

CLIMATE-SMART IRRIGATION TECHNOLOGIES AND STRATEGIES FOR FORAGE CROPS IN CALIFORNIA'S LOW DESERT

TECHNOLOGIES ET STRATÉGIES D'IRRIGATION INTELLIGENTES FACE AU CLIMAT POUR LES CULTURES FOURRAGÈRES DANS LE DÉSERT DE BASSE ALTITUDE DE CALIFORNIE

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ABSTRACT

California's low desert is one of the most productive forage-producing regions in the western United States, yet production depends heavily on Colorado River irrigation under extremely arid conditions. Increasing drought severity and declining water availability have intensified the need for climate-smart irrigation strategies. This study synthesizes field evaluations and monitoring-based assessments of irrigation technologies and adaptive water-management approaches implemented in low desert forage systems between 2018 and 2026. Data from more than 55 research-controlled plots and commercial field trials were used to evaluate surface irrigation automation, tailwater recovery, subsurface drip irrigation (SDI), precision sprinkler systems, deficit irrigation, and decision-support technologies. Automated surface irrigation using solar-powered canal gates and real-time water advance sensing reduced tailwater runoff to approximately 4% of applied irrigation water, while tailwater recovery systems captured and reused approximately 70% of runoff. Field-scale comparisons across 26 alfalfa fields showed that SDI increased average alfalfa yield from 23.7 to 26.2 Mg ha⁻¹ and improved water productivity relative to flood irrigation. Deficit irrigation trials achieved seasonal water conservation ranging from 100 to 700 mm depending on irrigation cutoff severity, with forage yield reductions of 4 to 18%. Multi-depth soil moisture monitoring further highlighted the importance of root-zone storage management for sustaining forage systems during prolonged drought. Integrated monitoring technologies, including evapotranspiration measurements, soil moisture sensing, automated monitoring systems, and remote sensing, improved irrigation scheduling and drought-adaptive management under variable desert conditions. Overall, the evaluated technologies reduced operational losses, improved forage yield and water productivity, and enhanced drought adaptation through more efficient use of irrigation water and stored root-zone moisture. These findings indicate that integrated drought-adaptive irrigation systems provide a practical pathway for improving agricultural water-use efficiency under increasing water scarcity in the low desert region.

Keywords: Climate-smart irrigation technologies; Forage crops; Deficit irrigation; Integrated monitoring technologies; Soil moisture sensing.

RÉSUMÉ

Le désert de basse altitude de Californie est l'une des régions les plus productives de l'ouest des États-Unis pour les cultures fourragères, mais la production y dépend fortement de l'irrigation à partir du fleuve Colorado dans des conditions extrêmement arides. L'aggravation de la sécheresse et la diminution de la disponibilité de l'eau ont renforcé la nécessité de stratégies d'irrigation intelligentes face au climat. Cette étude synthétise les évaluations sur le terrain et les analyses fondées sur le suivi de technologies d'irrigation et de méthodes adaptatives de gestion de l'eau mises en œuvre dans les systèmes fourragers du désert de basse altitude entre 2018 et 2026. Les données issues de plus de 55 parcelles expérimentales contrôlées et d'essais en champs commerciaux ont été utilisées pour évaluer l'automatisation de l'irrigation de surface, la récupération des eaux de ruissellement en bout de parcelle, l'irrigation goutte à goutte souterraine (SDI), les systèmes d'aspersion de précision,

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l'irrigation déficitaire et les technologies d'aide à la décision. L'irrigation de surface automatisée, faisant appel à des vannes de canal alimentées à l'énergie solaire et à la détection en temps réel de l'avancement de l'eau, a réduit le ruissellement en bout de parcelle à environ 4 % de l'eau d'irrigation appliquée, tandis que les systèmes de récupération ont capté et réutilisé environ 70 % du ruissellement. Des comparaisons à l'échelle de la parcelle dans 26 champs de luzerne ont montré que la SDI faisait passer le rendement moyen de la luzerne de 23,7 à 26,2 Mg ha⁻¹ et améliorait la productivité de l'eau par rapport à l'irrigation par submersion. Les essais d'irrigation déficitaire ont permis d'économiser de 100 à 700 mm d'eau sur la saison, selon l'ampleur de l'arrêt de l'irrigation, avec des réductions du rendement fourrager de 4 à 18 %. Le suivi de l'humidité du sol à plusieurs profondeurs a également mis en évidence l'importance de la gestion de la réserve en eau de la zone racinaire pour maintenir les systèmes fourragers pendant les sécheresses prolongées. Les technologies de suivi intégrées, notamment les mesures de l'évapotranspiration, les capteurs d'humidité du sol, les systèmes de suivi automatisés et la télédétection, ont amélioré la programmation de l'irrigation et la gestion adaptative de la sécheresse dans des conditions désertiques variables. Dans l'ensemble, les technologies évaluées ont réduit les pertes opérationnelles, amélioré le rendement fourrager et la productivité de l'eau, et renforcé l'adaptation à la sécheresse grâce à une utilisation plus efficiente de l'eau d'irrigation et de l'humidité stockée dans la zone racinaire. Ces résultats indiquent que les systèmes d'irrigation intégrés et adaptatifs à la sécheresse offrent une voie concrète pour améliorer l'efficacité de l'utilisation de l'eau en agriculture face à une pénurie d'eau croissante dans la région du désert de basse altitude.

Mots clés : Technologies d'irrigation intelligentes face au climat; Cultures fourragères; Irrigation déficitaire; Technologies de suivi intégrées; Capteurs d'humidité du sol.

INTRODUCTION

California's low desert region is among the most productive forage-producing areas in the western United States and supports major dairy and livestock industries through intensive year-round alfalfa production (Montazar and Putnam, 2023). However, agricultural productivity in the region depends heavily on irrigation supplied primarily by the Colorado River under extremely arid climatic conditions. Seasonal reference evapotranspiration (ET_0) commonly exceeds 1800 mm yr⁻¹, while peak summer crop water use may surpass 7.5 mm d⁻¹, resulting in some of the highest agricultural water demands in North America (Udall and Overpeck, 2017; Montazar et al., 2020). Increasing drought severity, long-term reductions in Colorado River water availability, and growing pressure for agricultural water conservation have intensified the need for more efficient and adaptive irrigation management strategies capable of sustaining forage productivity under limited water supplies.

Surface irrigation systems remain the dominant irrigation method for forage production in the region because of their relatively low installation cost and compatibility with large commercial fields (Grismer and Bali, 2001; Montazar and Afshar, 2025). However, conventional irrigation practices frequently experience operational losses associated with runoff, deep percolation, non-uniform water distribution, and inefficient irrigation scheduling. Under increasingly constrained water allocations, improving irrigation efficiency alone may no longer be sufficient. Instead, long-term agricultural sustainability increasingly depends on integrating irrigation modernization, adaptive drought management, and precision irrigation technologies within climate-smart production systems.

Recent advances in irrigation automation, subsurface drip irrigation (SDI), precision sprinkler systems, soil moisture monitoring, evapotranspiration-based irrigation scheduling, telemetry, and remote sensing technologies have created new opportunities for improving water management in arid forage production systems (Lamm et al., 2012; Putnam et al., 2015; Allen et al., 2011; Melton et al., 2022). In parallel, adaptive deficit irrigation strategies and root-zone storage management approaches have become increasingly important under drought-related irrigation allocation reductions such as the Deficit Irrigation Program (DIP) implemented in Imperial Valley, California (Montazar et al., 2026). These approaches aim to improve irrigation efficiency, maintain forage productivity, and enhance drought resilience through more strategic management of irrigation water and stored soil moisture.

The objective of this study is to synthesize field evaluations, commercial implementations, and monitoring-based assessments of climate-smart irrigation technologies and adaptive irrigation strategies for forage production systems in California's low desert. Evaluated systems included surface irrigation automation, tailwater recovery systems, subsurface drip irrigation, precision sprinkler systems, adaptive deficit irrigation management, and integrated irrigation decision-support technologies aimed at improving irrigation efficiency, water productivity, and drought adaptation under increasing water scarcity conditions.

TECHNICAL EVALUATION FRAMEWORK

This study integrates field observations, commercial-scale demonstrations, and irrigation monitoring datasets collected between 2018 and 2026 from more than 55 research-controlled plots and commercial forage fields under arid low desert production conditions. Evaluations were conducted across commercial forage production systems and at the UC Desert Research and Extension Center (DREC) in California.

Monitoring activities included irrigation performance evaluations, flow and runoff measurements, evapotranspiration monitoring using eddy covariance systems and field-based ET sensors, multi-depth soil moisture measurements, drainage salinity monitoring, and forage productivity assessments. Additional datasets included satellite-based evapotranspiration products, automated monitoring platforms, and remote sensing observations used to support irrigation scheduling and drought-adaptive water management. The integrated datasets were utilized to evaluate irrigation performance, operational feasibility, water conservation potential, salinity response, and drought adaptation across multiple forage irrigation systems under increasing water scarcity conditions in California's low desert region.

CLIMATE-SMART IRRIGATION TECHNOLOGIES AND STRATEGIES

Surface Irrigation Automation and Tailwater Recovery

Surface irrigation remains the dominant irrigation method for forage production systems in California's low desert because of its relatively low installation cost and compatibility with large commercial fields. However, conventional surface irrigation systems often experience substantial operational losses associated with runoff, deep percolation, non-uniform water distribution, and poor irrigation cutoff timing. Improving the performance of existing surface irrigation infrastructure therefore remains an important component of integrated water management under increasingly constrained Colorado River water supplies.

Previous field evaluations demonstrated that improved inflow regulation, irrigation cutoff management, precision land leveling, and runoff reduction can substantially improve irrigation efficiency (Grismer and Bali, 2001; Chávez et al., 2020; Fuentes and Chávez, 2020; Smith et al., 2018). Automated surface irrigation systems utilizing solar-powered canal gates and real-time water advance sensing stations were evaluated in commercial forage production fields in the Imperial Valley (Figure 1). During representative irrigation events, tailwater runoff represented only approximately 4% of total applied irrigation water, while overall irrigation efficiency approached 86% (Figure 2).

Tailwater recovery systems were additionally evaluated as a complementary strategy for improving on-farm water reuse under low desert conditions. These systems captured irrigation runoff through agricultural drainage channels and recirculated recovered water back to irrigated forage fields using portable and semi-permanent pumping infrastructure (Figure 3). Commercial-scale evaluations demonstrated that approximately 70% of irrigation runoff water could be recovered and reused under properly managed field conditions.

Field observations further indicated average electrical conductivity values near 3 dS m^{-1} in recovered drainage water, suggesting that tailwater reuse may be feasible for salt-tolerant forage systems such as alfalfa, bermudagrass, kleingrass when salinity is carefully managed. Overall, modernization of conventional surface irrigation systems through automation technologies and tailwater recovery infrastructure provides a practical and scalable strategy for improving irrigation efficiency, reducing operational water losses, and supporting adaptive forage production under increasing water scarcity conditions in California's low desert region.



Figure 1. Automated surface irrigation infrastructure utilized in forage production fields in Imperial Valley, California, including solar-powered automated canal gates and real-time water advance sensing stations. The system regulated irrigation inflow based on field water advance conditions to improve irrigation efficiency, reduce tailwater runoff, and optimize surface irrigation management.

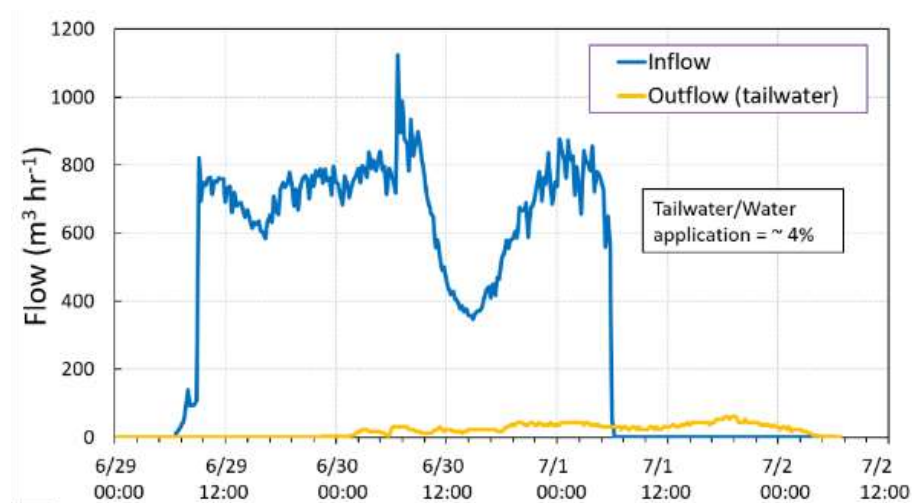


Figure 2. Inflow and tailwater runoff rates measured during an automated surface irrigation event in a kleingrass field in Imperial Valley, California. Irrigation inflow was dynamically adjusted based on real-time water advance conditions, while tailwater runoff remained minimal, representing approximately 4% of applied irrigation water.



Figure 3. Tailwater recovery infrastructure utilized in forage production systems in Imperial Valley, California. The system captures irrigation runoff through agricultural drainage channels and recirculates the recovered water back to irrigated fields to improve irrigation efficiency, reduce operational water losses, and enhance on-farm water reuse under low desert conditions.

Subsurface Drip Irrigation

SDI has emerged as an important irrigation modernization strategy for improving forage productivity and irrigation efficiency in arid forage production systems. Unlike conventional flood irrigation, SDI applies water directly to the root zone through buried drip lines, improving irrigation uniformity and reducing surface runoff and ponding. Field evaluations in Imperial Valley and Palo Verde Valley showed that SDI systems installed approximately 10–12 inches below the soil surface improved root-zone moisture regulation and reduced crop water stress between harvest cycles.

Commercial field comparisons demonstrated consistently greater alfalfa yield under SDI than under conventional flood irrigation (Figure 4). Across 26 commercial forage fields, including 13 SDI and 13 flood-irrigated fields, average yield increased from 23.7 Mg ha⁻¹ under flood irrigation to 26.2 Mg ha⁻¹ under SDI, representing an average increase of 10.4%. Seasonal actual evapotranspiration (ET_a) measurements using eddy covariance systems further showed that SDI improved water productivity rather than simply reducing crop water use (Figure 5). In two commercial alfalfa fields during their third production year, cumulative seasonal ET_a reached 1,505 mm under flood irrigation and 1,591 mm under SDI, while seasonal forage yield increased from 25.7 to 30.1 Mg ha⁻¹ with SDI management. Consequently, water productivity increased from 17.1 to 18.9 kg ha⁻¹ mm⁻¹ under SDI conditions.

Despite these benefits, successful SDI management in low desert environments requires careful salinity and system maintenance management. Because water is applied below the soil surface, salts may accumulate near the soil surface or between drip lines if periodic leaching is not provided. Drainage water monitoring showed periodic salinity increases associated primarily with reclamation leaching events and seasonal rainfall (Figure 6), indicating the importance of integrating SDI with occasional sprinkler or surface irrigation events to maintain long-term soil.

Operational challenges including rodent damage to buried drip lines, filtration maintenance, and leak detection also remain important considerations for long-term SDI performance (Figure 7). Nevertheless, field evaluations demonstrated that SDI provides a viable adaptive irrigation strategy for improving forage productivity and water productivity under increasingly constrained water supplies in California's low desert region.

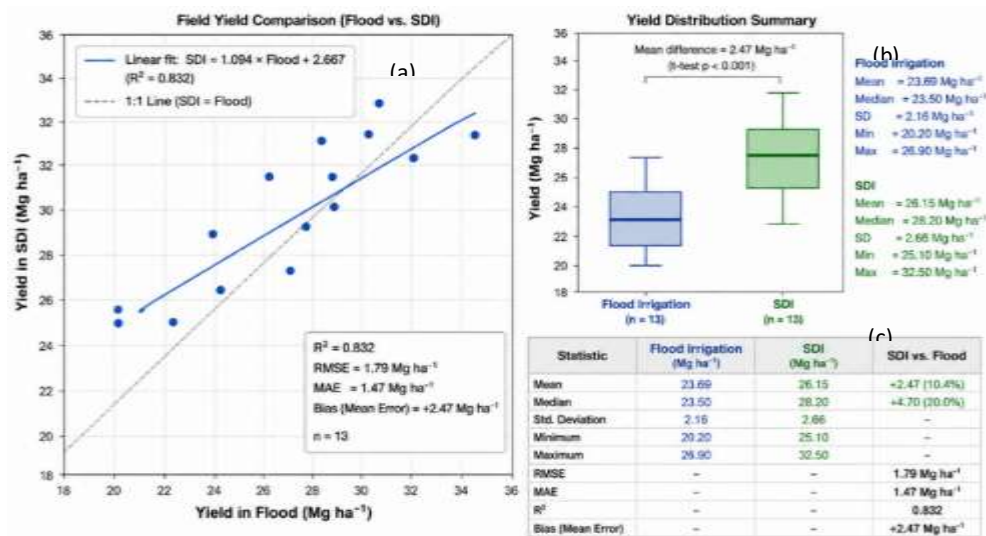


Figure 4. Comparison of alfalfa yield under conventional flood irrigation and subsurface drip irrigation (SDI) across 26 commercial fields, including 13 SDI and 13 flood-irrigated fields. (a) Relationship between SDI and flood-irrigated yields with linear regression and 1:1 reference line. (b) Yield distribution under both irrigation systems. (c) Summary statistics show that SDI increased average alfalfa yield by 2.47 Mg ha^{-1} (10.4%) relative to flood irrigation.

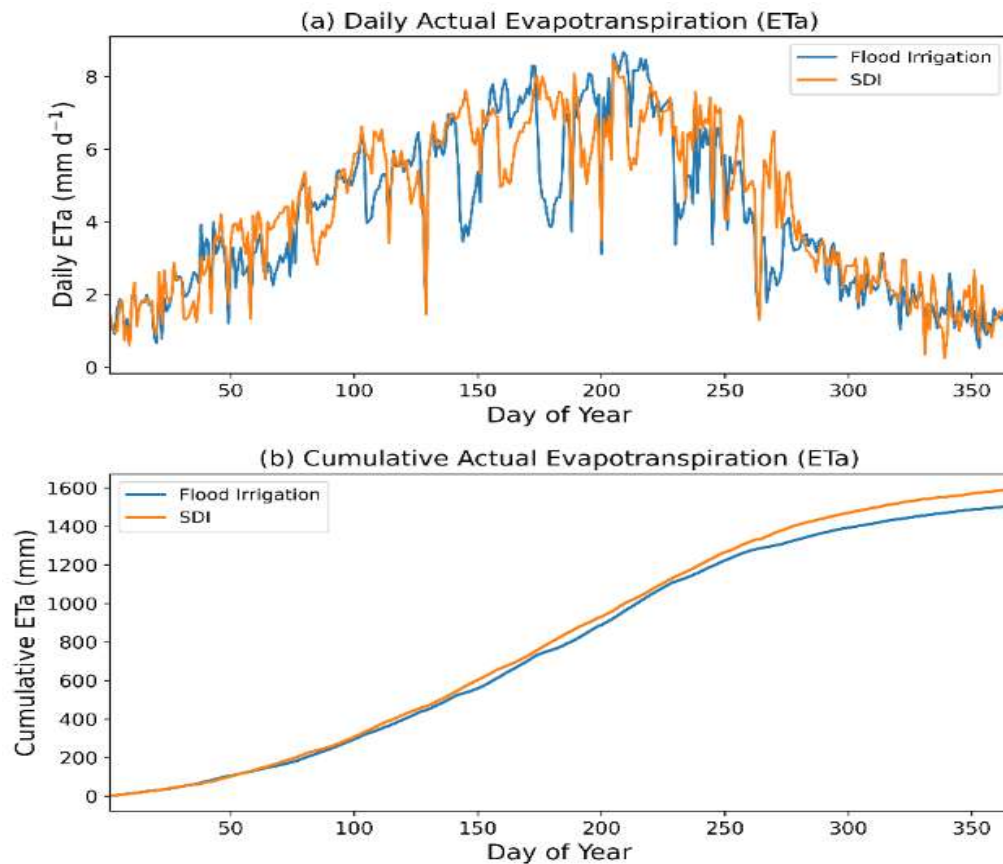


Figure 5. Comparison of actual evapotranspiration (ETa) between conventional flood irrigation and SDI in third-year alfalfa fields in Imperial Valley, California. (a) Daily ETa dynamics throughout the production season. (b) Cumulative seasonal ETa reaching 1,505 mm under flood irrigation and 1,591 mm under SDI

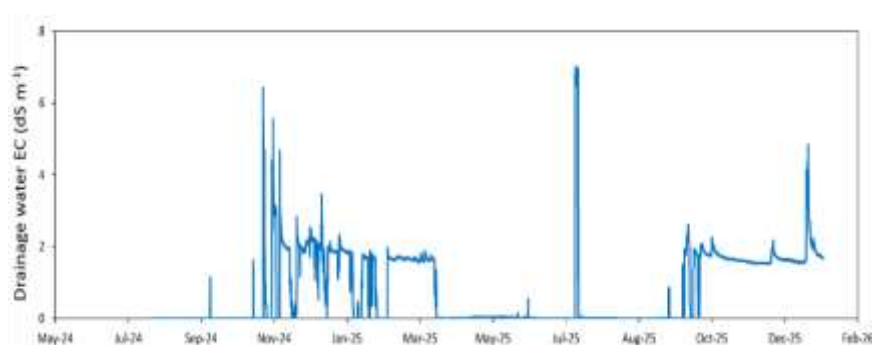


Figure 6. Electrical conductivity (EC) of drainage water measured in a forage field under subsurface drip irrigation in California's low desert. Periodic increases in drainage water salinity were primarily associated with sprinkler irrigation events utilized during fall and early winter for reclamation leaching of accumulated salts from the soil profile, with additional contributions from seasonal precipitation events.



Figure 7. Rodent damage observed in subsurface drip irrigation (SDI) tubing within a commercial alfalfa field. Rodent intrusion and chewing of buried drip lines may cause emitter leakage, reduced irrigation uniformity, system failure, and increased maintenance costs, representing one of the major operational challenges associated with long-term SDI management in low desert forage production systems.

Near Move and Precision Sprinkler Systems

Linear move sprinkler systems provide another option for modernizing forage irrigation in California's low desert, particularly where improved application uniformity, automation, and reduced labor demand are important. These systems may operate using canal-fed or drag-hose water supply configurations and can support low-pressure technologies such as LEPA, LESA, MESA, and LPIC (Figure 8). Precision sprinkler systems also provide potential opportunities for future variable-rate irrigation management in fields with substantial soil variability. Field evaluation of six linear move irrigation systems in desert alfalfa fields revealed an average seasonal water conservation of 265 mm relative to conventional surface irrigation, indicating strong potential for improving irrigation efficiency under commercial forage production conditions.

However, salinity management remains a major challenge under sprinkler irrigation systems in arid forage production environments. A salinity survey conducted after three years of operation in a commercial linear move irrigated alfalfa field showed substantial spatial variability in soil salinity at approximately 0.6 m depth, with EC values ranging from 2.69 to 14.03 dS m⁻¹ and an average ECE near 7.9 dS m⁻¹ (Figure 8C). These observations indicate that although precision sprinkler systems may improve automation and irrigation uniformity, periodic leaching and long-term salinity monitoring remain essential for sustaining soil productivity under low desert conditions. Overall, linear move sprinkler systems provide a promising precision irrigation option for forage production systems where improved irrigation operational flexibility, automation, and precision water management are priorities, provided that salinity accumulation is carefully managed over the long term.

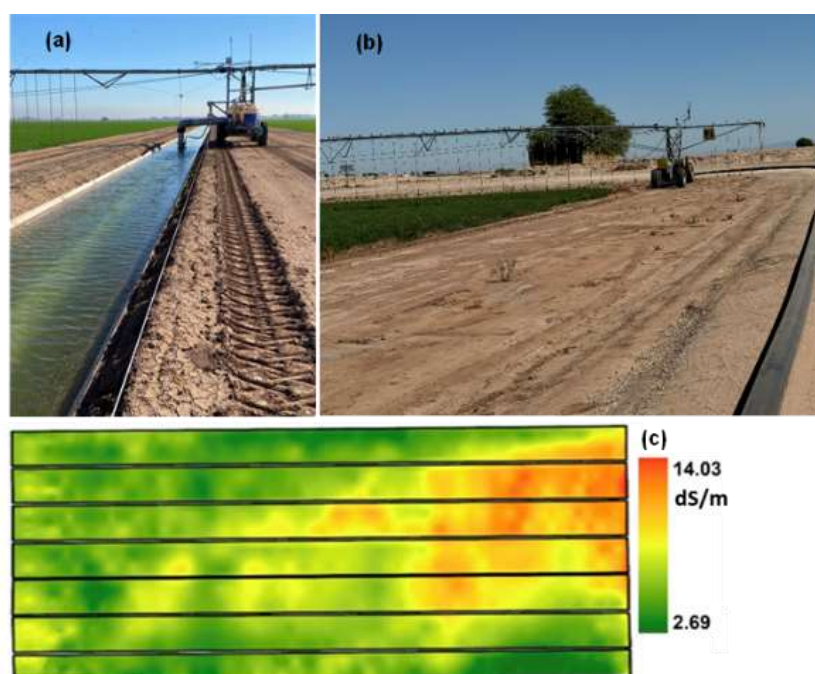


Figure 8. Precision linear move sprinkler irrigation systems utilized in commercial forage fields in Imperial Valley, California. (a) Canal-fed linear move system under low desert conditions. (b) Linear move system with drag-hose water supply. (c) Soil salinity distribution measured at 0.6 m depth after three years of irrigation management, showing spatial variability in electrical conductivity ranging from 2.69 to 14.03 dS m⁻¹.

Adaptive drought management through root-zone storage management

Long-term reductions in Colorado River water availability and implementation of drought-response conservation programs such as the Deficit Irrigation Program (DIP) have increased interest in adaptive irrigation strategies capable of sustaining forage production under reduced water allocations in California's low desert region. Because of its deep root system and tolerance to temporary water stress, alfalfa is particularly well suited for adaptive deficit irrigation management under arid desert conditions. Bermudagrass and kleingrass also showed strong drought tolerance under limited irrigation conditions.

Field trials conducted between 2019 and 2025 evaluated moderate, semi-severe, and severe summer deficit irrigation strategies in commercial alfalfa fields and at DREC.

As summarized in Table 1, substantial water conservation was achieved under all evaluated treatments, although greater water savings were generally associated with larger seasonal yield reductions. Moderate deficit irrigation conserved approximately 100–300 mm of irrigation water with relatively minor yield reductions of 4–5%, while severe deficit irrigation conserved up to 640–700 mm but reduced seasonal forage production by approximately 16–18% (4–4.5 Mg ha⁻¹). The findings illustrated that adaptive deficit irrigation strategically reduced seasonal irrigation applications while maintaining stand survival and partial forage productivity during drought allocation periods.

Field observations showed that desert alfalfa systems can temporarily transition from irrigation-driven production to storage-dependent survival during prolonged summer irrigation cutback periods. Figure 9 illustrates severe canopy stress and dormancy development under extended summer water deficits followed by strong recovery after irrigation resumed. Most stands survived extended irrigation cutoff by progressively utilizing stored soil water within the active root zone, with only minor stand loss observed in some varieties.

Table 1. Summary of water conservation and yield impacts associated with different summer deficit irrigation strategies evaluated in the low desert region, California. Values represent observed ranges from multiple field-scale irrigation trials conducted under arid low desert conditions.

Deficit Irrigation Strategy	Irrigation Management Description	Water Conserved (mm)	Seasonal Yield Reduction (%)	Seasonal Yield Loss (Mg ha ⁻¹)	Key Management Considerations
Moderate Deficit Irrigation	Skipping 1–3 irrigation events non-continuously during summer months	100–300	4–5	0.7–1.1	Minor yield impact with strong recovery potential
Semi-Severe Deficit Irrigation	Irrigation cutoff from early August through late September or early October	400–480	7–8	2.7–3.1	Greater water conservation with moderate yield penalties; requires careful monitoring of soil moisture and salinity
Severe Deficit Irrigation	Irrigation cutoff from early July through late September or early October	640–700	16–18	4.0–4.5	Maximum water conservation but increased risk of salinity accumulation; stand loss; and delayed recovery after rewatering

Multi-depth soil moisture monitoring provided important insight into root-zone depletion and recharge dynamics during deficit irrigation periods (Figure 10). Shallow soil layers responded rapidly to irrigation and evapotranspiration losses, whereas deeper soil layers functioned as longer-term storage reservoirs sustaining crop water uptake during extended irrigation cutoffs. Progressive depletion throughout the root zone occurred during summer deficit irrigation, while significant profile recharge generally occurred only after irrigation resumed during the fall and winter periods.

Salinity management also emerged as an important consideration under prolonged deficit irrigation conditions. Soil EC measurements showed moderate salt accumulation within portions of the root zone following semi-severe summer deficit irrigation (Figure 11). However, salinity levels generally remained within acceptable ranges for alfalfa production following subsequent irrigation recharge events. Overall, the results demonstrate that adaptive drought management in low desert alfalfa systems increasingly depends on strategic use of stored root-zone moisture combined with soil moisture monitoring, salinity management, and planned seasonal recharge irrigation under constrained water allocation conditions.



Figure 9. Commercial alfalfa fields under adaptive summer deficit irrigation management in Imperial Valley, California. (a) Alfalfa canopy stress and dormancy development under summer deficit irrigation. (b) Experimental alfalfa plot following two summer irrigation cutoffs during July and August. (c) Alfalfa recovery after rewatering, with only minor stand loss observed in some varieties.

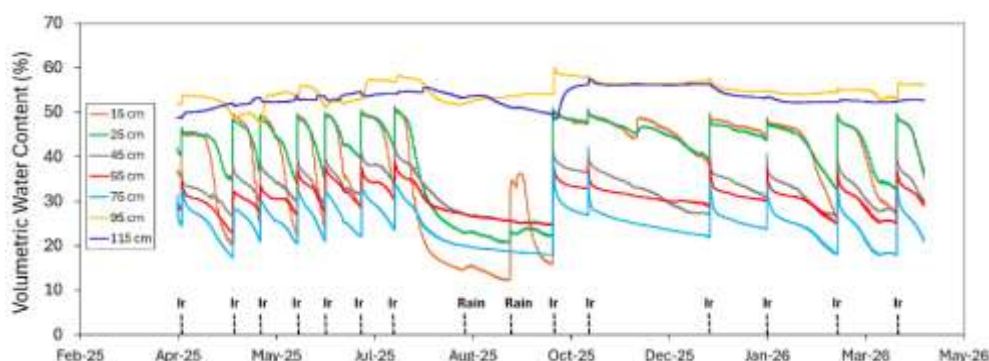


Figure 10. Temporal variation in volumetric soil water content measured at multiple depths (15–115 cm) in a commercial alfalfa field under deficit irrigation in Imperial Valley, California. Irrigation (Ir) and rainfall events are indicated along the time axis. The figure illustrates progressive root-zone depletion during deficit irrigation followed by profile recharge after irrigation or rainfall events, highlighting the importance of multi-depth soil moisture monitoring for evaluating root-zone storage and drought adaptation.

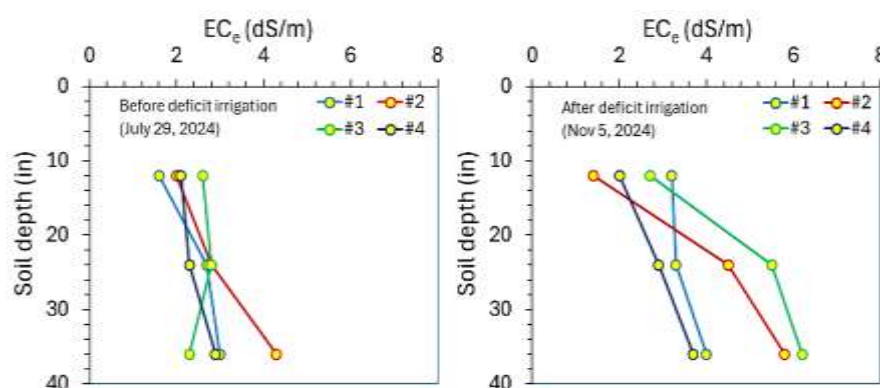


Figure 11. Soil EC_e distribution of observed values before and after implementing semi-severe deficit irrigation strategy in one of the experimental sites. Data collected on July 29 and November 5, 2024, from four soil core sampling locations at the site were used to develop these plots.

Precision Irrigation Scheduling and Decision-Support Technologies

Irrigation scheduling in low desert forage systems must balance crop evapotranspiration demand, soil water availability, salinity management, and drought-related allocation constraints. Field monitoring across commercial alfalfa fields in Imperial and Palo Verde Valleys showed that seasonal ET_a under full irrigation commonly ranged from 1381 to 1596 mm (Montazar and Putnam, 2023), while daily ET_0 frequently exceeded 8–10 mm d⁻¹ during peak summer conditions. Under such high atmospheric demand, even short irrigation delays may rapidly increase crop water stress. Recent advances in remote sensing ET platforms, particularly OpenET, have created new opportunities for field-scale irrigation monitoring and consumptive water-use assessment across large agricultural regions. Satellite-based ET products provide spatially distributed estimates of crop water use that support irrigation scheduling, drought-response management, and regional water conservation planning under constrained water supplies (Montazar et al., 2026).

However, ET estimates alone are often insufficient for fully characterizing root-zone water status under deficit irrigation conditions. Multi-depth soil moisture monitoring provides a critical complement to ET scheduling. These measurements directly track water movement, depletion, and recharge throughout the soil profile. Field observations showed that shallow soil layers may appear temporarily adequate while progressive depletion develops within deeper portions of the root zone due to incomplete irrigation recharge. Figure 12 presents several precision irrigation monitoring technologies deployed in commercial forage systems in California's low desert, including eddy covariance ET towers, Tule ET

sensors, OpenET remote sensing platforms, automated monitoring stations, and wireless soil moisture monitoring systems. Together, these technologies improve irrigation scheduling, drought adaptation, and real-time water management under highly variable desert production conditions.

CHALLENGES AND FUTURE OPPORTUNITIES

Despite significant advances in irrigation technologies and adaptive management strategies, several challenges continue to limit widespread implementation of climate-smart irrigation systems in California's low desert. As summarized in Table 2, each irrigation strategy provides distinct benefits and operational advantages, but also presents important technical, economic, and management limitations under arid desert production conditions.

Salinity accumulation remains one of the primary long-term technical challenges associated with SDI management in arid forage production systems. Field observations showed that insufficient leaching and incomplete profile recharge may result in progressive salt accumulation within portions of the root zone, particularly under extended drought conditions and reduced irrigation allocations. Periodic recharge and leaching irrigation events therefore remain essential components of sustainable irrigation management in low desert forage systems. Economic feasibility and long-term operational maintenance also remain important considerations for advanced irrigation systems. Technologies such as SDI, automated irrigation infrastructure, telemetry platforms, and precision monitoring systems require substantial initial investment and continued maintenance associated with filtration, rodent damage, sensor calibration, and system monitoring.



Figure 12. Precision irrigation monitoring technologies deployed in commercial forage production systems in California's low desert, including (a) eddy covariance evapotranspiration (ET) tower, (b) Tule evapotranspiration sensor, (c) automated weather and telemetry station, and (d) wireless soil moisture and environmental monitoring node. These integrated monitoring systems support evapotranspiration-based irrigation scheduling, root-zone storage management, drought adaptation, and real-time decision support frameworks.

Future climate-smart irrigation management in California's low desert will likely depend on greater integration of remote sensing, soil moisture monitoring, automation, and field-scale irrigation decision-support systems. Satellite-based evapotranspiration platforms such as OpenET, combined with real-time monitoring technologies, provide new opportunities for improving irrigation scheduling, drought adaptation, and agricultural water-use efficiency under increasing water scarcity conditions in arid regions.

Table 2. Summary of climate-smart irrigation technologies and adaptive irrigation strategies evaluated in forage production systems in California's low desert, including observed performance outcomes, operational limitations, and key management requirements under arid desert conditions.

Climate-Smart Irrigation Strategy	Primary Objective	Major Benefits	Observed Water Conservation / Performance	Major Limitations	Key Management Requirements
Surface Irrigation Automation	Reduce operational irrigation losses	Reduced runoff, improved irrigation efficiency, improved inflow management	Tailwater runoff reduced to ~4% of applied water; irrigation efficiency approached 86%	Infrastructure and automation costs	Water advance sensing, automated gate control, field leveling
Tailwater Recovery Systems	Reuse operational runoff water	Improved on-farm water reuse and reduced drainage losses	Approximately 70% of runoff water recovered and reused	Salinity and sediment management	Drainage monitoring, pumping infrastructure, water quality management
Subsurface Drip Irrigation	Improve root-zone irrigation efficiency and crop productivity	Increased alfalfa yield and improved water productivity	Yield increased by 10.4%; water productivity increased from 17.1 to 18.9 kg ha ⁻¹ mm ⁻¹	High installation cost, rodent damage, salinity accumulation	Filtration maintenance, salinity management, periodic leaching
Linear Move Sprinkler Systems	Improve irrigation uniformity and operational flexibility	Automation, reduced labor demand, precision application	~265 mm seasonal water conservation relative to surface irrigation; improved application uniformity	Salt accumulation under long-term operation	Periodic leaching, salinity monitoring
Adaptive Deficit Irrigation	Conserve water under reduced allocations	Significant seasonal water conservation	Seasonal water conservation of ~100–700 mm with 4–18% yield reduction depending on irrigation severity	Yield reduction and potential stand loss	Root-zone monitoring, seasonal recharge irrigation, salinity management
Precision Irrigation Monitoring and Decision-Support Technologies	Improve irrigation scheduling and drought adaptation	Real-time irrigation management and improved decision support	Improved irrigation scheduling and drought adaptation through integrated ET and soil moisture monitoring	Increased system complexity and monitoring requirements	Telemetry integration, ET monitoring, multi-depth soil moisture sensing

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