

QUANTIFYING CONSUMPTIVE WATER SAVINGS IN DEFICIT-IRRIGATED ALFALFA USING THE OPENET SATELLITE FRAMEWORK

QUANTIFICATION DES ÉCONOMIES D'EAU CONSOMMÉE DANS LA LUZERNE SOUMISE À UNE IRRIGATION DÉFICITAIRE À L'AIDE DU CADRE SATELLITAIRE OPENET

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ABSTRACT

Climate change is intensifying pressure on irrigated agriculture through rising temperatures, increasing evaporative demand, and growing competition for limited water supplies. Deficit irrigation has emerged as an important strategy for improving agricultural water-use efficiency; however, operational verification of consumptive water saving remains a major challenge for irrigation districts and conservation programs. This study evaluated the capability of the OpenET satellite framework to quantify reductions in consumptive water use under deficit irrigation using independent field-scale observations. A two-year analysis (2024–2025) was conducted across twenty commercial alfalfa fields in California's Imperial Valley under contrasting irrigation regimes. OpenET evapotranspiration (ET_{act}) estimates were evaluated under fully irrigated conditions using eddy covariance measurements and under summer deficit irrigation through comparison with soil-moisture-derived root-zone depletion. Under fully irrigated conditions, OpenET reproduced observed daily ET_{act} dynamics with strong agreement ($R^2 = 0.87$; $RMSE = 0.74 \text{ mm d}^{-1}$). Following summer irrigation cutoff, ET_{act} declined rapidly from 6–9 mm d^{-1} to sustained levels near 1–3 mm d^{-1} , corresponding with progressive root-zone depletion and reductions in NDVI. OpenET-derived depletion dynamics closely tracked soil-moisture observations, with $RMSE$ values below 8 mm across monitored deficit-irrigated fields. Across both study years, deficit irrigation reduced cumulative ET_{act} by 150–200 mm during the deficit period, corresponding to 40–50% lower crop water consumption relative to fully irrigated conditions ($p < 0.001$). Results demonstrate that satellite-based ET frameworks, when combined with independent field observations, can provide scalable and transparent verification of consumptive water-use reductions under real-world irrigation management. These findings demonstrate the potential of remote sensing to support climate-resilient irrigation management and agricultural water conservation in arid irrigated regions.

Keywords: Consumptive water savings; Climate change; Deficit irrigation; Agricultural water conservation; Arid irrigated regions.

RÉSUMÉ

Le changement climatique accentue les pressions exercées sur l'agriculture irriguée en raison de la hausse des températures, de l'augmentation de la demande évaporative et de la concurrence croissante pour des ressources en eau limitées. L'irrigation déficitaire s'est imposée comme une stratégie importante pour améliorer l'efficacité de l'utilisation de l'eau en agriculture ; toutefois, la vérification opérationnelle des économies d'eau consommée demeure un défi majeur pour les districts d'irrigation et les programmes de conservation. Cette étude a évalué la capacité du cadre satellitaire

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OpenET a quantifié les réductions de la consommation d'eau sous irrigation déficitaire à l'aide d'observations indépendantes à l'échelle de la parcelle. Une analyse sur deux ans (2024–2025) a été menée dans vingt champs commerciaux de luzerne de la vallée impériale, en Californie, soumis à des régimes d'irrigation contrastés. Les estimations de l'évapotranspiration réelle (ET_{act}) produites par OpenET ont été évaluées, en conditions de pleine irrigation, au moyen de mesures par covariance des turbulences et, en conditions d'irrigation déficitaire estivale, par comparaison avec l'épuisement de la réserve de la zone racinaire dérivé de l'humidité du sol. En conditions de pleine irrigation, OpenET a reproduit la dynamique journalière observée de l' ET_{act} avec une forte concordance ($R^2 = 0,87$; $RMSE = 0,74 \text{ mm j}^{-1}$). Après l'arrêt de l'irrigation estivale, l' ET_{act} a rapidement diminué, passant de 6–9 mm j^{-1} à des niveaux durables proches de 1–3 mm j^{-1} , parallèlement à l'épuisement progressif de la zone racinaire et à la baisse du NDVI. La dynamique de l'épuisement dérivée d'OpenET suivait étroitement les observations de l'humidité du sol, avec des valeurs de RMSE inférieures à 8 mm dans les champs sous irrigation déficitaire faisant l'objet d'un suivi. Pour les deux années de l'étude, l'irrigation déficitaire a réduit l' ET_{act} cumulée de 150–200 mm pendant la période de déficit, ce qui correspond à une consommation d'eau des cultures inférieure de 40–50 % à celle observée en conditions de pleine irrigation ($p < 0,001$). Les résultats montrent que les cadres d'estimation de l'ET par satellite, lorsqu'ils sont associés à des observations de terrain indépendantes, peuvent offrir une vérification transparente et déployable à grande échelle des réductions de la consommation d'eau obtenues dans des conditions réelles de gestion de l'irrigation. Ces conclusions démontrent le potentiel de la télédétection pour soutenir une gestion de l'irrigation résiliente au climat et la conservation de l'eau agricole dans les régions irriguées arides.

Mots clés : Economies d'eau consommée; Changement climatique; Irrigation déficitaire; Conservation de l'eau agricole; Régions irriguées arides.

INTRODUCTION

Climate change is intensifying pressure on irrigated agriculture through rising temperatures, increasing evaporative demand, persistent drought, and growing competition for limited water resources. In arid and semi-arid agricultural regions, improving irrigation resilience increasingly depends on quantifying actual consumptive water use rather than solely reducing applied irrigation volumes. This distinction is particularly important in water-limited river basins, where agricultural conservation programs increasingly require transparent verification of actual water savings to support drought adaptation and long-term water-management planning.

Deficit irrigation has emerged as an important water-conservation strategy in many arid agricultural systems because it intentionally reduces irrigation applications during selected growth periods to lower consumptive water use while maintaining acceptable crop productivity (Feres and Soriano, 2007; Pereira et al., 2012). In perennial forage systems such as alfalfa, summer irrigation cutoff has become a practical drought-response strategy in the southwestern United States due to the crop's ability to survive extended periods of water limitation and subsequently recover following irrigation resumption. However, accurately quantifying consumptive water-use reductions under deficit irrigation remains a major challenge for irrigation districts, water agencies, and agricultural conservation programs.

Reductions in applied irrigation do not necessarily translate directly into evapotranspiration (ET) reductions because field-scale consumptive water use is governed by complex interactions among atmospheric demand, soil-water availability, crop physiological response, and residual soil moisture storage (Pereira et al., 2025). Under deficit irrigation, progressive root-zone depletion and canopy stress can substantially alter ET dynamics relative to fully irrigated conditions. Quantification of actual consumptive water-use reductions therefore requires characterization of crop water use under evolving soil-water and vegetation conditions rather than reliance on irrigation application records alone. Satellite-based ET approaches have become increasingly important tools for large-scale agricultural water accounting and irrigation management. Among these platforms, OpenET integrates multiple remote-sensing-based ET models to provide operational field-scale ET estimates across the western United States (Melton et al., 2022).

These satellite-derived products offer important advantages because they provide spatially distributed estimates of actual crop water consumption across large agricultural regions. However, most evaluations of satellite-based ET products have focused primarily on well-watered agricultural systems, whereas deficit irrigation introduces additional soil-water and canopy controls that can substantially alter ET dynamics (Pereira et al., 2025; Pereira et al., 2012).

Under sustained water limitation, ET reductions are commonly accompanied by progressive root-zone soil-water depletion, declining vegetation activity, and reduced canopy transpiration. These coupled soil-moisture and canopy responses can complicate ET estimation under deficit irrigation because crop water use becomes increasingly constrained by available soil water rather than atmospheric demand alone. Independent field-scale observations are therefore necessary to evaluate whether satellite-derived ET estimates accurately capture reductions in consumptive water use under operational deficit-irrigation conditions.

The objective of this study was to evaluate the capability of OpenET to quantify reductions in crop water consumption under operational deficit-irrigated alfalfa systems using independent field-scale validation methods. OpenET performance was evaluated under fully irrigated conditions using eddy covariance measurements and under deficit irrigation using soil-moisture-derived root-zone depletion. The broader goal was to assess the potential of satellite-based ET approaches for operational verification of agricultural water conservation under climate-driven water-scarcity conditions.

MATERIALS AND METHODS

Study Area

The study was conducted during the 2024 and 2025 growing seasons in California's Imperial Valley, a highly productive irrigated agricultural region located within the lower Colorado River Basin of the southwestern United States. The region is characterized by a hot desert climate with extremely high atmospheric evaporative demand, minimal annual precipitation, and prolonged summer heat conditions. Annual reference evapotranspiration (ET_0) commonly exceeds 1,800 mm, while summer daytime air temperatures frequently exceed 43 °C. Under these conditions, crop water use is governed primarily by irrigation management and atmospheric demand rather than precipitation inputs.

Agricultural production in the Imperial Valley depends almost entirely on irrigation supplied by the Colorado River through the Imperial Irrigation District canal network. Alfalfa is the dominant perennial forage crop in the region and represents a major component of agricultural consumptive water use. Due to increasing drought pressure and regional water conservation efforts, temporary summer irrigation cutoff has become an increasingly common deficit-irrigation strategy for reducing crop water consumption while maintaining long-term stand viability. The study area consists primarily of fine- to medium-textured agricultural soils, including loam, clay loam, and silty clay loam classes that influence infiltration, root-zone water storage, and crop response to irrigation management.

Experimental Fields and Irrigation Treatments

A total of twenty commercial alfalfa fields were evaluated during the 2024 and 2025 growing seasons under contrasting irrigation management conditions (Table 1). Fields 1–10 were managed under deficit-irrigated (DI) conditions involving temporary summer irrigation cutoff, whereas Fields 11–20 were maintained under fully irrigated (FI) conditions with continuous seasonal irrigation. Deficit-irrigation durations generally ranged from approximately 60 to 78 days during periods of elevated atmospheric evaporative demand. Typical field sizes across monitored sites were approximately 30–32 ha.

All study sites were irrigated using conventional surface border-check systems representative of commercial forage production in California's Imperial Valley. Fully irrigated fields typically received

irrigation at intervals of approximately 7–12 days, with multiple irrigation events occurring between harvest cycles. In contrast, DI fields participated in operational water-conservation programs intended to reduce consumptive water use during peak summer evaporative conditions. Representative DI Field 5 (2024) and DI Field 2 (2025) were selected for detailed temporal evaluation of evapotranspiration dynamics, NDVI response, and

Table 1. Summary of commercial alfalfa fields and irrigation management conditions evaluated during the 2024–2025 growing seasons.

Field IDs	Irrigation Regime	Irrigation Management	Deficit Duration	Typical Field Size (ha)
Fields 1–10	Deficit irrigated (DI)	Temporary summer irrigation cutoff	~60–78 d	~30–32
Fields 11–20	Fully irrigated (FI)	Continuous seasonal irrigation	None	~30–32

Note: Representative DI Field 5 (2024) and DI Field 2 (2025) were selected for detailed temporal evaluation of ET_{act} , NDVI, and root-zone depletion dynamics during the deficit-irrigation period in this study.

Field Measurements and Monitoring

Detailed descriptions of the field instrumentation, monitoring configuration, and data-processing procedures are provided in Montazar et al. (2026). Field-scale actual evapotranspiration (ET_{EC}) under fully irrigated conditions was obtained from eddy covariance-based micrometeorological measurements installed in two representative commercial alfalfa fields (Fig. 1). Daily ET_{EC} was estimated using a residual energy balance approach, in which latent heat flux was calculated from net radiation, ground heat flux, and sensible heat flux observations. Sensible heat flux was derived from high-frequency three-dimensional wind measurements using a sonic anemometer, while net radiation and soil heat flux were measured using a net radiometer and soil heat flux plates, respectively. Surface energy-balance components were computed at sub-daily intervals and aggregated to daily ET_{EC} values.

Root-zone soil moisture monitoring was conducted within representative deficit-irrigated fields using TEROS-12 capacitance soil-moisture sensors installed at multiple depths through the alfalfa root zone. In the full monitoring setup, sensors were installed at 5, 20, 50, 80, 110, 140, 170, and 200 cm, and root-zone water storage was estimated by vertically integrating volumetric water content across the 0–200 cm profile. Soil-water depletion was then calculated from changes in profile water storage and used as an independent field-scale indicator of consumptive water limitation during irrigation-cutoff periods. Additional details regarding soil hydraulic characterization, root-zone depletion calculations, quality-control procedures, and uncertainty considerations are provided in Montazar et al. (2026).

OpenET-Derived ET_{act} Estimates

OpenET-Derived ET_{act} estimates were obtained from the OpenET platform, which integrates multiple remote-sensing-based evapotranspiration models, including SSEBop, SIMS, DisALEXI, eeMETRIC, geeSEBAL, PT-JPL, and EEMETRIC, to provide operational field-scale ET estimates across the western United States (Melton et al., 2022). In this study, the OpenET ensemble product, which represents the average of available model estimates, was evaluated for all monitored alfalfa fields during the 2024 and 2025 growing seasons.



Figure 1. Eddy covariance tower and soil moisture monitoring system installed in a representative commercial alfalfa field for continuous monitoring of field-scale actual ET and root-zone soil water conditions under operational irrigation management.

Under fully irrigated conditions, OpenET-derived ET estimates were evaluated against field-observed ET_{EC} using linear regression, coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean bias error (MBE). Temporal ET_{act} dynamics were evaluated before, during, and after irrigation-cutoff periods to assess the capability of OpenET to capture consumptive water-use responses under deficit irrigation management. In addition to ET estimates, normalized difference vegetation index (NDVI) observations derived from satellite imagery were evaluated to characterize temporal canopy response during deficit-irrigation periods. NDVI time series were used to assess vegetation dynamics before, during, and after irrigation cutoff and to support interpretation of ET suppression under progressive soil-water limitation.

Root-Zone Water Depletion and Statistical Analysis

Root-zone water depletion dynamics during the deficit-irrigation period were evaluated using both soil-moisture observations and OpenET-derived ET_{act} estimates. Soil-moisture-derived depletion was calculated from cumulative changes in root-zone water storage across the monitored soil profile following irrigation cutoff. OpenET-derived depletion was calculated from cumulative OpenET-derived ET_{act} over the same deficit-irrigation period. Agreement between observed and OpenET-derived depletion dynamics was evaluated using R^2 , RMSE, MAE, and MBE measures.

Cumulative OpenET-derived ET_{act} during the deficit-irrigation period was calculated separately for deficit-irrigated and fully irrigated fields across both study years to evaluate treatment-level differences in consumptive water use. Statistical differences in cumulative ET_{act} between irrigation treatments were evaluated using Welch's two-sample t-test.

RESULTS AND DISCUSSION

Evaluation of OpenET-Derived ET_{act} under Fully Irrigated Conditions

OpenET ensemble ET_{OpenET} estimates showed strong agreement with EC observations under fully irrigated conditions in a representative commercial alfalfa field (Fig. 2). Daily OpenET-derived ET_{OpenET} closely tracked observed ET_{EC} dynamics across the monitoring period, capturing both

short-term temporal variability and elevated summer evapotranspiration associated with high atmospheric evaporative demand.

Regression analysis between OpenET and EC observations produced a coefficient of determination of 0.87, with RMSE and MAE values of 0.74 and 0.60 mm d⁻¹, respectively. The near-unity regression slope and relatively low mean bias error indicated that OpenET ensemble estimates provided robust representation of field-scale crop water consumption under well-watered desert alfalfa conditions. Although some variability was observed during periods of rapid atmospheric fluctuations and irrigation transitions, overall agreement remained strong throughout the monitoring period.

These results demonstrate that the OpenET ensemble can reliably characterize baseline ET dynamics in highly productive irrigated forage systems under desert climate conditions, consistent with previous evaluations of OpenET across irrigated agricultural systems (Melton et al., 2022; Sabiston et al., 2024; Attalah et al., 2025). Accurate representation of fully irrigated ET is particularly important because it establishes the reference condition necessary for evaluating consumptive water-use reductions under deficit irrigation management.

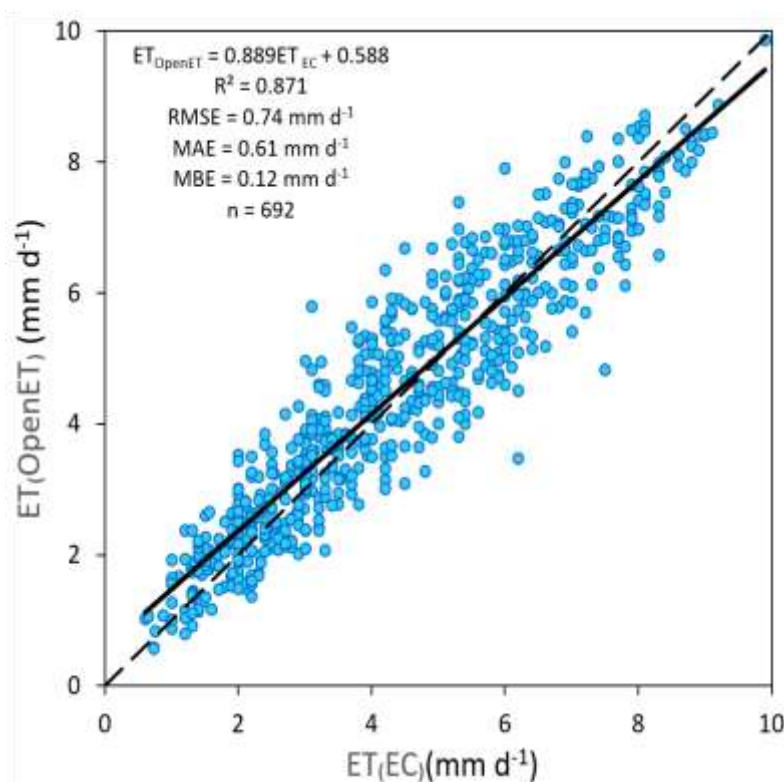


Figure 2. Comparison between daily OpenET ensemble actual evapotranspiration estimates (ET_{OpenET}) and field-observed actual evapotranspiration measurements derived from eddy covariance-based micrometeorological observations (ET_{EC}) across fully irrigated commercial alfalfa fields during 2024–2025. The solid line represents the linear regression fit and the dashed line represents the 1:1 relationship.

Evapotranspiration response under deficit irrigation

Deficit irrigation produced substantial and sustained suppression of actual evapotranspiration following summer irrigation cutoff in both study years (Fig. 3). Temporal ET_{act} dynamics showed a rapid response to irrigation termination, with evapotranspiration remaining substantially reduced throughout the irrigation-suspension period until irrigation resumed. Similar overall patterns were observed across monitored deficit-irrigated fields despite differences in seasonal conditions and short-term temporal variability.

In DI Field 5 during 2024, ET_{act} decreased from peak summer values near $7\text{--}9\text{ mm d}^{-1}$ to sustained levels generally between $1\text{ and }3\text{ mm d}^{-1}$ during the deficit period. Similar responses were observed in DI Field 2 during 2025 despite differences in short-term temporal variability and seasonal conditions. In both years, ET_{act} suppression persisted for approximately 60–80 days following irrigation termination, indicating prolonged soil-water limitation and reduced canopy transpiration.

The progressive reduction in ET_{act} demonstrates that irrigation termination substantially altered field-scale water-use dynamics under operational commercial management conditions. Prior to irrigation cutoff, ET_{act} behavior largely reflected elevated atmospheric demand and active canopy transpiration. Following deficit initiation, however, ET_{act} became increasingly constrained by available soil water, resulting in sustained suppression throughout the deficit period, consistent with established descriptions of evapotranspiration response under water stress (Allen et al., 2011; Pereira et al., 2012; Fereres and Soriano, 2007). These results further demonstrate the capability of the OpenET framework to detect large temporal shifts in crop water consumption associated with operational irrigation-management changes. The observed ET_{act} suppression was additionally accompanied by substantial reductions in canopy activity during the deficit period.

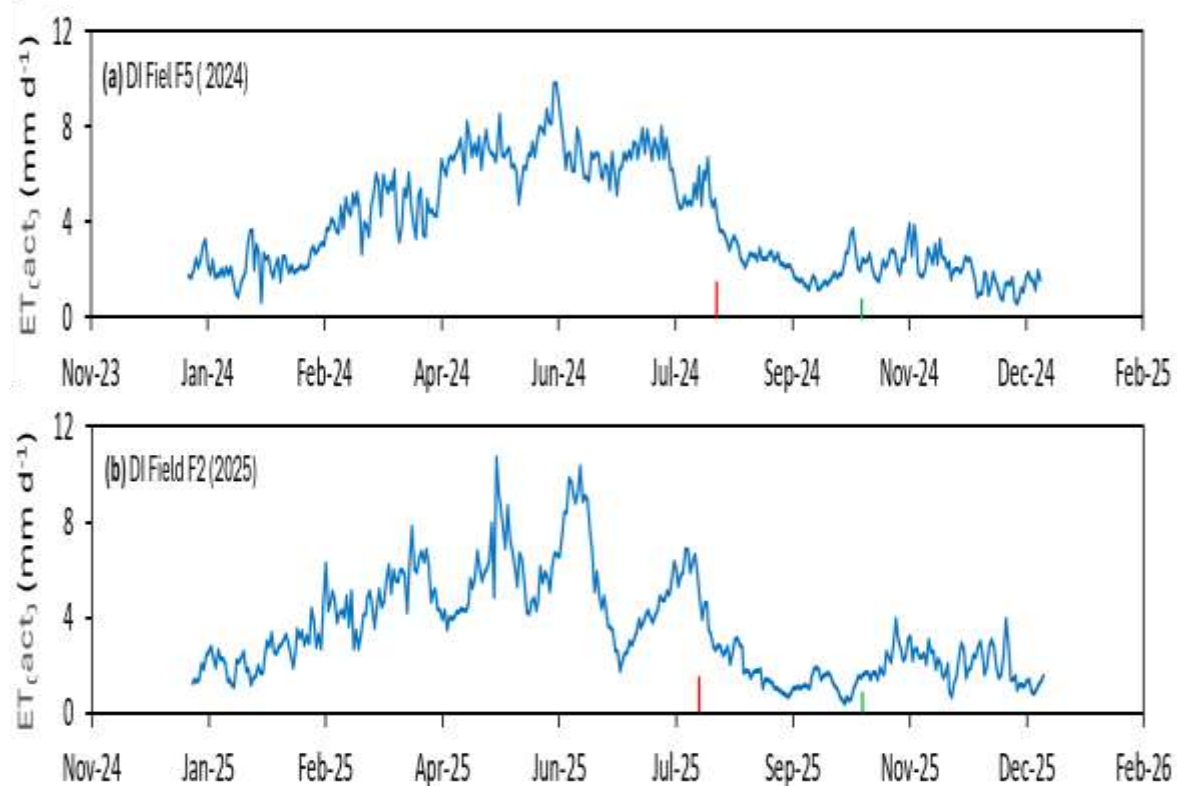


Figure 3. Daily OpenET-derived actual evapotranspiration (ET_{act}) dynamics for representative deficit-irrigated commercial alfalfa fields during 2024 and 2025. Red vertical lines indicate initiation of deficit irrigation following summer irrigation cutoff, while green vertical lines indicate termination of the deficit-irrigation period.

Vegetation response under deficit irrigation

NDVI dynamics further confirmed canopy response under deficit irrigation management (Fig. 4). Prior to irrigation cutoff, NDVI values remained elevated in both monitored fields, generally ranging between approximately 0.7 and 0.9 during periods of active growth. Short-term NDVI fluctuations corresponded closely with harvest events (black vertical lines), reflecting periodic biomass removal and canopy regrowth throughout the season.

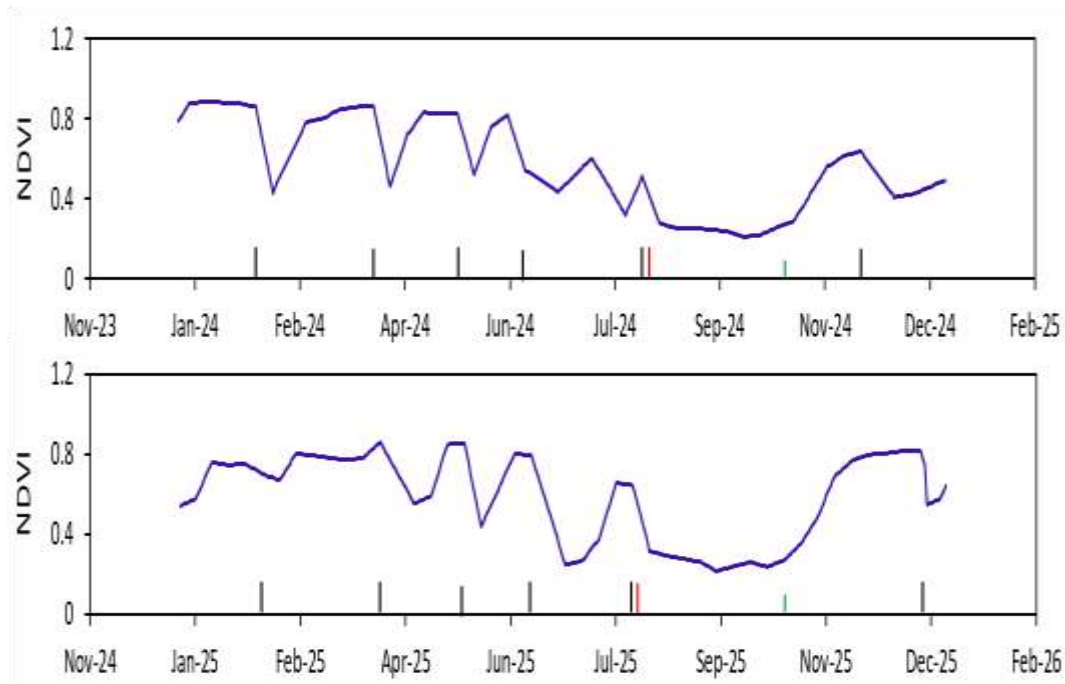


Figure 4. Temporal dynamics of normalized difference vegetation index (NDVI) for representative deficit-irrigated commercial alfalfa fields during 2024 and 2025 in California's Imperial Valley. Black vertical lines indicate harvest events. Red vertical lines indicate initiation of deficit irrigation following summer irrigation cutoff, while green vertical lines indicate irrigation resumption and termination of the deficit-irrigation period.

Following initiation of deficit irrigation (red vertical lines), vegetation activity declined substantially in both monitored fields and remained suppressed throughout the irrigation-cutoff period until irrigation resumed (green vertical lines). In both years, NDVI decreased to sustained values near approximately 0.2–0.4 during late summer and early fall, indicating reduced canopy vigor under sustained soil-water limitation. Following irrigation resumption, both ET_{act} and NDVI recovered progressively, indicating preservation of stand viability under temporary deficit irrigation.

The timing and persistence of NDVI reduction corresponded closely with the ET_{act} suppression shown in Figure 3. Although harvest events produced temporary reductions in canopy cover throughout the season, vegetation suppression during the deficit period was substantially more prolonged than harvest-related variability alone. These concurrent reductions in NDVI and ET_{act} indicate that deficit irrigation substantially altered canopy transpiration and vegetation dynamics under operational field conditions, consistent with established descriptions of vegetation and transpiration response under progressive soil-water limitation (Allen et al., 2011; Pereira et al., 2012).

Root-zone depletion dynamics under deficit irrigation

Root-zone soil moisture observations showed progressive depletion throughout the deficit-irrigation period in both monitored DI fields and closely corresponded with OpenET-derived depletion dynamics (Fig. 5). Following irrigation cutoff, root-zone depletion increased steadily as crop water use exceeded available soil-water replenishment, indicating sustained extraction of stored soil water during the deficit period. In DI Field F5 during 2024, observed root-zone depletion increased from approximately 40 mm in mid-July to nearly 230–235 mm by early October, while OpenET-derived depletion reached approximately 245 mm by the end of the deficit period. Similarly, in DI Field F2 during 2025, observed depletion increased from approximately 20 mm to nearly 180–185 mm, while OpenET-derived depletion reached approximately 185–190 mm during late September. In both years, depletion remained substantially below total available water (TAW), which averaged approximately 342 mm in Field F5 and 326 mm in Field F2, respectively.

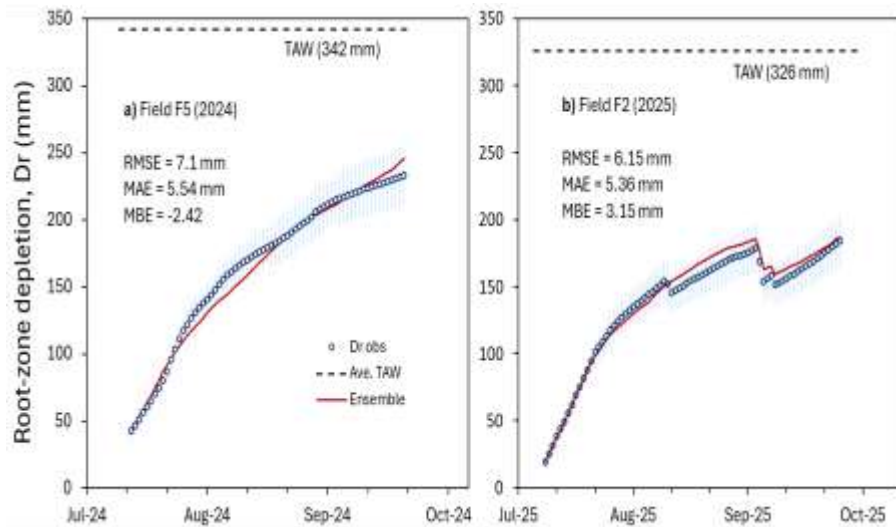


Figure 5. Root-zone soil-water depletion (D_r) derived from observed soil moisture measurements and OpenET-derived ET_{act} for representative deficit-irrigated commercial alfalfa fields during 2024 and 2025. Dashed horizontal lines indicate average total available water (TAW) within the monitored root zone. Vertical light blue bars indicate the standard deviation of soil-moisture-derived root-zone depletion estimates.

OpenET-derived depletion dynamics closely tracked observed soil-moisture-derived depletion throughout most of the deficit period. In Field F5, regression statistics produced RMSE and MAE values of 7.1 and 5.54 mm, respectively, with a small negative MBE of -2.42 mm, indicating slight underestimation of depletion relative to observations. Similarly, in Field F2, RMSE and MAE values were 6.15 and 5.36 mm, respectively, with a positive MBE of 3.15 mm, indicating minor overestimation of depletion by OpenET. These relatively small errors demonstrate strong agreement between satellite-derived and field-observed depletion dynamics despite extended irrigation cutoff periods and elevated atmospheric evaporative demand conditions.

The progressive increase in root-zone depletion provides important mechanistic evidence explaining the sustained ET_{act} suppression observed under deficit irrigation. As available soil water declined, canopy transpiration became increasingly constrained despite continued high atmospheric evaporative demand, consistent with classical descriptions of soil-water limitation under deficit irrigation (Allen et al., 2011; Pereira et al., 2012; Fereres and Soriano, 2007; Perry et al., 2017). The close correspondence between observed and OpenET-derived depletion dynamics further demonstrates that OpenET captured not only temporal reductions in ET_{act} but also the underlying progression of consumptive water limitation during irrigation cutoff.

These results support the capability of combining satellite-based ET frameworks with field-scale soil moisture monitoring to evaluate consumptive water-use reductions under operational agricultural water conservation programs. The observed depletion dynamics confirm that ET_{act} reductions during deficit irrigation reflected sustained soil-water limitation rather than short-term meteorological variability alone.

Quantification of consumptive water-use reductions under deficit irrigation

Cumulative ET_{act} during the deficit-irrigation period was consistently and substantially lower in deficit-irrigated fields compared to fully irrigated fields across both study years (Fig. 6). OpenET ensemble estimates showed clear separation between irrigation treatments, with all DI fields exhibiting markedly reduced cumulative ET_{act} relative to FI fields. No DI field exceeded the cumulative ET_{act} of any FI field, demonstrating a strong and consistent consumptive water-use response under operational deficit irrigation management.

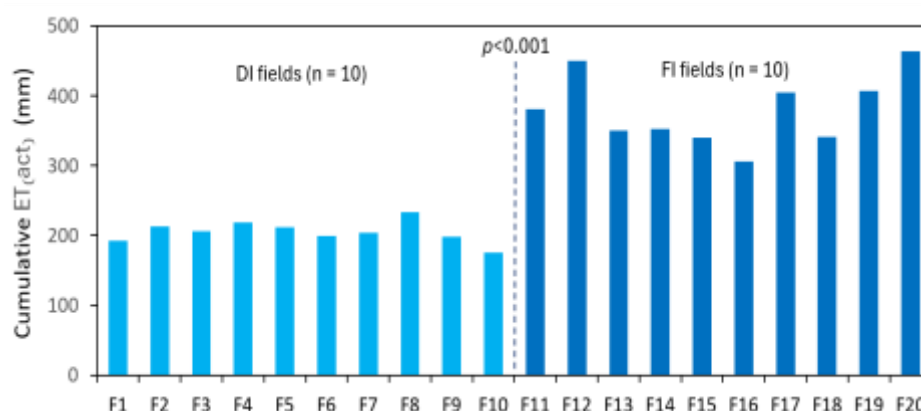


Figure 6. Cumulative ET_{act} during the deficit-irrigation period for deficit-irrigated (DI) and fully irrigated (FI) commercial alfalfa fields across the 2024 and 2025 growing seasons. Bars represent cumulative OpenET-derived ET_{act} estimates for individual fields. The dashed vertical line separates DI and FI treatment groups. Cumulative ET_{act} during the deficit period was consistently lower in DI fields than in FI fields, corresponding to 40–50% lower consumptive water use under deficit irrigation management (Welch's two-sample t-test, $p < 0.001$).

Across all DI fields, cumulative ET_{act} during the deficit period generally ranged from 175 to 235 mm, whereas FI fields ranged from 305 to 460 mm. Mean cumulative ET_{act} for DI fields during 2024 was 208 ± 15 mm, compared to 364 ± 55 mm for FI fields, corresponding to an average consumptive water reduction of 156 mm, or 43%. During 2025, mean cumulative ET_{act} was 202 ± 20 mm in DI fields and 404 ± 40 mm in FI fields, corresponding to a reduction 202 mm, or nearly 50%. Across both study years, deficit irrigation reduced consumptive water by 150–200 mm during the deficit period. Differences between DI and FI treatments were highly significant (Welch's two-sample t-test, $p < 0.001$).

The magnitude and consistency of ET_{act} reduction observed across experimental fields indicate that deficit irrigation can substantially reduce consumptive water use in low-desert alfalfa production systems during summer irrigation-cutoff periods, consistent with previous observations under operational alfalfa deficit-irrigation management in arid environments (Montazar et al., 2020; Montazar and Putnam, 2023). The close agreement between observed soil-moisture depletion and OpenET-derived depletion further confirmed that reductions in consumptive water use were associated with sustained soil-water limitation and reduced canopy transpiration.

From a water-management perspective, the results demonstrate that satellite-based ET frameworks such as OpenET can provide scalable and transparent verification of field-scale consumptive water-use reductions under real-world irrigation management. Across the monitored commercial fields, deficit irrigation reduced consumptive water use by approximately 1,500–2,000 $m^3 ha^{-1}$ during the deficit period, highlighting the potential of satellite-based ET monitoring to support operational drought-response programs and climate-resilient agricultural water conservation in arid irrigated regions. These findings further support the use of satellite-based ET monitoring as a practical tool for large-scale verification of agricultural water conservation under climate-driven water scarcity conditions.

CONCLUSIONS

This study demonstrated the capability of the OpenET satellite framework to quantify reductions in consumptive water use under operational deficit-irrigated alfalfa systems using independent field-scale observations for validation. Under fully irrigated conditions, OpenET reproduced eddy covariance ET_{act} observations with strong agreement. Following summer irrigation cutoff, ET_{act} declined substantially and corresponded closely with progressive root-zone soil-water depletion and declining NDVI, indicating sustained soil-water limitation and reduced canopy transpiration under deficit irrigation management. OpenET-derived depletion dynamics closely tracked soil-moisture observations. Across both study years, deficit irrigation reduced cumulative ET_{act} by 150–200 mm,

corresponding to 40–50% lower crop water consumption relative to fully irrigated conditions. These results demonstrate the potential of satellite-based ET frameworks to provide scalable verification of consumptive water savings for climate-resilient irrigation management and agricultural water conservation in arid irrigated regions.

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