Science of the Total Environment 990 (2025) 179851

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Reimagining alfalfa as a flexible crop for water security in the Southwestern USA

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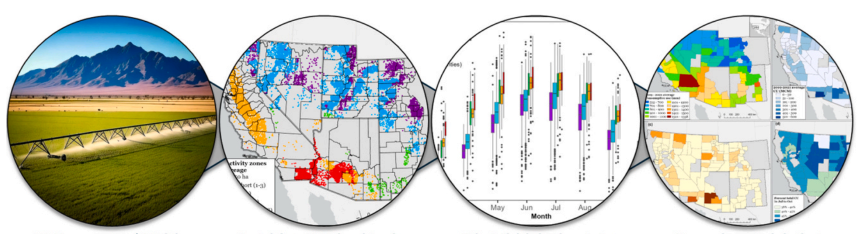
HIGHLIGHTS

- Alfalfa supports a $53B dairy/beef industry, aids wildlife, and poses low nitrate risk despite high water use criticism.
- This study tests summer deficit irrigation — no irrigation after July 1 — to sustain alfalfa production in arid regions.
- Deficit irrigation can save 16-50% of alfalfa's total water use on 926,000 ha (15.5% of U.S. irrigated alfalfa acreage).
- Summer deficit irrigation is viable if saved water sells for ≥$71 or ≥$44 per 1000 m^3, depending on county analysis.

GRAPHICAL ABSTRACT



Alfalfa supports a $53 billion dairy and beef industry in the southwestern USA, provides habitat for pollinators and migratory birds, and poses minimal nitrate pollution risk.

Sustaining alfalfa in arid regions by reducing water use through "summer deficit irrigation" is feasible in regions with multiple harvests, especially in the dry southwestern USA.

This deficit irrigation strategy maintains production, supports farmers and local businesses, and saves water over 15.5% of total irrigated alfalfa acreage in the USA

Economic analysis indicates summer deficit irrigation is financially feasible if the water saved is sold at least at $96 per 1,000 cubic meters, providing potential win-win outcomes.

ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Water resources
Deficit irrigation
Alfalfa
Water security
Regional water management

ABSTRACT

Alfalfa has been vilified as one of the thirstiest crops in the semi-arid southwestern USA and partially responsible for decreased water security in the Colorado, Rio Grande and San Joaquin River basins. We demonstrate that adoption of summer deficit irrigation in alfalfa production can yield large water savings and flexibility to adapt to changing water supplies with minimal on-field economic impact. We estimate that deficit irrigation of alfalfa can save 1333 to 4157 million cubic meters of water annually (16–50 % of total alfalfa water use) over 926,000 ha in the southwestern USA if summer deficit irrigation (suspended after July 1) were implemented. Cash-flow analyses, assuming a producer sells conserved irrigation water and forfeits revenue from alfalfa sales beyond August 1, indicate a possible win-win net benefit at a price point of greater than $71 (Tulare, CA) or $44

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https://doi.org/10.1016/j.scitotenv.2025.179851
Received 4 February 2025; Received in revised form 10 May 2025; Accepted 4 June 2025
Available online 16 June 2025

(Imperial, CA) per 1000 m^3 of irrigation water. We document the benefits of summer deficit irrigation for water conservation and farm and regional agricultural economic viability in rural communities. We acknowledge its practical challenges and risks as it will require infrastructure for water trading, support systems and mechanisms for producer decision-making, and improvements to field-level water accounting. These findings underscore the need to reassess the role of alfalfa in water management, not just as a water-intensive crop but also as a flexible one that may be a key instrument in achieving agricultural resilience against the backdrop of climate variability and recurring droughts.

1. Introduction

Alfalfa (*Medicago sativa*) is often criticized for being the thirstiest crop in the southwestern USA (Richter et al., 2020; Fu, 2022; Richter et al., 2024). This forage crop underpins the dairy and beef sectors, which collectively contribute $157 billion annually to the US agriculture (U.S. Department of Agriculture, 2024). Additionally, it provides habitat for pollinators and migratory bird species and stands out as one of the few field crops that poses minimal risk of contributing excess nitrate to groundwater. Several scientific efforts to reduce agricultural water use in the water scarce southwestern USA propose contraction of cultivated area of alfalfa (Marston et al., 2018, 2020; Richter et al., 2020, 2024). Here, we propose that alfalfa production can be sustained in arid and semi-arid climates by strategically reducing water consumption. We explored the management practice of summer deficit irrigation where irrigation is suspended after July and hay revenue is forfeited between August and October while the saved water is sold for other beneficial uses.

While pertinent to ongoing water security concerns in the southwestern USA, agricultural water scarcity is a global issue, as freshwater resources are under increasing pressure due to population growth, urbanization, and climate change (Jasechko et al., 2024). Since 1900, global water consumption has increased almost ten-fold (Gleick, 2003) while the world population increased five-fold. Today, food production, especially irrigated agriculture, accounts for 70 % of global groundwater withdrawals and 90 % of the global water consumption (Siebert et al., 2010). A hotspot region in the world is the central and southwestern USA, that in our analysis includes six states (AZ, CA, CO, NM, NV, UT; SW herein) of which 59,583 km^2 are irrigated to grow livestock feed, vegetables, fruits, nuts, and other specialty crops worth $118 billion annually (USDA NASS, 2022). While urban water demand has declined in the region in the past 15 years (30 % in California alone) (Cooley et al., 2022), agricultural water use across the US has increased despite widespread adoption of improved technology (Hrozencik and Aillery, 2021). Among the over 400 different crops grown in the SW, forage crops such as alfalfa and other forage products (e.g., grass hay and haylage, irrigated pastures, corn and sorghum silage) have received growing criticism as being the leading contributor to declining flows in watersheds across the western US (Richter et al., 2020). Alfalfa alone accounts for over a quarter of all water consumed within the Colorado River basin (Richter et al., 2024). Alfalfa production typically uses between 0.76 and 2.03 m^3/m^2 of water per year depending on climate, soil type, and topography (Lindenmayer et al., 2011; Bali et al., 2024). It is an irreplaceable feed for livestock operations due to its high levels of energy, protein, calcium, and digestible fiber content (Higginbotham et al., 2008; Jungers et al., 2020). Alfalfa provides refuge for wildlife, including endangered species of migratory birds, its deep root system facilitates nitrogen fixation and carbon storage for improved soil health and water quality (Qi et al., 2023; Randall et al., 1997), and alfalfa grown for seed provides habitat for native pollinators and food for honey production (Putnam et al., 2001; Fleskes et al., 2012; Meese, 2016; Fernandez et al., 2019). While alfalfa acreage has declined in the southwestern USA in recent years due to competing crops and water scarcity, it offers great water savings potential and benefits to producers due to its high tolerance to salt (Fan et al., 2023), tolerance to intentional flooding for groundwater recharge (Dahlke et al., 2018; Boyko et al., 2021; Bali et al., 2023; Levintal et al., 2023), and its seasonal water use efficiency (WUE: kg of alfalfa produced per unit of applied water), which starts high in spring and declines over the year (Frate et al., 1988, 1991; Hanson et al., 2007; Cabot et al., 2017; Montazar et al., 2020; Putnam et al., 2021; Bali et al., 2024).

Considerable research has been devoted in the last 20 years to identifying ways to reduce consumptive water use in irrigated agriculture, particularly in arid and semi-arid regions where irrigation assumes >70 % of the consumptive water use (Richter et al., 2017). For example, the introduction of drip and subsurface drip irrigation has allowed for smaller, more precise, and more frequent inputs of water and fertilizer that have reduced deep percolation (Amali et al., 1997) and early season evaporation (Hanson and May, 2006), reduced weed pressure (Shrestha and Kazama, 2007), and increased plant nitrogen uptake efficiency (Li et al., 2003). As a result of using subsurface drip fertigation systems (systems where liquid fertilizer is applied with irrigation water), crop quality and yield have increased in many cropping systems, most notably alfalfa, cotton, and tomato, which have seen yield increases of about 22 %, 19 % and 38 %, respectively (Ayars et al., 2015; Lamm, 2016). However, growing water scarcity due to climate change and more efficient irrigation technology have also resulted in a water savings paradox, especially greater net consumptive use (CU) due to expansion of cropped areas and reduced groundwater recharge and return flows to streams (Scott et al., 2014). Richter et al. (2017) summarized various measures to reduce agricultural consumptive water use including i) irrigation optimization (Barker et al., 2023); ii) crop substitution (Molden et al., 2003; Bastiaanssen and Steduto, 2017); iii) reduction in acres of farmland in production (idling or fallowing); and iv) application of less than optimal water rates through deficit irrigation. Richter et al. (2017) also concluded that the most effective and most straightforward measure to implement is land fallowing, in part due to the assumption that all (irrigation) water should be compensated for and water saved through fallowing is the easiest to quantify and administer under U.S. Western water law.

To date, several water savings strategies have been tested on alfalfa (Hanson et al., 2007; Ismail and Almarshadi, 2013; Li et al., 2023) but most studies are focused on the plot scale (Lindenmayer et al., 2011; Montazar et al., 2020). To our knowledge, no study has evaluated the economic feasibility and potential for water savings at the regional to sub-continental scale. Given alfalfa's unique ability to yield substantial biomass in proportion to applied water, its cultivation can be optimized as part of a broader strategy to manage water efficiently. Commercial alfalfa is typically grown for 3 to 6 years with 1 to 12 cuttings per year depending on climate, cultivar genetics, irrigation, soil type, and other factors (Putnam et al., 2005). By leveraging the adaptability of alfalfa to match variable water availability, farmers can reduce reliance on continuous water supply, thereby aligning agricultural practices with sustainable water management goals.

In this study, we quantify the intra-annual water "savings" potential of alfalfa production systems under summer deficit irrigation in the southwestern USA and use two case-studies in central and southern California to determine the economic feasibility of this management scheme for a range of market water rate scenarios. Our goal is to identify where and how alfalfa can offer water use flexibility to contribute to a more secure water future for agricultural landscapes in water scarce regions globally.

2. Methods

2.1. Study area

This study focuses on the southwestern United States and 6 of the 7 states involved in the Colorado River Compact—Arizona (AZ), California (CA), Colorado (CO), New Mexico (NM), Nevada (NV), Utah (UT), and Wyoming (WY, not included in our study) (Figs. S1–1 and S1–2). The region lies roughly between latitudes 31°N and 43°N and longitudes 102°W and 125°W, covering a vast area with elevations ranging from sea level in California's coastal areas to over 4000 m a.s.l. in the Rocky Mountains of Colorado. The climate in this region is Mediterranean in California and New Mexico, mostly arid to semi-arid in Arizona and Nevada and alpine in the higher elevations of Colorado and Utah. California and New Mexico feature both Mediterranean and desert climates, while Utah experiences semi-arid to arid conditions. The primary land use in the region is agriculture, particularly in California's Central Valley and Colorado's plains, which are major agricultural hubs. The region has a combined farm output of $118 billion per year (USDA NASS, 2022) and due to its semi-arid climate agricultural production is highly dependent on groundwater and interstate water sharing agreements. The study area for this analysis was derived in ArcGIS Pro version 3.3 using a combination of United States Geological Survey (USGS) watershed boundaries (USGS, 2024) and administrative boundary data of state and county boundaries (US Census, 2024) within the southwestern U.S.A. as detailed in the Supplemental materials (Text S1).

2.2. Data sources

For the analysis of consumptive water use and alfalfa production areas in the southwest U.S.A. several geospatial and tabular data sources were used as summarized in Table 1.

Table 1
Geospatial and crop statistics data sources.

Geospatial datasets	Spatial resolution	Temporal resolution	Source	Access location
Watershed Boundary Data by 2-digit Hydrologic Unit (HUC2)	–	–	United States Geological Survey	https://www.usgs.gov/national-hydrography/access-national-hydrography-products
National Hydrography Dataset by 8-digit Hydrologic Unit (HUC8)	–	–	United States Geological Survey	https://www.usgs.gov/national-hydrography/access-national-hydrography-products
Cropland Data Layer (CDL)	30 m	2017, 2019–2021	USDA National Agricultural Statistics Service	https://croplandcros.scinet.usda.gov/
USDA NASS Census of Agriculture Data	–	2017	USDA National Agricultural Statistics Service	https://www.nass.usda.gov/Statistics_by_State/index.php
Administrative boundaries (state, county)	–	2018	United States Census	https://www.census.gov/data.html
GRIDMET	4 km	2019–2021	Climatology Lab	https://www.climatologylab.org/gridmet.html
Cal-SIMETAW	4 km	2019–2021	California Department of Water Resources	https://water.ca.gov/Programs/Water-Use-And-Efficiency/Land-And-Water-Use/Agricultural-Water-Use-Models
OpenET ensemble data	30 m	2019–2021		https://etdata.org/

2.3. Estimation of alfalfa production areas and productivity zones

Areas of alfalfa production were determined from the 30-m resolution USDA National Agricultural Statistics Service Cropland Data Layer (2023) (USDA-NASS CDL) for the years 2017 (comparison year) and 2019–2021 (years of interest). The USDA-NASS CDL dataset maps over 100 crop categories grown in the United States from remote sensing data. To determine alfalfa area from 2019 to 2021, CDL land use data were downloaded for the entire U.S.A. for the years 2019, 2020, 2021 and alfalfa production areas were identified (crop value = 36) using the Extract by Attributes function. All raster calculations and subsequent analyses were performed using the native equal-area Cropland Data Layer projected coordinate system, NAD 1983 Contiguous USA Albers. We included pixels that were alfalfa for all three years in our analysis and compared the area in hectares by state (Table S2–3).

To check the accuracy of the alfalfa acreage represented in the USDA NASS CDL data, estimates were compared to the 2017 Census of Agriculture (USDA NASS, 2017), conducted by the USDA NASS every 5 years. The Census of Agriculture is a complete count of U.S. farms and ranches and the people who operate them. The most recent year for which the Census of Agriculture survey was available for all six states was 2017 (Table S2–2). The survey provides acreage estimates of total crop area harvested as well as acreage of irrigated crop area harvested. A detailed comparison of USDA NASS CDL alfalfa acreage with the Census of Agriculture alfalfa acreage is detailed in Supplemental materials Section S2.

The length of the alfalfa growing season is variable in the Southwest and is primarily driven by climate. Depending on growing season length, the number of alfalfa harvests (also called cuttings) during the growing season vary, impacting total hay yield and consumptive water use of the crop. To estimate the consumptive water use in the various alfalfa production areas across the southwestern U.S.A. we downloaded climate data from the Climate Toolbox (climatetoolbox.org) and estimated the number of harvests (i.e. cuttings) per growing season using a growing degree day (GDD) approach that is based on daily mean air temperature (Eq. (1)):

$$\text{Number of cuttings} = \frac{\left[\text{DOY}_{\text{autumnalhardfreeze}} - 12 - \text{DOY}_{\text{GDD}_{700}}\right]}{30} - 1 \quad (1)$$

where DOY is the day of the calendar year, $DOY_{autumnalhardfreeze}$ is the day when the first hard freeze (4.4 °C) occurs in the fall (after August 1st) and $DOY_{GDD_{700}}$ is the day of the year when 700 growing degrees have been reached. After the number of harvests were predicted with Eq. (1), alfalfa production areas were grouped into the following five productivity zone based on the number of cuttings: *extra-short* (1–3 cuttings per season), *short* (3–4 cuttings), *medium* (5–6 cuttings), *medium-long* (7–8 cuttings), *long* (9+ cuttings). The productivity zones calculated with Eq. (1) were assigned to each alfalfa pixel in the 2019, 2020, 2021 USDA NASS CDL layer before estimating consumptive water use. See more information on how Eq. (1) was developed in Supplemental materials (S3).

2.4. Estimation of consumptive water use

The consumptive water use (CU) of alfalfa was estimated for each alfalfa production area and productivity zone using the ensemble evapotranspiration (ET_{ens}) data product from OpenET (etdata.org), an online platform that was launched in 2021 to address a lack of water use data in the Western U.S. (Melton et al., 2021). The OpenET ensemble product combines evapotranspiration from six ET models including the SSEBOP (Senay, 2018), geeSEBAL and METRIC (Allen et al., 2011a,b), disALEXI (Anderson et al., 2007), SIMS (Melton et al., 2012) and PT-JPL (Fisher et al., 2008) products. For this study, OpenET raster data were retrieved from Google Earth Engine for the alfalfa production polygons within the study area. Section S4 in the Supplemental materials details the GIS analysis steps of how CU was estimated for each alfalfa pixel. In brief, polygons were created where there were continuous pixels of alfalfa and a 30-m buffer was removed to minimize edge effects. This new area is referred to as "shrunk field boundaries", and monthly Open ET_{ens} values were obtained for those polygons (a mean value for each shrunken polygon). We kept a monthly value for a polygon if was at least 1 mm of ET_{ens}, anything below that was considered 0. Some pixels were not included in our shrunk field boundaries (removed because they were a small field or were on an edge). Other pixels did not have an OpenET estimate because the OpenET ensemble product is only available for locations where >4 of the 6 ET models provide an ET estimate for that area. For pixels that did not have a monthly OpenET estimate, the average monthly Open ET_{ens} value was assigned based on county, level 8 hydrologic unit code (HUC8), and alfalfa productivity zone (Text S4.1).

Validation of the OpenET-based consumptive water use included the following comparisons. First, we compared the OpenET ETens estimates to the METRIC and SSEBOP models (both are included in the ensemble product) (Table S4–1) to better understand the spread in ET values that the ensemble product contains because of averaging ET estimates from six different ET models. Both METRIC and SSEBop have been used in previous studies for measuring actual evapotranspiration (ET_a) in irrigated alfalfa fields (Melton et al., 2021; Samani et al., 2007, 2013; Kelley and Olson, 2022). Next, we calculated crop evapotranspiration (ET_c) in Table S4–1 using crop coefficients developed by Sanden et al. (2003) (Table S4–2) and monthly reference evapotranspiration (ETo) using GRIDMET temperature data for each HUC8 polygon and county. Finally, we compared ET_{ens} to other published, site-specific data in Table S4–3 with a published ground-truthed study from each zone.

2.5. Hydro-economic analysis

To determine the on-farm economic impact of different alfalfa water management options including summer deficit irrigation, we expanded on the 2016 cost studies from the University of California (Clark et al., 2016). Our case-study for fixed costs (operations, management, and overhead) is a 121-ha (300-acre) farm located in the central and southern Central Valley in Tulare County and Imperial County, California. Variable costs (alfalfa revenue and water applications/sales) are presented for Tulare and Imperial counties. Tulare is a highly agricultural area and represents certain aspects of both the northern/southern agricultural regions of California. Similar California studies with fixed costs are listed in Table S5–1.

We assume that a grower pays for water based on the applied water (AW) rate and sells water (benefits) based on the amount of consumptive use (CU). To capture the dynamic nature of water prices over many years, we created an index based on historic water prices from the Nasdaq Veles California Water Index (NQH2O) and multiplied by several hypothetical water cost means to show a range. Daily water prices for California's five most active surface water markets (Surface Water, Central Basin, Chino Basin, Main Basin, Mojave Basin – Alto Subarea) are publicly posted on https://nasdaq.com (NASDAQ, 2023) and shown in Fig. S6–1. For Tulare County, we assumed a mean water price of \$50 to \$500 per acre-foot [\$41 to \$405 per 1000 m^3], and changed the actual monthly price based on this index to produce Table S6–1 (and resulting in variable cost table in Table S5–3). Alfalfa hay prices for Tulare County and Imperial County were obtained from Agriculture Commissioner Statistics (respectively, Tables S7–1 and S7–2).

We present a simple cash flow analysis of alfalfa crops motivated by a profit maximization framework. The net returns in the analyses are defined as the difference between the revenues obtained from alfalfa cuttings (including forgone cuttings) minus the average production costs plus the revenues from water sales. We estimate and compare the net present value per unit area of 4 years of monthly cash flows between the "business as usual" scenario, and the scenario with deficit irrigation and sales of unused irrigation water. We employed an interest rate of 10 % and a range of water rates from \$41 to \$405 per 1000 m^3. We checked the robustness of the alfalfa price assumptions for 25 % lower and 50 % higher alfalfa prices and repeat the analysis for interest rates of 5 % and 15 % as part of our sensitivity check.

We also applied a similar analysis in alfalfa farming in Imperial County in California, a region supplied entirely from surface water for the Colorado River, yet one that transfers water to urbanized areas in California's south coast. Lastly, we provide insights from similar deficit irrigation transfers in other states including Colorado, New Mexico and Utah.

3. Results and discussion

3.1. Consumptive water use of alfalfa by productivity zone

There were approximately 925,800 ha of alfalfa grown in the SW region during 2019–2021 (Fig. 1, Table 2). The extra-short (1–3 cuttings per season), short (3–4 cuttings), medium (5–6 cuttings), medium-long (7–8 cuttings), and long (9+ cuttings) zones represented 21 %, 45 %, 3 %, 17 %, and 13 % of the total area, respectively (Fig. 1, Table 2).

The average annual CU of alfalfa as estimated using OpenET ET_{ens} data (Melton et al., 2021) in the extra-short, short, medium, medium-long, and long productivity zone were 701, 812, 1058, 1048, and 1244 mm, respectively with a total average of 895 mm over the entire region (Table 2). CU generally increased with season length and number of cuttings irrespective of region or year (Figs. 1, 2a–b). Much of the 'medium' zone alfalfa is located at elevations higher than the medium-long or long zones, characterized by hot summer conditions, but greater risk of early frosts or cold spring conditions. Much of the medium-long zone (78 %) is located in California, mostly in the Central Valley known for its water scarcity issues (Hanak et al., 2019).

Total annual CU for alfalfa was 8282 million cubic meters (mcm) across the southwestern USA (Table 2 and Fig. 2b). San Bernardino (CA), De Baca (NM), Imperial (CA), La Paz (AZ) and Mohave (AZ) counties had the highest average annual alfalfa CU per hectare ranging between 1302 and 1558 mm/ha yr^{-1}, while Imperial (CA) and Maricopa (AZ) counties had the highest total CU (509 and 497 mcm) among all counties. Our estimation of alfalfa CU (2737 mcm) for the combined upper and lower Colorado River is much lower than the latest estimate by Richter et al. (2024) who state an average annual alfalfa CU of 5952 mcm for the basin (excluding Mexico) for 2000–2019 (27 % of basin CU). Our study excludes 8.3 % of the US-Colorado River watershed located in Wyoming, which is unlikely to make up the discrepancy. The lower CU estimates presented here are not surprising given that satellite-based ET predictions were consistently lower than on-the-ground studies (Table S4–3), but even if estimated CU were corrected for the likely underestimation (31 % see Table S4–3), the total alfalfa CU would only increase to 3585 mcm, representing 16.5 % of the total CU of the Colorado River. Our lower CU estimates could also be related to the decreasing trend in alfalfa acreage in the USA, which decreased by 38 % between 2001 and 2022.

In each productivity zone, CU varied widely at the field level (Fig. 1b) and between years, likely reflecting variability in growing conditions caused by water supply, fertilizer, salinity, or other factors within zones. Alfalfa CU saw a marked decline in 2021 compared to 2019 (Fig. 1b), likely due to the extreme and widespread drought across

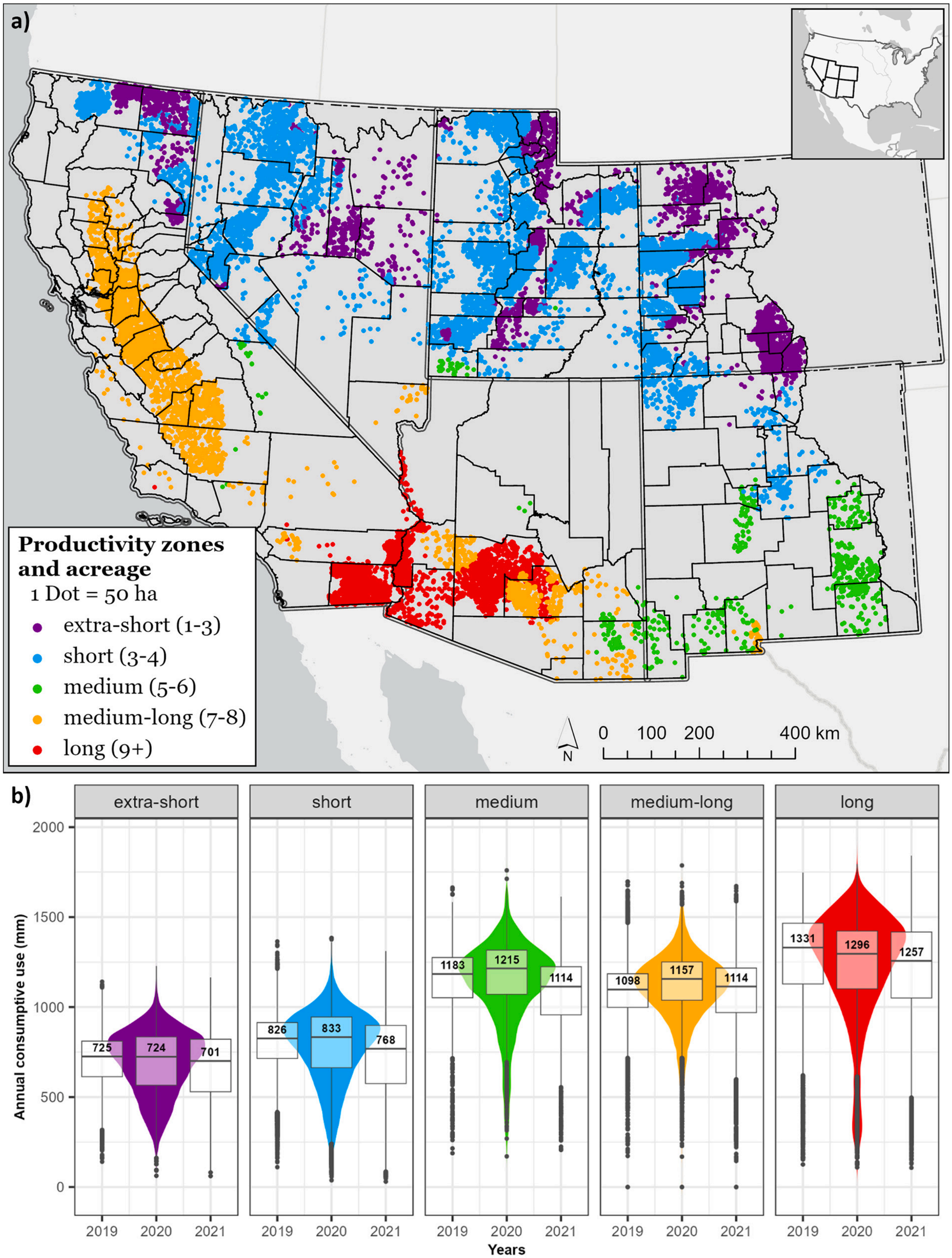

Fig. 1. (a) Dot-density map of the southwestern USA showing areas with alfalfa production in years 2019–2021. Productivity zones are shown by color and number of cuts in parentheses (SI 3). Alfalfa acreage was determined based on 2019–2021 USDA National Agricultural Statistics Service Cropland Data Layer (2023) validated with USDA NASS Census of Agriculture (2021) (SI 3). CDL-estimated state-wide acreage was on average 12 % different from USDA NASS Census of Agriculture (SI Table 3–3). (b) Color-filled violin plots show distribution in annual CU across all alfalfa fields and years by productivity zone; box plots show the annual CU across fields for each year with the numbers indicating the median value. CU is estimated based on the OpenET ET_{ens} product (mm).

Table 2
Consumptive Water Use (CU) (mm and mcm: million cubic meters) of alfalfa per state and productivity zone. Values are an estimated average annual for 2019 to 2021. CU is defined as the proportion of the used water that is not returned to the system (Ward and Pulido-Velazquez, 2008).

	Cuttings[a]	Zone	Area[a]	Yield[c]	Annual CU[d]	Jul–Oct CU[d]	Annual CU[d]	Jul–Oct CU[d]
			[ha]	[t ha^{-1}]	[mm]	[mm]	[mcm]	[mcm]
Total	1–3	Extra-short	196,821	7.6	701	361	1380	710
	3–4	Short	415,678	9.4	812	404	3374	1680
	5–6	Medium	31,286	15	1058	470	331	147
	7–8	Medium-long	158,826	14.6	1048	476	1664	756
	9+	Long	123,167	18.4	1244	502	1532	618
	Total	All	925,778	12.5	895	422	8282	3910
Arizona	3–4	Short	2					
	5–6	Medium	4027	14.2	1211	554	42	19
	7–8	Medium-long	28,369	15.7	1223	536	310	130
	9+	Long	69,172	19.3	1221	519	826	343
	Total	All	101,571	16.9	1159	485	1178	493
California	1–3	Extra-short	33,389	9.2	717	349	238	113
	3–4	Short	34,880	13.4	845	419	266	124
	5–6	Medium	1090		1087	531	7	3
	7–8	Medium-long	127,166	14.5	1046	480	1321	611
	9+	Long	53,952	17.4	1279	515	706	275
	Total	All	250,476	14.1	1013	449	2538	1126
Colorado[b]	1–3	Extra-short	104,819	4.3	698	353	730	384
	3–4	Short	82,898	5.9	808	405	679	344
	Total	All	187,717	5.2	751	388	1409	728
Nevada[b]	1–3	Extra-short	19,806	8.4	733	372	146	76
	3–4	Short	93,483	10.1	809	403	740	364
	5–6	Medium	37					
	7–8	Medium-long	1237		955	420	10	4
	9+	Long	43		1267	551	1	0
	Total	All	114,606	9.6	782	388	751	368
New Mexico[b]	1–3	Extra-short	1423		748	348	10	5
	3–4	Short	14,995	9.8	968	470	142	69
	5–6	Medium	24,587	15.5	1105	485	266	117
	7–8	Medium-long	2050		1038	471	23	10
	Total	All	43,055	14.3	1025	466	441	201
Utah	1–3	Extra-short	37,384	8	723	371	256	132
	3–4	Short	189,419	9	817	408	1548	779
	5–6	Medium	1545	12.2	996	491	16	8
	7–8	Medium-long	5					
	Total	All	228,353	8.9	797	402	1819	919

[a] There were instances (47 ha total, most in Utah) where a pixel was classified as alfalfa in 2019, 2020, and 2021, but the number of cuttings according to Eq. (1) was <0. These fields were excluded as we assume that growing alfalfa is not viable in these areas.
[b] Colorado, Nevada, and New Mexico do not account for the entire state, only the portion within level 2 Hydrologic Unit Code of the regions of interest.
[c] Yield data were downloaded from USDA NASS county level statistics which were available for different years for each state: Arizona (2017–2018), California (2019–2021), Colorado (2018), Nevada (2018), New Mexico (2020–2021), Utah (2017).
[d] Water use is reported for all alfalfa pixels, extrapolated from areas for which OpenET data were available based on our methodology (SI Section 4.1). Consumptive use (CU) is the average of HUC8 & county & productivity zone values, which is the weighted average ET estimated for individual fields using OpenET ensemble data.

the region during 2020 and 2021. Previously, estimating alfalfa water use over large areas has been extremely difficult. Recent advances in remote-sensing approaches, however, are providing this information for multiple growing seasons (Sabie et al., 2024; Wobus et al., 2024). Although we employ similar methods, our estimation of CU based on OpenET ET_{ens} data seemed to reflect climate-induced differences in alfalfa CU accurately, as there are limitations to using OpenET data to quantify alfalfa CU due its cutting cycles (e.g. ~28 days between harvest periods) relative to satellite data acquisition cycles (Cai and Sharma, 2010; Ayanu et al., 2012; Moyers et al., 2023; Sabie et al., 2024) (SI 4–2).

We made comparisons with eddy covariance or surface renewal energy balance plot data from Hanson et al. (2011) to verify the estimated CU for the short, medium-long, and long production zones and from Boyko et al. (2021) for the medium zone as summarized in Table S4–3. These local comparisons indicate ET_{ens}-based predictions likely underestimate alfalfa CU in all zones (except for short zone) by 11 % to 31 %. Underestimation increases with the number of cuttings per zone (Table S4–3). Because plot-based ET estimates from Hanson et al. (2011) and Boyko et al. (2021) were collected across different years, these ET estimates do not allow a direct validation of Open ET_{ens} estimates or individual ET models but rather a corroboration of general ET trends within our productivity zone model. Ground-truthing CU at the field or plot-scale is challenging because CU represents the portion of water lost to evapotranspiration that does not return to the source, making direct measurement difficult (Jensen, 1974). However, there are several approaches considered scientifically sound such as the soil water balance, eddy covariance and surface renewal methods, or lysimeters (Allen et al., 2011a,b; Moyers et al., 2023), which serve our purpose of comparison for a given area and system. Surface renewal and eddy covariance are the most used biometeorological methods to estimate alfalfa crop evapotranspiration in the western states (Sanden et al., 2008; Hanson et al., 2011; Wagle et al., 2019).

Underestimations by ET_{ens} could likewise be due to misclassification of crop types (Espinoza et al., 2023) or errors in the length of growing season predictions. Assuming crop/length predictions were correct, a low reading could also reflect i) field sites where CU is in fact lower because the crop receives less than the optimal irrigation amount - comparing estimates for more field sites would increase the likelihood of capturing these cases; or ii) we are more likely to predict an artificially low ET_a because of timing mismatches between the growing/cutting cycle of alfalfa and the remote sensing data acquisition days. A comparison of monthly K_c values based on Open ET_{ens} and reference ET data estimated with gridMET climate data ($K_c = \text{OpenET}_{ens}/ET_o$ where ET_o is

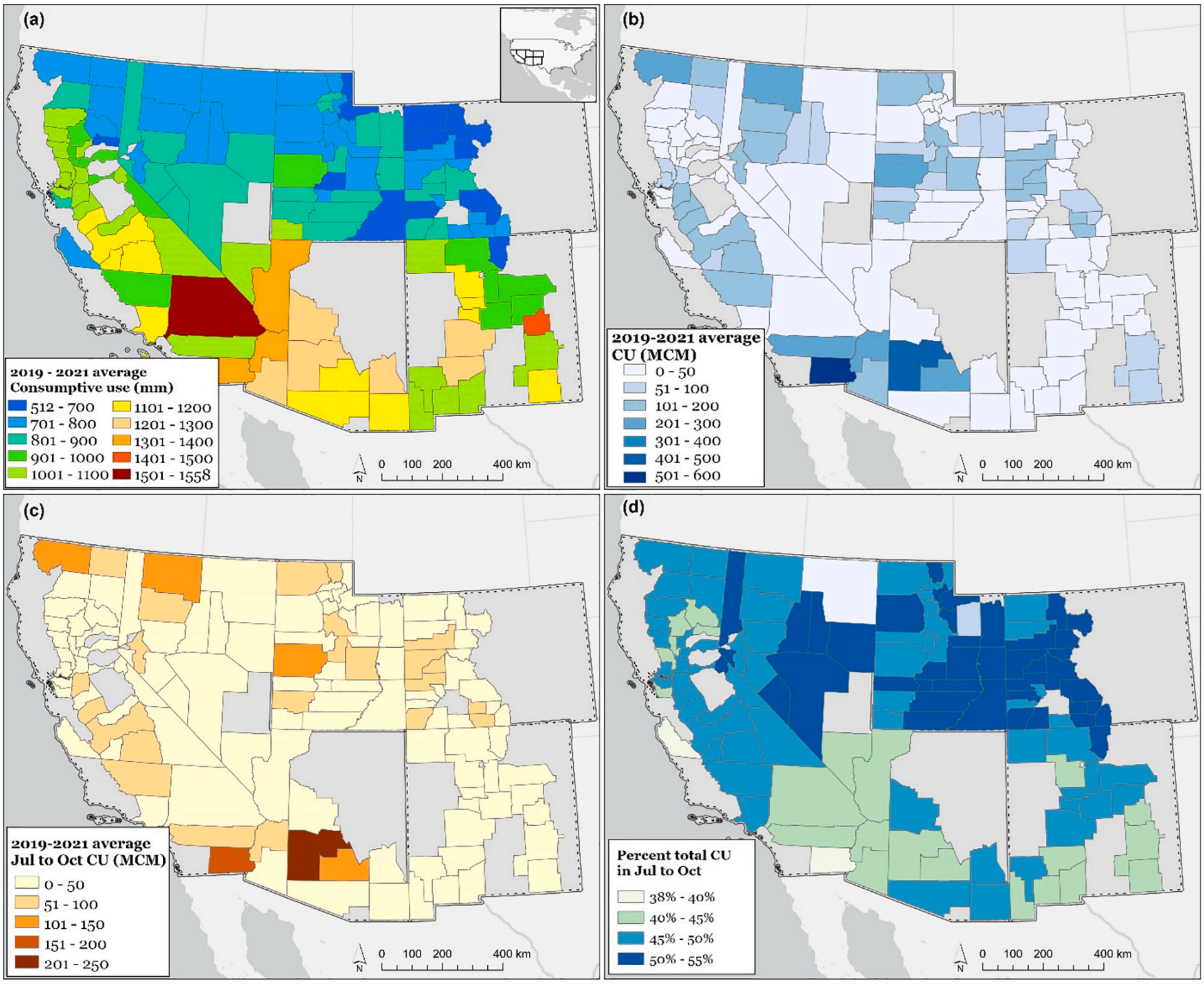

Fig. 2. Average annual (2019 to 2021) consumptive use (CU) of alfalfa (mm) (a) and million cubic meters (mcm) (b) by county as estimated by OpenET ensemble. Average annual (2019 to 2021) July to October consumptive use (mm) (c) and percent July to October CU of total CU (d) by county as estimated by OpenET ensemble.

reference ET) shows relatively low K_c values across seasons and productivity zones compared to reported values (Fig. 3). Typical K_c values for alfalfa according to field studies range from 0.8 to 1 for most months (Sanden et al., 2003), while our K_c values range from 0.6 to 0.7. The two zones with the longest growing seasons have lower K_c values in the second half versus first half (Fig. 3), which further suggests that Open ET_{ens} estimates of CU are representatively low, perhaps because growers under-irrigate (by choice or by necessity) in the summer months. Even if fields are already underirrigated, there is still potential to reduce water applications further, as described in the next section.

3.2. *Water savings and economics of summer deficit irrigation as management strategy*

Employing alfalfa summer deficit irrigation (suspending irrigation from July to October), provides the potential for both applied water savings and avoidance of declining WUE from lower yields and higher CU due to higher air temperatures in the summer. Table 3 shows estimated consumptive use across scenarios and definitions of water conserved (applied water or consumptive use). We estimate between 1333 and 4157 mcm of potential water savings (16–50 % of total alfalfa CU in the study area) from using summer deficit irrigation depending on how it is implemented (Table 3). Because OpenET ensemble predictions were less than on-site comparisons (except for the short zone, Table S4–3), we believe these values are on the conservative side.

We assessed five scenarios with varying assumptions about how many acres of alfalfa are implementing summer deficit irrigation. Where only 3/5th of the alfalfa fields are included (Scenarios #4 and #5), we assume that summer deficit irrigation is only applied to alfalfa fields in their 2nd, 3rd, or 4th year (Table 3). Scenarios #3 and #5 assume a lower portion of fields in the "short" zone, to account for the feasibility of practicing deficit irrigation in "short" productivity zones where growers harvest only 3 to 4 times, resulting in more on/off-farm impacts because more water is used relative to annual totals (Fig. 2c–d). Per our calculations, 51 % of the total water use occurs between July and October in short zones compared to 45 % in medium-long and 40 % in long zones. Alfalfa yield is linearly related to consumptive use (Lindenmayer et al., 2011), and therefore relative yield during that period would be the same. Additionally, fields in short zones would only be on their 3rd or 4th cuttings after July compared to the 7th to 9th cut in long zones and therefore would likely comprise higher quality hay of higher economic value, confirming that on/off-farm impacts are likely to be greater in short zones. The change in profitability arising from changes in the factor of production of alfalfa crops (Fig. S7–3) could have direct effects on farm operations on-site (on-farm) or indirect effects through downstream uses of alfalfa on the local community (off-farm).

To examine these trade-offs between water savings and economic

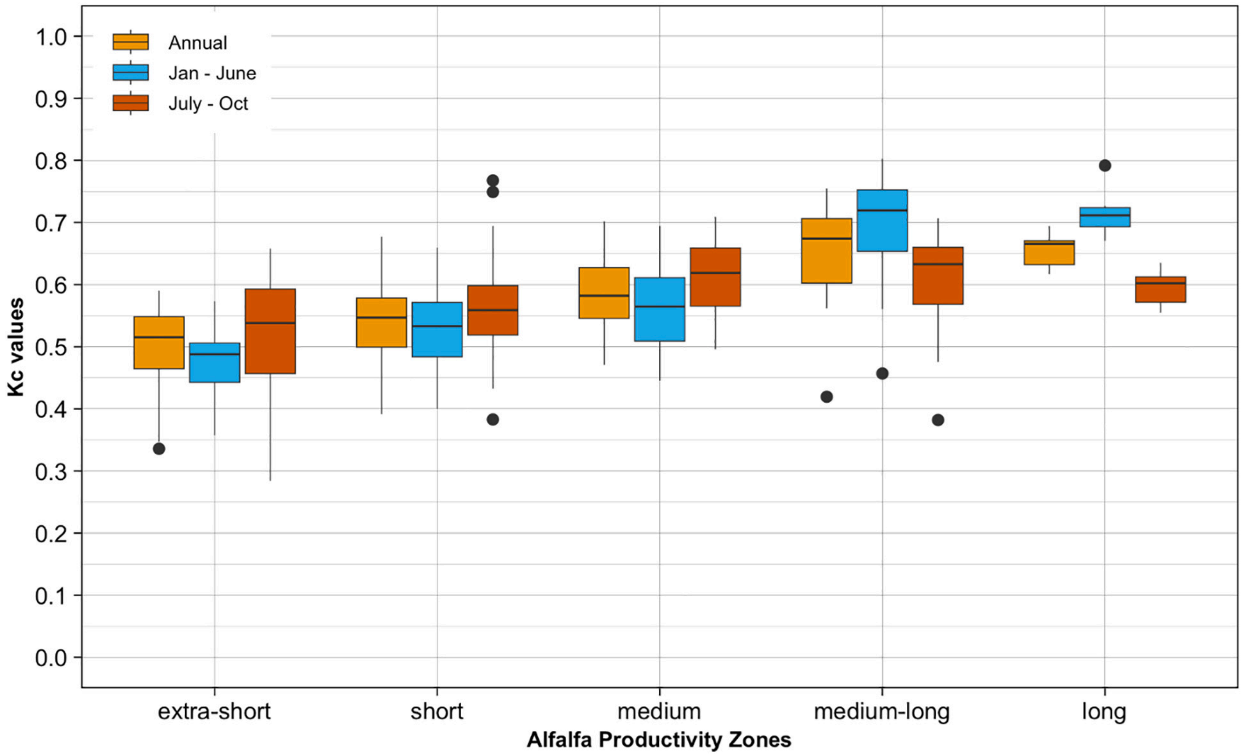

Fig. 3. Crop coefficient (K_c) by productivity zone for the first half (Jan-June), second half (July-Dec), and full year. K_c is estimated as the ratio of ET_{ens} and reference ET (ET_o) estimated with gridMET climate data and the FAO-56 method. Typical K_c values for alfalfa at the peak of the growing season (May–Aug) is 0.95 in California (Sanden et al., 2003) and in NM, in between ~0.3 to 0.5 immediately after harvest and greater values (>1.0) about 7 days later (Sabie et al., 2024).

Table 3
Scenarios of alfalfa summer deficit water conservation strategy application.

Scenario	Assumptions	Water savings as predicted by Open ET_{ens} from July to October (mcm)
#1: 100 % of alfalfa in short, medium, medium-long, long	Water saved is equal to applied water assuming 77 % irrigation efficiency (ET_{ens}/0.77)[a]	4157
#2: 100 % of alfalfa in short, medium, medium-long, long	Water saved is equal to consumptive use (ET_{ens}).	3201
#3: 100 % of alfalfa in medium, medium-long and long 50 % of land in short		2361
#4: 3/5th of all alfalfa fields		1921
#5: 3/5th of land in medium, medium-long, and long, 25 % of land in short		1333

[a] ET_{ens} is under-predicting by 11–30 % (Table S4–3).

impact we present case studies from Tulare and Imperial counties in CA that consider a range of alfalfa hay and water prices during the four-year period of analysis. These include fixed costs of establishment, production, operation, and maintenance (assumed to be the same for Tulare and Imperial) (Table S5–2). Dynamic prices of alfalfa (revenue) and water costs (revenue or expense) changed by month and county (Tables S5–1, S5–2, S5–3, and S5–4). In our calculations, we find only a marginal difference in net present value when the benefit was applied as CU instead of AW when the prices are lower, but the differences were substantial as prices were higher (data not shown). In other words, the assumptions about the compensation process (CU vs. AW) become more significant as the cost of water increases. The cash flows analysis shows why the flexibility of alfalfa production may be synergistic with water conservation goals and farm overall revenue. Water opportunity cost generally increases in the summer months due to low precipitation and peak ET demands for most crops in the growing season, whereas revenues from keeping alfalfa in production (which is a function of hay quality and yield) are generally declining.

Fig. 4 (also Table S7–3) shows the net present value per hectare for alfalfa growers in Tulare and Imperial Counties for a range of water sales rates. As we would expect with rising water costs, the net present value decreases in both counties. The net present value in Imperial County is lower than Tulare County for all water costs ($41 to $405 per 1000 m^3 or $50 to $500 per acre-foot). Furthermore, the difference between the two scenarios, that is, the business-as-usual scenario and the summer deficit irrigation plus water sales scenario, can reflect the opportunity cost of water use. In Tulare County, in the absence of water trade, when the cost of water is $122 per 1000 m^3 ($150 per acre-foot), the foregone value over 4 years is $1642 per hectare (Panel A of Table S7–3). As the water cost increases, the foregone value increases significantly. For example, when the cost of water is $324 per 1000 m^3 ($400 per acre-foot), the foregone value over 4 years is $8304 per hectare in Tulare County (Panel A of Table S7–3). Panel B of Table S7–3 in contrast shows the forgone value of water in Imperial County in the absence of deficit irrigation water trading, estimated at $6615 per hectare at a water cost is $324 per 1000 m^3.

For Tulare County, we estimate that a grower's preference might tip towards selling water versus selling remaining summer and early fall alfalfa cuts for hay when the mean water rate is at least $139, $51, and $62 per 1000 m^3 in 2019, 2020, and 2021, respectively, which captures a range of dry to wet production years (Fig. S7–1). For Imperial County, the tipping point is $92 for 2019, $34 for 2020, and $36 for 2021 (Fig. S7–2). The difference in net present value (from 2018 to 2021) between summer deficit irrigation and business as usual ranges (for mean water costs between $41 and $405 per 1000 m^3) from −$1023 to

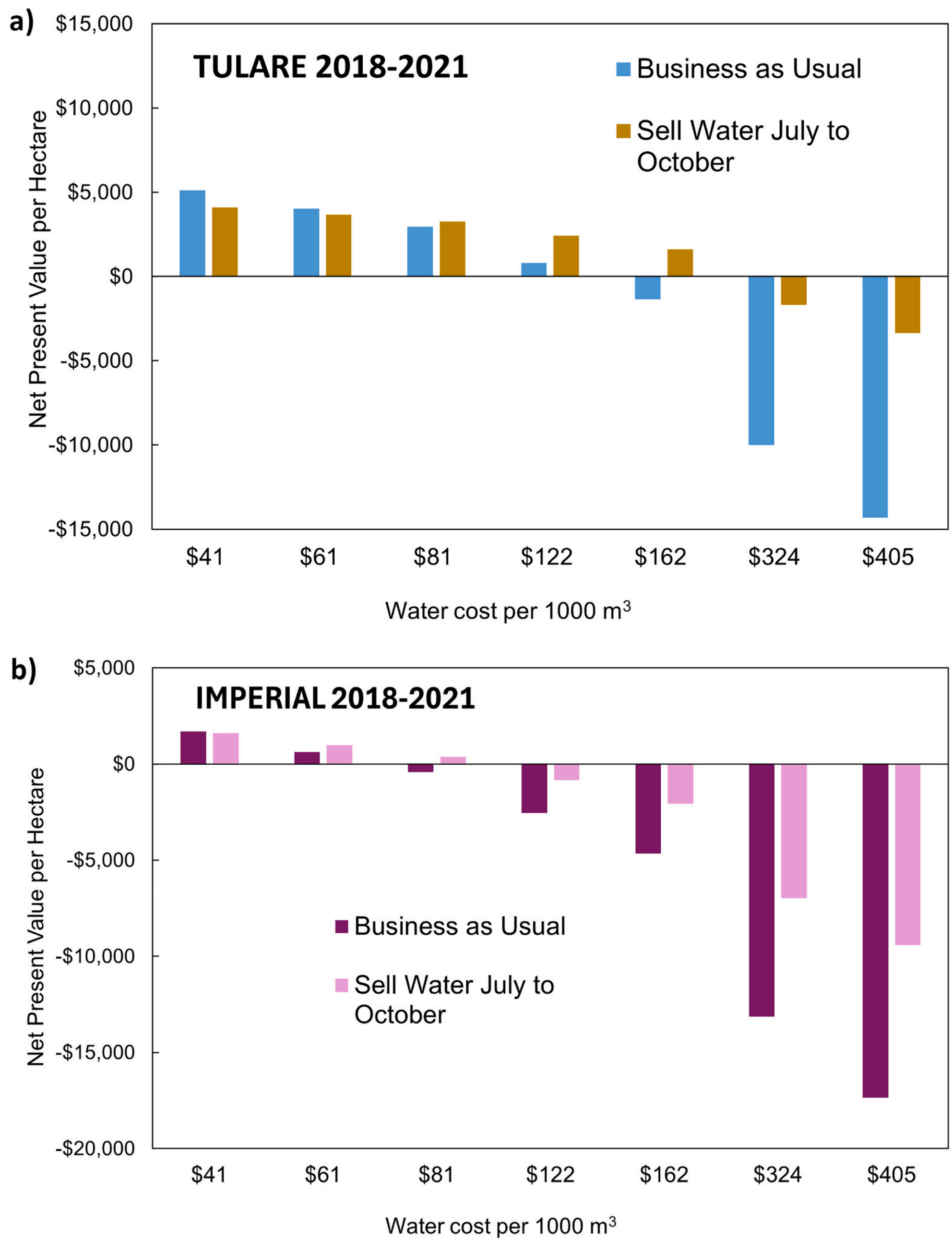

Fig. 4. Comparison between business as usual (BAU) and summer deficit irrigation management net present value per hectare for the period of analysis (2018–2021) for Tulare (top) and Imperial counties (bottom). See SI 5 through 7 for details on cost benefit analysis assumptions.

$10,969 per ha for Tulare and −$86 to $7951 for Imperial County. The annualized value ranges from −$323 to $3460 per hectare per year for Tulare County and −$27 to $2508 for Imperial County.

For Tulare County, we also examine the potential effects of 25 % lower or 50 % higher alfalfa prices on the financial feasibility of summer deficit irrigation compared to business as usual (Fig. 5). Lower historical alfalfa prices make summer deficit irrigation management more attractive at water costs above $47 per 1000 m^3. In contrast, alfalfa prices 50 % higher than historical require water costs above $122 per 1000 m^3 to make summer deficit irrigation management financially feasible.

Different interest rates did not significantly change results from our baseline. For example, in Tulare County, the net present value ranges between −$1169 and $12,847 per hectare when the interest rate is 5 % (range of −$897 to $9383 for 15 %) when the mean water cost is between $41 and $405 per 1000 m3. For comparison's sake, the difference between the two above scenarios is between −$1023 and $10,969 when utilizing the baseline interest rate per period (i.e., 10 %). With a 5 % and 15 % interest rate, the annualized value remains quantitatively equivalent to our baseline results.

The high water savings potential of alfalfa crops is due to its relatively high yet flexible water usage and agronomic attributes, such as its ability to enter dormancy during water shortage and recover with irrigation water without much damage to the crops (Takele and Kallenbach, 2001). While many studies have considered the economic and ecological merits of water saving through deficit irrigation of alfalfa crops, the cost-effectiveness of these tools to address water conservation issues in arid and semi-arid regions remain insufficiently understood. Notably, deficit irrigation case studies include Colorado Water Trust, Colorado Compact Water Bank, Colorado River System Conservation Pilot Program, and

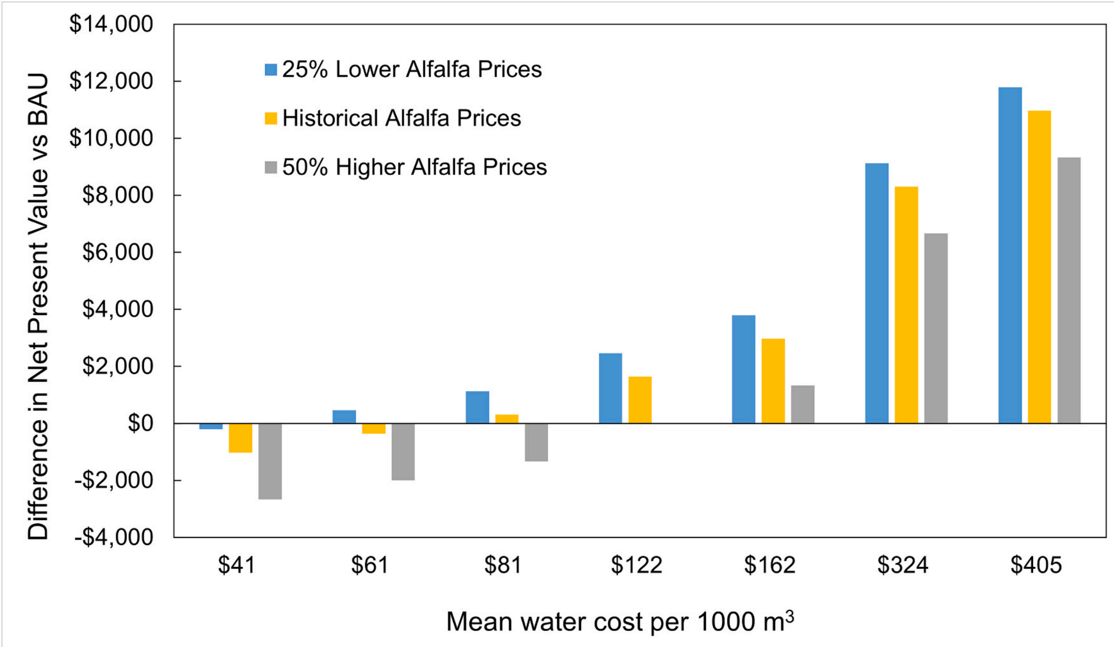

Fig. 5. Difference in net present value ($/hectare) between business as usual (BAU) and summer deficit irrigation management in Tulare County for the period of analysis (2018–2021). A positive value indicates it is beneficial to implement summer deficit irrigation.

Colorado State Engineer Rules on Alfalfa and Grass for Temporary Fallowing.

Alfalfa growers in Palo Verde Valley in California experience variability in profit arising from different timing of crop cutting (Montazar et al., 2020) where the early season cutting typically results in higher prices compared to late season cutting. The late season cuttings may result in a reduction in profit due to differences in biomass quality and yield between alfalfa crops particularly in the Colorado River Basin (Udall and Peterson, 2017; Lindenmayer et al., 2011). Deficit irrigation of alfalfa crops and the possibility of the saved water sales, particularly in the absence of government-led crop subsidies can compensate growers for lost profits, when there is tight competition for water use during drought periods in our study region. Figs. S7–3 and S7–4 show differentiated economic value of alfalfa crop for Nevada, Utah, Colorado, and New Mexico (also these states are extra-short and short productive zones of alfalfa crops) in our study region. In regions where alfalfa production has lower economic returns, water sales through idling or deficit irrigation become a more attractive option than growing the crop, provided willing water buyers exist.

The range of water rates employed in our study are comparable to similar transfers in other western states' regions. In Colorado, the U.S. Department of Interior Bureau of Reclamation, pays alfalfa growers between $162 and $307 per 1000 cubic meters (or $200 and $379 per acre-foot) for using deficit irrigation or to fallow/idled land and between $267 and $324 per 1000 cubic meters (or $330 per acre-foot and $400 per acre-foot) in lower Colorado Basin (U.S. Department of Interior Bureau of Reclamation, 2021). However, in the lower deserts of California and Arizona, the Water Users Association requested between $556 and $1059 per 1000 cubic meters (or $686 and $1306 per acre-foot) for using deficit irrigation or to fallow/idle land. In Utah, the System Conservation Pilot Program pays farmers between $130 and $527 per 1000 cubic meters (or $160 and $650 per acre-foot). In New Mexico, the Lower Rio Grande Groundwater Conservation Program pays farmers for not using groundwater between $988 and $1977 per hectare (or $400 and $800 per acre).

From the farmer's point of view, the true cost of water for crop production is not realized. For example, the Imperial Irrigation District charges farmers $49 per hectare (or $20 per acre), while the Coachella Valley Water District charges approximately $91 per hectare (or $37 per acre), which is often lower than the actual cost of water delivery, particularly when such values are translated into a volumetric basis (i.e., per 1000 cubic meters). Farmers in San Diego paid the county water authority for irrigation water between $611 and $841 per 1000 cubic meters (or $754 and $1038 per acre-foot) over 2019–2021, on average. These high water opportunity costs underscore the potential of deficit irrigation in alfalfa to support both farm income from water transfers and reducing more costly water shortages from higher value agricultural commodities or urbanized water use (Buck et al., 2023).

Table S5–5 provides the cost of producing alfalfa in California, Utah, Colorado, and New Mexico. Production costs for alfalfa in California averaged $3784 per ha in 2020; $1344 per ha in Colorado was averaged over 2019–2021; $1473 per ha in Utah in 2019, and $1708 per ha in New Mexico averaged over 2019–2021 from various cost and return studies.

Figs. S7–3 and S7–4 provide the value of the alfalfa crop and monthly crop prices for each state in our study region, averaged over 2019–2021. Fig. S7–4 shows the average alfalfa crop value for each state in our study region. The value of the alfalfa crop is calculated by multiplying the average yield and average per unit price between July and October (season for deficit irrigation). Yield and per unit prices are directly obtained from the USDA National Agricultural Statistical Services (NASS). Arizona has the highest value of alfalfa during July through October, with $3928/ha, followed by California ($3716/ha), New Mexico ($2857/ha), Nevada ($2287/ha), Colorado ($2028/ha), and Utah ($1932/ha). The dollar values imply that a deficit irrigation season with a water cost higher than the economic return of the alfalfa crop provides an incentive to switch to water uses other than alfalfa irrigation.

Considering the extent of the medium-long and long growing areas (281,993 ha), and a range from $200 to $370 per ha per year to account for production economics and water pricing outside of California's San Joaquin Valley, financial gains from water saved from summer deficit irrigation versus continuing cuttings in the season may range from $56 to $104 million per year.

Summer deficit irrigation has fewer limitations than other alternatives for agricultural water savings in the southwestern USA, such as improved irrigation efficiency, increased productivity, or fallowing of land. Improved irrigation efficiency (less evaporative and deep root zone losses), along with crop management changes that include a combination of agronomic (e.g., no tillage or mulching to decrease soil evaporation) (Mitchell et al., 2012) or microirrigation practices can be costly for modest water savings. Further, there has been evidence that improving irrigation efficiency alone can result in higher CU (Contor and Taylor, 2013; Grafton et al., 2018) when the water is reallocated, reflecting Jevon's Paradox (Alcott et al., 2012), where increased efficiency of a resource leads to increased use. Recent studies of fallowing (Hanak et al., 2023) point to unintended economic and environmental consequences. Bare land can lead to increased weeds and dust, loss of greenspace, loss of wildlife habitat and food sources, decreased food access and security, invasion of noxious weeds, and other related effects (Putnam et al., 2001; Pfister et al., 2011). Bare land fallowing can directly lead to more water use once land goes back into production due to lack of a mulching effect and soil water retention capabilities due to decreased organic inputs and soil structure (Adil et al., 2022). Economic effects on towns and rural communities can be devastating. As an alternative, we highlight the potential of summer deficit irrigation for water conservation. We acknowledge, however, the challenges of putting it into practice. Water measurement and accounting will be a primary concern as tracking late-season curtailments will be much more difficult and costly than full season fallowing. Further, technical challenges and agronomic risks, such as salinity and stand degradation, of summer deficit irrigation need to be overcome (Putnam et al., 2021). Even when environmental conditions such as drought may be dire, alfalfa growers may not have the ability to shift water supply, resources, plans, or contracts throughout the year due in part due to the complexity of priority rights to surface water allocations (Cantor et al., 2022). These challenges with summer deficit irrigation can and should be overcome to fully utilize the flexibility of alfalfa in addressing climate change and water scarcity impacts. Investment into summer deficit irrigation is worthwhile as it will help ensure farm viability and national and global food security.

4. Conclusion

Summer deficit irrigation, where alfalfa is not irrigated after July 1st, is a water savings strategy that could save between 1333 and 4157 mcm (16–50 % of total alfalfa water use predictions) of water annually in the southwestern USA. Summer deficit irrigation could also be an attractive strategy for alfalfa growers particularly if market water prices at the peak of the growing season are high enough to offset the remaining alfalfa cutting revenues. As an alternative to idling, summer deficit irrigation for alfalfa allows maintaining the crop at a lower productivity yet generating benefits from saved-water sales to other crop categories that can make a business case for acquiring the saved water. In the case of Tulare and Imperial counties, water prices above \$71 and \$44 per 1000 m^3 may warrant the adoption of summer deficit irrigation. Considering the decline in alfalfa acreage due to competing crops and tight competition for water in recent years and the increasing cost of alfalfa production in the southwest, our study presents a case for cost-effective tools to address water conservation issues in arid and semi-arid regions of the United States.

CRediT authorship contribution statement

Emily Waring: Visualization, Investigation, Formal analysis, Writing – review & editing, Writing – original draft. **Helen E. Dahlke:** Visualization, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **John T. Abatzoglou:** Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Josué Medellín-Azuara:** Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Matt A. Yost:** Validation, Methodology, Conceptualization, Writing – review & editing. **Khaled M. Bali:** Validation, Methodology, Data curation, Writing – review & editing. **Colleen C. Naughton:** Conceptualization, Writing – review & editing. **Daniel H. Putnam:** Validation, Methodology, Writing – review & editing. **Robert Sabie:** Validation, Methodology, Writing – review & editing. **Siddharth Kishore:** Formal analysis, Methodology, Writing – review & editing. **Nicholas R. Santos:** Methodology, Formal analysis, Data curation, Writing – review & editing. **Joshua H. Viers:** Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: All authors report financial support was provided by U.S. Department of Agriculture.

Acknowledgments

This study was supported by Agriculture and Food Research Initiative Competitive Grant 2021- 69012-35916 from the USDA National Institute of Food and Agriculture. JMA, JTA, and JHV were partially supported by the AI Research Institutes program supported by NSF and USDA-NIFA under the AI Institute: Agricultural AI for Transforming Workforce and Decision Support (AgAID) award No. 2021-67021-35344. We thank the SecureWaterFuture.net program for discussions on this review topic, and S. Naumes and L. Parker for team science coordination.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179851.

Data availability

All data used are publically available.

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