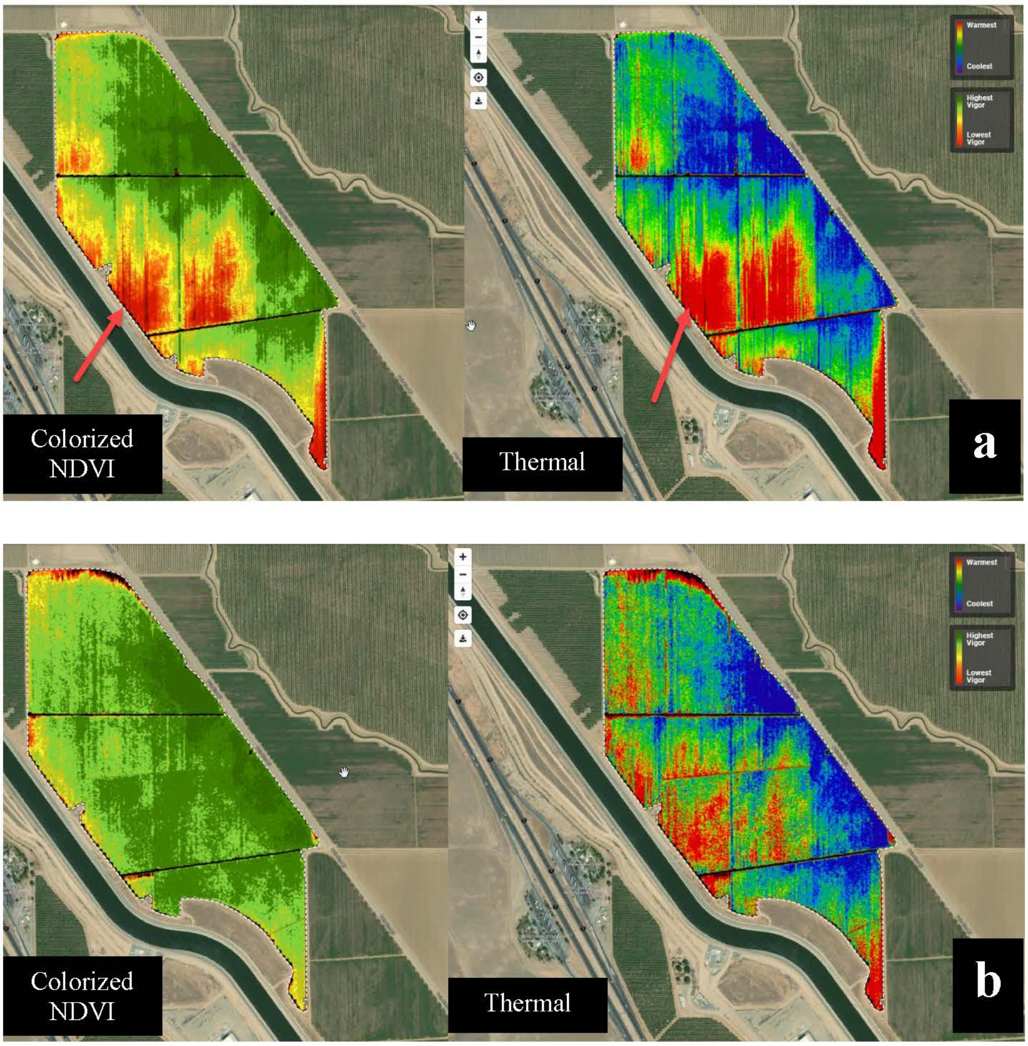

Figure 3. Remote-sensing imagery-based IDSS provided by Ceres Imaging Inc. (Oakland, CA, USA) for evaluating distribution uniformity using colorized NDVI and thermal maps. (**a**) Warmest areas of the field were under water stress and showed lowest vigor at early crop growth stage because of low dripline pressure due to topographical differences; (**b**) Increased pressure of driplines after identifying the stress led to more uniform distribution of water application with homogenous crop vigor saving an estimated yield worth USD 20,000.

10. IDSS Evaluation and Ongoing Work in California

In this rapidly growing field of products and services, detailed information on the utility, user friendliness, reliability, accuracy and precision of IDSS is of primary importance to the end user. The purpose of the Hub project is to evaluate the irrigation decision support systems to optimize irrigation water use efficiency and reduce energy use on farms for conveyance, pumping and distribution of irrigation water in California. The current evaluation of IDSS is based on scientific validation, user friendliness and inputs from advisory groups. User-friendly decision support tools are important for maximizing benefits by enhancing productivity and simplifying the spatiotemporal environmental parameters [182,183]. For IDSS, innovation, validation and adoption are cyclical, iterative processes engaged in by the agricultural technology industry, applied or Cooperative Extension researchers and growers (Figure 4). In the cyclical process of innovation–validation–adoption, it is helpful to form a project advisory group to achieve a more practical, secure and cohesive approach [179]. This user feedback is pivotal for implementing and improving new IDSS technologies [184]. The primary focus of the advisory group members is to assist in shaping the process of research that can simplify the later steps for adoption [185,186].

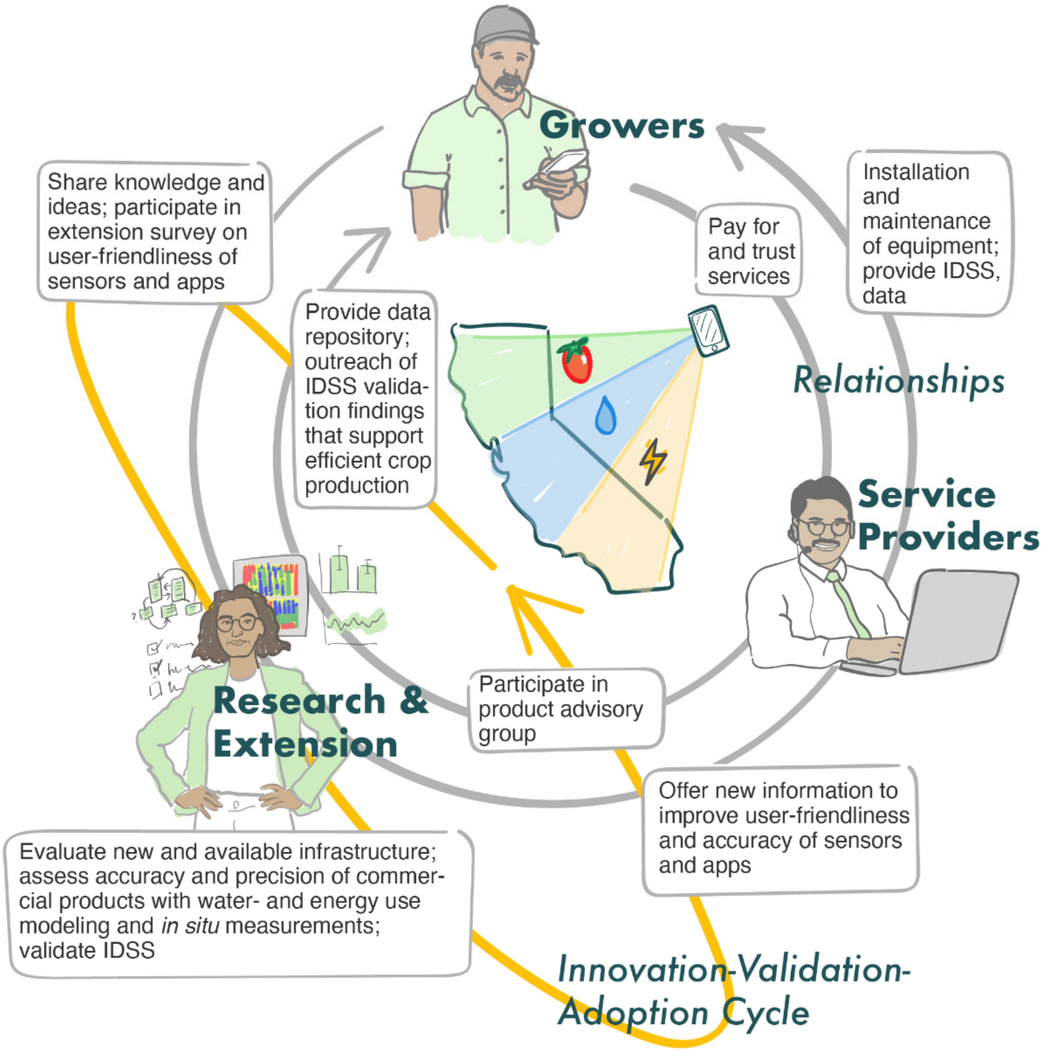

Figure 4. Innovation–adoption–validation cycle of irrigation decision support system. Artwork by Dr. Bonnie McGill.

Ideally, IDSS should be assessed for data accuracy, linearity, precision, response time and reliability [187,188]. This can be carried out using research-grade equipment with eddy covariance and neutron probe measurements of key water budget components, as well as estimates of leaf area index, to better understand and predict the K_c values. Different complexity may be required for different end users (i.e., farm manager versus irrigators). The system's user friendliness can be assessed by user interview or survey that generally focuses on: (a) graphic interface features, (b) graphic interface ease of use, (c) field placement decision support, (d) comprehensiveness, (e) update frequency, (f) reliability, (g) system value and (h) unanticipated costs [189,190]. In addition, the performance evaluation of IDSS is important based on soil and crop type. Performance evaluation should be based on statistical analysis and comparison based on root mean square error (RMSE), RMSE-observation-based standard deviation ratio (RSR), mean bias error and index of agreement [191].

11. Conclusions

Irrigation decision support systems (IDSS) may greatly benefit the >400 crops grown throughout the State of California to support diverse challenges, including drought, energy, nitrogen and salinity management. Here, we conducted a comprehensive review of existing IDSS available to California growers, their underlying science, incentive policies and anticipated outcomes. Effective energy, water, nitrogen and salinity management in California under regulatory policies, such as the Sustainable Groundwater Management Act, require the integration of different strategies to improve precision irrigation scheduling, uniform water and nutrient application, and the soil–plant–water monitoring. In addition to water management, these policies also aim to manage groundwater and require the record keeping of water use, nitrogen (N) leaching, salinity management and energy consumption. Most of the irrigation decision support tools used in California are based on fewer components of the water budget, and none of the available IDSS provide estimation of all parameters together. For example, soil-based IDSS consider soil water potential or volumetric water content, while crop canopy IDSS are based on crop evapotranspiration. These IDSS can potentially be used in combination to obtain the overall inflow and outflow of water to and from the soil–plant–atmospheric continuum of the crops. However, heterogeneity in agronomic and field soils can lead to poor management practices at certain locations in agricultural fields. Remote sensing IDSS are useful in determining the spatial scale information based on spectral data, but the interpretation of multispectral/thermal imagery is complicated and difficult for growers to base decisions for water, nutrient and salinity hotspots. In a nutshell, there has been an identifiable need for the co-management of irrigation decision support, nitrogen and salinity management and energy efficiency. The integration of IDSS for nexus benefits is a cyclical process of innovation by service providers/researchers, validation by extension research professionals and adoption by growers. Therefore, for a widescale adoption of these tools, the synergetic evaluation of point-based and spatial IDSS needs to be studied and validated on different scales (farm to county). Not only is the information presentation and availability important; the integration within the farm management hierarchy is equally significant. The recommended information on water, nitrogen, salts and energy management must be clearly and simply transmitted to and from farm managers to individual irrigators.

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Abbreviations

Nitrogen (N), ET_o (reference evapotranspiration over a grass surface), K_c (crop coefficient), ET_c (potential crop evapotranspiration based on ET_o and K_c), AWC (plant available soil water content), NDVI (Normalized Difference Vegetation Index).

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