# Climate-smart water technologies and strategies for a resilient forage production system

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## Abstract

Water scarcity is an emerging challenge threatening forage production in the western and southwestern United States, exacerbated by climate change and increased demand for irrigation water from municipal and industrial sectors. In addition to alfalfa, there are vast areas of pasture and forages that have their lifeline hooked to limited water supplies affected by climate change and drought in these regions, and therefore, adopting innovative irrigation technologies and practices are crucial to tackle the water crisis and reduce agricultural water consumption. This review aims to identify, compile, and assess a wide array of water-smart and novel on-farm water

*Advances in Agronomy*
ISSN 0065-2113, https://doi.org/10.1016/bs.agron.2025.01.001

conservation techniques and practices that may assist farmers coping with the issue. The article summarizes proven as well as cutting-edge and pioneering irrigation research and climate-smart water technologies applicable to forage production systems. The large scale of forage production combined with the growing needs for enhanced water productivity, presents future opportunities to effectively utilize these tools and techniques. This could help shape a new era of water management and efficiency, ensuring a more sustainable and resilient forage production system.

## 1. Introduction

Livestock farming is a cornerstone of agricultural economy in the western and southwestern United States, significantly contributing to both the nation's dairy and beef supply and supporting national food security. The success of this industry heavily relies on a sustainable forage supply which is increasingly threatened by water scarcity, particularly in irrigated farming systems. The depletion of groundwater resources poses a serious challenge, with projections suggesting that more than 24 % of irrigated farmlands could convert to dryland farming in the semi-arid Southern High Plains of the U.S. by 2100 (Deines et al., 2020). Shifting to dryland agriculture, changing crop choice and modifying irrigation practices will likely be part of the solutions to mitigate groundwater depletion, though they could also impact regional economics and total forage production.

Over the last 23 years, the Colorado River Basin has experienced severe drought, with its reservoir levels dropping to historic lows. The Colorado River provides water to cities, farmlands and tribal communities across seven U.S. states and northern Mexico. Irrigated pasture and forage crops are the major water users in the basin, and ongoing water shortage presents significant challenges for livestock farming. Efficient water use is thus becoming a critical factor for sustaining agriculture in the region. The U. S. dairy industry, recognizing these challenges, has set environmental stewardship goals for 2050 which include optimizing water use on the farm (DMI, 2020).

In California, the nation's top dairy-producing state, the adoption of innovative water management practices has led to a considerable reduction in water use on dairy farms. Over the past 50 years, water use per gallon of milk produced has decreased by more than 88 % (Naranjo et al., 2020). This has been achieved through improved water productivity in forage production and the use of byproducts such as almond hulls, cottonseed, and citrus pulp in the diet. Advances in animal and crop genetics and management have also contributed to this reduction, leading to an 89.7 % decrease in land requirements for forage production in 2014 compared to 1964 (Naranjo et al., 2020).

The major forage crops in this region include annual cool-season grains like wheat, triticale, and oats; warm-season crops such as corn, sorghum, and sudangrass; and perennials like alfalfa, bermudagrass, and kleingrass. Alfalfa, in particular, is a major water user, grown on approximately 6.8 million acres of cropland in 11 Western states (US Department of Agriculture – National Agricultural Statistical Service USDA-NASS, 2019). Given its extensive acreage and long growing season, alfalfa is a prime candidate for water-saving strategies. The overall objective of this review is to identify, compile, and assess proven as well as cutting-edge and pioneering water management techniques and practices that can improve sustainable forage production under limited water resources. It particularly aims to discuss a wide array of applied climate-smart and innovative on-farm water conservation technologies and practices in forage production systems. First, we review the efficacy of irrigation water delivery systems in relation to water conservation, focusing on surface irrigation, sprinkler irrigation, and subsurface drip irrigation. Technologies that assist with optimizing irrigation scheduling and timing, particularly ET-based irrigation, soil moisture and plant stress sensing, are also discussed. We then explore management interventions, including variable irrigation rate, drought management and deficit irrigation techniques, conservation agricultural practices, choosing drought-tolerant forages, and the role of genetic improvement, breeding, and biotechnology.

## 2. On-farm irrigation water delivery systems

Irrigation management is one of the most important drivers of developing sustainable and climate resilient forage production systems. Surface, sprinkler, and subsurface drip irrigation (SDI) are common water delivery systems in forage crops (Putnam, 2012); however, each system has its own set of advantages and disadvantages (Table 1).

### 2.1 Surface irrigation

Surface irrigation systems including furrow, border, and basin irrigation, are traditional, widely used, and cost-effective methods in forage fields. However, managing these systems efficiently is challenging due to high water demand and considerable time required for water to advance across the field.

**Table 1** Advantages and disadvantages of on-farm irrigation water delivery systems as applied to alfalfa and other forage crops.

| Irrigation system | | Advantages | Disadvantages |
|---|---|---|---|
| Surface | Border irrigation (or check flood) | Ability to deliver large quantities of water in a short time; low cost; good fit with heavier soils with good internal drainage; ability to irrigate deeply and fill soil profile; controls gophers in crops such as alfalfa; excellent ability to leach salts; very low energy use; potential wildlife benefit. It dominates irrigation systems for forage crops such as alfalfa, bermudagrass, sudangrass, kleingrass, and teff in California. | Must have large water supplies. Often there is poor distribution uniformity. Tail water accumulation and damage to crops is common. Labor requirements are high. Diseases in very heavy soils. Scald risk during high temperatures in alfalfa. High deep percolation on sandy soils. |
| | Furrow irrigation | Water distribution uniformity (DU) can be greater than border irrigation; protection of alfalfa crowns from excess flood water by draining into ditches; keeps wheel traffic completely off crowns; avoidance of disease and scald. A very common practice for crops such as wheat, corn, sorghum. It has the rank $2^{nd}$ after border irrigation for irrigating alfalfa in the low desert of California. | Off-site tail water runoff. Erosion from ditches. Salt movements onto bed centers. Often requires modification of equipment to adjust to bed dimensions. |
| | Level basin/ furrow irrigation | Superior DU. Ability to deliver water deep into soil profile. Flood system flushes salts and control rodents. | Requires smaller basins and fields. Requires very large head of water during irrigation to rapidly fill basins. Scald risk during high temperatures. High deep percolation on sandy soils. |

| | | | |
|---|---|---|---|
| Sprinkler | Center pivot irrigation | High DU with good nozzles. Low maintenance and labor. Ability to apply small amounts of water to meet crop needs. High flexibility of scheduling. Fertigation practical. Ability to automate and operate remotely. | High capital cost. Energy requirements due to pumping needs. Evaporative losses can be substantial. Wheels create ruts. |
| | Linear or lateral move irrigation | Good fit with high-value square fields (unlike pivots). High DU. Low labor requirement. Does not lose productivity in corners. Fertigation practical. Ability to automate. | High capital cost. Maintenance of system is more challenging than pivots – requires water delivery system (ditch or hoses). Energy requirements due to pumping needs. Evaporative losses can be substantial. Back-and-forth pattern creates challenges for distribution and timing, unlike pivots. |
| | Wheel line/ side roll irrigation | Inexpensive system. Wheels assist in the movement of pipes. It can be used in smaller fields, unlike pivots. Can be moved from field to field. | Distribution uniformity is not always ideal, depending upon configuration and nozzling. Labor intensive. The back-and-forth pattern creates challenges for distribution and timing. Evaporative losses can be substantial. |
| | Solid set irrigation | Robust system when installed as permanent system. Less labor than moveable pipe or wheel lines, but not as labor-saving as pivots. 'In place' system. | Interference with harvesting and tillage operations. Expensive to install buried pipe. Distribution uniformity is not always ideal, depending upon configuration. Evaporative losses can be substantial. |

*(continued)*

**Table 1** Advantages and disadvantages of on-farm irrigation water delivery systems as applied to alfalfa and other forage crops. (*cont'd*)

| Irrigation system | | Advantages | Disadvantages |
|---|---|---|---|
| | Movable pipe | Low capital cost, high flexibility system– can use pipes on other fields/crops. Excellent for standing establishment. | Very high labor requirements. Distribution uniformity is not always ideal, depending upon configuration. Interference with harvests. |
| | Travelling gun sprinkler irrigation | Continuous movement contributes to uniformity. Adaptable to irregular fields, obstructions, and undulating terrain. Low labor requirement. Extremely portable and storable. | The system can be applied to most forages, while its large droplets and high application rates are best suited to coarse soils with high intake rates and crops that provide good ground cover. High day time temperatures result in evaporation loss. Not suitable in areas with high winds. |
| Drip | Subsurface drip irrigation | Higher yields due to timing and high DU and lack of soil drying. Ability to fertigate. Ability to apply small amounts of water to meet crop needs and finesse irrigation schedule. Crop rotation with row crops such as tomato, sunflower, corn, cotton is feasible. Longer stand longevity. | High cost. Maintenance of system, particularly gopher management and leaks. May require periodic alternative irrigation techniques (e.g. sprinklers or flood) to manage salts and gophers. Water quality may be a limitation due to filtering requirements. |

Multiple irrigation events between harvests in alfalfa and perennial grasses often result in water applied exceeding the soil water depletion level, leading to percolation below the crop root zone, depending on soil textures (Chávez and Fuentes, 2018; Chávez and Fuentes, 2019; Nie et al., 2019).

Various techniques can be used to enhance efficiency in surface irrigation systems. Studies conducted in the low desert of California showed that reducing surface runoff can yield up to 15 % water savings without significant impact on alfalfa and sudangrass yields (Grismer and Bali, 2001). High water application efficiency in surface irrigation systems is achievable by applying the optimal flow rate and maintaining greater water distribution uniformity, changing average irrigation efficiency from 51 % to 81 % in sorghum, alfalfa, and wheat fields (Grismer and Bali, 2001; Chávez et al., 2020; Fuentes and Chávez, 2020; Smith et al., 2018, Salahou et al., 2018; Bali et al., 2018). Techniques such as land leveling for uniform irrigation, reducing field length, using blocked-end furrows, implementing cut-back irrigation approach, setting appropriate irrigation cutoff time, and surge irrigation are effective in improving efficiency in surface irrigation systems. Additionally, automated surface irrigation systems that utilize automated gates and wetting front advance sensors can further improve irrigation efficiency and reduce operating costs (Fig. 1). Utilizing this technology may reduce scalding (due to flooding and high temperature injury) in alfalfa grown on heavy soils by eliminating standing water at the end of the field. It can also improve the quality of drainage waters by reducing deep percolation, surface runoff, and phosphorus and sediment loads (Bali et al., 2018; Bali et al. 2014; SWRCB, 2008). Fig. 2 demonstrates the variations in inflow and outflow (tailwater runoff) rates during an irrigation event in a kliengrass field equipped with automated surface irrigation. The average tailwater ratio (the ratio of tailwater runoff to water applied) was reduced to nearly 4.3 % of irrigation water applied as a result of the highly efficient irrigation system.

Tailwater recovery system is another water conservation tool for reusing irrigation water. It is particularly feasible for fields equipped with subsurface drainage systems, where recoverable irrigation runoff, subsurface drainage outflows, or rainfall runoff are anticipated (NRCS, 2024). Both portable and permanent tailwater recovery systems are commonly adopted by farmers in the Imperial Valley of California. These practices are currently used in alfalfa, bermudagrass, and kleingrass fields in this region (Fig. 3). Unpublished data from the research conducted in the Imperial Valley indicates an average electrical conductivity of 3 dS $m^{-1}$ for on-farm

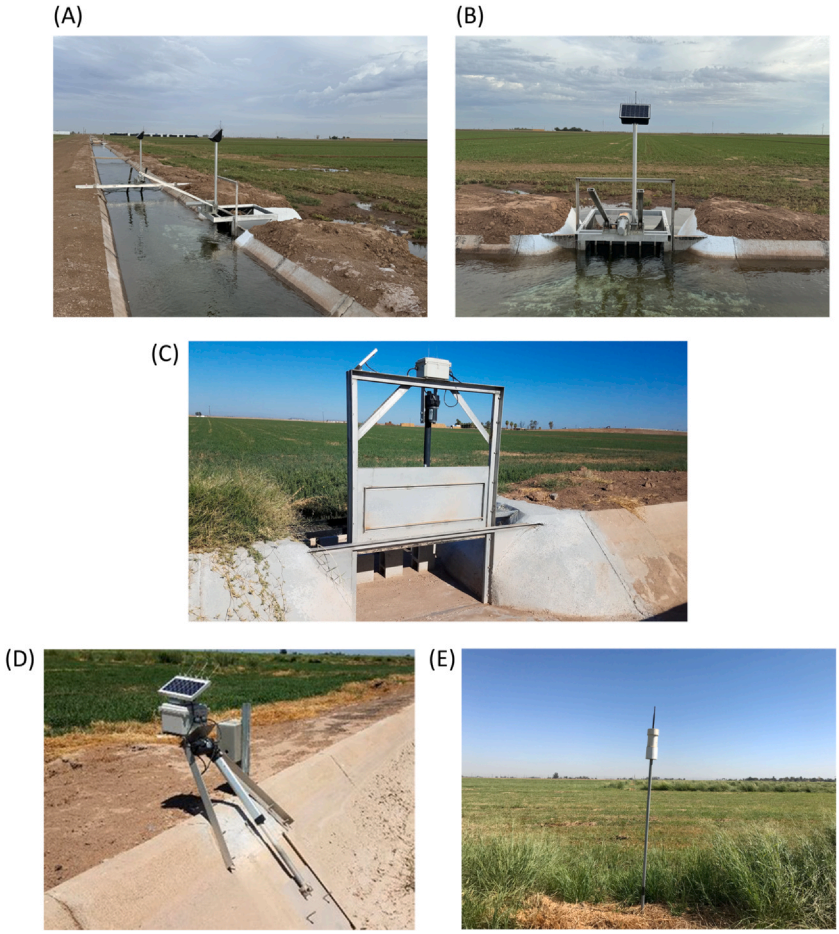


**Fig. 1** Automated surface irrigation system in Imperial Valley, CA. Three different automated gates (A–D) and water advance sensor station (E) are demonstrated in kleingrass and alfalfa fields. The gates opening and inflow rates vary during irrigation event based on the real time data received from the water advance sensors.

drainage water, which can be reused for irrigating certain forages and sugarbeets (unpublished data from the first author). The research also shows that this technology may conserve an average of 70% of tailwater runoff.

## 2.2 Subsurface drip irrigation

SDI technology is renowned for its promises on water and fertilizer conservation and high level of automation in forage crops (Alam et al., 2002; Avila et al., 2003; Lamm, 2016; Berrada, 2005; Kazumba et al.; 2010,

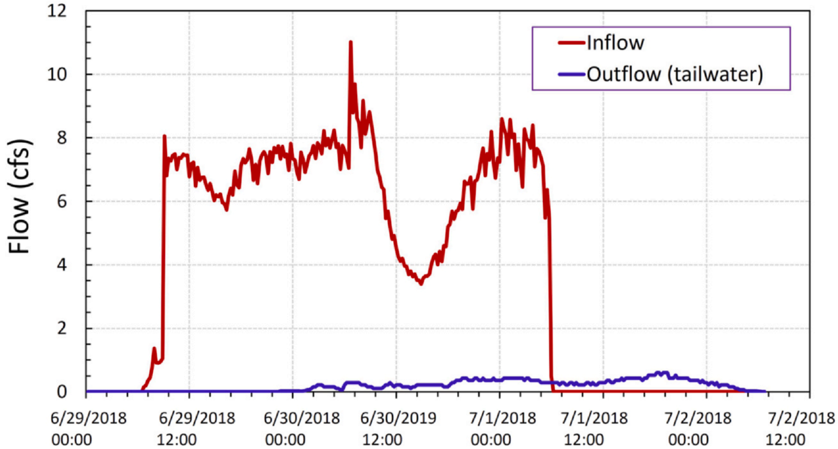


**Fig. 2** Inflow rate and tailwater runoff rate over an irrigation event in a kleingrass field equipped with automated surface irrigation.

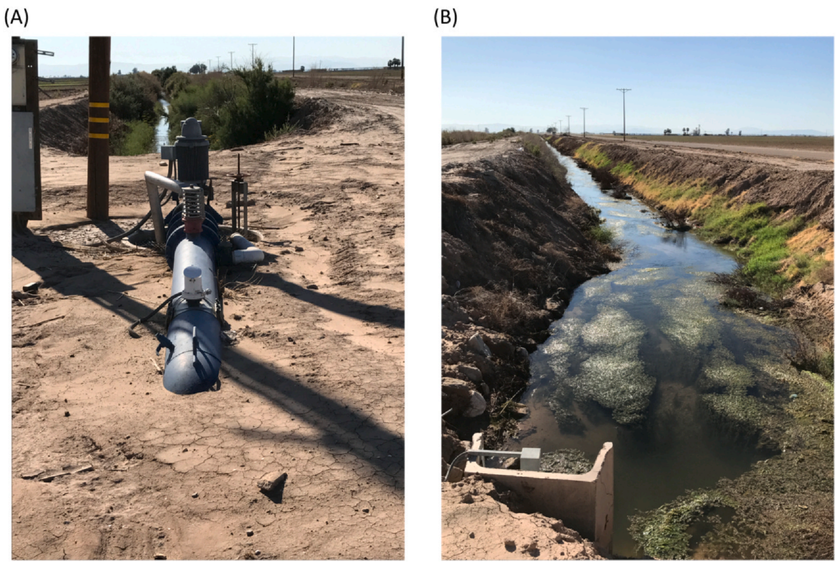


**Fig. 3** Tailwater recovery system in Imperial Valley, CA. This figure shows a semi-permanent tailwater recovery system pump and accessories; (A) and the open drainage canal as its water supplier (B).

Kieffer and Campbell, 2009; Lamm et al., 2012; Ismail and Almarshadi, 2013; Zaccaria et al., 2017; Sidhua et al., 2021). SDI can reduce water use and increase yields, and as a result enhance economic profitability and water productivity of forages. For alfalfa and potentially other perennial grasses, it offers the potential for more uniform water distribution over time and space, aligning irrigation with crop water needs throughout the growing season (Fig. 4). These advantages may reduce water stress and result in rapid regrowth after each harvest and greater yields compared to surface irrigation (Putnam et al., 2015). Alfalfa hay yield in the SDI system was found to be nearly 22 %–25 % greater (Hutmacher et al., 2001; Godoy et al., 2003) than those in surface irrigated fields, while water use was reduced by an average of 15 %. Farmers in the desert regions of California and Arizona have reported an average increase of 25 % (6.2 Mg $ha^{-1}$) in alfalfa yields over their border surface irrigated fields (Fig. 5). In another study conducted in California, researchers predicted an average increase of 7.9 Mg $ha^{-1}$ in hay yields as a result of shifting from flood irrigation to SDI in the major alfalfa-growing counties and regions in California.

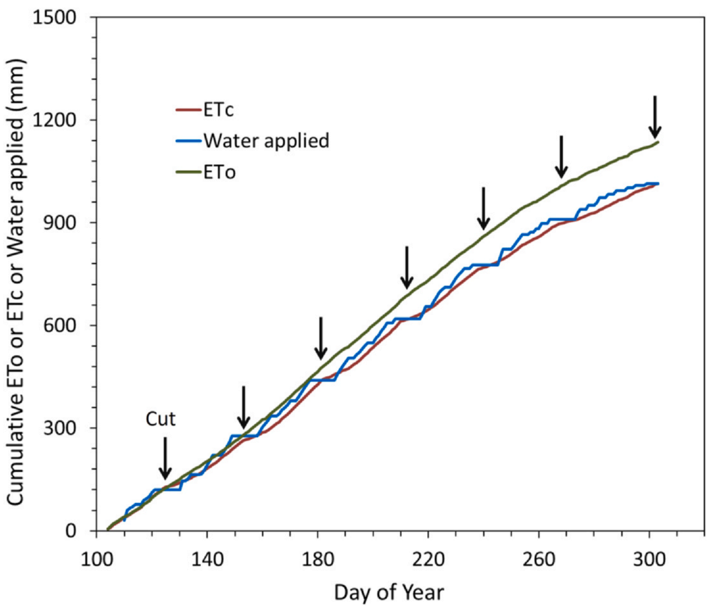


**Fig. 4** Daily alfalfa ET and irrigation water applied at an ET-based SDI irrigated trial in Davis, CA. *The data adopted from Montazar et al. (2016). ET stands for evapotranspiration. ETc and ETo are alfalfa crop water requirements andreference or potential ET.*

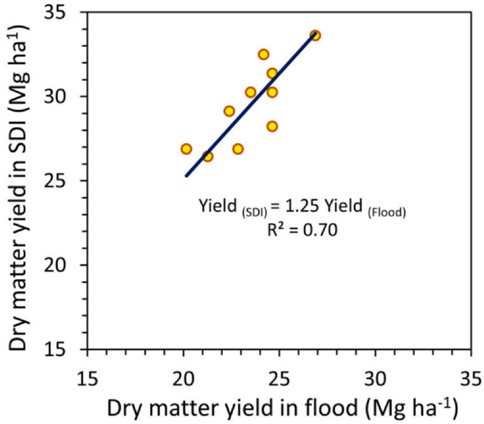


**Fig. 5** Yields reported by alfalfa farmers for their subsurface drip irrigated fields vs. border surface irrigated fields. *The data from 20 alfalfa sites in the low deserts of California and Arizona are adopted for this analysis the data adopted from Montazar et al. (2018).*

(Montazar et al., 2017). The researchers found that SDI led to positive profitability for alfalfa production in long-season regions of California but not in the short-season Intermountain areas.

Other documented benefits of SDI in alfalfa include longer stand life, healthier root systems, improved uniformity of crop growth, and enhanced weed control due to drier soil surfaces (Alam et al., 2002; Hutmacher et al., 2001; Henggeler, 1995; Lamm et al., 2012). Montazar et al. (2018) reported an average water conservation of 1200 $m^3$ $ha^{-1}$ (this is equivalent of 15 % less applied water) from converting surface flood irrigation to SDI in the low desert of California.

Farmers may face several challenges when irrigating alfalfa and other perennial grasses using SDI system, including high investment cost, maintenance issues, rodent control, crop germination and establishment, and crop rotation. Alfalfa fields under SDI can become ideal habitats for gophers, necessitating continual monitoring (Fig. 6). Extensive rodent infestation and lack of timely maintenance may lead to abandonment of the system if serious issues arise. Effective solutions include gopher fencing, setting traps, burrow fumigation, and ongoing monitoring and removal (Montazar et al., 2018; Baldwin et al., 2013).

High capital cost and economic feasibility of implementing SDI in forage crops could be concerns for farmers. Researchers determined that an average yield increase of 4.3 Mg $ha^{-1}$ is necessary to offset the costs


**Fig. 6** Large leak (A) and drip-tape damages (B and C) due to gopher issue in an alfalfa field in Dixon, CA.

associated with converting flood irrigation to SDI, based on a 12-year price relationship in California (Montazar et al., 2017). Various incentive programs provided by the federal and states governments can assist farmers in installing SDI systems. For instance, the State Water Efficiency and Enhancement Program (SWEEP: https://www.cdfa.ca.gov/oefi/sweep/) in California offers financial assistance in the form of grants to implement irrigation systems that reduce greenhouse gas emissions and conserve water. The Environmental Quality Incentives Program (EQIP: https://www.nrcs.usda.gov/programs-initiatives/eqip-environmental-quality-incentives) is another financial assistance program managed by the USDA's Natural Resources Conservation Service NRCS, 2024. This program offers technical and financial assistance to agricultural producers to address natural resource concerns, conserve water, and improve water quality.

Salinity management in arid and semi-arid regions is another pitfall of the SDI system for perennial forage crops. Soil salinity buildup can occur between and above driplines. Effective irrigation scheduling in combination with occasional irrigation using sprinkler or surface irrigation are practical strategies to control salinity in regions with low annual precipitation (Montazar et al., 2018). Additionally, narrower dripline spacings should be considered to achieve a certain degree of overlap among wetted areas and help dilute salt concentrations (Zaccaria et al., 2017). An additional benefit of narrower dripline spacing, such as using76 cm instead of 102 cm, is that it creates favorable conditions for rotating alfalfa with other forage crops such as corn, wheat, and bermudagrass.

A conceptual framework was introduced for the design and management of SDI system to maximize yield, while minimizing deep percolation water losses to groundwater in alfalfa production (Kandelous et al., 2012). For this purpose, researchers utilized a multi-criteria optimization model (AMALGAM) along with HYDRUS-2D. Studies showed that the root distribution system significantly affects the design and management practices of SDI in alfalfa, including optimal irrigation water application, irrigation scheduling, and deep percolation losses (Kandelous et al., 2012; Gärdenäs et al., 2005; Eltarabily et al., 2024), as water uptake by plant roots influences the spatial and temporal patterns of soil water availability.

The feasibility of utilizing the SDI system to apply reclaimed water and dairy effluent for forage crops presents a significant advantage for dairy farms. A comparison of sprinkler and SDI systems irrigating bermudagrass turf with reclaimed water in Arizona found no significant differences in turf growth, appearance, and soil electrical conductivity (Suarez-Rey et al., 2000). Other researchers reported successful use of lagoon effluent for forage crops in California and Kansas using SDI (Norum et al., 2001). The SDI system was effectively installed and utilized to apply treated swine wastewater effluent and reclaimed water for bermudagrass, alfalfa, and sudangrass production (Palacios et al., 2005; Palacios et al., 2008). Bermudagrass treated with wastewater effluent had significantly higher hay yields and nutrient biomass removal rates compared to those treated with commercial fertilizers. However, the researchers recommended cleaning sand filters every week and drip lines every 6 months.

## 2.3 Sprinkler irrigation

Sprinkler irrigation allows more flexible irrigation scheduling compared to conventional surface irrigation. Various types of sprinkler irrigation systems are used in forage fields including center pivot, linear move, solid set sprinklers, wheel line systems, and big gun sprinklers.

A growing number of forage production areas in the western U.S. and other countries are irrigated using center-pivot systems due to the advantages of these systems in improving irrigation efficiency, automation, and labor costs (Li et al., 2023). Converting to center pivot irrigation from surface irrigation may reduce water usage by 50 % and increase hay yields by 20 % in alfalfa (Rendell et al., 2020). Converting from surface irrigation to center pivot increased annual pasture and millet yields (all grazed), allowing stocking rates to rise from 3 cows $ha^{-1}$ to 4 cows $ha^{-1}$ and from 5 cows $ha^{-1}$ to 10 cows $ha^{-1}$, respectively (Rendell et al., 2020).

Center pivot systems can tolerate greater topographical changes, making them more suitable for forage fields that cannot be reshaped for surface irrigation systems. A center pivot with a radius of 420 m can effectively irrigate between 50–53 ha of a quarter section. End guns and corner systems can be added to increase the irrigated area and better utilize available field space, but such systems are expensive and require a greater water supply (Wang et al., 2012). A recent study provided a scientific basis for the optimal design of center pivot sprinkler system with an end gun for a square field (Hui et al., 2024). The study found that end gun compensates for insufficient irrigation of overhang and enhances overall irrigation system performance. Also, end gun with larger nozzle diameter and smaller operating pressure is preferred for irrigating corners.

Linear or Lateral Move Sprinkler Irrigation Systems are an adaptation of center pivot sprinkler systems, designed for fields where the shape or elevation changes make center pivot irrigation unsuitable. The linear move sprinkler irrigation system is composed of a series of towers that suspend the irrigation system and move laterally in the direction of the rows. Water can be supplied to the towers either from an open ditch adjacent to the first tower and parallel to the direction of travel, or by a flexible hose typically 30–60 m length, using a drag hose system (Fig. 7). The flexible hose is supplied through risers connected to a buried pipeline. Use of a linear move system is normally limited to irrigating rectangular shaped fields.

The four types of new generation of linear move and center pivot sprinkler irrigation systems that are considered as low-pressure systems and addressed as the best management practices include: (1) Low Energy Precision Application (LEPA); (2) Low Pressure In-Canopy (LPIC); (3) Low Elevation Spray Application (LESA); (4) Medium Elevation Spray Application (MESA). These systems are proven to enhance irrigation efficiency, reduce energy and water costs, and increase crop yields (Holt, 2023; O'Shaughnessy et al., 2019; Nakawuka et al., 2014).

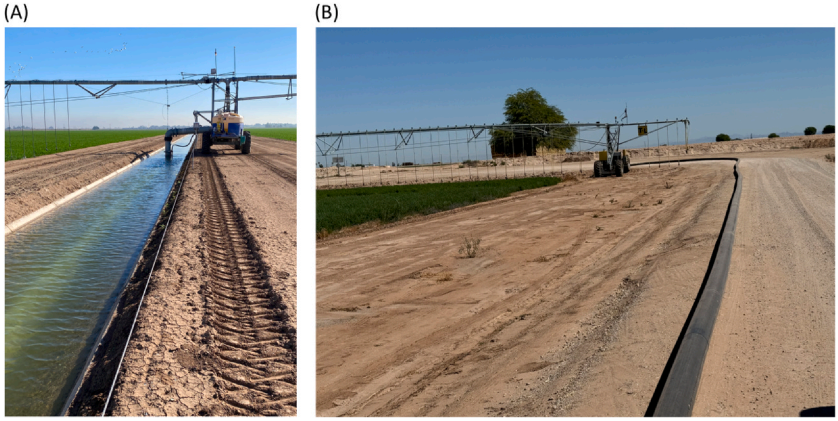


**Fig. 7** Alfalfa fields under linear move sprinkler irrigation systems (A) open ditch water supplier and (B) drag hose system in the Imperial Valley, CA.

Center pivot and linear move irrigation systems design and operation are primarily limited by soil infiltration rates (Brown, 2008; Kranz et al., 2005; Evans, 2001; Nakawuka et al., 2014). Surface runoff can be problematic on soils with low infiltration rates, requiring additional design and management consideration to prevent it. Boom systems have been proposed to decrease runoff by reducing the water application rate in center pivots and linear move systems. Both center pivot and linear move irrigation systems may struggle to provide sufficient water for high water use crops like alfalfa during the summer months in arid regions. The frequent light water applications associated with these systems can lead to high soil surface salinity, which must be leached during the fall and winter months when system capacity exceeds crop water requirements. Proper management of water application to match crop water needs and allow for adequate leaching may help control soil salinity. Salt accumulation (average ECe of 6.7 dS $cm^{-1}$) was observed at depths of 30–90 cm in two alfalfa fields with silty clay soil after two years of using a linear move sprinkler system in California's low desert of (unpublished data from the first author).

Local environmental conditions may also have an important influence on sprinkler irrigation efficiency with regard to evaporation water losses as well as water distribution uniformity (Montazar and Sadeghi, 2008). Wind, as a major factor affecting water losses, is an important consideration in the design and management of sprinkler systems (Montazar and Moridnejad, 2007). Evaporation loss rates depend on climate demand (the energy available for evaporation and the air's capacity to store and transmit water vapor), the duration that water droplets are in the air, and the surface area of the water droplets. Smaller droplets evaporate faster due to their larger surface area relative to their volume. Strategies to mitigate evaporation loss include adjusting operating conditions to increase droplet size and avoiding high climate demand periods. For instance, the evaporation losses have been reported to be higher at daytime irrigation events than at nighttime irrigation events (Cavero et al., 2008; Playán et al., 2005; Urrego-Pereira et al., 2013). Daytime sprinkler irrigation in the Ebro Valley, Spain did not affect alfalfa forage yield, despite higher evaporation water loss. Evaporation losses were found to range from 4 % during nighttime irrigation to 10 % during daytime events, and water distribution uniformity was slightly lower during daytime irrigation. (Cavero et al., 2016; Stambouli et al., 2013). The alfalfa yields linearly increased as the solid-set sprinkler irrigation applied increased from 55 % to 130 % of crop water requirements.

## 3. Technologies that assist with optimizing irrigation timing and scheduling

Efficient irrigation timing and scheduling are critical for improving water use efficiency and conserving water. Applying water when crops need it most optimizes water usage, reduces losses due to evaporation and runoff, and enhances soil moisture retention. Additionally, it lowers energy consumption for water pumping and distribution, resulting in cost savings and reduced environmental impact. Efficient scheduling also helps farmers comply with water use regulations, promoting sustainable agricultural practices and long-term viability. Technologies that can assist farmers with improved irrigation timing and scheduling include:

### 3.1 ET-based irrigation scheduling

Crop evapotranspiration (ET) is one of the most important parameters in hydrological, environmental, and agricultural studies, playing a key role in designing and managing irrigation projects, as well as in water management for both irrigated and dryland farming. Accurate estimates of forage crops water use are essential for efficient irrigation management, developing drought strategies, implementing deficit irrigation practices, and achieving optimum forage production.

Measurement of crop ET is likely the most difficult component to quantify among the various components of the water balance. Several methods of ET measurement have been discussed by researchers (Broner et al., 2003; Payero et al., 2003; Farahani et al., 2007; Rana and Katerji, 2000; Allen et al., 2011). The most common methods for ET measurement can be categorized into hydrological approaches (soil water balances and lysimeter measurements), and micrometeorological approaches (eddy covariance, surface renewal, and Bowen ratio energy balances). Remotely sensed energy balances, satellite-based ET using vegetation indices, and scintillometer systems are also methods developed as a result of the rapid developments in instrumentation, data acquisition and remote data access, and techniques over the past few decades (Li et al., 2023; Cleugh et al., 2007; Fisher et al., 2017).

In perennial forage crops like alfalfa, ET is primarily influenced by the harvest schedule, time of year, climate and weather conditions, water availability, and irrigation management practices. Seasonal ET for alfalfa has been estimated to range between 800 and 1600 mm, depending on climate and the length of the growing period (FAO, 2002; Jorgensen and Fath, 2008).

A two-year study using the eddy covariance (EC) method in Northern California reported seasonal ET ranging from 1249 to 1381 mm under surface irrigation across six harvest periods (Hanson et al., 2007; Hanson et al., 2008). In the low desert of California, ET varied from 1385 to 1596 mm in commercial alfalfa fields with eight to nine harvests per season (Montazar and Putnam, 2023; Fig. 8), while across the U.S. Great Plains, alfalfa ET ranged from 615 to 1448 mm (Broner and Schneekloth, 2003). Fig. 9 illustrates daily water consumption across different harvest cycles and seasons in alfalfa fields. This variability emphasizes the importance of utilizing accurate, real-time ET data and tools for effective irrigation management in alfalfa cultivation.

A study was conducted to map actual ET of irrigated alfalfa at a very high-resolution of 7 cm pixel$^{-1}$ using unmanned aerial system (UAS) based multispectral and thermal infrared imagery, employing variants of the METRIC energy balance model (Chandel et al., 2020). Chávez et al. (2012) utilized airborne imagery data with METRIC and reported daily ET errors of 9 % for corn and sorghum. High spatiotemporal resolution ET mapping allows for more effective monitoring of spatial crop water requirements, overcoming challenges posed by cloud cover interference and limitation in imagery acquisition.

ET-based irrigation scheduling uses real-time crop ET estimates to determine the irrigation amount and timing. It assists irrigation managers in deciding when to initiate irrigation and how much water to apply based on

**Fig. 8** A fully automated surface renewal and eddy covariance evapotranspiration (ET) tower in a commercial alfalfa field in Palo Verde, CA.

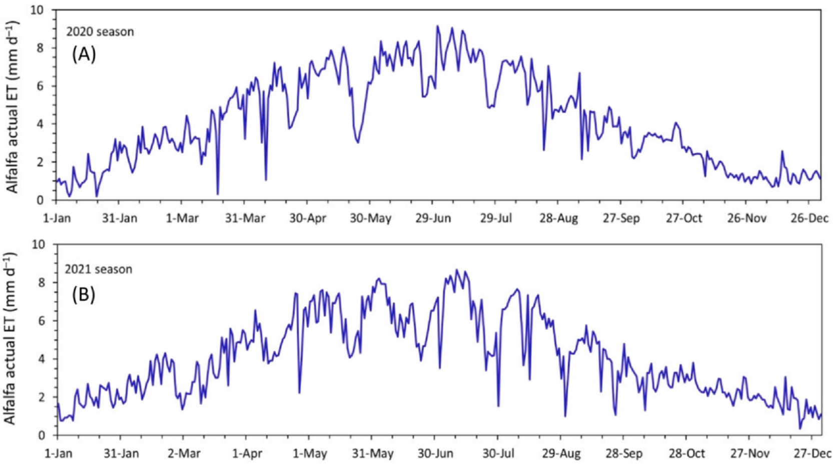


**Fig. 9** Actual ET measured using the residual of energy balance method from an eddy covariance tower over two crops season of 2020 and 2021 in the Palo Verde Valley, CA. *Data adopted from* *Montazar and Putnam (2023)*.

the plant water requirements and soil processes. As a result, it helps optimize water application efficiency and conserve water. A common practice of estimating real-time ET is using daily reference evapotranspiration (ETo) and proper crop coefficient (Kc) values of different crop growth phases. In California, in addition to CIMIS (California Irrigation Management

Information System) ETo data from the CIMIS stations network, satellite-based daily ETo maps (Spatial CIMIS) are developed on a 2-kilometer grid for the entire state, which is an important contribution of data for irrigation management. In California and western states of the U.S, several tools are available that make ET-based irrigation scheduling for forage crops more feasible and user-friendly:

**(1)** OpenET (accessible at https://openetdata.org/) is a new online platform that uses satellites for mapping actual ET at the scale of individual fields, and currently can be used across the western U.S. It is a satellite-based water data resource launched by National Aeronautics and Space Administration (NASA) and United States Geological Services (USGS). It builds upon decades of investment by NASA, USGS, NOAA, and the European Space Agency (ESA) to develop, launch, and operate a constellation of Earth observing satellites and to develop a platform for data processing and distribution to provide automated and widely accessible ET data at user-defined spatial scales and timeframes (Volk et al., 2024).

OpenET generates daily, monthly, and cumulative ET data at a spatial resolution of 30 m × 30 m. This satellite-based tool includes six models that are developed based on full or simplified implementations of the surface energy balance (SEB) approach or relies on surface reflectance data and crop type information to compute ET as a function of canopy density using a crop coefficient approach for agricultural lands. The model acronyms are eeMETRIC, geeSEBAL, DisALEXI, SSEBop, PT-JPL, and SIMS. In addition, OpenET provides the OpenET ensemble values calculated from an ensemble of the above six models.

A three-year eddy covariance of actual ET data measured in a commercial alfalfa field in the Palo Verde Valley, California was used to verify the OpenET ensemble ET (Fig. 10). The alfalfa field was harvested 25 times over the study period (1096 days). The results shown in Fig. 10 illustrate a relatively good agreement between the OpenET ensemble daily crop water use estimates and the eddy covariance ET data over the experimental period. The slope of the best fit line for the ensemble model was 0.73, with overall RMSE (Root Mean Square Error) and MAE (Mean Absolute Error) values of $1.19\ mm\ d^{-1}$ and $0.37\ mm\ d^{-1}$, respectively. However, more data from multiple sites and crops are required to comprehensively evaluate the performance of OpenET models in forage crops.

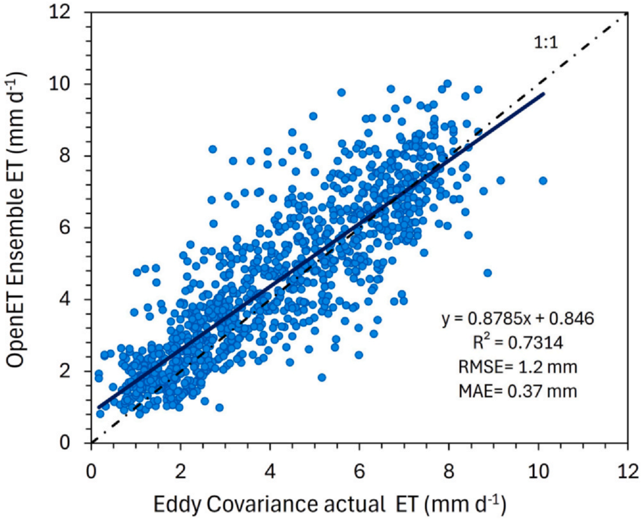


**Fig. 10** A comparison of the OpenET ensemble estimated daily ET versus the measured daily actual ET using eddy covariance at an experimental site in the Palo Verde Valley, CA. *A three-year data set (2019–2021) was adopted for this analysis eddy covariance data for the alfalfa site adopted from Montazar and Putnam (2023).*

**(2)** IRRISAT (accessible at https://irrisat-cloud.appspot.com/), harnesses satellite imagery to estimate crop water consumption via a cloud-based interface.

**(3)** EEFlux (The Earth engine evapotranspiration flux) model (accessible at https://eeflux-level1.appspot.com/), a Google Earth Engine platform, employs the METRIC algorithm and relies on Landsat's thermal and shortwave bands to calculate evapotranspiration.

**(4)** FRET (Forecast Reference EvapoTranspiration; accessible at https://digital.weather.gov/) is a new alternative to weather station ETo that provides ETo forecasts at a 2.5-km grid resolution for the entire continental United States. FRET will assist farmers to forecast ETo up to the next six days and more effectively schedule irrigation.

**(5)** Tule Technology (Tule Technologies Inc.; accessible at https://tule.ag/) is the commercially available surface renewal-based technology for measuring actual evapotranspiration. The sensor remotely reports daily actual ET data back to the Tule app, providing actionable information for irrigation decisions on a daily basis (Fig. 11).


**Fig. 11** A tule technology sensor installed in an alfalfa field under SDI in Imperial Valley, CA.

To estimate evapotranspiration, thermal imaging is typically used as an indicator of canopy radiometric temperature, where higher and lower temperatures indicate relatively lower and higher rates of ET, respectively. Some of the energy balance models commonly used in ET estimation include Two-Source Energy Balance (TSEB), Surface Energy Balance Algorithm for Land (SEBAL), Surface Energy Balance System (SEBS), Mapping EvapoTRanspiration using Internalized Calibration (METRIC) and High-Resolution Mapping of EvapoTranspiration (HRMET) (Knipper et al., 2020; Singh and Senay, 2015; Bhattarai et al., 2016; Lian and Huang, 2016; Wagle et al., 2017; Lu et al., 2017; Senkondo et al., 2019). Some of the ET maps and crop stress indices have been integrated into several IDSS (Irrigation Decision Support Systems), such as Ceres Imaging (Oakland, CA, USA), Irriwatch (Maurik, The Netherlands) and OpenET.

## 3.2 Utilizing soil moisture sensing

Soil moisture sensing can be used as a tool to monitor soil water status over the crop season at the desirable depths throughout the soil profile and is indeed useful for irrigation management in forage crop production. Soil moisture probes are widely used to determine the real-time soil water potential or volumetric water content. Soil moisture sensing can be an impactful tool for refining and improving irrigation management of forages. Using soil moisture sensors may save water without reducing yield, suggesting it is a viable option for stretching limited water supplies (Yost and Holt, 2020). In Australian dairy farm, integrating wireless soil moisture sensor networks and automated surface irrigation resulted in an average water conservation of 38% compared to conventional border surface irrigation (Dassanayake et al., 2009).

Understanding the effects of irrigation events on soil moisture offers farmers valuable insights into the current growing conditions, helping them determine the frequency and duration of irrigation necessary to maintain adequate moisture for the crops being grown. For alfalfa and perennial forages, it may provide useful information on the water status of the soil early in the irrigation season and the right time for the first irrigation event. The tool is contingent on having a well-maintained irrigation system with a good distribution uniformity, and to optimize economic benefits of water use in forage production. Soil moisture sensor is a proven and useful irrigation tool that can provide answer to the following critical questions:

- What is the water status of the soil early in the irrigation season?
- When is the right time for the first and subsequent irrigation?
- Is the soil profile full after each irrigation?
- How long should each irrigation event last?
- Should the current irrigation practice be adjusted?

As a real example, soil water potential (tension) observations are demonstrated for three alfalfa sites in the Palo Verde Valley, California in Fig. 12. At site 1, a total of 11 irrigation events occurred during the study period with a cumulative water applied of 1575 mm. Soil water tension readings never exceeded 70 kPa, indicating that the farmer could potentially skip a couple of irrigation events and/or apply less water per irrigation in this field. In contrast, Site 2 had 12 irrigation events and a cumulative water application of 1765 mm for the same period. Here, alfalfa occasionally experienced moderate water stress around cuttings when soil water

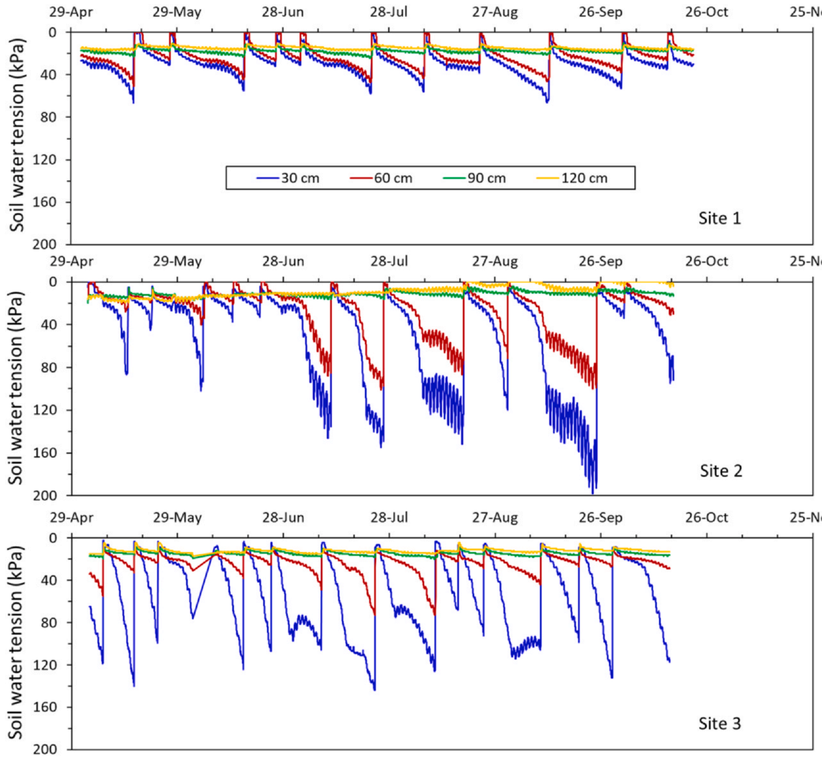


**Fig. 12** Soil water tension data (Watermark Irrometer) at three alfalfa sites in the Palo Verde Valley, California. The predominant soil texture of sites 1–3 are clay, sandy loam, and loam in the top 0.6 m, respectively. The measurements are reported in a similar period for all sites (early May through mid-October 2019). The alfalfa sites were under different irrigation regimes and cutting schedules. Each site had five cuttings during the period and site 3 had the greatest alfalfa dry matter yields across the three sites. *Data adopted from Montazar and Putnam (2023).*

tension exceeded 70 kPa. This site has a lower soil water holding capacity compared to Site 1. At Site 3, a total of 14 irrigation events were recorded, with a cumulative water application of 1476 mm over a similar period.

Despite having a greater number of irrigation events at site 3, the total amount of water applied was lower (due to lighter irrigation events) compared to the other two sites, yet this alfalfa field was adequately irrigated. Over the course of this study five cuttings occurred at each site, and the total dry matter yield at Site 3 was 0.95 Mg ha$^{-1}$ higher than at Site 1 and 1.28 Mg ha$^{-1}$ higher than at Site 2. This data clearly demonstrates that proper irrigation scheduling in alfalfa fields can not only maximize hay yields but also serve as an effective tool to conserve water and enhance water productivity.

Some commonly used soil moisture sensors can be combined with various telemetry devices to access data through cloud-based storage applications (Susha Lekshmi et al.; 2014, Rusu et al., 2019; Vuran and Silva, 2009; Salam et al., 2019). The accuracy of different types of soil moisture sensors varies based on the sensing technology used and the properties of the soil (Taghvaeian et al., 2021). For instance, electromagnetic sensors tend to exhibit larger errors in soils with higher clay content. Additionally, the salinity of soil and/or irrigation water is can further increase sensor error.

An extensive range of soil moisture sensors has already been commercialized and is currently used in forage crops. These sensors are primarily dominated by a few key technologies, including granular matrix or gypsum block sensors, tensiometers, time domain reflectometry (TDR) sensors, and Frequency Domain Reflectometry (FDR) or capacitance sensors (Busscher, 2009; Jha et al., 2022; Hardie, 2020) (Table 2). A broad range of emerging proximal soil moisture sensing techniques were identified over the past two decades, including actively heated fiber optics (AHFO), high capacity tensiometers, paired acoustic radio/seismic transceiver approaches, microwave-based approaches, radio frequency identification (RFID), hydrogels and seismoelectric approaches (Hardie, 2020). Commercially available soil moisture monitoring packages have evolved noticeably over the last decade, particularly in the way the data is transmitted and displayed. Farmers now have a variety of options regarding the type of moisture sensor, data transmission, data display and cost.

## 3.3 Plant water stress sensing

Crop water stress occurs when there is a deficiency in water supply, which is observed through the plant's physiological responses to water deficit. It corresponds with a closure of stomata and a decrease in the transpiration rate, leading to an increase in canopy temperature. To implement optimal irrigation strategies, it is important to accurately monitor crop water stress and apply irrigation water before the stress escalates beyond the target level. The crop water stress index (CWSI) has been widely applied and evaluated over the past four decades for a range of field crops, including wheat, soybean, alfalfa, and maize. (Idso, 1982; Idso et al., 1981; Idso et al., 1984; Stegman, 1986; Taghvaeian et al., 2012; Taghvaeian et al., 2013; Irmak et al., 2000). As a plant-water-status indicator, the CWSI measures the relative transpiration rate of a plant, based on canopy and air temperatures along with the vapor pressure deficit. Portable or auto-logged permanent infrared thermometer measurements are essential sensors for measuring the plant canopy temperature.

**Table 2** A summary of commercialized soil moisture sensors.

| Technology | Measurement (key parameters) | Manufacture | Example of models |
|---|---|---|---|
| Granular matrix | Soil water potential | Metergroup (or Decagon), Irrometer | MPS-2/6, Watermark, Teros 21 |
| Tensiometer | Soil water potential | Hortau, Irrometer, Metergroup | HXM80, R/SR/S, Teros 31/32 |
| TDR (volumetric) | Volumetric moisture content (soil temperature and soil salinity) | Acclima, Campbell Scientific, Metergroup, Environmental Sensors, Spectrum Technologies | TDT, TDR315H/ TDR310H/ TDR3, SoilVue 10, CS650/CS655/ CS616, TDR 200, Teros 10/11/12, Gro-Point classic |
| FDR or Capacitance (volumetric) | Volumetric moisture content (soil temperature and soil salinity) | AquaCheck, AquaSpy, Metergroup, Sentek (Sentek Technologies), Spectrum Technologies, CropX | Probe, EC5, 10HS, 5TM, 5TE, Enviroscan, WaterScout SM 100, SM 300, Teros 54, CropX |

DeJonge et al. (2015) used six indices to quantify water stress in maize including CWSI, Degrees Above Non-Stressed (DANS), Degrees Above Canopy Threshold (DACT), Time Temperature Threshold (TTT), Integrated Degrees Above Non-Stressed (IDANS), and Integrated Degrees Above Canopy Threshold (IDACT). The study found a high correlation between canopy temperature and leaf water potential. This study also suggested the DACT as the most convenient index, as it requires only canopy temperature measurement and has strong relationships with other indices and crop water measurements.

Remote sensing technologies have increasingly been used to evaluate spatial patterns of plant water stress (Govender et al., 2009; Taghvaeian et al., 2012; Taghvaeian et al., 2013). These technologies have made significant contributions to efficient irrigation practices and have emerged as effective tools for estimating actual evapotranspiration, allowable depletion, and plant water stress (Ozdogan et al., 2010; Thenkabail et al., 2009; Ozdogan and Gutman, 2008). The transpiration rate, temperature, cooling, and heating effects can also be detected by remote-sensing systems and further processed for crop water stress assessment (Idso, 1982). The canopy temperature remote-sensing method has garnered significant attention in crop water stress studies (Nanda et al., 2018) and has been identified as a scientifically validated approach for evaluating crop water status in or near real-time (Taghvaeian et al., 2013).

## 4. Management interventions affecting water productivity

Several management approaches and technologies are suggested in this section to envision more water-efficient and productive irrigated forage systems in water-limited regions, including:

### 4.1 Variable rate irrigation to address temporal and spatial variabilities

Variable rate irrigation (VRI) technology can assist farmers in addressing temporal and spatial variabilities caused by differences in soil textures and conditions, and/or topography within a large field, allowing for the application of precise amount of water to each location. Compared to uniform rate irrigation (URI), VRI technology can contribute to water conservation at the field scale. Researchers have found the advantages of VRI in conserving water and increasing water productivity in crops such as alfalfa and sudangrass in the North China Plain (Li et al., 2023). Compared to URI, VRI demonstrated significant water conservation, particularly during the rainy seasons, with average reductions of 22.2% for sudangrass, and 12.6% alfalfa. Similarly, greater water productivity was achieved for winter wheat (Li et al., 2019) and corn (Sui and Yan, 2017) using VRI compared to URI.

Variable rate irrigation systems are reliable for ensuring uniform water application and accurate water delivery within management zones (MZs) (Perry et al., 2003; King et al., 2006, O'Shaughnessy et al., 2015; Sui and Fisher, 2015; Sui et al., 2020; Haghverdi et al., 2016). Adopting VRI may reduce pumping for irrigation, leading to reductions in greenhouse gas emissions (Trost et al., 2013; Lo et al., 2016), energy savings (Hedley et al., 2009), and decreased runoff and deep percolation losses (Daccache et al., 2015; Gonzalez Perea et al., 2018).

Considering soil property-related parameters and soil variability is the most effective way to make irrigation decisions (Zhao et al., 2017). Apparent soil electrical conductivity (ECa), which has a close relationship with the crop yield potential (Corwin and Lesch, 2003), can be used for VRI systems. However, there is limited information available on the effects of spatial ECa variability on irrigation, yield, and water productivity (Li et al., 2023). Soil available water content is the primary attribute for delineating MZs, while satellite imagery, ECa, and yield maps can provide useful auxiliary data (Li et al., 2018; Haghverdi et al., 2015; Bellvert et al., 2012). Recent developments in UAV (Unmanned Aerial Vehicle) data acquisition technologies may also provide useful information for VRI (Von Bueren et al., 2014).

Theoretically, applying a specific irrigation program to each MZ using VRI within a field could result in water conservations compared to uniformly irrigating the entire field (Hedley et al., 2009; Evans et al., 2013; Perea et al., 2018). However, only a limited number of studies have demonstrated the water-saving benefits of these systems for forage crops (Li et al., 2019; Vories et al., 2017; Sui et al., 2020; O'Shaughnessy et al., 2019), which warrants further research. Despite its potential benefits, VRI technology has been used less than expected so far, though awareness among farmers and researchers is growing (LaRue and Evans, 2012). The new generation of low-energy center pivot and linear move irrigation systems provide an ideal platform for adopting VRI technology and precision irrigation in forage crops. VRI technology offers clear advantages, particularly in fields with soil variability or where multiple forages are grown under the same irrigation system, making it an optimal tool for more site-specific irrigation management.

## 4.2 Drought management and water deficits strategies

Drought has been a major limiting factor in global agricultural production (Geng et al., 2016), with more than half of the world's agricultural land facing drought challenges (Orloff et al., 2015). Although fallowing regimes are compelling due to their simplicity during droughts, they come with several unintended negative consequences, including reduced food production and its economic impacts, effects on farm workers, diminished economic health of communities, degradation of air quality and soil health, and the erosion of long-term agricultural economic viability. Alfalfa and perennial grasses are crucial food sources for the livestock industry, however, with water supplies becoming increasingly scarce, improving water use efficiency in these forages is essential. Forage crop yields are considerably affected by water deficits, as nearly the entire aboveground biomass is harvested. Compared with alfalfa, most forage pasture and grasses are less drought tolerant due to having a shallower root system (Gelley et al., 2020). To improve livestock farming resilience to drought and water constraints, farmers may include C4 annual and perennial forages, which have greater production efficiency during drought than commonly used C3 forages (Orloff et al., 2005; Higginbotham et al., 2008).

Deficit irrigation strategies are recommended as a sustainable crop production and drought strategy to maximize water productivity and to stabilize alfalfa yields while conserving irrigation water (Hanson et al., 2007; Yost et al., 2021; Orloff et al., 2005). The overall effectiveness of deficit irrigation largely depends on the type of forages and the specific irrigation strategy adopted (Montazar et al., 2020; Orloff et al., 2005).

Deficit irrigation practices for forage crops can be employed in various ways to minimize negative impacts and maximize forage profit. These strategies include modifying irrigation schedules, concentrating irrigation to critical crop growth phases, reducing irrigation application rates, and terminating irrigation events earlier than usual.

Generally, 60–95% of full yields can be obtained with deficit irrigation that apply 50% to 75% of the full seasonal water requirements for alfalfa during the summer, depending on soil type (Montazar et al., 2020). This is partly due to the yield pattern of alfalfa (Fig. 13), where yields decline in late summer even under full irrigation. Late summer also coincides with the highest evapotranspiration demand. Alfalfa, with its deep root system, can utilize residual soil water and exhibits lower water use efficiency during late summer compared to the early season. Since alfalfa is harvested multiple times a year, farmers may opt to skip selected harvests, reducing water costs while still maintaining high overall production. On most soils (except sandy soils) alfalfa can recover from late-season water deficits when re-watered, enabling continued production in the following years.

For alfalfa, four basic deficit irrigation strategies are proposed for drought mitigation (Ottman et al., 1996; Orloff et al., 2005; Montazar et al., 2020): (1) cease irrigation on some alfalfa fields while fully irrigating others, (2) apply deficit-irrigate across the entire alfalfa field throughout the growing season, (3) fully irrigate fields in the early-to-mid season, then stop irrigation during the summer, and (4) fully irrigate fields in the early-to-mid season, followed by moderate deficit irrigation during the summer. The impacts of these irrigation strategies are site specific, with the optimal

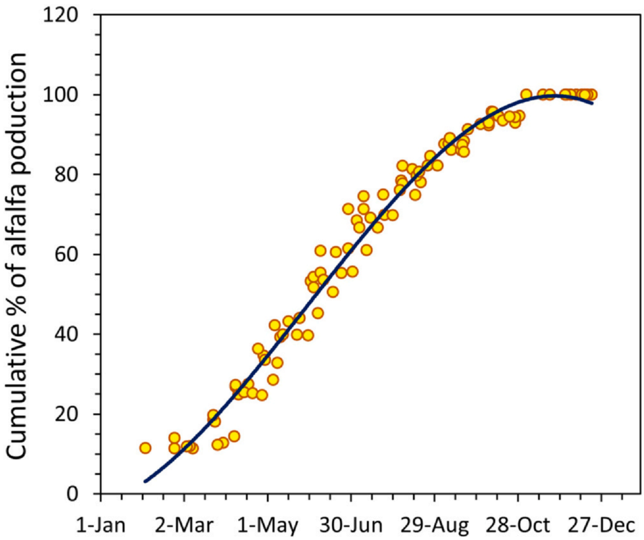


**Fig. 13** Cumulative percentage of alfalfa production over the crop season in the low desert region. *Data adopted from Montazar and Putnam (2023).*

approach varying based on soil types and conditions, groundwater contribution, crop cultivar, and climate and cultural practices. For instance, implementing moderate summer water deficits in Palo Verde, California, resulted in conserving 600–1200 $m^3$ $ha^{-1}$ water, with a corresponding alfalfa yield reduction of 0.5–1.5 Mg $ha^{-1}$ (Montazar et al., 2020). In contrast, a severe deficit irrigation practice (cutting off irrigation for the entire summer), conserved 2300–2600 $m^3$ $ha^{-1}$ of water, but resulted in a more significant yield loss of 3.7–4.9 Mg $ha^{-1}$ in California's low desert region (Montazar and Putnam, 2023). The Deficit Irrigation Program (DIP), as a summer water conservation practice, is currently adopted by some farmers in the Imperial Valley. The Imperial Irrigation District (IID) incentivizes these practices on a voluntary basis for farmers cultivating alfalfa, bermudagrass, and kleingrass to reduce IID's consumptive use of Colorado River water. The impact of mid-summer irrigation cut-off—where no irrigation occurs from June until the following spring—on alfalfa forage yield and quality has been investigated by several researchers in California, Arizona, and Nevada (Sanden et al., 2007; Ottman, 2011; Robinson et al., 1994; Putnam et al., 2000; Khalilian et al., 2022; Lana et al., 2017). These studies showed that withholding irrigation during mid-summer reduced alfalfa yields by 29–55% compared to fully irrigated alfalfa but did not significantly affect plant stand. Although yield losses due to water deficits can be economically significant, the costs of re-establishing the plant stand are relatively low and pose a minor risk with deficit irrigation strategies. Additionally, deficit irrigation has had few, and sometimes positive, impacts on forage quality of alfalfa, small grain, corn silage, and teff grass hay (Orloff et al., 2005).

Western states of the U.S. account for approximately 50% of US dairy production, which heavily relies on local forage sources, particularly alfalfa (Brummer, 2013). During drought years and times of limited water supply, it is important to consider the seasonal production patterns of alfalfa. Maximizing production during early growth periods and implementing deficit irrigation during periods of relatively low yield and quality, such as mid-to-late summer, can be effective. Deficit irrigation practices on alfalfa could provide a source of seasonally available water, specifically in summer when water is more needed. These strategies may serve as an effective water conservation tool if adequate economic incentives are provided to farmers to offset the risk of yield losses associated with reduced water applications.

## 4.3 Choosing drought-tolerant forages

Selecting suitable crop species is a fundamental step in establishing a resilient forage production system in water-scarce regions. Some species, like corn, are predominant forage crops due to their desirable yield and quality attributes. However, corn's high-water requirement and inability to cope with drought and heat under limited water supply make it a less favorable crop choice when water availability is limited (Jahansouz et al., 2014).

Certain species are naturally adapted to dry climates and water-scarce conditions. Often native to arid regions, these species have evolved mechanisms that make them more suitable for cultivation in challenging environments (Tardieu et al., 2018). For instance, crops with deep rooting systems can access water from deeper soil layers, sustaining growth during prolonged dry periods (Ludlow and Muchow, 1990). Additionally, physiological adaptations such as rapid stomatal closure and biochemical responses like the synthesis of osmolytes and antioxidants help these species maintain cellular functions under drought stress, enabling them to endure and recover (Kapoor et al., 2020).

Selecting drought-tolerant species to replace traditional drought-sensitive forage species offers opportunities for improving water productivity while producing forage for livestock in water-limited environments.

Sorghum, specifically, is gaining attention as an excellent replacement for silage corn in the west and southwest USA (Getachew et al., 2016). Research suggests that sorghum can be a more water-efficient crop compared to corn, especially in water-limited or drought-prone environments (Jahansouz et al., 2014; Bhattarai et al., 2020a; Nematpour et al., 2021). It has been reported that sorghum can survive and produce comparable dry matter yield with significantly lower water requirements compared to corn (Miron et al., 2005).

Sorghum silage qualities vary greatly depending on the cultivar. Conventional forage sorghum hybrids generally have lower nutritional quality and digestibility compared to corn silage (Mccary et al., 2020), mainly due to lower NDF digestibility (Mccary et al., 2020) and the possibility of containing anti-nutritional components such as phenolic compounds (De Oliveira et al., 2007). In contrast, brown midrib (BMR) sorghum hybrids contain less lignin, resulting in higher NDF digestibility (Sánchez-Duarte et al., 2019). A meta-analysis of nine dairy cow feeding studies revealed that lactation performance improved when cows were fed diets formulated with BMR sorghum silage compared to conventional sorghum silage, but performance was not different for cows fed BMR sorghum silage and conventional corn silage diets (Sánchez-Duarte et al., 2019).

Some researchers have shown that sorghum silage can be an adequate alternative forage in dairy cows with no negative effects on milk quality (Buonaiuto et al., 2021; Pino and Heinrichs, 2017). Another study reported that feeding forage sorghum silage, properly supplemented with corn meal, as a total replacement for corn silage, maintained milk composition and did not negatively influence milk coagulation properties (Cattani et al., 2017). It has been suggested that carefully replacing corn silage with sorghum silage does not negatively impact dairy cow productivity or milk yield and quality. However, limiting the dietary proportion of sorghum silage (Li et al., 2020) and supplementing diets with concentrates (Cattani et al., 2017) have been suggested to mitigate any potential negative impacts of replacing corn silage with sorghum silage on animal performance.

Currently, the complete substitution of sorghum silage for corn silage is not recommended in dairy rations. However, improving sorghum forage quality through breeding and genetic improvement will further enhance the suitability of this drought-tolerant species in animal rations. Rapid advancements in high-throughput experimental and data processing technologies have significantly accelerated sorghum genomic research in recent years (Hao et al., 2021). High-yield and high-quality modern hybrids of sorghum can provide significant water-saving opportunities for forage production, ultimately contributing to a more sustainable livestock industry in arid and semi-arid regions. However, if a sorghum-containing diet requires additional concentrates for proper balance, it is essential to consider the water footprint of these concentrates to determine whether net water savings are achieved from substituting sorghum for corn.

## 4.4 Genetic improvement to develop climate resilient forages

Improving tolerance to abiotic and biotic stresses, particularly drought, while maintaining or enhancing yield and nutritive value, should be the primary breeding goals for alfalfa and other forage species in water-limited environments. Stress-tolerant varieties that can produce maximum yield under stress conditions and demonstrate high yield potential when those conditions are alleviated are highly desirable (Putnam et al., 2001; Volaire et al., 2014).

Historically, alfalfa breeders have focused on enhancing disease and insect resistance, winter hardiness, and forage quality, with less emphasis on drought resistance. Developing drought-resistant cultivars is crucial for sustaining forage production as water availability continues to decline and the impacts of drought become more severe and frequent (Ray et al., 2015; Volaire et al., 2014). Breeding for improved tolerance in alfalfa to variable water environments has resulted in release of several cultivars and germplasms, including 'Wilson' (Melton et al., 1989) and 'Nu-Mex Bill Melton' (Ray et al., 2012).

While traditional alfalfa breeding relies on recurrent phenotypic selection, incorporating molecular marker-assisted breeding can enhance genetic gain per unit time and cost, accelerating alfalfa improvement (Li and Brummer, 2012). Omics approaches have been successfully used to evaluate crop wild relatives under various treatments, leading to the discovery of numerous stress-tolerant genes in different wild relatives (De Faveri et al., 2023). Although omics studies have been less applied to forage crops, they could be valuable tools for identifying and developing climate-resilient forage crops.

Equally important to productivity under stress, an additional aspect of stress tolerance in alfalfa is the plant's ability to survive prolonged stress, such as a complete irrigation curtailment during summer months, allowing it to regain full productivity once watering resumes (Janssen et al., 2004). In some cases, the plant's survival during stress periods may be more critical than its productivity under stress. Developing cultivars adapted to water stress will ensure that plant stands do not decline over time, particularly as such stresses are expected to become more common in the future.

Salinity tolerance is closely related to water limitations, as reduced osmotic pressure minimizes plant water uptake. Therefore, evaluating and breeding for both salt tolerance and water deficit tolerance are essential.

The impact of irrigation and drought resiliency on reduced-lignin alfalfa hybrids—the first genetically engineered alfalfa cultivars commercialized for improved forage digestibility (United States Department of Agriculture, Animal and Plant Health Inspection Service USDA-APHIS, 2014)-remains unknown. Research is needed to address these significant knowledge gaps and to better understand the performance of low-lignin alfalfa hybrids in water-deficit situations.

## 4.5 Conservation agricultural practices to boost water productivity

Conservation practices, such as cover cropping and conservation tillage, have potential to impact water productivity. Conservation tillage may directly and indirectly enhance the water productivity of forage crops in water-limited environments. Direct effects include increased soil water storage (Lampurlanés et al., 2016), reduction in evaporation and infiltration (Hatfield et al., 2001), and increased top-soil water content (Liu et al., 2013; Wang et al., 2021). Indirectly, conservation tillage positively influences soil physicochemical properties and soil quality (Dikgwatlhe et al., 2014; Turmel et al., 2015; Clay et al., 2019), which can improve plant growth and yield per unit of available water. A review of 119 published articles indicated that conservation tillage could be effective in increasing precipitation storage, soil water conservation, and crop yield in regions with medium to low mean annual precipitation and medium to high mean annual temperature (Adil et al., 2024).

While the benefits of conservation tillage are well-documented, the impact of cover crops on soil moisture dynamics varies with soil and climate conditions (Nielsen et al., 2015). Cover cropping could improve soil physicochemical properties and soil health, but their effects on soil moisture can be mixed. Cover crops extract soil moisture and transpire it during their growth cycle, which can reduce soil water content available for succeeding crops (Nielsen et al., 2015; Kahimba et al., 2008; Blanco-Canqui et al., 2015). Conversely, cover crop residue can reduce unproductive soil moisture loss through evaporation and increase water holding and infiltration capacities (Blanco-Canqui et al., 2015; Heitman et al., 2023). In arid regions with limited water resources, this competition for soil moisture may necessitate additional irrigation for cover crop establishment and growth. Therefore, the trade-offs between the benefits of cover crops in improving soil properties and the potential drawbacks related to soil moisture depletion underscore the need for strategic planning when integrating cover crops into forage production systems in such regions.

## 5. Conclusions

The high water demands of forage crops, coupled with extreme weather events in the western and southwestern United States, have intensified the pressure on forage-producing farms to reduce water usage. Adopting advanced irrigation technologies and best management practices is essential for achieving greater efficiency and water savings. Transitioning from conventional surface irrigation to more efficient systems, such as low-energy precision application linear move and center pivot sprinklers, as well as subsurface drip irrigation, has shown promise in conserving water, fertilizer, and energy. These systems also enhance forage yields and reduce labor costs.

ET-based irrigation scheduling, along with soil moisture and plant water stress monitoring, are robust tools that benefit farmers by enhancing efficiency, conserving water, and improving forage yield and quality. Satellite-based ET tools such as OpenET, IrriSat, FRET, along with commercial ET sensors such as Tule technology, are useful and relatively easy to adopt at the field scale. Farmers increasingly prefer soil moisture sensors with recent advancements in telemetric operations and web-based or mobile applications.

Recent years have seen significant development in precision technologies for forage production, including high-resolution satellite images, unmanned aerial vehicle- based data acquisition technologies, and variable rate irrigation technology. Drought management and optimal water deficit strategies can serve as highly effective water conservation tools if adequate economic incentives are provided to farmers to offset the risk of yield losses associated with reduced water applications.

Advanced breeding of alfalfa and perennial grass can produce cultivars that, when combined with the aforementioned technologies, make water conservation even more achievable. These enhanced cultivars can further boost forage yield, quality, and water-use efficiency under water deficit conditions and drought.

Given the large-scale nature of forage production and the growing demand for improved water-use efficiency, there are substantial opportunities to adopt these tools and technologies effectively. This could lead to a new era of improved irrigation management and efficiency in forage crops.

## Acknowledgment

This study was funded by the US Dairy Checkoff through Dairy Management Inc.

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