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Field evaluations of the CropManage decision support tool for improving irrigation and nutrient use of cool season vegetables in California

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ABSTRACT

Vegetable growers on the central coast of California are under regulatory pressure to reduce nitrate loading to ground and surface water supplies. California also implemented legislation that limits agricultural pumping in regions such as the central coast where the aquifers have been over-extracted for crop irrigation. Growers could potentially use less N fertilizer, address water quality concerns, and conserve water by improving water management and matching nitrogen applications to the N uptake pattern of their crops. Two tools available to growers, the soil nitrate quick test (SNQT) and reference evapotranspiration (ETo) data have been previously shown to improve the management of water and fertilizer nitrogen in vegetable production systems. However, adoption of these practices has not been widespread. These techniques can be time consuming to use, and vegetable growers often have many crops to manage. To address such time constraints, the CropManage online application (cropmanage.ucanr.edu) was developed to facilitate implementation of the SNQT and evapotranspiration-based irrigation scheduling. CropManage additionally helps growers account for plant available N from background levels of nitrate in irrigation water. Trials were conducted in commercial vegetable fields in the Salinas Valley during 2012–2019 to evaluate CropManage fertilizer and irrigation recommendations relative to the grower practice. Results demonstrated that in many cases fertilizer or irrigation reductions could be attained by following CropManage recommendations without jeopardizing yield. In lettuce, the total fertilizer N applied under CropManage guidance was reduced by an average of 31 % compared to the grower standard practice. Lettuce yield within the CropManage treatment averaged 107 % of the grower practice. CropManage guidance in broccoli reduced N and applied water by 24 % and 27 %, respectively, compared to the grower standard practice, while average yield was similar between treatments. Management tools such as CropManage can support operational efficiencies and compliance with regulatory targets designed to improve groundwater quality.

1. Introduction

The central coast of California has a mild Mediterranean climate moderated by its proximity to the Pacific Ocean, and is a major producer of vegetables consumed in the US. Most medium to large vegetable production operations in this region produce two to three crops per field each season in small plantings ranging from 2 to 6 ha. Due to their high value, cool season vegetables are typically intensively fertilized and irrigated to attain maximum yield and quality. Hartz et al. (2007) reported that average applied fertilizer for lettuce in this region was 184 kg N ha^{-1} while plant uptake of N for crisphead and romaine lettuce averaged 130 kg ha^{-1} and 107 kg ha^{-1}, respectively (Breschini and Hartz, 2002). Several studies in California have documented that 40–50 % of the above-ground biomass of lettuce and 65–75 % of the above-ground biomass of broccoli remains in the field as residue after harvest (Bottoms et al., 2012; Mitchell et al., 1999; Smith et al., 2016). After being tilled into the soil, crop residues typically breakdown rapidly and mineralize to release significant amounts of nitrate-N (Hartz, 2020; Mitchell et al., 1999; Smith et al., 2016). Residual soil nitrate from fertilizer and from crop residues can be easily leached during irrigations and rain events during the winter. As many as one third of coastal valley wells have nitrate concentrations exceeding the US EPA drinking water standard of

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10 mg L^{-1} N due in part to decades of intensive vegetable production (Harter et al., 2012). Additionally, extraction of groundwater for irrigation has led to saltwater intrusion into coastal aquifers (Monterey County Water Resources Agency MCWRA, 2017).

Growers on the central coast currently face water quality regulations that will restrict the use of nitrogen fertilizer. The Agriculture Order adopted by the Central Coast Regional Water Quality Control Board CCRWQCB (2021) requires that growers estimate nitrogen loading to groundwater through annual reports of applied nitrogen and nitrogen removed in harvested product. The Order sets limits on how much loading of nitrate to the groundwater will be allowed in the future. Additionally, the Sustainable Groundwater Management Act, passed by the state legislature after the drought in 2014, will possibly limit pumping in Salinas Valley sub-basins where groundwater has been severely depleted (Salinas Valley Basin Groundwater Sustainability Agency SVBGSA, 2022).

Growers could potentially use less N fertilizer, address water quality concerns, and conserve water by improving water management and matching nitrogen applications to the N uptake pattern of their crops. Two tools available to growers, the soil nitrate quick test (SNQT) and reference evapotranspiration (ETo) data from the California Irrigation Management Information System (CIMIS) (Hart et al. 2009), have been shown to help better manage water and fertilizer nitrogen in vegetable production systems. The SNQT was introduced to central coast vegetable growers in the early 2000s (Hartz et al., 2000; Breschini and Hartz, 2002) and ET-based irrigation scheduling, which can inform the timing and volume of irrigation events, was made possible on the central coast with the establishment of a network of CIMIS weather stations in the 1990s (Temesgen et al., 2005). However, implementation of these tools by vegetable growers has not been widespread. One reason may be that these techniques can be time consuming to use, and vegetable growers typically have many crops for which they make daily decisions on fertilization, irrigation, pest control, and tillage. To address the time constraints in managing water and fertilizer on a field-by-field basis, a freely available web-based decision support service (DSS), called CropManage (CM) (cropmanage.ucanr.edu) was developed to facilitate implementation of the SNQT and ET based irrigation scheduling (Cahn et al., 2015, 2022). Additionally, CM enables growers to account for the N fertilizer contribution from background levels of nitrate in their irrigation water, and maintain records of water and fertilizer applications for regulatory compliance.

Prescriptive DSS could potentially help conserve water supplies and address nitrate contamination of groundwater if adopted on a large scale in vegetable production regions such as the central coast. A number of DSS have been developed for irrigation scheduling in the US and Europe (Cahn and Johnson, 2017; Gallardo et al., 2020). Examples are SmartIrrigation (Migliaccio et al., 2016), WISE (Bartlett et al., 2015) and Irrigation Scheduler (Peters et al., 2016) in the US. Examples in Europe include Irrigation-Advisor (Mirás-Avalos et al., 2019) (Spain), ISS-ITAP (Montoro et al., 2011) (Spain), IRRINET (Mannini et al., 2013) (Italy), and Irrigasys (Simionesi et al., 2020) (Portugal). In addition, a number of DSS have been developed for prescribing N fertilizer such as N-Expert (Feller, 2015) (Germany), Azofert (Machet et al., 2017) (France), and Planet (DEFRA, 2014) (England, Wales, Scotland). However, few DSS, such as CropManage, have combined both irrigation and N management decision support, and have been calibrated for vegetable production (Gallardo et al., 2020). In Europe VegSys (Gallardo et al., 2011) is a prescriptive DSS developed at the University of Almeria, Spain originally for irrigation and nutrient recommendations of greenhouse vegetables, and more recently expanded to open field grown vegetables (Giménez et al., 2019). Fertirrigere (Battilani, 2006) has been calibrated for irrigation and macro nutrient management of processing tomatoes in Italy. GesCoN (Elia, Conversa, 2015) was developed at the University of Foggia, Italy for water and fertigation management of open field vegetable production.

Since the initial CM release, efforts to gain grower adoption have included introductory presentations at industry meetings and intensive hands-on trainings. These outreach activities combined with expansion of supported crop types and improved model accuracy have helped widen acceptance of CM as a decision support service in the vegetable industry. As of the end of 2022, CM had approximately 3300 user accounts, and the online service has provided more than 63,000 irrigation and 20,000 fertilizer recommendations since 2011.

Another aspect to achieving grower adoption of CM is through field trials on commercial farms, designed to formally compare fertilizer, water application, and yield under CM and grower practices in adjacent large plots. This paper presents results of twenty large-scale trials conducted in commercial broccoli, crisphead and romaine lettuce fields to test the hypothesis that CM guidance can reduce fertilizer N and/or water applications relative to the grower's standard (GS) practice while producing similar yields.

2. Material and methods

2.1. Software description

CropManage is a database driven web application, currently hosted on Amazon Web Service at https://cropmanage.ucanr.edu (Cahn, 2022). It was initially developed in 2008 as a spreadsheet program and first launched to the public as a web-based service in 2011 (Cahn et al., 2013, 2015) and has since undergone several major updates to stay current with advances in online software technology. Users can access CM through a web browser on their smart phone, tablet, laptop or desktop computer. The user-interface was developed in concert with collaborating growers and designed for intuitive navigation. Multiple users from the same farming operation can view farm and planting information. A designated farm "owner" decides which users have access to the information, as well as the level of access.

To begin using CM, growers follow an onboarding routine to securely enter and archive information about their farms, such as locations of fields, soil types, N concentration of the irrigation water, fertilizer types, and source of weather data. CM uses open source web services, such as Google Maps and UC Davis SoilWeb to facilitate this process. The user selects the crop type and field location, and enters the planting and expected harvest dates, as well as information about the irrigation system. The user can adjust soil property and crop development parameters for entered plantings. A structured query language (SQL) database, which manages information associated with farms and plantings, is used to drive the irrigation and N fertilizer decision support modules. The database minimizes the need for re-entry of information each time an irrigation or fertilizer application is made.

CM automatically retrieves reference ET data from CIMIS and uses a crop coefficient model based on canopy development (Gallardo et al., 1996; Allen and Pereira, 2009) to estimate crop water requirements. Users can choose to associate multiple nearby weather stations with their farm or use gridded data from spatial CIMIS. Cahn et al. (2022) summarized the irrigation equations used in CM, which are based on Gallardo et al. (1996) and FAO 56 (Allen et al., 1998). Briefly, a crop coefficient model is used to estimate the transpiration and soil evaporation components of crop evapotranspiration (ETc). The transpiration coefficient is related to development of canopy cover using the equations:

$$Fc = Cmax/(1 + \exp(A + B*DAP/(Maxday*MaxFc)))/100 \quad (1)$$

where Fc is the fraction of ground covered by the crop canopy, Cmax is the expected maximum percent cover of the canopy, DAP is days after planting, A and B are fitted parameters that are specific to crop type and planting configuration, and Maxday is total days between planting and end of crop (harvest). Maxday can be adjusted to account for crop cycle variation due to time of year, and is a number typically known to growers with reasonable certainty for specific varieties and planting dates. The model converts canopy cover to a transpiration coefficient (T):

$$T = C^*Fc + D^*Fc^2 \quad (2)$$

where C and D are fitted parameters specific to the crop type. This equation derives from a relationship between field crop daily transpiration rate and solar radiation interception, which is strongly related to Fc, as proposed by Gallardo et al. (1996). Parameter values for Eqs. 1 and 2 in broccoli, romaine, and crisphead lettuce are presented in Table 1.

A soil evaporation coefficient (Ke) represents the daily soil evaporation component of ETc. For sprinkler irrigation and rainfall, which wet the entire field surface, Ke is set to 1.0 on the day of the event, 0.4 the following day, 0.05 two days post-event, and zero thereafter. For surface drip irrigation, which wets less than 30 % of the soil surface, Ke values are 0.3 on day of the event, 0.1 the following day, 0.05 two days post-event, and zero thereafter. As a simplification, CM then sets daily Kc to the greater of T and Ke:

$$Kc = \max(T, Ke) \quad (3)$$

Estimated crop ET is calculated by summing daily ETc values since the last irrigation or significant rain event capable of saturating the soil to the depth of the root zone. Estimated ETc minus rainfall is automatically converted to an irrigation runtime based on user-entered information on the application rate, uniformity of the irrigation system, and a desired leaching fraction for salinity control as described by Cahn et al. (2022).

Fertilizer N recommendations for vegetables are based on comparing soil nitrate test values with a threshold for optimal growth and by estimating future crop N needs using N uptake demand curves. Crop N uptake of many cool season vegetables has been extensively researched during the past decade through field sampling of commercially grown crops (Bottoms et al., 2012; Smith et al., 2016). CM estimates crop N uptake using the equation:

$$CropNi = \frac{TotN^*a}{1 + e^{-\left(\frac{fsi - yo}{b}\right)}} \quad (4)$$

Where CropN is N (kg ha^{-1}) in aboveground biomass on day *i*, TotN is the total N in the aboveground biomass at crop maturity (harvest), *fs* is the fraction of the season and varies between 0 at planting and 1 at maturity, and *a, b,* and *yo* are fitted parameters in Table 2. Future N uptake is estimated from the difference in crop N uptake between day *i* and *i+fertilizer interval* using Eq. 5:

$$\text{Future N uptake} = CropN_{i+\text{interval}} - CropN_i \quad (5)$$

where *i* is the day of the fertilizer application, and *fertilizer interval* is the number of days between fertilization events.

The soil nitrate sufficiency thresholds employed by CM vary during the season to correspond with the development stage and N uptake rate of the crop. The thresholds generally begin low during the early season when crop N uptake is lowest, and plateau at a maximum value midway through the crop cycle, and then subsequently decrease as the crop reaches maturity (Table 2). By comparing a soil nitrate test value taken before a planned fertilizer application with the soil N threshold, the estimated N requirements of the crop can be adjusted as needed. The N fertilizer recommendation is also adjusted for N available in irrigation water, and N mineralized from soil organic matter and incorporated crop residues. Fig. 1 illustrates how CM calculates an N fertilizer recommendation, first using the Eqs. 4 and 5 for estimating future crop N uptake, and secondly crediting for soil nitrate and nitrate in irrigation water. Users retrieve a recommended fertilizer rate by entering the date of a planned fertilizer application, an approximate interval of days to the next planned fertilizer application, and select a desired formulation of fertilizer N. The recommendation is provided in units of nitrogen (kg N ha^{-1}) or units of fertilizer (kg ha^{-1}, L ha^{-1}).

Additional features of the CM decision support service include automatic retrieval of fractional cover estimates from NASA's Satellite Irrigation Management Support (SIMS), which are based on normalized difference vegetation index data derived from Earth-observing satellite imagery (Johnson and Trout, 2012; Melton et al., 2012; Pereira et al., 2020). The user can then compare fractional cover estimates from SIMS with a modeled canopy development curve for a planting and change the parameters of the curve to better fit actual field conditions. CM also supports automated collection and posting of data from soil sensors and flowmeters that may be installed in a field to monitor water application volumes and soil moisture. The sensors serve to confirm accuracy of water applications and are not required to obtain an irrigation recommendation or otherwise operate the model. CM includes visualization graphics for displaying a calculated soil water balance over the season based on methodology outlined in FAO 56 (Allen et al., 1998), and for comparing actual applied water or nitrogen fertilizer with the recommended amounts. The software supports an application programming interface (API) so that data can be directly imported and exported to and from third-party software.

2.2. Commercial-scale field trials

Twenty large scale field trials were conducted in commercial broccoli *(Brassica oleracea* var. *italica)*, crisphead *(Lactuca sativa* var. *capitata)* and romaine lettuce *(Lactuca sativa* var. *longifolia)* fields across 17 farms in the Salinas Valley between 2012 and 2019 (Table 3). Soil textures varied from sandy loam to clay loam among field sites (Table 3). Total reference ET and precipitation were calculated for each crop using data available from the CIMIS station closest to the trial sites (Table 3). These trials served to both validate and refine the CM algorithms and to

Table 1
Canopy cover and transpiration coefficient parameter values used in Eqs. 1 and 2 for broccoli, crisphead and romaine lettuce.

Crop type	Eqn. [1] parameter values					Eqn. [2] parameter values	
	Cmax[w]	Totday[x]	MaxFc[y]	A	B	C	D
	%	days					
Broccoli summer, 2 rows, 1-m bed[z]	98	88	0.78	6.736	-11.847	1.75	-0.65
Broccoli winter, 2 rows, 1-m bed	89	137	0.78	5.676	-8.493	1.75	-0.65
Crisphead lettuce summer, 5 rows, 2-m bed	85	65	1	6.825	-12.770	1.5	-0.39
Crisphead lettuce summer, 6 rows, 2-m bed	85	65	1	8.234	-14.110	1.5	-0.39
Crisphead lettuce summer, 2 rows, 1-m bed	80	65	1	6.780	-11.610	1.5	-0.39
Romaine lettuce summer, 2 row, 1-m bed	80	64	1	6.200	-11.500	1.5	-0.39
Romaine lettuce summer, 5 row, 2-m bed	85	64	1	6.500	-10.830	1.5	-0.39
Romaine lettuce summer, 6 row, 2-m bed	85	64	1	6.200	-11.976	1.5	-0.39

[w] Maximum canopy cover at crop maturity
[x] Total days to harvest
[y] Fraction of season to reach maximum canopy
[z] Summer maturing broccoli planted in 2 rows on 1-m wide beds

Table 2
Crop N uptake parameters in Eq. 4 and seasonal soil nitrate sufficiency thresholds for broccoli, crisphead and romaine lettuce.

Crop type and planting configuration	TotN[w]	a[x]	b	yo	Days to harvest	Early N threshold (fs[y] = 0)	Mid-season threshold	Late season threshold (fs = 1)	Beginning of mid threshold	End of mid threshold
	kg ha^{-1}					———— ppm NO_3-N ————			– fraction of season –	
Broccoli summer, 2 rows, 1-m bed[z]	377	1.084	0.129	0.697	88	15	20	10	0.15	0.60
Broccoli winter, 2 rows, 1-m bed	279	2.205	0.148	1.027	137	15	20	10	0.15	0.60
Crisphead lettuce summer, 5 or 6 rows, 2-m bed	146	1.109	0.110	0.767	65	15	20	15	0.20	0.75
Crisphead lettuce summer, 2 rows, 1-m bed	168	1.017	0.075	0.719	65	15	20	15	0.20	0.75
Romaine lettuce summer, 2 row, 1-m bed	134	1.202	0.110	0.828	64	15	20	15	0.20	0.75
Romaine lettuce summer, 5 or 6 row, 2-m bed	162	1.116	0.114	0.763	64	15	20	15	0.20	0.75

[w] Total N in above ground biomass at crop maturity
[x] a, b, and yo are parameters in Eq. 1
[y] fraction of season
[z] summer maturing broccoli planted in 2 rows on 1-m wide beds

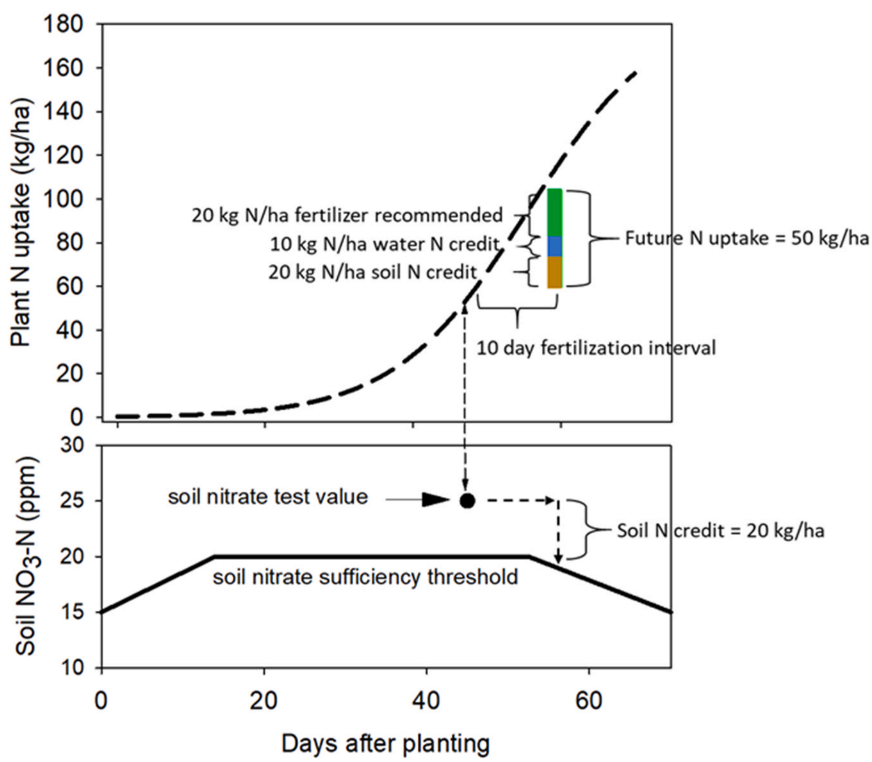

Fig. 1. Fertilizer N recommendation (20 kg N ha^{-1}) is calculated by using Eq. 1 for estimating future crop N uptake (50 kg N ha^{-1}) during a 10-day interval and crediting for available mineral N in soil (20 kg N ha^{-1}) and irrigation water (10 kg N ha^{-1}).

demonstrate best-practices to growers in terms of potential reductions in nitrogen fertilizer and/or water application. The SNQT was used to monitor nitrate concentration in the root zone of the crops. A composite sample of the 0–30 cm was collected 1–2 days before fertilization events and the nitrate values were entered into CM to generate a fertilizer recommendation. Soil samples were collected after harvest to evaluate residual soil N in the profile for the 0 – 30 cm depth at the lettuce trial sites and the 0 – 90 cm depth at the broccoli sites. Trials presented in this paper were conducted in large plots (0.1–0.5-ha), where treatments were not replicated. The experimental objective of each trial varied depending on the participating grower's interest and site limitations. At some sites the CM recommendations for both N fertilizer and water were compared with a grower standard (GS). At other sites, either water or N fertilizer recommendations from CM were compared with GS. CM and GS treatments were established in adjacent plots within the same field and were usually more than 12-m wide and the length of the field to accommodate evaluation of marketable yield using commercial equipment and professional harvest crews. Lettuce trials were harvested in a single pass and broccoli trials were harvested in 2–3 passes, at 4–5-day intervals. Water and nitrogen fertilizer applications were applied to plots separately. Flowmeters (Seametrics AG2000, Kent, WA, USA) interfaced with a datalogger were installed on the mainline of the irrigation system of each treatment plot to automatically retrieve and post irrigation events in CM. All irrigation and fertilizer applications and soil

Table 3
Summary of field trial sites comparing CM and GS treatments. Plot size of treatments ranged from 0.1 to 0.5 ha. Reference ET (ETo) and precipitation values represent totals from the CIMIS station closest to each site summed from planting to harvest.

Site number	Crop	Bed width (m)	Plant date	Harvest date	Irrigation method	Soil	ETo (mm)	precip.[y] (mm)
1	broccoli	1	6/20/2013	9/11/2013	sprinkler/drip[x]	Salinas clay loam	388	0
2	broccoli	1	7/3/2013	10/9/2013	sprinkler/drip	Cropley silty clay	410	0
3	broccoli	1	5/14/2015	8/11/2015	sprinkler/drip	Elder sandy loam	489	0
4	broccoli	1	7/28/2015	10/29/2015	sprinkler/drip	Mocho silty clay loam	390	0
5	broccoli	1	8/21/2017	11/18/2017	sprinkler/drip	Pico fine sandy loam	316	10
6	head lettuce	2	6/28/2012	9/5/2012	sprinkler	Mocho silty clay loam	346	0
7	head lettuce	2	8/11/2012	10/7/2012	sprinkler/drip	Chualar loam	225	0
8	head lettuce	1	8/3/2013	10/18/2013	sprinkler/drip	Elder sandy loam	314	4
9	head lettuce	1	4/11/2014	6/16/2014	sprinkler/drip	Pacheco clay loam	220	14
10	head lettuce	1	4/18/2014	6/29/2014	sprinkler/drip	Mocho silt loam	422	0
11	head lettuce	1	3/11/2016	5/19/2016	sprinkler/drip	Gorgonio sandy loam	244	39
12	head lettuce	1	4/2/2016	6/9/2016	sprinkler/drip	Elder sandy loam	286	12
13	head lettuce	1	7/1/2017	8/28/2017	sprinkler/drip	Gorgonio sandy loam	273	0
14	head lettuce	1	8/3/2017	10/16/2017	sprinkler/drip	Salinas clay loam	359	1
15	head lettuce	1	3/30/2018	6/14/2018	sprinkler/drip	Mocho silty clay loam	448	5
16	romaine	1	8/10/2012	10/20/2012	sprinkler/drip	Cropley silty clay	267	0
17	romaine	1	7/16/2013	9/24/2013	sprinkler/furrow	Salinas clay loam	305	2
18	romaine	2	7/20/2013	9/19/2013	sprinkler/drip	Chualar loam	270	0
19	romaine	1	3/27/2017	5/31/2017	sprinkler/drip	Cropley silty clay	267	20
20	romaine	1	8/31/2019	11/14/2019	drip	Pico fine sandy loam	260	3

[x] crop established using sprinklers and irrigated post-establishment until harvest with drip
[y] precipitation

test results for the treatments were archived in CM. Irrigation methods included sprinkler, surface drip, and furrow, but at most sites the crops were established with sprinklers and irrigated by drip thereafter. Early in the crop cycle applications of nitrogen fertilizer were made by tractor. Subsequent nitrogen fertilizer applications were made by fertigation after drip systems were installed and operational. All fertilizer was applied by tractor at sites exclusively irrigated by sprinkler or furrow. The fertilizer source and application method (placement) were always the same for the CM and GS treatments. Timing of applications sometimes varied between treatments depending on the results of the SNQT.

Relative yield was calculated for the CM treatment compared to the GS treatment to normalize for yield variation among sites. Marketable yield, relative yield, and soil nitrate-N values at harvest for CM and GS were statistically compared using SAS 9.4 (SAS Institute Inc., Cary, NC, USA) general linear means procedure, where each site was considered a replication of the CM and GS treatments. Treatment main effects and treatment × year interactions were evaluated for statistical significance at the $p \leq 0.05$ level. The interaction term between treatment × year was not found to be statistically significant for marketable yield, relative yield, and soil nitrate-N and therefore only the main effects of the treatments are discussed in the results section. Student's t-test contrasts were performed to determine if CM and GS treatments were statistically different at the $p \leq 0.05$ level.

For comparative purposes, a survey of N use data for broccoli and lettuce produced in the region from 2014 to 2017 was obtained from the CCRWQCB through a public information request. A total of more than 500 farms were included in the broccoli analysis and more than 400 farms in the lettuce analysis. The dataset was sorted by crop type and year, and summarized using the frequency analysis function in Excel Microsoft Office. Data from each farm represented the average reported fertilizer N rate applied to broccoli, crisphead and romaine lettuce crops for the corresponding year.

Table 4
Applied water, N fertilizer, and yields of large-scale commercial field trials in broccoli comparing CropManage (CM) recommendations with a grower standard practice (GS). Trial objectives are noted as nitrogen management (N), water management (Water) or both (Water/N). Statistical differences between treatment means for soil nitrate-N, marketable yield, were evaluated using a t-test. Means with different letters are statistically different at the p ≤ 0.05 confidence level.

Site #	Objective	Treatment	Applied water: Total	Applied water: Post Establishment	Applied N	Soil nitrate-N at harvest[x]	Marketable Yield	Relative Yield
			mm	mm	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	%
1	Water	CM	517	328	186	204	16,523	105
		Grower	850	662	186	26	15,699	100
2	Water	CM	497	385	209	93	20,382	97
		Grower	898	786	209	54	20,930	100
3	Water/N	CM	519	411	172	16	12,897	93
		Grower	587	479	190	6	13,934	100
4	N	CM	478	356	132	332	7746	96
		Grower	478	356	231	261	8068	100
5	Water/N	CM	323	243	185	23	13,067	97
		Grower	381	311	223	38	13,472	100
Average		CM	466	345	177	134 a	14,123 a	98 a
		Grower	639	519	208	77 a	14,421 a	100 a

[x] total nitrate-N in the 0 − 90 cm soil layer

3. Results and discussion

3.1. Broccoli field trials

The broccoli trials demonstrated that guidance from the decision support service can reduce nitrogen fertilizer and water application without jeopardizing yield. Average seasonal water use of the CM treatment was 27% below GS across the five broccoli field trials (Table 4). During the post-establishment phase, which was when CM recommendations were implemented, average applied water for the CM treatment totaled 345 mm, which was 34 % less than the GS average. By comparison, a two-year replicated trial conducted on a USDA research farm in the Salinas Valley reported that 236–272 mm of water applied post-establishment following CM recommendations maximized broccoli marketable yield (Johnson et al., 2016). Hence additional opportunity to further reduce water applications during the post-establishment phase of the commercial trials, without jeopardizing yield, may have been possible. However, because these commercial field trials relied on the growers' staff to manage irrigations, closely following the CM recommendations was not always possible due to other field operation priorities, such as pest control sprays and weed cultivation, and the irrigation crew was not always available to run the irrigation system at the optimal time. While the average applied water was higher in the CM treatments than what was reported by Johnson et al. (2016), a key benefit of the commercial field trials is that they benchmark reductions in applied water that are achievable when CropManage is used within the constraints of commercial production conditions.

In the three trials (sites 3,4,5) where nitrogen applications were also guided by CM, fertilizer N use was reduced by 24% relative to GS. The average rate of fertilizer N applied in the GS at the five broccoli sites (208 kg N ha^{-1}) was substantially less than the typical amount of N that broccoli takes up in the above ground biomass. Smith et al. (2016)

Table 5
Applied water, N fertilizer, and yields of large-scale commercial field trials in lettuce comparing CropManage (CM) recommendations with a grower standard practice (GS). Trial objectives are denoted as nitrogen management (N), water management (Water) or both (Water/N). Statistical differences between treatment means for soil nitrate-N, marketable yield, were evaluated using a t-test. Means with different letters are statistically different at the $p \leq 0.05$ confidence level.

				Applied water			Soil nitrate-N at harvest[x]		
Site #	Objective	Crop	Treatment	Total	Post Establishment	Applied N		Marketable Yield	Relative Yield
				mm		kg ha^{-1}			%
6	N	crisphead	CM	511	248	161	75	73,658	102
			Grower	511	248	206	–[y]	72,082	100
7	N	crisphead	CM	203	123	167	304	21,028	98
			Grower	203	123	237	406	21,425	100
8	N	crisphead	CM	345	108	69	89	43,081	117
			Grower	335	99	139	266	36,726	100
9	N	crisphead	CM	122	59	30	47	23,152	107
			Grower	122	59	60	64	21,705	100
10	N	crisphead	CM	511	294	132	45	12,705	128
			Grower	511	294	280	112	9932	100
11	Water/N	crisphead	CM	191	128	156	35	61,305	102
			Grower	213	156	173	101	60,050	100
12	Water/N	crisphead	CM	376	135	36	75	46,998	99
			Grower	401	160	69	50	47,512	100
13	Water/N	crisphead	CM	231	126	8	144	50,169	108
			Grower	201	95	71	259	46,547	100
14	Water/N	crisphead	CM	431	207	132	121	30,471	121
			Grower	450	225	174	194	25,232	100
15	N	crisphead	CM	597	246	103	63	44,852	96
			Grower	546	196	174	108	46,513	100
16	Water/N	romaine	CM	234	96	198	112	20,613	103
			Grower	282	126	198	112	20,103	100
17	N	romaine	CM	371	194	182	96	17,535	98
			Grower	371	194	295	373	17,874	100
18	N	romaine	CM	257	103	80	178	30,303	109
			Grower	257	103	108	178	27,914	100
19	N	romaine	CM	213	112	143	67	45,413	110
			Grower	218	116	135	56	41,285	100
20	N	romaine	CM	183	97	144	49	30,463	105
			Grower	175	84	215	131	28,907	100
Average			CM	318	152	116	100 a	36,783 b	107 b
			Grower	320	152	169	172 b	34,920 a	100 a

[x] total nitrate-N concentration in the 0–30 cm soil layer
[y] missing data

reported that broccoli grown in the Salinas Valley accumulated an average of 367 kg N ha^{-1} in the above ground biomass during an 84-day growth cycle and that growers applied an average of 209 kg N ha^{-1}. The analysis of applied N data reported by growers to the CCRWQCB showed that an average of 229 kg N ha^{-1} was applied as fertilizer to broccoli at vegetable farms in the central coast region from 2014 to 2017. The shortfall between N supplied by fertilizer and N accumulated in the above ground biomass was likely supplied by the root system accessing soil N mineralized from incorporated crop residues of the previous vegetable crop and the ability of broccoli roots to grow to a 1-m depth which allows the crop to uptake nitrate that may have leached earlier in the season (Smith et al., 2016). By evaluating soil N status before fertilizer events, additional savings in N fertilizer were attained under the CM treatment, which averaged 163 kg N ha^{-1} for sites 3, 4, and 5. Improved water management may have also helped retain nitrate-N in the root zone during the season. On average, a greater amount of soil mineral N remained in the profile of the CM treatment compared to the GS at harvest, although the treatments were not statistically different (Table 4).

Despite applying less N and water on average, broccoli yields of the CM treatment were not statistically different than the GS practice (Table 4). CropManage plots averaged 98 % of the GS yield. The interaction between treatment and year was also not statistically significant, which would suggest that there was no substantial effect of year on treatments.

3.2. Lettuce field trials

Water management was an objective of 5 of the 15 lettuce trials (Table 5). In four of those trials, applied post-establishment water of the CM treatment averaged 15 % less than the GS treatment. In the fifth trial (site 13) there were few opportunities to reduce irrigation volumes because the applied water of the GS was less than estimated crop ET.

Across all 15 lettuce trials, the average total applied water volumes were similar between the CM and GS treatments (Table 5). Average volume during the post-establishment phase (152 mm) was within the 119–183 mm range reported for the CM treatment in replicated irrigation trials previously conducted in the Salinas Valley for crisphead and romaine lettuce (Johnson et al., 2016; Cahn et al., 2022), demonstrating that on average water was managed efficiently after crop establishment for both treatments. In contrast, the establishment phase of the crop used an average of 168 mm. Since plant transpiration is lowest during establishment, there may be additional opportunities to apply less water during this early phase. For instance, Cahn et al. (2022) reported using 82 mm for sprinkler establishment of romaine lettuce and Johnson et al., 2016 reported 104–112 mm for sprinkler establishment of crisphead. It should also be noted that at site 15 an operator error was made on one of the early post-establishment events in the CM treatment, and an additional 50 mm of water was applied. The average total water applied for all sites (~320 mm) was at the low end of the 300–450 mm range reported for lettuce produced commercially in the Salinas Valley (Smith et al., 2011), which would suggest that water was reasonably well managed in both treatments.

An average of 31% less fertilizer N was applied in the CM treatment compared to GS. Applied fertilizer N in the CM and GS treatments averaged 116 and 169 kg N ha^{-1}, respectively (Table 5). The average N fertilizer applied to the CM treatments was somewhat less than the amount of N taken up by lettuce in the aboveground biomass, which typically ranges from 134 to 156 kg ha^{-1} (Bottoms et al., 2012). Fertilizer savings in CM were mainly achieved by crediting for residual mineral N in the root zone of the soil and N available from irrigation water. Mineral N concentrations in irrigation water applied to sites 9 – 15, 19, and 20 ranged from 17 to 84 mg L^{-1} N. In some trials (sites 8, 9, 12, 13, 18), the GS fertilizer N rate may have been lower than is typically used by the industry because the cooperating growers were intentionally experimenting with reduced fertilizer N applications. The average N fertilizer rate for lettuce reported to the CCRWQCB by growers on the central coast for years 2014 – 2017 was 205 kg N ha^{-1}. Also, Hartz et al. (2007) reported an average application of 184 kg N ha^{-1} for 78 lettuce fields surveyed on the California central coast. Hence average potential N savings following the CM recommendations relative to industry standard practice may have ranged between 37% and 43%.

Across all lettuce sites CM marketable yield was generally equal to or greater than the GS (averaging 107% of the GS yield) and the average CM yield was statistically above the average GS yield (Table 5). The treatment × year interaction was not statistically significant, which also suggests that treatment differences were not influenced by year. These results demonstrated that although less fertilizer was used in the CM treatment, timing of fertilizer applications to match crop N demand resulted in increased yield. At site 13, where the GS irrigation was below the crop ET requirement, a higher yield was measured under the CM treatment where more water was applied to match crop ET demand.

Soil nitrate at harvest was statistically less in the 0–30 cm depth for the CM treatment (Table 5). The average residual amount of N in the top 30 cm of the soil averaged 100 kg N ha^{-1} in the CM treatment and 172 kg N ha^{-1} in the GS treatment. Since water was generally managed similarly for the GS and CM treatments during the post-establishment phase, the lower concentration of N in the soil at harvest in the CM treatment is likely due to lower N fertilizer application and greater reliance on residual soil N to meet crop requirements. Achieving less residual soil N at harvest is desirable to prevent nitrate leaching losses during the pre-irrigation of subsequent crops or during winter rain events.

3.3. Implications for reducing nitrate leaching losses and protecting water quality

The results of the large-scale field trials reported here demonstrated that it is possible for vegetable growers to reduce nitrogen applications while still achieving commercial production targets. A similar result was also demonstrated in lettuce grown in the Salinas Valley by Bottoms et al. (2012) by accounting for residual soil nitrate in the soil at the time of the first fertilizer application. In those field trials no attempt was made to adjust irrigation practices to better match crop water needs. Seven trials reported in this study evaluated the combination of improved water and N management on N fertilizer use. Reducing N fertilizer based on soil nitrate values without attention to water management could potentially result in N deficiency and yield loss if crops were over-irrigated. Cahn et al. (2022) also showed that under-irrigation of romaine lettuce at 75% of estimated crop ET resulted in reduced N fertilizer recovery compared to treatments irrigated at full crop ET. Therefore, decision support services that assist with optimizing both water and nitrogen would provide the most potential for efficient management of N fertilizer without risk to yield.

In addition to crediting residual mineral N in the soil, the CM treatment in these trials factored in nitrate available in irrigation water as part of the fertilization recommendation. At some lettuce sites (sites 9, 12, and 13) the combination of crediting for high concentrations of N in both soil and irrigation water resulted in seasonal N rates ranging from 8 to 36 kg ha^{-1} without yield reduction (Table 5). Replicated field trials in broccoli and lettuce conducted by Cahn et al. (2017) also demonstrated the fertilizer value of elevated levels of nitrate in irrigation water. Those trials simulated groundwater with elevated nitrate concentrations by continuous injection of nitrate salts into the irrigation water. The trials reported here were irrigated with the existing wells at the field sites without adjustment to the background level of N in the irrigation water and therefore may be more convincing to farmers of the fertilizer value of N in groundwater.

Harter et al. (2012) discussed crop uptake of nitrate from irrigation water as a cost-effective strategy to remediate groundwater nitrate contamination but noted that this approach would only be effective if farmers curtailed the amount of N fertilizer applied to their crops. Use of decision support services such as CM could assist growers in determining the appropriate amount of fertilizer to apply so that crops maximize uptake of N supplied from groundwater. In areas with high nitrate sources of water, vegetable growers could potentially contribute to remediation of nitrate in groundwater by optimizing plant uptake of nitrate present in irrigation water and minimizing nitrate leaching losses from the root zone through careful water management.

3.4. Implications for grower adoption of decision support services

As discussed by Gallardo et al. (2020), challenges with publicly available prescriptive DSS include sustaining these services as computer and software technology rapidly advances, and achieving grower adoption. CropManage, which was developed as a web-based application, requires several updates per year to improve service to users and maintain a secure and reliable cloud-based application. While CM currently serves 3300 users, there is still potential for more adoption by the vegetable industry statewide. Grower adoption is a continuing challenge as many farmers are comfortable with their current irrigation and N management practices and satisfied with the resulting crop yields. The US National Census indicates that only 1.5 % of farms in California use computer models for irrigation scheduling and about 14 % use reference ET data (NASS National Agriculture Statistical Service, 2018).

However, implementation of the Sustainable Groundwater Management Act in high priority basins in California, such as in the Salinas Valley, could potentially lead to limits in groundwater withdrawals by agriculture, and increase the need for efficient water management to maximize the land area that can be farmed. Additionally, water quality regulations on the central coast of California will limit the total amount of N from fertilizer, water, and organic amendments that can be annually applied to a unit of agricultural land (CCRWQCB 2021). These limits, based on calculations of applied minus removed N in harvested product, begin relatively high at 448 kg N ha^{-1} in 2025 but will be reduced to 224 kg ha^{-1} by 2031, at which point they will become challenging for most vegetable farmers to meet as they are accustomed to rotating multiple crops per season in the same field. Under more regulatory pressure in the upcoming years, grower interest in DSS such as CropManage may likely increase.

4. Conclusions

A series of trials were performed in commercial broccoli and lettuce fields to compare management regimes guided by CropManage (CM) with grower practices from 2012 through 2019. Guidance from CM served to reduce water and/or nitrogen applications while maintaining crop yields. Fertilizer rates were accurately determined by crediting for available N in the soil and irrigation water, and closely evaluating crop N needs. The CM treatments experienced a 24 % reduction in N application in broccoli and 31% reduction in lettuce relative to the grower practice, which was already less than the industry averages for the region. Evapotranspiration based irrigation scheduling guided by CM was shown to be a reliable tool for determining crop water needs, resulting in applied water reduction to broccoli of 27% relative to the grower practice. No significant water reduction was shown for lettuce although there is evidence that participating growers were relatively efficient irrigators compared to regional industry average, and applied water across both CM and GS treatments in lettuce generally tracked with estimated crop ET. These results should provide additional assurance to lettuce/broccoli growers and the broader vegetable industry that the CM decision support system can support operational efficiencies and facilitate compliance with regulatory targets to improve groundwater quality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

Allen, R.G., Pereira, L.S., 2009. Estimating crop coefficients from fraction of ground cover and height. Irrig. Sci. 28, 17–34. https://doi.org/10.1007/s00271-009-0182-z.
Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. U.N. Food and Agriculture Organization, Rome. https://www.fao.org/3/x0490e/x0490e00.htm (accessed 22 March 2023).
Bartlett, A.C., Andales, A.A., Arabi, M., Bauder, T.A., 2015. A smartphone app to extend use of a cloud-based irrigation scheduling tool. Comput. Electron. Agric. 111, 127–130. https://doi.org/10.1016/j.compag.2014.12.021.
Battilani, A., 2006. Fertirrigere V2.11: a multi-target DSS to manage water and nutrient supply at macrozone level. Acta Hort. 724, 111–118 https://doi.org/10.17660/ActaHortic.2006.724.13.
Bottoms, T.G., Smith, R.F., Cahn, M.D., Hartz, T.K., 2012. Nitrogen requirements and N status determination of lettuce. HortSci 47, 1768–1774. https://doi.org/10.21273/HORTSCI.47.12.1768.
Breschini, S.J., Hartz, T.K., 2002. Presidedress soil nitrate testing reduces nitrogen fertilizer use and nitrate leaching hazard in lettuce production. HortSci 37, 1061–1064. https://doi.org/10.21273/HORTSCI.37.7.1061.
Cahn, M., Johnson, L., 2017. New approaches to irrigation scheduling of vegetables. Horticulturae 3, 1–20. https://doi.org/10.3390/horticulturae3020028.
Cahn M., Smith, R., Hartz, T.K., 2013. CropManage-A web-based irrigation and nitrogen management tool. In: Proceedings of the 2013 California Plant and Soil Conference Visalia, CA pp. 90–95. https://ucanr.edu/sites/calasa/files/160703.pdf (accessed 2 May 2023).
Cahn, M., Smith, R., Murphy, L., Hartz, T., 2017. Field trials show the fertilizer value of nitrogen in irrigation water. Calif. Agr. 71 (2), 62–67. https://doi.org/10.3733/ca.2017a0010.
Cahn, M.D., 2022. Introduction to CropManage. CropManage knowledge base. https://help.cropmanage.ucanr.edu/2019/04/26/introduction-to-cropmanage/ (accessed 2 May 2023).
Cahn, M.D., Johnson, L.F., Benzen, S.D., 2022. Evapotranspiration based irrigation trials examine water requirement, nitrogen use, and yield of romaine lettuce in the Salinas Valley. Horticulturae 8, 857. https://doi.org/10.3390/horticulturae8100857.
Cahn, M.D., Hartz, T.K., Smith, R.F., Noel, B.J., Johnson, L.F., Melton, F.S., 2015. CropManage: An online decision support tool for irrigation and nutrient management. In: Proceedings of the Western Nutrient Management Conference, Int'l Plant Nutrition Institute, Reno. https://www.westernnutrientmanagement.org/proceedings/?action=year_abstracts (accessed 22 March 2023).
Central Coast Regional Water Quality Control Board (CCRWQCB), 2021. General waste discharge requirements for discharges from irrigated lands. Order No. R3–2021-0040. https://www.waterboards.ca.gov/centralcoast/water_issues/programs/ilp/docs/ag_order4/2021/ao4_order.pdf (accessed 20 March 2023).
DEFRA 2014. PLANET (Planning Land Applications of Nutrients for Efficiency and the environment) nutrient management decision support tool. V3.3, released August 2014. https://www.planet4farmers.co.uk/Content.aspx?name=PLANET (accessed 5 May 2023).
Elia, A., Conversa, G., 2015. A decision support system (GesCoN) for managing fertigation in open field vegetable crops. Part I—methodological approach and description of the software. Front. Plant Sci. 6, 319. https://doi.org/10.3389/fpls.2015.00319.
Feller, C., 2015. N-Expert – Fertiliser Recommendations for Field Vegetables. https://n-expert.igzev.de/news/?lang=en (accessed 5 May 2023).
Gallardo, M., Elia, A., Thompson, R.B., 2020. Decision support systems and models for aiding irrigation and nutrient management of vegetable crops. Agric. Water Manag. 240 (2020), 106209 https://doi.org/10.1016/j.agwat.2020.106209.
Gallardo, M., Jackson, L.E., Schulbach, K.F., Snyder, R.L., Thompson, R.B., Wyland, L.J., 1996. Production and water use in lettuces under variable water supply. Irrig. Sci. 16, 125–137. https://doi.org/10.1007/BF02215620.
Gallardo, M., Giménez, C., Martínez-Gaitán, C., Stöckle, C.O., Thompson, R.B., Granados, M.R., 2011. Evaluation of the VegSyst model with muskmelon to simulate

crop growth, nitrogen uptake and evapotranspiration. Agric. Water Manag. 101, 107–117. https://doi.org/10.1016/j.agwat.2011.09.008.

Giménez, C., Thompson, R.B., Prieto, M.H., Suárez-Rey, E., Padilla, F.M., Gallardo, M., 2019. Adaptation of the VegSyst model to outdoor conditions for leafy vegetables and processing tomato. Agric. Syst. 171, 51–64. https://doi.org/10.1016/j.agsy.2019.01. 003.

Hart, Q.J., Brugnach, M., Temesgen, B., Rueda, C., Ustin, S., Frame, K., 2009. Daily reference evapotranspiration for California using satellite imagery and weather station measurement interpolation. Civ. Eng. Environ. Syst. 26, 19–33. https://doi.org/10.1080/10286600802003500.

Harter, T., Lund, J., Darby, J., Fogg, G., Howitt, R., Jessoe, K., Pettygrove, G., Quinn, J., Viers, J., Boyle, D., Canada, H., DeLaMora, N., Dzurella, K., Fryjoff-Hung, A., Hollander, A., Honeycutt, K., Jenkins, M., Jensen, V., King, A., Kourakos, G., Liptzin, D., Lopez, E., Mayzelle, M., McNally, A., Medellin-Azuara, J., Rosenstock, T., 2012. Addressing nitrate in California's drinking water with a focus on Tulare Lake Basin and Salinas Valley groundwater. Report for the State Water Resources Control Board Report to the Legislature. Center for Watershed Sciences, University of California, Davis. 78 p. http://groundwaternitrate.ucdavis.edu (accessed 21 March 2023).

Hartz, T.K., Bendixen, W.E., Wierdsma, L., 2000. The value of presidedress soil nitrate testing as a nitrogen management tool in irrigated vegetable production. HortScience 35, 651–656. https://doi.org/10.21273/HORTSCI.35.4.651.

Hartz, T.K., Johnstone, P.R., Williams, E., Smith, R.F., 2007. Establishing lettuce leaf nutrient optimum ranges through DRIS analysis. HortScience 42, 143–146. https://doi.org/10.21273/HORTSCI.42.1.143.

Hartz, T.K., 2020. Efficient nutrient management in California vegetable production. UCANR publication 3555. 112 pp. ISBN-13: 978–1-62711–070-9.

Johnson, L.F., Trout, T.J., 2012. Satellite NDVI assisted monitoring of vegetable crop evapotranspiration in California's San Joaquin Valley. Rem. Sens. 4, 439–455. https://doi.org/10.3390/rs4020439.

Johnson, L.F., Cahn, M.D., Martin, F.N., Melton, F.S., Benzen, S.D., Farrara, B.F., Post, K., 2016. Evapotranspiration-based irrigation scheduling of head lettuce and broccoli. HortScience 51, 935–940. https://doi.org/10.21273/HORTSCI.51.7.935.

Machet, J.-M., Dubrulle, P., Damay, N., Duval, R., Julien, J.-L., Recous, S., 2017. A dynamic decision-making tool for calculating the optimal rates of N application for 40 annual crops while minimising the residual level of mineral N at harvest. Agronomy 7, 73. https://doi.org/10.3390/agronomy7040073.

Mannini, P., Genovesi, R., Letterio, T., 2013. IRRINET: large scale DSS application for on-farm irrigation scheduling. Procedia Environ. Sci. 19, 823–829 https://doi.org/10.1016/j.proenv.2013.06.091.

Melton, F.S., Johnson, L.F., Lund, C.P., Pierce, L.L., Michaelis, A.R., Hiatt, S.H., Guzman, A., Adhikari, D.D., Purdy, A.J., Rosevelt, C., Votava, P., Trout, T.J., Temesgen, B., Frame, K., Sheffner, E.J., Nemani, R.R., 2012. Satellite irrigation management support with the terrestrial observation and prediction system. IEEE/JSTARS 5, 1709–1721. https://doi.org/10.1109/JSTARS.2012.2214474.

Migliaccio, K.W., Morgan, K.T., Vellidis, G., Zotarelli, L., Fraisse, C., Zurweller, B.A., Andreis, J.H., Crane, J.H., Rowland, D.L., 2016. Smartphone apps for irrigation scheduling. Trans. ASABE 59, 291–301.

Mirás-Avalos, J.M., Rubio-Asensio, J.S., Ramírez-Cuesta, J.M., Maestre-Valero, J.F., Intrigliolo, D.S., 2019. Irrigation-advisor – a decision support system for irrigation of vegetable crops. Water 11 (11), 2245. https://doi.org/10.3390/w11112245.

Mitchell, J., Hartz, T., Pettygrove, S., Munk, D., May, D., Menezes, F., Diener, J., O'Neill, T., 1999. Organic matter recycling varies with crops grown. Calif. Agr. 53 (4), 37–40. https://doi.org/10.3733/ca.v053n04p37.

Monterey County Water Resources Agency (MCWRA), 2017. Recommendations to address the expansion of seawater intrusion in the Salinas Valley Groundwater Basin, https://www.co.monterey.ca.us/home/showdocument?id=57396 (accessed 21 March 2023).

Montoro, A., López-Fuster, P., Fereres, E., 2011. Improving on-farm water management through an irrigation scheduling service. Irrig. Sci. 29, 311–319 https://doi.org/10.1007/s00271-010-0235-3.

NASS (National Agriculture Statistical Service) 2018. Census of agriculture: 2018 Irrigation and water management survey. Table 23. Methods used in deciding when to irrigate. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Farm_and_Ranch_Irrigation_Survey/fris_1_0023_0023.pdf (accessed 12 May 2023).

Pereira, L.S., Paredes, P., Melton, F., Johnson, L., Wang, T., López-Urrea, R., Cancela, J. J., Allen, R.G., 2020. Prediction of crop coefficients from fraction of ground cover and height. Background and validation using ground and remote sensing data. Agric. Water Manag. 241, 106197 https://doi.org/10.1016/j.agwat.2020.106197.

Peters, R.T., Hoogenboom, G., Hill, S. 2016. Simplified irrigation scheduling on a smart phone or web browser. http://irrigation.wsu.edu/Content/Fact-Sheets/ISMManual_IA.pdf (accessed on 5 May 2023).

Salinas Valley Basin Groundwater Sustainability Agency (SVBGSA), 2022. Salinas Valley Groundwater Basin 180/400-Foot Aquifer Subbasin 2022 Update 495 p. https://svbgsa.org/wp-content/uploads/2022/09/180400–2022-GSP-09292022.pdf (accessed 21 March 2023).

Simionesei, L., Ramos, T.B., Palma, J., Oliveira, A.R., Neves, R., 2020. IrrigaSys: A web-based irrigation decision support system based on open source data and technology. Computers and Electronics in Agriculture 178, 105822. https://doi.org/10.1016/j.compag.2020.105822.

Smith, R.F., Cahn, M.D., Hartz, T.K., Love, P., Farrara, B.F., 2016. Nitrogen dynamics of cole crop production: implications for fertility management and environmental protection. HortScience 51, 1586–1591. https://doi.org/10.21273/HORTSCI11335-16.

Smith, R.F., Cahn, M., Daugovish, O., Koike, S., Natwick, E., Smith, H. Subbarao, K., Takele, E., Turini, T., 2011. Leaf lettuce production in California. Publication No. 7216, UC Agricultural and Natural Resources, Richmond CA. https://anrcatalog.ucanr.edu/pdf/7216.pdf.

Temesgen, B., Eching, S., Davidoff, B., Frame, K., 2005. Comparison of some reference evapotranspiration equations for California. J. Irrig. Drain. Eng. 131, 73–84. https://doi.org/10.1061/(ASCE)0733-9437(2005)131:1(73).