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Estimating actual evapotranspiration of various agricultural water optimization practices using the soil moisture- based evapotranspiration model

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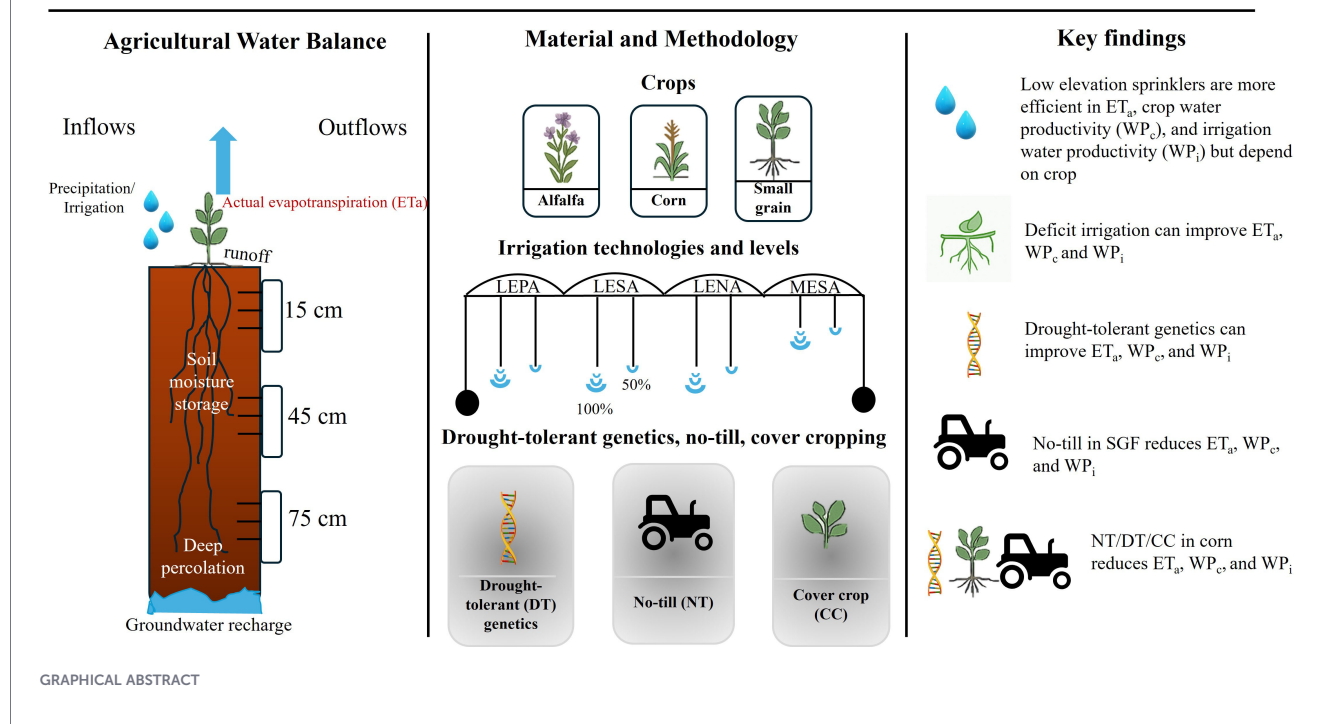
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Accurate estimation of actual evapotranspiration (ET_a) is important for optimizing agricultural water use. A recently developed soil moisture-based ET (SMET) model allows estimation of ET_a in small plot trials. This study evaluated how four irrigation technologies [low-elevation Nelson Advantage (LENA[®]), low-elevation precision application (LEPA), low-elevation spray application (LESA), and mid-elevation spray applicators (MESA)], two irrigation levels (100% and 50% of ET_c), three crops [alfalfa (*Medicago sativa*), silage corn (*Zea mays* L.), and small grain forage (SGF) (*Triticum aestivum*, *Hordeum vulgare*, and *Secale cereale* × *Triticum aestivum*)], drought-tolerant (DT) genetics, no-till (NT), and cover cropping (CC) in some crops affect ET_a , crop water productivity (WP_c), and irrigation water productivity (WP_i). The field trials were conducted at Vernal and Cedar City, Utah, during 2022–23. Soil moisture sensors were installed at 15, 45, and 75 cm depths at both sites in each treatment. Results from the study show that low-elevation sprinkler technologies (i.e., LEPA, LESA, LENA[®]) had higher WP_c and WP_i compared to MESA in alfalfa, small grain forage, and grain corn, while MESA was higher in silage corn when averaged across irrigation levels and management treatments. Deficit irrigation at 50% of ET_c has mixed effects on WP_c and WP_i , while deep sensor installation is required for precise ET_a estimations. The DT genetics of alfalfa improved WP_c and WP_i compared to the non-DT genetics; however, no-till in SGF and the combined effect of DT genetics, NT, and CC in silage or grain corn reduced WP_c and WP_i , likely due to lower crop stands under NT. These findings suggest that low-elevation irrigation technologies, moderate deficit irrigation, and DT genetics can improve WP_c and WP_i .

KEYWORDS

actual evapotranspiration, cover cropping, crop water productivity, deficit irrigation, drought-tolerant genetics, irrigation technologies, no-tillage

Estimation of actual evapotranspiration of various agricultural water optimization practices



1 Introduction

In arid and semi-arid regions of the world, water scarcity contributes to major crop production reductions. In the Western US, agriculture is the largest consumer of water in a region that faces increasing urban growth and less projected winter snowpack (Siirila-Woodburn et al., 2021). One of the largest irrigation sources in this region is the Colorado River Basin, which diverts water to seven Western US states. This basin has experienced six major multi-year droughts between 1906 and 2015. Looking forward, the upper half of the basin has a predicted reduction in average water flow from 6–31% if there is a 1–4°C temperature increase scenario (Woodhouse et al., 2021). Similarly, the Great Salt Lake Basin is also facing major scarcity issues, as from 1989 to 2022, the lake's water level declined by 0.1 m per year, with agriculture accounting for 71% of water depletion, and 80% of the water in agriculture is consumed to raise alfalfa and grass hay (Richter et al., 2025). In addition to surface water challenges, the Parowan-Cedar Valley groundwater basin faces over-withdrawals as groundwater levels have declined by 30 m over the past 50 years, with a land surface subsidence rate of 5 cm every year (Smith et al., 2023). These hydrologic pressures highlight the need for management strategies that improve water use without compromising crop productivity.

A key component for evaluating such strategies is actual evapotranspiration (ET_a), defined as the total water flux from the crop-soil system to the atmosphere through plant transpiration and soil evaporation under prevailing atmospheric and soil-moisture conditions (Ahmad et al., 2025). Unlike potential or reference evapotranspiration, ET_a reflects the water actually consumed by

the crop-soil system and therefore provides a direct measure of crop water use (FAO, 2025). These distinctions are important in comparing agricultural water-optimization strategies, as improvements in yield or irrigation efficiency do not necessarily indicate reduced consumptive water use. Management practices may alter the timing, magnitude, or partitioning of water loss while producing similar agronomic outcomes. Quantifying ET_a is therefore essential for irrigation scheduling, crop water assessment, interpretation of water productivity, and evaluation of management practices intended to conserve water under water-limited conditions (Salman et al., 2025).

Multiple agricultural water optimization strategies are being used, including improved sprinkler packages, deficit irrigation, drought-tolerant genetics, and conservation-related soil and crop management. Among irrigation technologies, low-elevation systems such as low-energy precision application (LEPA), low-elevation sprinkler application (LESA), and low-elevation Nelson Advantage (LENA[®]) have demonstrated superior water application efficiency, varying between 88–95%, compared to 78% in conventional mid-elevation spray application (MESA) systems (Sarwar et al., 2019; Sullivan et al., 2023; Crookston et al., 2025). Deficit irrigation is also widely used in water-limited environments to reduce irrigation inputs below full crop water demand to maintain acceptable yields and improve water productivity. Deficit irrigation at 25, 50, and 75% of estimated ET resulted in equivalent sweet corn (*Zea mays* var. *saccharata*) yield compared to full irrigation, and application of 25% of full irrigation had the highest crop water use efficiency of 53.5 kg m⁻³ among treatments in a trial in Florida (Teshome et al., 2023). In Colorado, three deficit irrigation

strategies (stop irrigation after 1st cutting, stop irrigation after 2nd cutting, spring and fall irrigation) decreased alfalfa yield by 3.1, 3.5, and 6.5 Mg ha⁻¹; consumptive water use (ET) by 282, 272 and 482 mm, while increasing crop water use efficiency from 32.7, 31.1, and 35.1 kg ha⁻¹ mm⁻¹, respectively compared to full irrigation (Lindenmayer et al., 2008). In Türkiye, deficit irrigation increased crop water use efficiency and irrigation water use efficiency to 0.27–0.56 and 0.46–1.77 kg m⁻³, respectively (Er and Kuslu, 2025; Er and Kuslu, 2026). Drought-tolerant (DT) genetics offer another method for water optimization as they may enhance resilience by modulating physiological and molecular responses, such as stomatal regulation, root architecture, and stress-responsive signaling pathways, to optimize water use (Wei et al., 2025). Corn plants under water stress conditions have shown an improved total root length and total root surface area at the seedling stage, suggesting a valuable genetic resource for drought tolerance (Li et al., 2015). Depending on the resilience mechanisms, some DT corn hybrids have demonstrated a 6.5% yield increase under drought conditions and a 1.9% increase under favorable conditions across 10,000 on-farm locations in the corn belt of the US (Gaffney et al., 2015). Conservation agriculture, such as No-till (NT) cultivation (avoid tillage of the soil and retains 60–90% crop residue on the soil surface) and cover cropping (CC), helps improve soil water storage at shallow depths by increasing soil aggregation and organic matter. Cover cropping can improve crop water use efficiency by 5%, but can decrease the profile soil water storage (Wang et al., 2021).

Quantifying ET_a in field experiments remains challenging. Direct approaches such as lysimeter, Eddy Covariance, and remotely sensed ET products are valuable, but they often have important limitations for treatment-intensive small-plot studies. However, scale, cost, and/or feasibility constraints often limit their usage in small plot research trials. Lysimeters and eddy covariance systems are costly and require technical skills, while satellite-based ET products are constrained by pixel size, mixed surface effect, and plot scale incompatibility in small experimental fields (Abdelmajeed and Juszczak, 2024; Volk et al., 2024). Soil-water-balance approaches based on *in situ* moisture measurements offer a practical alternative, and recent work by Hess et al. (2021) has shown that soil moisture can provide a strong relationship ($R^2 = 0.88$) between lysimeters and soil moisture sensors for ET estimation when integrated appropriately with atmospheric demand.

Despite growing interest in agricultural water-optimization strategies, an important knowledge gap remains in understanding how these practices compare in terms of actual consumptive water use.

Previous studies have largely emphasized yield, forage quality, or irrigation efficiency for individual practices, with few ET_a-based comparisons across multiple management strategies within a common experimental framework. Therefore, the study aims to use the soil moisture-based evapotranspiration (SMET) model as a low-cost, plot-scale method for ET_a estimation in treatment-intensive field settings. The SMET model uses volumetric water content and tall reference ET (ET_r) data to estimate ET_a (Hargreaves, 2023). The objective of this study was to quantify the effects of irrigation technologies, irrigation levels, crop genetics, no-tillage, and cover cropping on ET_a, crop water productivity (WP_c), and irrigation water productivity (WP_i) in alfalfa, corn, and small-grain forages under the same management in the Intermountain West, US. The results will help strengthen agricultural water balance assessments in water-limited irrigated systems.

2 Materials and methods

2.1 Experimental site characteristics

The study was conducted during the 2022 and 2023 growing seasons at established water-optimization research sites near Cedar City and Vernal, Utah, USA. Site characteristics, soil physicochemical properties, and monthly climatic conditions are presented in Table 1 and 2. Soil texture, classification, and related soil property data were obtained from SoilWeb based on the USDA-NRCS soil survey database (O'Geen, 2023), whereas study-year weather data were obtained from the Utah Climate Center (Utah Climate Center, 2025) and 30-year climate normals from the NOAA National Centers for Environmental Information 1991–2020 U.S. (NOAA National Centers for Environmental Information, 2021). The two sites differ with soil properties governing water retention and flow, with Cedar City having coarser-textured, more conductive soil and Vernal having finer-textured soil with greater organic matter and available water capacity. Interannual and site-level differences in temperature and precipitation further provided distinct environmental conditions for evaluating crop water use responses across treatments.

2.2 Treatment description

The study was conducted to investigate strategies for water optimization, including irrigation technologies, irrigation levels, crop

TABLE 1 Site characteristics and soil physicochemical properties of the experimental locations at Cedar City and Vernal, Utah, USA.

Site	GPS coordinates (elevation)	Soil texture and classification	pH	BD (g cm ⁻³)	OM (g kg ⁻¹)	EC (dS m ⁻¹)	Saturated hydraulic conductivity (mm hr ⁻¹)	Available water capacity (cm cm ⁻¹)	Carbonates (% of < 2 mm)
Cedar City	37.66° N, 113.14° W (1682 m)	Sandy loam (Coarse-loamy, mixed (calcareous), mesic Xeric Torriorthents)	8.5	1.5	18	1	102	0.12	13
Vernal	40.46° N, 109.56° W (1667 m)	Clay loam (Coarse-loamy, mixed (calcareous), mesic Xeric Torriorthents)	8.5	1.5	31	1	10	0.17	8

TABLE 2 Monthly and 30-year normals average air temperature (°C) and precipitation (mm) across Cedar City, Vernal, and Wellsville during the study period (2019–2023).

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average air temperature (°C)													
Cedar City	2022	-1.3	-1.6	4.6	8.9	13.4	20.8	23.3	20.7	18.4	9.5	0.1	-1.1
	2023	-2.1	-2.0	1.8	7.9	13.4	16.5	23.9	20.3	15.9	9.8	4.1	0.8
	30-year normal	0.0	1.4	5.4	8.7	13.9	19.8	23.7	22.8	18.1	11.2	4.6	-0.4
Vernal	2022	-4.2	-4.0	3.4	7.8	12.3	19.6	23.5	22.4	18.6	9.1	-1.6	-9.2
	2023	-8.6	-10.7	-3.1	6.1	14.9	17.7	23.0	21.4	16.3	9.2	1.9	-2.8
	30-year normal	-6.9	-2.9	3.8	8.2	13.6	18.9	22.6	21.4	16.2	8.9	1.4	-5.6
Precipitation (mm)													
Cedar City	2022	0	4	14	15	0	0	75	74	40	21	32	19
	2023	37	7	43	7	5	23	4	36	37	4	18	5
	30-year normal	20	28	36	31	25	13	34	33	22	34	27	29
Vernal	2022	1	5	32	9	15	18	12	13	23	34	17	12
	2023	63	8	25	4	1	9	3	14	9	4	3	0
	30-year normal	16	14	17	19	26	15	14	21	31	29	13	16

types, crop genetics, tillage, and cover cropping. At both sites, four sprinkler irrigation technologies: LEPA, LESA, LENA[®], and MESA, were installed on a linear move irrigation system and were designed to apply the same amount of irrigation water (Figure 1). The linear move systems operated at a pressure of 280 kPa at Cedar City and 210 kPa at Vernal.

Two irrigation treatments were applied in each of the four technologies by adjusting sprinkler nozzle sizes to apply full and half

irrigation rates. The full-irrigation treatment received 100% of the modeled crop evapotranspiration (ET_c), whereas the deficit-irrigation treatment received 50% of that amount. Irrigation was scheduled based on modeled ET_c using the crop coefficient method ($ET_c = ET_r \times K_c$) in the Irrigation Scheduler program (Peters and Hill, 2022). Crop type varies by location, year, and crop. Grain corn was planted in 2022 and followed by fall-planted SGF in 2023 at Cedar City, while at the Vernal site, SGF was planted in 2022 and followed by silage corn in

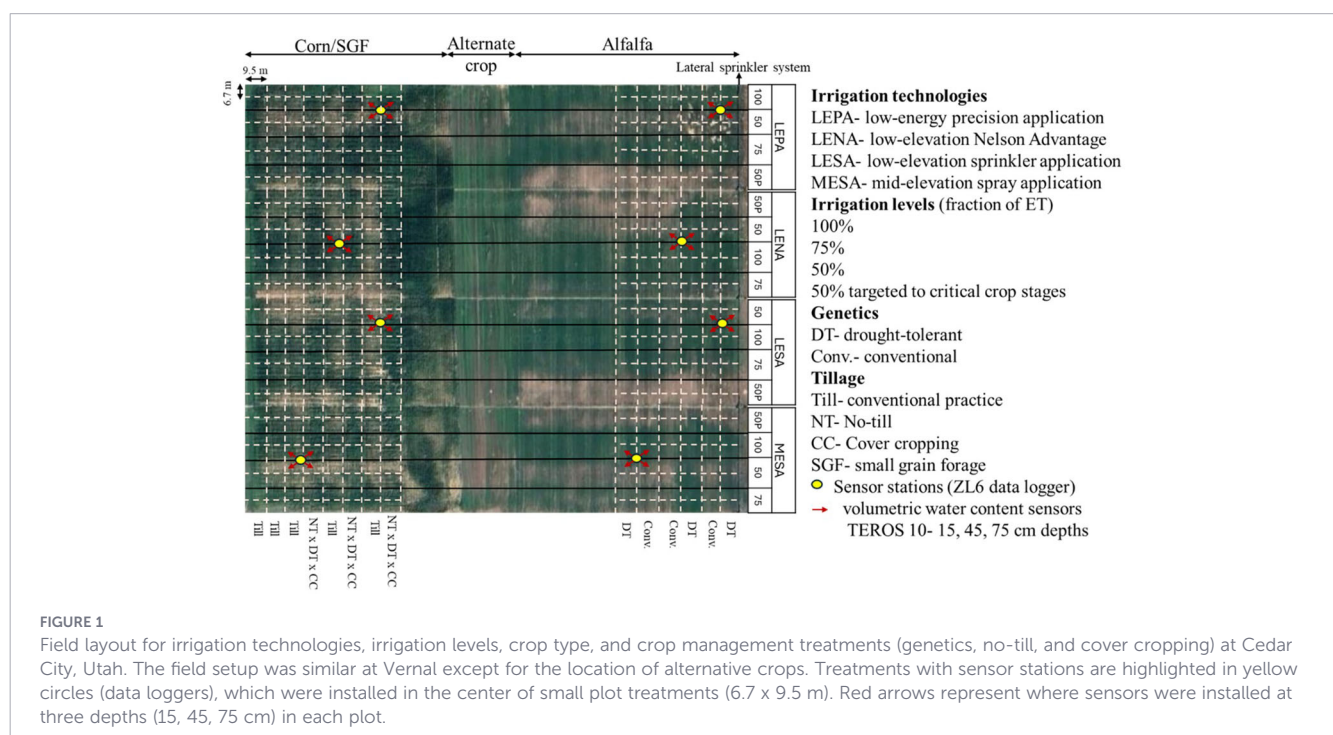


FIGURE 1

Field layout for irrigation technologies, irrigation levels, crop type, and crop management treatments (genetics, no-till, and cover cropping) at Cedar City, Utah. The field setup was similar at Vernal except for the location of alternative crops. Treatments with sensor stations are highlighted in yellow circles (data loggers), which were installed in the center of small plot treatments (6.7 x 9.5 m). Red arrows represent where sensors were installed at three depths (15, 45, 75 cm) in each plot.

2023 (Table 3). Alfalfa was planted in 2021 at each site. DT alfalfa (Ladak II variety) and corn (DKC 47–27 hybrid) were planted to compare with non-DT alfalfa (WL 319 HQ at Vernal and IFA 414 at Cedar City) and corn (DKC 46–36 at both sites) varieties. Alfalfa seeding rate for both varieties at each site was 21.1 kg ha⁻¹ (Cedar City) and 22.4 kg ha⁻¹ (Vernal) and was planted at 13 mm depth. Corn was planted at a seeding rate of 88,980 plants ha⁻¹ at 5.1 cm deep.

Irrigation technologies and levels were implemented similarly at both sites for all crops, but genetics, tillage, and cover cropping treatments varied by crop. In alfalfa, DT genetics were compared with non-DT genetics. In SGF, tillage treatments were compared (till and NT), while in corn, the combined effect of DT, NT, and CC was compared to conventional (conv) control practices. The experiment design and detailed description of treatments were reported by Sullivan et al. (2023) and Crookston et al. (2025) in previous studies. Soil moisture sensors were installed at 100% and 50% of full irrigation in all irrigation technologies of each crop to estimate ET_a. Sensor measurements were recorded every 15 minutes in all treatments for two entire growing seasons at each site for a total of four site-years of data for each treatment. Replications of treatment data within site-year were not possible due to resource limitations related to the initial cost of equipment and the labor to maintain sensors. Treatments were compared independently, considering one factor at a time. The yield data collected from the respective plots where sensors were installed were used to calculate crop water productivity (WP_c, Kg ha⁻¹ mm⁻¹) and irrigation water productivity (WP_i, kg ha⁻¹ mm⁻¹), as mentioned in Equations 1 and 2, respectively.

$$WP_c = \frac{\text{marketable yield } (Y, \text{ kg ha}^{-1})}{\text{actual evapotranspiration } (ET_a, \text{ mm})} \quad (1)$$

$$WP_i = \frac{\text{marketable yield } (Y, \text{ kg ha}^{-1})}{\text{irrigation water applied } (I, \text{ mm})} \quad (2)$$

2.3 SMET model description

The ET_a was estimated for each treatment using a soil moisture-based evapotranspiration (SMET) model. The SMET model, developed by Hargreaves (2023) and published as Hashemi et al. (2025), was previously calibrated and validated using eddy covariance measurements from a tower located adjacent to the Vernal study site. This site-specific calibration enhances model performance for estimating ET_a under the soil, climate, and management conditions represented in the present experiment. The SMET model estimates ET_a as a function of ET_r and soil moisture depletion (Δθ) as presented in Equation 3:

$$ET_a = \begin{cases} \infty (ET_r - \Delta\theta) & \text{if } \Delta\theta < 0 \rightarrow ET_r^+ = 0 \\ 2 \infty ET_r & \text{if } \Delta\theta \geq 0 \rightarrow \Delta\theta^- = 0 \end{cases} \quad (3)$$

Where ET_a, ET_r, and Δθ are in mm day⁻¹, and α is a dimensionless calibration constant. The Δθ accounts for soil water extraction during the drying period. The 'α' acts similarly to a crop coefficient depending on the calibration dataset. Eureka software helped in the initial guess of 0.30 for alpha, which was optimized using the SMET model fitting process, yielding a value of 0.43. For the final ET_a calculations, alpha (0.43) was multiplied by the difference between the ET_r and the absolute value of the Δθ when the change in soil moisture is negative; however, when the change is positive, twice the value of alpha is multiplied by the ET_r.

TABLE 3 Cropping sequence, genetics, irrigation levels, and management treatments across sites and years at Cedar City and Vernal, UT, USA during 2022–23.

Site	Study years	Crop	Genetics	Irrigation level treatment	Tillage	Cover Crop
Cedar City	2022–2023	Alfalfa	DT (Ladak II) vs. non-DT (IFA 414)	2022–740 mm (100%) and 370 mm (50%) 2023–624 mm (100%) and 312 mm (50%)	–	–
	2022	Grain corn	DT (DKC 47–27) vs. non-DT (DKC 46–36)	765 mm (100%) 383 mm (50%)	Till vs. NT	Included (with DT + NT treatment)
	2023	Small grain forage	–	712 mm (100%) 356 mm (50%)	Till vs. NT	–
Vernal	2022–2023	Alfalfa	DT (Ladak II) vs. non-DT (WL 319 HQ)	2022–556 mm (100%) and 278 mm (50%) 2023–360 mm (100%) and 180 mm (50%)	–	–
	2022	Small grain forage	–	710 mm (100%) 355 mm (50%)	Till vs. NT	–
	2023	Silage corn	DT (DKC 47–27) vs. non-DT (DKC 46–36)	500 mm (100%) 250 mm (50%)	Till vs. NT	Included (with DT + NT treatment)

2.4 Data extraction

Volumetric soil water content was measured using 96 TEROs 10 sensors (Meter Group, Pullman, WA, USA) connected to 16 ZL6 data loggers at each site, with data accessed via the Zentra Cloud platform. All the sensors were factory calibrated according to mineral soils. The sensors were installed at depths of 15, 45, and 75 cm in each experimental plot with sensors. For quality assurance and control, the soil moisture sensor data were screened to be within a certain threshold. To maintain the continuity of the data, any single missing value that was between two known values in time was gap-filled using the average of those adjacent values. If there were multiple consecutive missing values, they were denoted as missing data. The model requires one soil moisture measurement per day, for which midnight soil water content data were used. The midnight water content was converted into total water depth for the entire soil profile by multiplying it by the corresponding soil depth range and summing for the full sensor set. Meteorological data were obtained from the nearest Utah Climate Center weather stations with coordinates of 37.67° N, -113.13° W (Cedar City) and 40.45° N, -109.56° W (Vernal) (Utah Climate Center, 2025). ET_r was computed using the American Society of Civil Engineers (ASCE) Standardized Reference Evapotranspiration as presented in Equation 4 (Allen et al., 2005).

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} \mu_2(e_s - e_a)}{\Delta + \gamma(1 + C_d \mu_2)} \quad (4)$$

Where ET_r is reference evapotranspiration (mm d^{-1}), R_n is the net solar radiation ($\text{MJ m}^{-2}\text{d}^{-1}$), G is soil heat flux ($\text{MJ m}^{-2}\text{d}^{-1}$), T mean daily ($^{\circ}\text{C}$), μ_2 mean daily wind speed (m s^{-1}), e_s saturation vapor pressure (kPa), e_a mean actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$), C_n numerator constant that changes with reference type and calculation ($\text{K mm s}^3 \text{Mg}^{-1} \text{d}^{-1}$) and C_d denominator constant that changes with reference type and calculation time step (s m^{-1}).

2.5 Crop coefficient

Crop ET (ET_c) was estimated using the mean crop coefficient method following FAO 56 (Allen et al., 1998). The K_c values were obtained from FAO 56 with initial, development, middle, and late season lengths as provided in Table 12 of FAO 56. The parameters K_{cini} , K_{cmid} , K_{cend} , start day, L_{ini} , L_{dev} , L_{mid} , and L_{late} for both crops, across both years and sites are presented in Figures 2a, b. FAO 56 does not provide initial K_c estimates for small-grain forage, restricting its usage for further correlation analysis with the SMET model. The ET_c was used as a cross-comparison to the ET_a from SMET because of the uncertainty associated with the empirical nature of both methods.

2.6 Statistical analysis

Statistical analyses were conducted to evaluate the effects of irrigation technologies, irrigation levels, crop genetics, and site-year variability on actual evapotranspiration, crop water productivity, and irrigation water productivity in alfalfa. Paired two-sample

t-tests were used to assess differences between treatment groups. Statistical significance was evaluated at $\alpha = 0.05$, and all tests were conducted using two-tailed hypotheses. Comparisons were performed both across site-years and within individual sites where applicable.

3 Results

3.1 Reference evapotranspiration

The ET_r data for both sites for the growing season from 2022–2023 are presented in Figure 3 as reported from the Utah Climate Center. Cedar City had greater ET_r than Vernal during the growing season in both years. However, ET_r in 2023 was greater than in 2022 at both sites. At Cedar City, ET_r ranged from 2–18 mm in 2022 and between 2–13 mm during 2023, while it ranged between 2–13 mm in 2022 and 2–12 mm in 2023 at Vernal from the end of the winter to the peak of the growing season during June to July.

3.2 Performance of the SMET model

The SMET model was developed for full-season assessments. The daily 100% irrigation level estimated ET_a across irrigation technologies using the SMET model followed the general pattern of FAO 56 ET_c . In 2022, the model demonstrated a strong correlation with FAO 56 with R^2 values of 0.98 and 0.99 at Cedar City and Vernal, respectively. Similar results were observed at Vernal in 2023, where the model maintained a correlation of 1.0, indicating perfect predictive accuracy. Daily comparisons of SMET also showed a strong correlation (R^2 ranging from 0.80 to 0.87), as shown in Figure 4. The findings suggest that the SMET is similar to ET_c models and can be used to estimate ET_a .

3.3 SMET estimated evapotranspiration

In alfalfa, ET_a varied significantly across sites, years, irrigation levels, and genetic treatments. Across sites, ET_a was significantly greater at Cedar City than at Vernal ($p = 0.0039$). Over the years, ET_a in 2022 was significantly higher than that in 2023 ($p = 0.0038$). During 2022, the combined ET_a for all crops averaged at both sites was 574 mm compared to 480 mm in 2023. Between sites, Cedar City (596 mm) had greater ET_a than Vernal (466 mm) due to the prevailing climatic conditions at each site (Figure 5). For alfalfa, ET_a was greater during the first cut than subsequent cuttings in 2022 at both sites. However, in 2023, the second cutting had more ET_a than other cuttings at both sites except for 50% LEPA (DT, conv), LENA[®] (100 and 50%), LESA 100% (DT), and MESA (100% and 50% conv) at Cedar City. The variation in ET_a between the first and later cuttings ranged from 1 mm to 150 mm during 2022 across both sites.

3.3.1 Irrigation technologies

Irrigation technologies did not significantly affect ET_a among crops, sites, and years, irrespective of irrigation levels, genetics, and

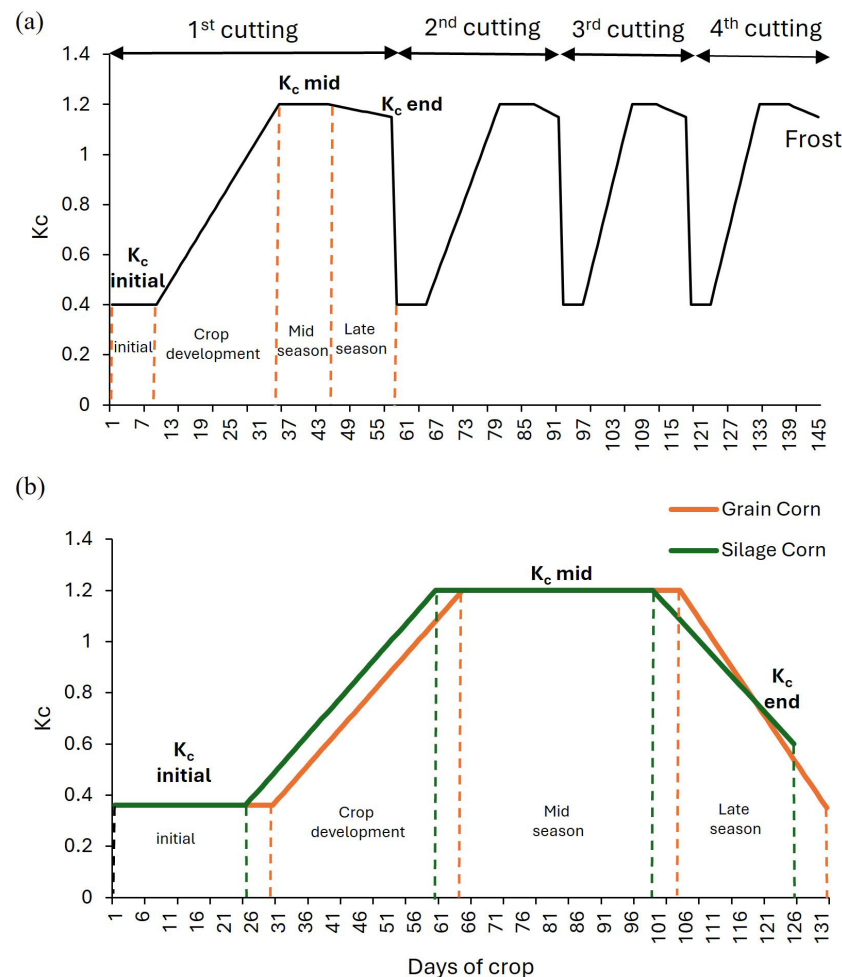


FIGURE 2

Crop coefficient for alfalfa (a) and grain & silage corn (b) based on local climatic conditions, depending on crop developmental stages at Cedar City and Vernal from 2022–23.

conservation practices at either site, but followed a particular trend. The LESA system had higher ET_a for three of the four site-years of alfalfa, increasing ET_a by 37 mm (2022 Vernal), 47 mm (2023 Cedar City), and 40 mm (2023 Vernal), while LEPA had higher ET_a (14 mm) during 2022 at Cedar City compared to MESA for the whole growing season (Figure 6). Similar results were observed in SGF, where LENA[®] had higher ET_a at Vernal in 2022 (514.6 mm), while LESA had higher ET_a at Cedar City in 2023 (560 mm) compared to MESA (481 and 549 mm, respectively). However, in grain corn, MESA (673 mm) had higher ET_a compared to low elevation sprinklers, with LENA[®] (665 mm) having the most similar ET_a to MESA, while for silage corn, LEPA (556 mm) had higher ET_a than MESA (546 mm) and other systems. It is important to note that volumetric water content data were missing from June 17th to July 12th for corn in LEPA in 2022 at Cedar City, which led to variation in ET_a estimations; therefore, the ET_a estimates for the treatment should be interpreted cautiously. In general, although numerical differences in ET_a were observed among irrigation technologies, these differences were not statistically significant and were not consistent across crops and site-years. Therefore, the observed responses are presented as descriptive site- and crop-specific patterns rather than definitive effects of irrigation technology on ET_a .

3.3.2 Irrigation levels

Irrigation level significantly influenced ET_a , with full irrigation resulting in greater ET_a than DI ($p = 0.0023$). In 2022 at Cedar City, ET_a increased from 657.2 to 714.6 mm in alfalfa and from 611.2 to 666.3 mm in corn under 50% and 100% ET_c , respectively (Figure 7). At Vernal in 2022, ET_a increased from 491.7 to 534.1 mm in alfalfa and from 471.6 to 483.7 mm in SGF. In 2023 at Cedar City, ET_a increased from 484.2 to 526.2 mm in alfalfa and from 538.6 to 561.0 mm in SGF, while at Vernal it increased from 319.1 to 355.2 mm in alfalfa and from 530.0 to 546.1 mm in corn. Overall, the reduction in ET_a under deficit irrigation ranged from 12.1 to 57.4 mm across site-years and crops. Full irrigation consistently produced greater ET_a than deficit irrigation across crops and site-years, highlighting that the 50% ET_c treatment reduced seasonal crop water use. However, the magnitude of this reduction varied among crops and site-years.

3.3.3 Drought-tolerant genetics, tillage, and cover cropping

Genetics, tillage, and cover cropping treatments varied by crop. Alfalfa had two genetics (DT vs non-DT) treatments, SGF had

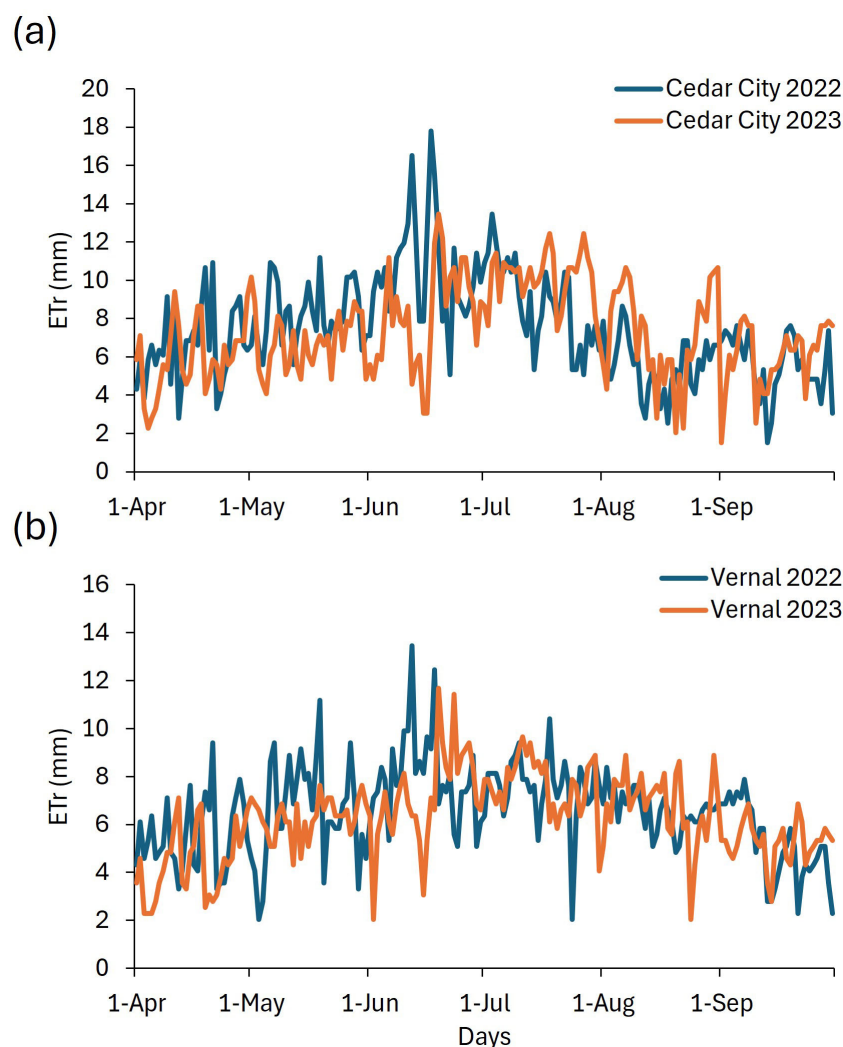


FIGURE 3

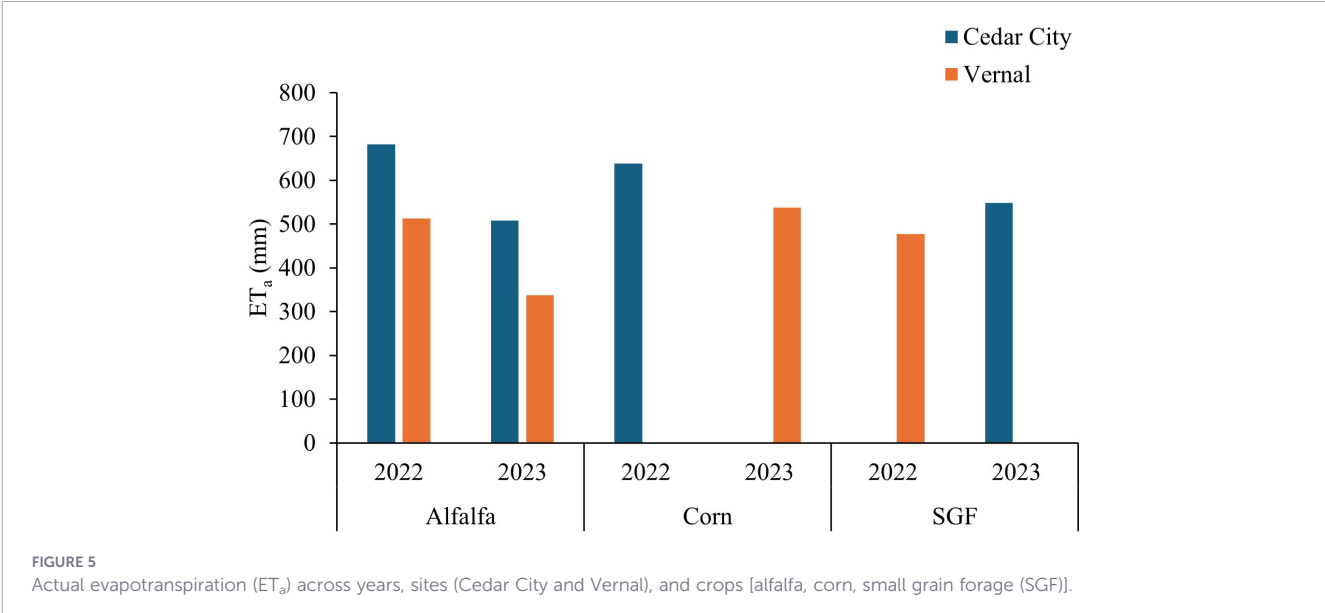
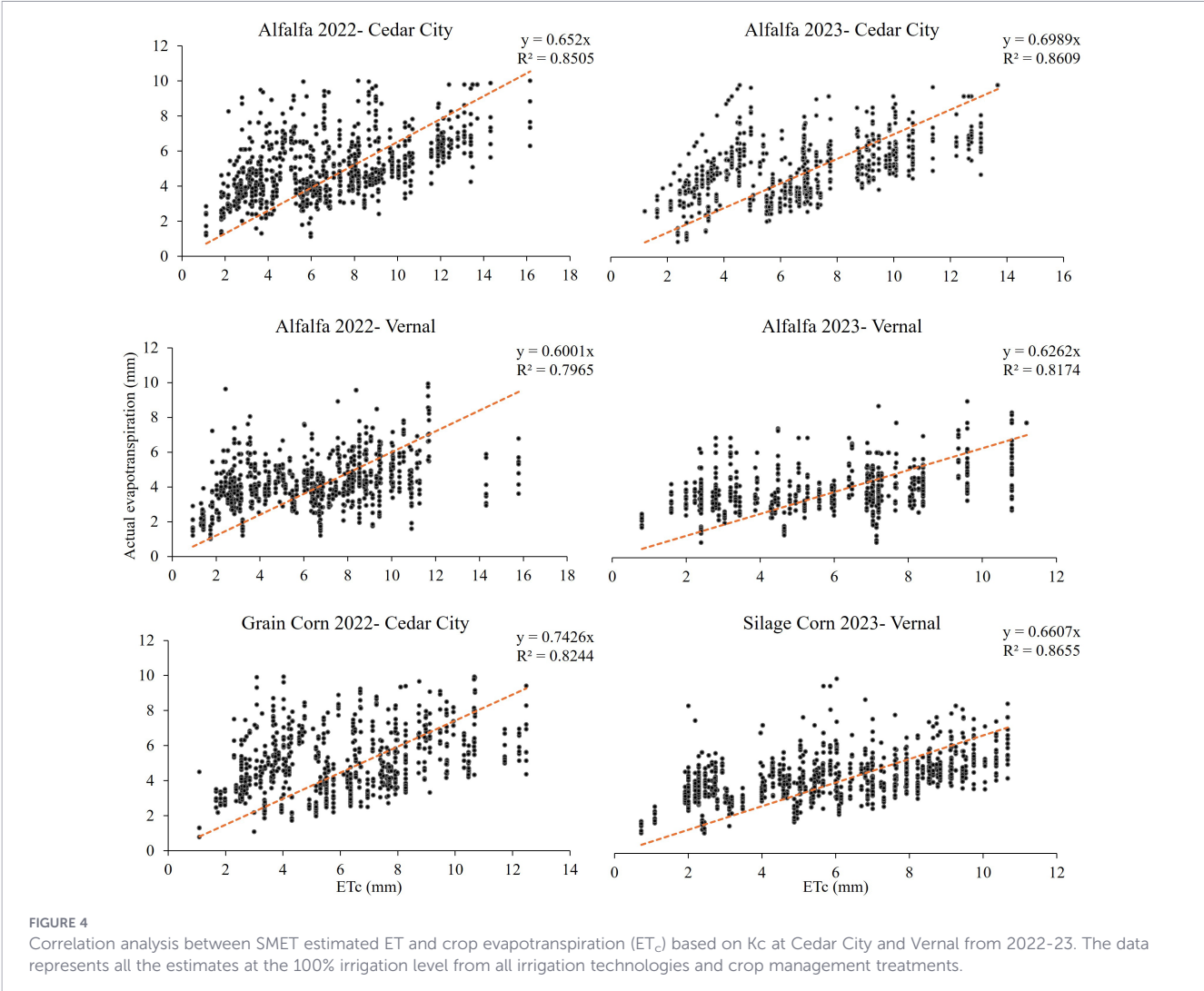
Tall reference evapotranspiration (ET_r) data from Utah Climate Center for Cedar City (a) and Vernal, Utah, USA (b).

tillage treatments, and corn had two treatments (DT, NT, and CC vs control) as a conventional non-treated treatment (Figure 1; Table 3). The DT genetics of alfalfa had higher ET_a than conventional varieties ($p = 0.035$), with Vernal ($p = 0.0084$) showing significant differences, while at Cedar City, there were no significant differences observed. The DT alfalfa treatment had higher ET_a compared to conventional varieties, ranging from 7 to 24 mm (Figure 8). In alfalfa, the DT treatment consistently had greater ET_a than the conventional treatment across all site-years, increasing from 669.9 to 693.7 mm at Cedar City in 2022, from 507.5 to 518.3 mm at Vernal in 2022, from 504.5 to 511.9 mm at Cedar City in 2023, and from 331.6 to 342.7 mm at Vernal in 2023. In SGF, conventional tillage had 16 mm greater ET_a than NT at Vernal in 2022, and 4 mm greater at Cedar City in 2023. In corn, the combined NT + DT + CC treatment reduced ET_a relative to control at Cedar City in 2022 (632.7 vs. 644.7 mm), but increased ET_a at Vernal in 2023 (549.9 vs. 526.1 mm). Overall, treatment effects were consistent in alfalfa and SGF, where DT alfalfa and conventional tillage in SGF had higher ET_a, but inconsistent in corn, where the

combined NT + DT + CC treatment decreased ET_a at Cedar City and increased it at Vernal.

3.4 Crop yield

Yield responses varied across site-years, crops, irrigation technologies, and management treatments. In alfalfa, yield was higher under the 100% ET_c treatment than under 50% ET_c, ranging from 3365 to 5757 kg ha⁻¹ under 100% ET_c and from 1710 to 5427 kg ha⁻¹ under 50% ET_c across sites, years, technologies, and genetics (Supplementary Table 1). Drought-tolerant alfalfa produced yields comparable to or greater than the conventional treatment, with values ranging from 1717 to 5757 kg ha⁻¹ for DT and from 1710 to 5524 kg ha⁻¹ for the conventional treatment. In annual crops, yield responses were more variable, with grain and silage corn yields ranging from 285 to 8115 kg ha⁻¹ in the treatment and from 581 to 10311 kg ha⁻¹ in the conventional treatments, with conventional management outperforming the treatment plots (Supplementary Table 2). In SGF, yields ranged from 944 to 5604 kg ha⁻¹ in the



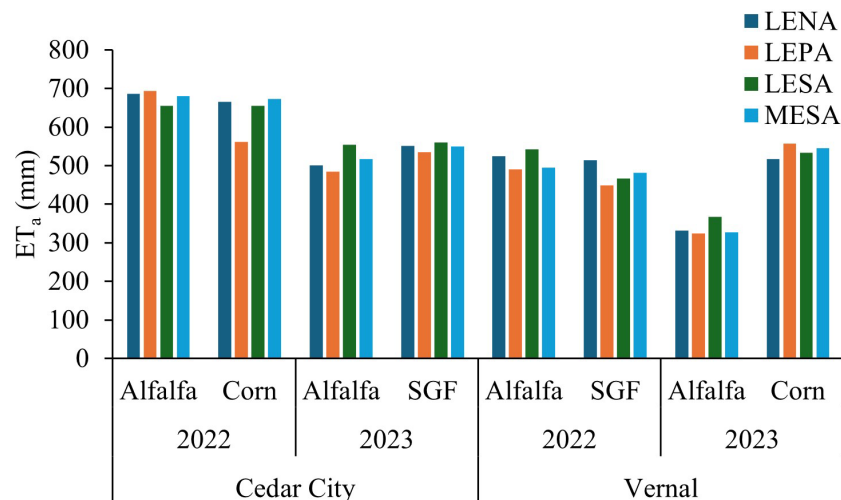


FIGURE 6

The effect of irrigation technologies: low-elevation Nelson Advantage[®] (LENA), low-elevation precision application (LEPA), low-elevation spray application (LESA), and mid-elevation spray application (MESA) on actual evapotranspiration (ET_a) for different crops [alfalfa, corn grain at Cedar City and silage at Vernal, and small grain forage (SGF)]. Note: Volumetric water content data were missing from June 17th to July 12th for grain corn in LEPA in 2022 at CC, which led to variation in estimated ET_a.

treatment plots and from 1680 to 7472 kg ha⁻¹ in the conventional plots, although treatment plots exceeded the conventional treatment under some irrigation technologies and irrigation levels. Across crops, low-elevation irrigation systems had numerically greater yields than MESA in alfalfa and SGF, whereas corn responses were less consistent. Overall, the yield data indicates that agronomic responses to irrigation and crop management were strongly crop and site-specific.

3.5 Crop water productivity

The Crop water productivity (WP_c) in alfalfa varied significantly across sites, years, irrigation technologies, irrigation levels, and genetic treatments. Across sites, WP_c was significantly ($p = 0.0105$) greater at Vernal (24.6 kg ha⁻¹ mm⁻¹) than at Cedar City (15.5 kg ha⁻¹ mm⁻¹). Interannual differences were also observed,

where 2023 had significantly higher WP_c than 2022 ($p = 0.0147$), with 23.3 kg ha⁻¹ mm⁻¹ and 16.8 kg ha⁻¹ mm⁻¹ WP_c, respectively (Tables 4, 5).

Irrigation technology also significantly ($p = 0.0237$) influenced WP_c, with LEPA (22.5 kg ha⁻¹ mm⁻¹) resulting in higher WP_c compared to MESA (17.8 kg ha⁻¹ mm⁻¹) across site-years. At Cedar City, the LEPA (17.1 kg ha⁻¹ mm⁻¹) had significantly ($p = 0.0073$) higher WP_c than MESA (13.8 kg ha⁻¹ mm⁻¹), but the difference was non-significant at Vernal (Tables 4, 5). In general, LEPA had the greatest WP_c in three of four site-years in alfalfa, while the trends were mixed for SGF, with LENA having higher WP_c at Cedar City in 2023 and LESA with higher WP_c at Vernal in 2022. Corn harvested as grain at Cedar City in 2022 had greater WP_c in LENA, while harvested as silage had greater WP_c in MESA technology. Irrigation level also had a higher WP_c in full irrigation (17.0 kg ha⁻¹ mm⁻¹) than DI (14.0 kg ha⁻¹ mm⁻¹) at Cedar City ($p =$

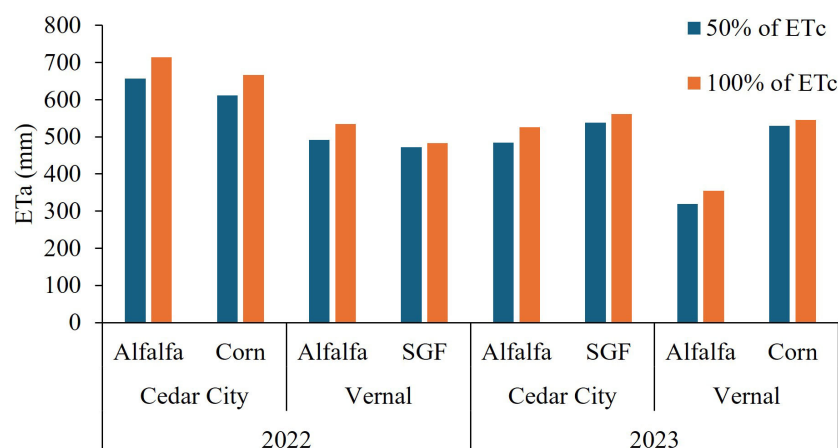


FIGURE 7

Effect of irrigation levels (50% or 100% of ET_c) on actual evapotranspiration (ET_a) of alfalfa, corn, and small grain forage (SGF) at Cedar City and Vernal, UT during 2022–23.

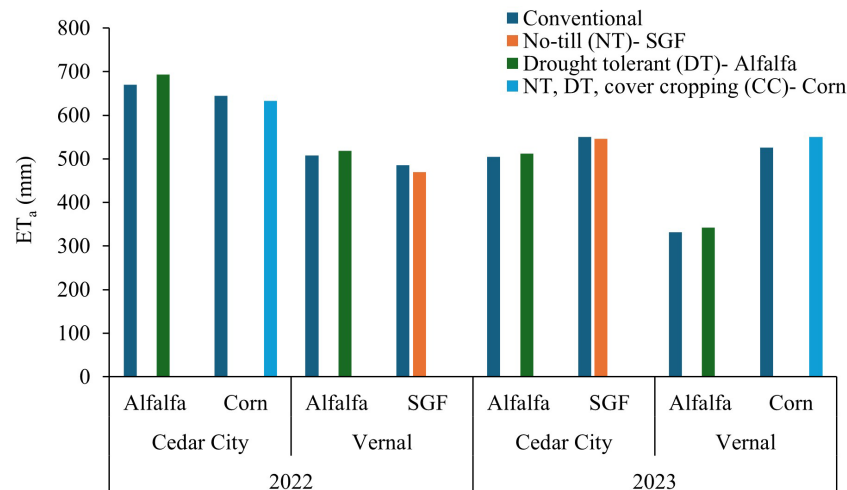


FIGURE 8

Effect of crop genetics [conventional and drought-tolerant (DT)] of alfalfa, no-till (NT) of small grain forage (SGF), and the combined effect of NT, DT genetics, and cover cropping (CC) of grain corn at Cedar City and silage corn at Vernal on actual evapotranspiration (ET_a) during 2022–23.

0.0294), while no significant differences were observed at Vernal (Tables 4, 5). In SGF and corn, trends were also consistent with full irrigation having higher WP_c than DI, except LENA (grain corn, Cedar City-2022) and LESA (SGF, Cedar City-2023).

The DT genetics of alfalfa (20.8 kg ha⁻¹ mm⁻¹) had significantly ($p = 0.0042$) higher WP_c than conventional varieties (19.3 kg ha⁻¹ mm⁻¹), but no significant results were observed among sites (Tables 4, 5). In general, DT genetics of alfalfa had higher WP_c than conventional varieties for 6 out of 8 irrigation level treatments under four technologies across all site-years. In SGF, the conventional treatment had a greater WP_c than NT in 63% of times compared to NT practice among all technologies and site-years. Similar results were observed in corn, where the combined effect of DT, NT, and CC also had less WP_c than conventional practices due to a lower crop stand under NT treatments.

3.6 Irrigation water productivity

Irrigation water productivity (WP_i) in alfalfa was influenced by irrigation technology and irrigation level. Among irrigation technologies, LEPA (28.3 kg ha⁻¹ mm⁻¹) had significantly ($p = 0.0274$) higher WP_i compared to MESA (22.7 kg ha⁻¹ mm⁻¹). In general, trends for WP_i were more consistent across sites and years than WP_c, where low-elevation (LENA[®], LEPA, and LESA) irrigation technologies performed better for alfalfa, SGF, and grain corn across all site-years, while MESA had greater WP_i than other technologies in silage corn (Tables 4, 5).

Irrigation level also had a significant effect, with DI (33.1 kg ha⁻¹ mm⁻¹) having significantly ($p = 0.0427$) higher WP_i than full irrigation (19.8 kg ha⁻¹ mm⁻¹) across site-years, while no significant effects were observed within sites (Tables 4, 5). The DT genetics of alfalfa did not significantly affect WP_i but were numerically higher in DT than conventional varieties for all site-years except LEPA 50% (Vernal, 2022), LESA 50% (Cedar City, 2023), and MESA 50% (Cedar City, 2023) (Tables 4, 5). Results for WP_i for NT in SGF and the combined effect of DT, NT, and CC for corn were also not

significant, but conventional practices had higher WP_i than conservation practices numerically among all sites and years (Tables 4, 5).

4 Discussion

The greater ET_a observed at Cedar City than at Vernal indicates that higher atmospheric demand and local hydroclimatic conditions control seasonal crop water use. This study shows that irrigation technology, irrigation level, and crop-management strategy influenced ET_a, WP_c, and WP_i, but the magnitude and direction of response depended strongly on crop and site-year. A key pattern observed was that low-elevation sprinkler packages generally improved water productivity in alfalfa, SGF, and grain corn, whereas responses in silage corn were less consistent. At the same time, DI reduced applied water more than it reduced ET_a, and DT alfalfa increased both ET_a and WP_c relative to the conventional cultivars.

4.1 Low-elevation sprinkler technologies shifted more water toward productive transpiration

Although irrigation technology effects on ET_a were not statistically significant, the directional trends were agronomically meaningful. In alfalfa, SGF, and grain corn, low-elevation technologies produced higher ET_a and higher water productivity than MESA. This pattern is consistent with previous irrigation-efficiency studies showing that LESA, LEPA, and related low-elevation application systems reduce wind drift (2–5%) and spray losses relative to MESA (15–20%) under advective conditions (Sarwar et al., 2019). Molaei et al. (2023) further showed that wind drift and spray losses are much larger in MESA than in LESA, and they can temporarily suppress ET by cooling and humidifying the canopy boundary layer. The greater ET_a observed under low-elevation packages likely

TABLE 4 Effect of irrigation technologies, levels, and crop genetics on crop water productivity (WP_c), i.e., plant biomass produced ($kg\ ha^{-1}$) per unit ET (mm^{-1}) and irrigation water productivity (WP_i), i.e., plant biomass produced ($kg\ ha^{-1}$) per unit water applied (mm^{-1}) for alfalfa at Cedar City and Vernal during 2022–23.

Site-Year	$WP_c\ (kg\ ha^{-1}\ mm^{-1}\ of\ ET)$														
	LEPA					LENA®					LESA				
	100% ET_c		50% ET_c			100% ET_c		50% ET_c			100% ET_c		50% ET_c		
	DT	topConv	topDT	topConv		topDT	topConv	topDT	topConv		topDT	topConv	topDT	topConv	
Cedar City-2022	16.5	16.8	9.6	9.4		12.8	12.8	11.4	9.1		–	–	18.3	14.8	
Cedar City-2023	26.2	19.0	22.2	16.8		19.5	19.0	19.3	15.8		15.8	18.8	–	–	
Vernal-2022	25.2	28.7	22.7	23.0		23.7	21.2	23.5	20.5		23.0	19.5	24.7	18.5	
Vernal-2023	28.7	28.9	37.1	28.7		33.6	28.2	26.9	26.4		24.9	26.7	24.2	23.2	
$WP_i\ (kg\ ha^{-1}\ mm^{-1}\ of\ irrigation\ water\ applied)$															
Cedar City-2022	16.8	15.8	17.3	16.5		12.4	12.4	19.8	16.8		16.8	16.8	33.1	25.2	
Cedar City-2023	22.0	14.6	30.6	26.7		16.1	15.3	29.6	25.9		14.8	15.8	23.7	33.1	
Vernal-2022	25.7	24.5	37.1	39.0		22.0	21.5	41.5	38.3		23.7	19.3	48.2	33.8	
Vernal-2023	28.4	26.4	63.7	48.4		33.3	25.9	53.8	48.4		24.9	24.5	46.9	44.5	

LENA® (low-elevation Nelson Advantage), (LEPA) low-elevation precision application, (LESA) low-elevation spray application, (MESA) mid-elevation spray application, DT- drought-tolerant, and Conv- conventional. AT Cedar City, in LEPA, the 100% irrigation level (2022) and 50% irrigation level (2023) sensor data were unavailable and designated as “–”.

reflects greater delivery of water to the soil-plant system and a larger fraction of water routed to transpiration rather than to non-beneficial atmospheric loss. The weaker response in corn is also biologically plausible because taller canopies can intercept spray and reduce the relative aerodynamic disadvantage of MESA. Yield results during earlier years from the study area also align with the ET_a , where MESA had higher or comparable yield with low elevation technologies at 3 of the 4 site-years (Sullivan et al., 2023). Mattar et al. (2022) also showed that wind drift and evaporation losses in sprinkler irrigation are strongly controlled by wind speed, operating pressure, nozzle diameter, and riser height, highlighting the importance of sprinkler configuration in determining effective water delivery.

4.2 Deficit irrigation reduced ET_a

Deficit irrigation at 50% ET_c moderately reduced ET_a relative to full irrigation. Since DI in our study was applied based on ET_o and 50% of the full irrigation level was applied to crops, the reductions in ET_a ranged from 2–17% below full irrigation. This does not follow the general trends of reduced ET_a with less applied water, suggesting the ET_c model may have been an overestimation. It is also possible that SMET overestimated ET_a under deficit soil conditions, possibly due to water use below the deepest sensor (75 cm). For example, both the 50% and 100% irrigation levels had similar soil water storage in the zone, while water in 100% level may have moved below 75 cm, which was not captured with SMET and might have reduced the ET_a estimations. Because ET_a was estimated from soil moisture measurements limited to 75 cm, this interpretation should be treated cautiously under deficit irrigation, where deeper water extraction may have occurred. These results emphasize the potential of DI as a water-saving practice, but more precise ET_a measurements would require deeper sensor installations. Similar outcomes have been reported in both alfalfa and maize, where moderate deficit irrigation reduced irrigation water more strongly than seasonal ET and sometimes improved water productivity when yield losses remained limited (Montazar et al, 2020; Jiao et al, 2024). In China, applying a moderate water deficit during the branching and budding stages of alfalfa growth resulted in a reduction of 150 mm in ET compared to full irrigation throughout the season (Liu et al, 2022).

4.3 Drought-tolerant alfalfa increased ET_a and WP_c

The consistent increase in ET_a and WP_c under DT alfalfa indicates that drought tolerance was expressed not as reduced water use, but as more effective water acquisition and conversion into biomass. Drought-adapted genotypes can differ in root system architecture, hydraulic function, osmotic adjustment, and stomatal regulation, all of which influence water uptake and biomass maintenance under stress (Li et al, 2015; Mega et al, 2019; Lombardi et al, 2021). This mechanism is relevant for alfalfa, where root system architecture strongly affects both resource capture and post-harvest regrowth, where selection for root traits has been linked to improved biomass performance and environmental adaptation (Bucciarelli et al, 2021; Pan et al, 2023). Thus, the greater ET_a and WP_c observed in DT alfalfa aligned with previously reported drought-adaptation mechanisms related to root function and plant water relations.

TABLE 5 Effect of irrigation technologies, levels, and no-till for small grain forage (SGF) and combined effect of crop genetics/no-till/cover cropping for corn (grain corn at Cedar City and silage corn at Vernal) on crop water productivity (WP_c), i.e., plant biomass produced (kg ha^{-1}) per unit ET (mm^{-1}) and irrigation water productivity (WP_i), i.e., plant biomass produced (kg ha^{-1}) per unit water applied (mm^{-1}) at Cedar City and Vernal during 2022–23.

WP _c (kg ha ⁻¹ mm ⁻¹ of ET)																	
Site-Year	Crops	LEPA				LENA [®]				LESA				MESA			
		100% ET _c		50% ET _c		100% ET _c		50% ET _c		100% ET _c		50% ET _c		100% ET _c		50% ET _c	
		Trt	Conv	Trt	Conv	Trt	Conv	Trt	Conv	Trt	Conv	Trt	Conv	Trt	Conv	Trt	Conv
Cedar City-2022	Grain corn	4.0*	12.1*	3.5	6.2	5.7	6.4	4.7	9.9	4.0	4.7	3.7	4.0	3.2	4.2	1.0	2.2
Cedar City-2023	SGF	21.5	19.5	17.0	22.5	–	–	20.7	29.4	22.0	17.8	19.5	23.5	20.7	17.8	18.8	15.8
Vernal-2022	SGF	9.9	15.3	7.9	9.1	13.1	9.1	6.9	10.4	15.8	13.8	9.6	11.1	7.9	15.1	4.9	11.1
Vernal-2023	Silage corn	23.2	26.4	14.1	11.1	21.7	34.3	16.3	25.2	9.9	29.6	7.7	17.3	36.8	44.5	6.4	21.5
WP _i (kg ha ⁻¹ mm ⁻¹ of irrigation water applied)																	
Cedar City-2022	Grain corn	1.5*	4.9*	5.4	10.4	5.7	6.4	4.7	9.9	3.7	4.0	6.2	6.4	2.7	4.0	1.7	3.7
Cedar City-2023	SGF	15.3	14.1	25.9	36.3	–	–	32.6	45.0	19.5	14.6	29.6	32.1	15.8	14.8	26.7	25.4
Vernal-2022	SGF	6.2	9.9	10.1	11.6	9.4	7.2	9.1	15.1	11.4	8.6	12.1	14.6	5.2	10.1	6.7	15.3
Vernal-2023	Silage corn	24.9	26.2	35.6	24.5	23.0	34.8	33.8	50.6	12.1	30.6	14.3	35.6	39.5	50.1	13.6	45.7

LENA[®] (low-elevation Nelson Advantage), (LEPA) low-elevation precision application, (LESA) low-elevation spray application, (MESA) mid-elevation spray applicators, (Trt)- It's a combined effect of drought-tolerant genetics, no-tillage, and cover cropping for corn and NT in small-grain forage. *In the LEPA 100% irrigation-level Trt and Conv treatment plots at Cedar City (2022) for corn, volumetric water content (VWC) data were missing from June 17th to July 12th, leading to variation in the estimated ET from soil moisture-based evapotranspiration (SMET). The LENA[®] 100% DT/NT/CC treatment VWC data was missing due to sensor errors.

4.4 Lower ET_a , WP_c , and WP_i under NT-based annual systems

In SGF and corn, conventional management resulted in greater WP_c and WP_i than NT or the combined NT + DT + CC treatment. The concurrent reductions in ET_a , WP_c , and WP_i under these treatments suggest that lower plant stand and weaker early-season establishment under no-till conditions, as surface residue can reduce seed-soil contact, interfere with furrow closing, and delay emergence, thereby limiting early growth and subsequent biomass accumulation (Aikins et al., 2019; Rogovska et al., 2016). In maize-based systems, cooler and wetter seed-zone conditions under residue-retaining tillage can further delay emergence and early development, which may contribute to reduced seasonal performance (Boomsma et al., 2010). This interpretation is consistent with evidence that NT effects on crop productivity are strongly site specific and can be neutral or negative when management is not fully adapted to local soil, climate, residue, and fertility conditions (Pittelkow et al., 2015). Cover crops may improve near-surface soil water storage and water-use efficiency, but their effects on profile water availability and yield are variable and depend on termination timing, biomass production, and climate (Wang et al., 2021). While long-term conservation practices can enhance soil structure and soil health, these benefits often require multiple years to develop and may not be expressed in short-term annual productivity responses (Mitchell et al., 2024). Therefore, the lower performance of the NT and CC based treatments observed in the study should be interpreted as a short-term, site-specific response rather than a general conclusion about conservation practices.

4.5 Study limitations and future research needs

This study provides a critical understanding of a wide range of water optimization practices on ET_a , WP_c , and WP_i under the same management conditions. Future research should refine treatment-level ET_a estimates at the farm scale using remote sensing tools to cover the replication effects of practices. Further improvement in deficit irrigation should be made by extending soil moisture measurements deeper in the profile and accounting for drainage.

5 Conclusion

The actual evapotranspiration varied across crops, irrigation technologies, and years, with alfalfa generally exhibiting the highest ET_a . Irrigation technologies did not significantly affect ET_a , however, low-elevation systems showed numerically greater ET_a than MESA. Deficit irrigation strategies did not reduce much ET_a , which might be due to overestimates of the ET_c model used for irrigation levels, the SMET predicted ET_a , or partial root-zone coverage (≤ 75 cm) with the installed soil moisture sensors. The DT genetics of alfalfa had a marginally greater ET_a than conventional, while for corn and SGF, reduced crop stands under NT likely reduced the ET_a

compared to conventional practices. Alfalfa, SGF, and grain corn were the most water-productive crops in terms of WP_c and WP_i under all three low-elevation sprinkler systems, while silage corn was more water productive under mid-elevation sprinkler systems. Deficit irrigation had mixed effects on WP_c and WP_i , but often had greater water productivity than full irrigation. In general, DT genetics improved water productivities in alfalfa, while the conventional treatment had greater productivity compared to tillage and combined genetics, tillage, and cover crop treatment in SGF and corn, respectively. Overall, these findings highlight that optimizing irrigation technology and crop management can improve water productivity, but outcomes are influenced by crop type and local conditions and should be considered with caution in terms of replication. Integrating low-elevation systems with appropriate management practices offers a practical pathway to enhance water productivity. These results provide insights for producers and water managers to refine irrigation strategies under increasing water scarcity in their regions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

TSi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. MH: Conceptualization, Data curation, Validation, Visualization, Writing – review & editing. MY: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. TSu: Conceptualization, Data curation, Visualization, Writing – review & editing. AT-R: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. BB: Conceptualization, Supervision, Validation, Visualization, Writing – review & editing. CR: Conceptualization, Data curation, Visualization, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2026.1836461/full#supplementary-material>

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