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Impacts of water optimization practices on soil health and soil water infiltration

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Water scarcity is a major challenge for agriculture in arid and semi-arid regions. This study evaluates the long-term effects of deficit irrigation (DI) and land management practices, including no-tillage (NT), crop genetics, crop types, and cover cropping (CC), on soil health and water infiltration. Field experiments were conducted from 2019 to 2024 at three sites in Utah, USA, to study the effects of conservation practices in Wellsville, Vernal, and Cedar City. Two irrigation levels (100% and 50% of crop evapotranspiration) were applied using mid-elevation spray application sprinklers on a lateral irrigation system. Five cropping systems were evaluated: tilled corn (*Zea mays*), NT corn, tilled corn with CC, NT drought-tolerant corn with CC, and conventional alfalfa (*Medicago sativa*). Soil health was assessed using soil organic matter (SOM), soil respiration, autoclave citrate-extractable (ACE) protein, permanganate oxidizable carbon (POXC), and aggregate stability. Field-saturated hydraulic conductivity (K_{fs}) was measured using dual-head infiltrometers. Deficit irrigation had minimal effects on SOM (except at Vernal, 10.2% increase under DI) and aggregate stability. Soil respiration was 28% higher under full irrigation at Vernal, and ACE protein decreased from 1.57 to 1.41 g kg⁻¹ under DI at Cedar City. Conservation practices such as NT and perennial alfalfa systems also had greater microbial activity across sites. Cover cropping increased K_{fs} to 24.62 cm h⁻¹, compared with 5.55 and 3.42 cm h⁻¹ under conventional tillage and NT at Vernal in 2023, respectively. The results demonstrate that moderate reductions in irrigation can be compatible with maintaining soil health in cooler regions, whereas warmer environments may require more conservative water reductions.

KEYWORDS

deficit irrigation, infiltration, permanganate-oxidizable carbon, soil organic matter, soil respiration

1 Introduction

Water is one of the most limiting resources in agriculture in arid and semi-arid regions like the western United States. Projected increases in urban expansion, reduced winter snowpack, watershed depletion, and prolonged drought conditions have significant pressure on water resources in the western United States (1, 2). These challenges highlight the urgent need to improve water use efficiency in irrigated agricultural systems. In Utah, approximately 445, 154 ha of irrigated farmland managed by 11, 000 farms contribute an estimated \$2.3 billion annually to the state's economy, highlighting the importance of irrigation to

agricultural productivity and economic stability (3). However, irrigation water-saving strategies should be assessed not only for their effects on crop production, but also for their impact on soil function. Soil regulates the storage, movement, and plant availability of water, and its biological and physical properties play a key role in determining whether reduced-irrigation practices sustain or impair long-term agroecosystem resilience.

Deficit irrigation (DI) can influence soil moisture dynamics by regulating microbial activity, residue decomposition, nutrient cycling, and plant growth (4). Soil organic matter (SOM) is a key indicator of soil health that regulates soil carbon storage, soil structure and aggregation, nutrient cycling, microbial activity, and soil physical properties such as bulk density, water retention, and infiltration (5). These functional improvements are largely governed by soil organic carbon (SOC), which is a chemically and biologically active fraction of SOM that regulates carbon stabilization, microbial energy supply, and long-term soil biogeochemical processes (6–8). A three-year study in the Texas High Plains found that SOC was lower in both drip-irrigated and dryland fields converted from irrigated center-pivot systems, with severe water deficits reducing fungal abundance more than bacteria, highlighting early indicators of declining soil health under reduced water supply (9). A multi-year field study in western Kansas showed that DI altered organic matter dynamics by reducing biomass-derived carbon inputs and enhancing wetting-drying induced mineralization, limiting SOM accumulation and SOC stabilization (10). The effects of water optimization strategies on SOM may take several years to become evident in semiarid regions because of inherently slower turnover; therefore, early changes in SOM are often evaluated using labile carbon indicators such as permanganate oxidizable carbon (POXC). These labile carbon fractions are more sensitive to management changes and can serve as early signals of improvement or degradation in soil health.

Soil respiration reflects microbial decomposition and is therefore sensitive to the combined effects of soil water content, temperature, aeration, and carbon availability (11, 12). Similarly, autoclave citrate-extractable (ACE) protein is associated with microbial biomass and organic nitrogen pools and may respond more strongly to cropping systems that provide continuous residue and root inputs than to irrigation level alone (13–15). Soil health is increasingly defined as the continued capacity of soil to function as a living system, and this function depends on the integrated performance of biological, physical, and chemical processes (16). In irrigated agroecosystems, soil regulates key water-related functions, including infiltration, storage, redistribution, drainage, and plant water supply, and these functions are strongly governed by soil hydraulic behavior, structure, and biologically mediated pore development (17, 18). Consequently, the extent to which reduced-irrigation practices enhance or compromise long-term agroecosystem resilience depends on whether they preserve the soil's capacity to regulate water flow and storage while maintaining biological activity and structural integrity (16, 18).

Conservation practices such as no-till (NT), cover cropping (CC), and perennial forage systems can further modify these soil processes by altering disturbance, surface cover, rooting patterns, and carbon inputs.

A 15-year study in California's San Joaquin Valley demonstrated that NT and CC practices led to improvements in soil aggregation, infiltration rates, soil nitrogen (N) content, water-extractable organic carbon, and microbial activity compared to a tilled system (19). Furthermore, this study reported increases in total soil carbon (TC) and total nitrogen (TN) under NT and CC systems, with up to 53% more C and 47% more N in the 0–15 cm depth compared to conventional practices after 15 years of treatments (19). Reduced tillage generally preserves surface residues and minimizes aggregate disruption, whereas cover crops and perennial systems can enhance rhizosphere activity and increase organic inputs that support aggregation, microbial activity, and habitat development (20–22). However, these responses are not uniform, as in semiarid irrigated soils, the benefits of conservation management may be constrained by limited moisture availability, low residue production, and site-specific soil properties, so improvements are often detected more readily in biologically sensitive indicators than in more stable physical and chemical attributes (23, 24).

Field saturated hydraulic conductivity (K_{fs}) is also a sensitive indicator of water movement in soil, referring to the rate at which water moves through soil under near-saturated conditions, measured directly in the field, where natural soil structure, macropores, and heterogeneity are preserved (25). The responses of K_{fs} to management practices can vary. For example, in silt loam soil with a rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth.) cover crop, saturated hydraulic conductivity (K_s) increased by 166% at 0–5 cm, 194% at 5–10 cm, and 359% at 10–15 cm compared to no-cover crop control (26). In contrast (27), reported no differences in soil porosity or K_s between wheat (*Triticum aestivum* L.) and hairy vetch CC and fallow under strip tillage in sandy loam soil, and (28) also observed no significant effect of CC on K_s in silt loam. Long-term conventional tillage has been shown to enhance infiltration rates due to greater formation of large, flow-active pores in surface layers (29), and NT or reduced tillage systems may limit infiltration by reducing pore connectivity, despite other soil health benefits. Although NT can lead to temporary reductions in infiltration due to surface crusting, it may provide long-term benefits in enhancing water conservation and soil moisture storage, especially under arid conditions (30). Soil organic matter can also enhance K_s or K_{fs} indirectly by promoting aggregation, biological activity, macropore formation, and pore continuity; however, this relationship is not universal because hydraulic conductivity near saturation is also strongly governed by soil texture, antecedent moisture, wettability, and the connectivity of structural pores (31, 32).

Despite growing interest in water-saving irrigation strategies and conservation practices, limited research is available on how these management approaches influence soil health and hydraulic properties in irrigated systems of the semiarid western United States. This study evaluates the effects of deficit irrigation and conservation practices on soil health indicators and soil hydraulic behavior. Therefore, the objective of this study was to evaluate how long-term deficit irrigation and conservation management practices influence soil function in semiarid irrigated forage systems, using soil health indicators and field-saturated hydraulic conductivity as complementary measures of biological and physical change.

2 Materials and methods

2.1 Experiment sites

The water optimization study was initiated over three years, with sites established near Wellsville, UT (41.667° N, 111.920° W) in 2019, Vernal, UT (40.462° N, 109.562° W) in 2020, and Cedar City, UT (37.665° N, 113.142° W) in 2021. The soil type and soil properties at the three sites are listed in Table 1. The University of California-Davis SoilWeb tool was used to obtain soil classifications (33). Soil samples were collected across the entire plot area during establishment at a depth of 30 cm to assess background soil pH, soil texture, and salinity. These soil properties were analyzed at the Utah State University Analytical Lab in Logan, UT. The Wellsville and Cedar City sites have sandy loam soil, whereas the Vernal site has clay loam soil.

2.2 Treatments

Four to five types of irrigation technologies were tested at each site. Each irrigation technology was randomly assigned to one span (48–55 m) of a lateral-move irrigation system at each site. Four irrigation rates were nested within each irrigation technology. The Wellsville site had low-elevation Nelson Advantage (LENA), mid-elevation spray application (MESA), low-elevation spray application (LESA), mobile drip irrigation (MDI), and low-elevation precision application (LEPA) sprinklers from 2019 to 2023. Cedar City had LENA, MESA, LESA, and LEPA from 2021 to 2023. Vernal had MESA, LESA, MDI, and LEPA from 2020 to 2021, but the MDI system was replaced by LENA from 2022 to 2023. The flow rates of the lateral-move irrigation systems were 91, 100, and 145 m³ h⁻¹ for the Logan, Vernal, and Cedar City sites, respectively. The operating pressure was 207 kPa at the Logan and Vernal sites and 276 kPa at the Cedar City site.

Irrigation levels at all sites were set, to the extent possible, as fractions of estimated evapotranspiration (ET). The four levels (100% ET, 75% ET, 50% ET, and a second 50% ET rate that prioritized water to critical crop growth stages) were achieved by adjusting the nozzle size in each treatment. For the 50% partial level, the nozzles were alternated between 100%, 50%, or 0% settings to obtain an average rate of approximately 50% throughout the season. Each of the sprinkler application levels was randomly allocated to one-quarter of each span of the lateral-move irrigation system. To minimize overlap in application rates between treatments, directional sprinklers with semi-circular patterns were installed between plots in the MESA system because of the larger throw pattern

compared to other types of sprinklers. Detailed descriptions of sprinkler application efficiencies and water productivity are presented in (34, 35).

In this study, we chose to soil sample at two irrigation levels (100% and 50%) and all crop management treatments within the MESA irrigation system at each site. The MESA system was selected because it is the most common system used by growers in the western U.S. Within MESA and the two irrigation levels at each site, five crop management treatments were randomly assigned to plots and were each replicated three times. The five subplot factor treatments were as follows:

1. Conventional 3-way small grain forage or silage corn with tillage.
2. Conventional 3-way small grain forage or silage corn with NT.
3. Conventional 3-way small grain forage or silage corn with CC and NT.
4. Drought-tolerant 3-way small grain forage or silage corn with CC and NT.
5. Conventional alfalfa with tillage.

The cover crops were planted in the fall after silage corn harvest (September) and in the summer, following the 3-way small grain forage (July). All cover crops were terminated before corn planting in early to mid-May the following spring using glyphosate applied at a rate of 93.5 L ha⁻¹.

Soil health samples were collected using hand soil probes in the first week of June 2024 (after 5 years at Wellsville, 4 years at Vernal, and 3 years at Cedar City). Twelve cores (3.2 cm in diameter), each 15 cm deep, were extracted from each treatment plot and composited into a single sample per plot. The soil samples were kept cool during transport and sent to Ward Laboratories (Kearney, NE, USA) for analysis. Five soil health parameters were selected for this assessment: SOM, soil respiration, ACE protein, POXC, and aggregate stability.

2.3 Field-saturated hydraulic conductivity

The K_{fs} measurements for all sites-years were measured using dual-head infiltrometers (SATURO), an instrument developed by Meter Group, WA, USA. As per the user manual, K_{fs} and infiltration can be used interchangeably. At most of the sites, a 5 cm insertion ring was used, but if there were too many macropores in the soil that did not allow the ring to hold water, a 10 cm ring was installed. Rings were installed gently with a hammer into the soil to

TABLE 1 Baseline soil physicochemical properties at three research sites in Utah, USA, including soil texture classification, soil organic matter (g kg⁻¹), pH, salinity (dS m⁻¹), and sodium adsorption ratio (SAR).

Site	Soil texture	Soil organic matter (g kg ⁻¹)	Soil pH	Salinity (dS m ⁻¹)	SAR
Cedar City	Sandy loam, silty clay loam (Coarse-loamy, mixed (calcareous), mesic Xeric Torriorthents)	18	7.6	1.60	1.23
Vernal	Clay loam, loam (Fine-loamy, mixed, superactive, calcareous, mesic Typic Torriorthents)	31	7.6	0.58	0.25
Wellsville	Loam (Fine-silty, mixed, mesic Aquic Calciustolls)	27	7.4	0.57	0.62

These values characterize the initial soil conditions and highlight inherent differences among the three sites in Cedar City, Vernal, and Wellsville.

ensure good contact with the soil and minimal disturbance to the outer area around the ring. The instrument was configured according to the soil type of each site as listed in Table 2. Water depth, pressure head, and water flux readings were collected every minute during total run times of 95 to 150 minutes. At Vernal K_{fs} data were collected in fall 2023 and in spring 2024 for a simultaneous data collection procedure at all three sites.

2.4 Statistical analysis

To evaluate the effects of DI and crop management practices on soil health indicators, a mixed model analysis of variance (ANOVA) was conducted using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). The dependent variables were five key soil health parameters and K_{fs} . The independent variables were two irrigation treatments (100% and 50% ET replacement), and five crop management practices (NT, CC, DT×NT×CC, conventional 3-way small grain forage or silage corn, and conventional alfalfa). The model included the fixed effects of site (Wellsville, Vernal, and Cedar City), irrigation levels, treatment, and their interactions (site × irrigation rate × treatment). Replication (three) was treated as a random effect nested within site, and interactions involving replication were also considered as random effects to account for variation within blocks. Residual diagnostics, including residual plots and boxplots, were generated to assess assumptions of normality and homogeneity of variance. Least squares means were estimated for each main and interaction effect using the PDIF procedure of SAS, with pairwise comparisons set at a significance level of $\alpha = 0.05$.

3 Results

3.1 Climatic characteristics and project history

Climatic conditions varied among the three study locations and played a key role in soil health and infiltration responses. Cedar City was consistently the warmest site, with June–August air temperatures commonly reaching 20–23°C (e.g., 22.0°C in June 2021, 23.3°C in July 2022). Precipitation at Cedar City was low and erratic, with several months receiving 0–5 mm (e.g., 0 mm in May–June 2022) followed by occasional summer peaks such as 105 mm in

July 2021 (Table 3). Vernal exhibited intermediate temperature regimes, with summer averages typically between 17–24°C (e.g., 22.2°C in June 2021, 23.5°C in July 2022) and moderate precipitation variability. Precipitation events tended to be small and scattered, with many months receiving ≤ 15 mm, except in higher rainfall years such as July 2021 (53 mm). Wellsville was the coolest and generally wetter site. Growing-season temperatures were several degrees lower than the other locations, with April temperatures as low as 4.5°C (2023) and summer highs around 21–22°C (e.g., 21.5°C in August 2019). Wellsville also experienced the greatest precipitation inputs, with repeated months exceeding 40–60 mm, such as June 2020 (64 mm) and August 2023 (75 mm). These climatic gradients align strongly with the site-specific outcomes observed later in this study.

3.2 Deficit irrigation effects on soil health properties

There was a significant effect of DI on SOM among sites (Table 4). At the Vernal site, the DI irrigation treatment had 10.2% higher SOM than the full irrigation treatment. However, no significant differences were observed between irrigation levels at the Wellsville site (Figure 1). The Cedar City site had the lowest SOM values among all sites for both irrigation level treatments, but was also not affected by DI. For soil respiration, the main effect of irrigation treatment was also not statistically significant (Table 4). Soil respiration was highest at the Vernal site under full irrigation, approximately 28% higher than under the DI irrigation level (Figure 2a). At Wellsville, soil respiration was slightly higher under full irrigation (30.6 ppm C) compared to the DI treatment (28.6 ppm C) (Figure 2b). However, at the Cedar City site, the results were opposite, and soil respiration was slightly higher under 50% irrigation than 100%, although the difference was not statistically significant (Figure 2c).

The effect of DI on ACE protein also varied by site (Table 4). At Vernal, ACE protein concentration was highest in the 50% irrigation level among all treatments and sites (Figure 3). However, there was no significant change in the ACE protein concentration observed at Wellsville under DI (Figure 3). In contrast, at Cedar City, the ACE protein concentration decreased significantly from 1.57 g kg⁻¹ under 100% irrigation to 1.41 g kg⁻¹ under 50% irrigation (Figure 3). The POXC did not show significant main effects of irrigation or treatment (Table 4). The effect of DI on soil aggregate

TABLE 2 Configuration of the automated dual-head infiltrometer (SATURO) used across study sites.

Sites	Year	Soak time (minutes)	Low-pressure head (cm)	High-pressure head (cm)	Hold time at pressure (minutes)	Pressure cycles (counts)	Total run time (minutes)
Cedar City	2024	30	5	15	20	3	150
Vernal	2023	25	5	10	20	3	145
Vernal	2024	15	5	20	25	2	115
Wellsville	2024	15	5	15	20	2	95

The table summarizes site-specific instrument settings, including soak time, low- and high-pressure heads, hold duration, number of pressure cycles, and total run time, each adjusted to accommodate differences in soil texture and field conditions at Cedar City, Vernal, and Wellsville, UT, USA.

TABLE 3 Monthly 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	2021	-1.5	1.1	3.7	9.7	14.1	22.0	23.2	21.1	17.3	8.4	5.6	0.5
	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
Vernal	2020	-7.7	-4.1	4.6	8.5	14.6	18.7	22.8	23.7	16.2	9.1	1.8	-7.2
	2021	-7.2	-2.6	3.7	8.2	14.4	22.2	24.4	21.0	16.8	7.9	3.7	-3.2
	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
Wellsville	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
	2019	-5.5	-2.6	2.9	9.1	11.8	17.5	22.5	21.5	15.2	2.9	1.3	-5.7
	2020	-3.2	-4.6	4.1	7.9	13.7	16.6	21.4	22.3	15.3	8.7	2.1	-5.7
	2021	-4.0	-0.3	3.3	7.6	13.0	22.1	24.8	19.9	15.7	8.3	3.8	-1.5
	2022	-6.3	-4.6	3.7	5.9	10.8	17.8	24.5	21.8	17.7	9.0	-1.5	-5.4
	2023	-6.5	-8.3	-2.5	4.5	14.7	16.3	23.6	21.2	15.6	8.7	1.7	-2.0
Precipitation (mm)													
Cedar City	2021	6	4	7	6	3	1	105	35	13	54	0	31
	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
Vernal	2020	3	2	9	8	12	27	2	0	2	0	6	4
	2021	8	7	11	16	25	15	53	29	19	46	2	27
	2022	1	5	32	9	15	18	12	13	23	34	17	12
Wellsville	2023	63	8	25	4	1	9	3	14	9	4	3	0
	2019	1	0	1	1	1	0	0	0	1	17	9	37
	2020	21	6	51	8	12	64	4	4	6	9	23	13
	2021	21	24	26	28	17	0	31	48	21	88	16	44
	2022	15	2	20	18	62	16	0	57	37	24	54	44
	2023	43	19	73	37	15	47	6	75	50	48	31	27

stability also varied numerically by site, but there was no significant effect (Table 4). At Vernal and Wellsville, aggregate stability was slightly higher under DI treatment compared to full irrigation, whereas at Cedar City, aggregate stability was slightly higher under 100% irrigation (62.8%) compared to the DI treatment (57.8%). Overall, the effects of DI on soil health indicators were limited and highly environment-dependent.

3.3 Effect of soil and crop management on soil health

Soil and crop management practices did not significantly affect SOM, and no interactions with site or irrigation were observed (Table 4). Management practices significantly influenced soil respiration, whereas the site × treatment interaction was not significant

TABLE 4 Significance of F-tests for the effect of site (S), irrigation level (I), treatment (T), and their interactions on soil organic matter (%), soil respiration (ppm C), Ace-protein (g kg⁻¹), POX-carbon (ppm C), and aggregate stability (%) across three sites in Utah.

Source of variation	Organic matter (OM)	Soil respiration	ACE protein	POX-carbon	Aggregate stability
----- P > F -----					
Site (S)	<.0001	0.0001	0.0001	<.0001	<.0001
Irrigation level (I)	0.1117	0.1640	0.6555	0.7383	0.9420
Treatment (T)	0.2612	0.0178	0.0322	0.6564	0.1687
S × I	0.0002	0.0537	0.0007	0.1846	0.0958
S × T	0.6989	0.4590	0.0085	0.7496	0.2683
I × T	0.6714	0.2139	0.4262	0.0553	0.9314
S × I × T	0.7677	0.0014	0.3548	0.0847	0.8651

Significant effects were considered at $p \leq 0.05$.

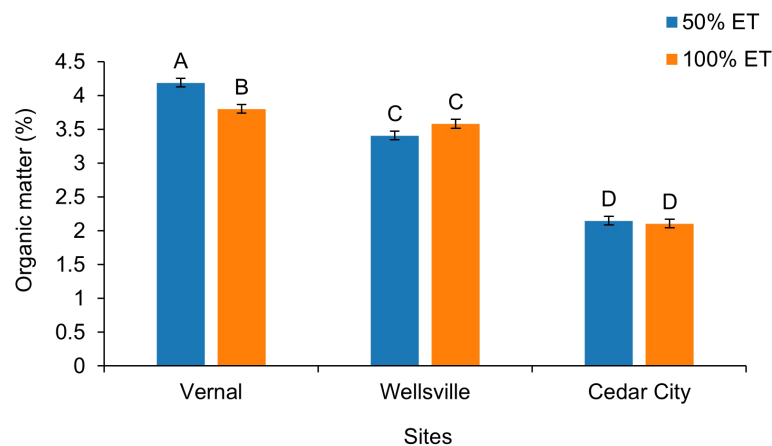


FIGURE 1

Effect of deficit irrigation (50% estimated evapotranspiration (ET) vs. 100% ET) on soil organic matter (%) during 2024 at Vernal, Wellsville, and Cedar City, UT, USA. Bars represent treatment means ($\pm$ SE), and letters denote significant differences among treatments within each irrigation level according to LSD at $\alpha = 0.05$.

(Table 4). The combination of drought-tolerant (DT) corn genetics, NT, and CC had the highest soil respiration (Figure 2), regardless of site and DI. The DT×NT×CC treatment was 29.3% higher than the treatment with only a cover crop. The NT treatment had the second-highest soil respiration (Figure 2), with 28.4% greater respiration than the CC treatment, which showed the lowest soil respiration concentration. The NT treatment also showed relatively high ACE protein concentration compared to other treatments (Figure 4). Other treatments at Vernal, including CC, NT × CC, and conventional corn genetics with tillage, ranged between 1.88 and 2.02 g kg⁻¹ and were not significantly different from one another. At Wellsville, ACE protein concentrations were slightly lower compared to Vernal; however, there were no significant differences among the treatments. Protein concentration at Wellsville ranged from 1.85 g kg⁻¹ for conventional corn with tillage to 2.03 g kg⁻¹ for the CC treatment (Figure 4). The Cedar City site consistently exhibited the lowest ACE protein values regardless of management, ranging from 1.40 g kg⁻¹ for conventional corn with tillage to 1.54 g kg⁻¹ for the NT treatment, with no significant difference among treatments (Figure 4). Soil POXC was not affected by the main effect of treatment nor the site × treatment interaction (Table 4). Aggregate stability did not respond significantly to management practices, and no interactions with site or irrigation were detected (Table 4). Overall, management practices influenced biological indicators more consistently than SOM, POXC, or aggregate stability, suggesting that management effects were detectable but variable among soil health metrics.

3.4 Combined effects of deficit irrigation and soil and crop management on soil health

The SOM did not differ significantly among management treatments, and no interactions with site or irrigation were observed (Table 4). However, a significant site × irrigation interaction was observed ($P = 0.0002$), indicating that irrigation effects on SOM differed among locations. Soil respiration showed significant responses to

management practices and a significant three-way interaction among site, irrigation, and treatment (Table 4), indicating that the effect of management practices under different irrigation levels varied across sites. At Vernal, the highest soil respiration was observed in the NT treatment under full irrigation, followed by the DT×NT×CC treatment (Figure 2a). Under DI conditions, the soil respiration decreased by 57% from 70 to 30 mg kg⁻¹ of C (Figure 2a) in the NT treatment and by 27% from 53 to 38 mg kg⁻¹ of C in the DT×NT×CC treatment compared to 100% irrigation. In contrast, soil respiration increased by 69% under DI in the conventional corn with tillage treatment, whereas no change was observed in the conventional alfalfa treatment (Figure 2a). At Wellsville, soil respiration followed patterns similar to those observed at Vernal. The DT×NT×CC and conventional corn with tillage treatment showed higher respiration values under full irrigation (36.7 and 32.3 mg kg⁻¹ of C, respectively) compared with DI (31.3 mg kg⁻¹ of C for both treatments). A slightly higher soil respiration was observed in the CC and conventional alfalfa treatments at 100% irrigation (26.9 and 32.0 mg kg⁻¹ of C, respectively) compared to DI (24.0 and 29.0 mg kg⁻¹ of C, respectively). However, under NT conditions, DI increased soil respiration by 34% compared to 100% irrigation (Figure 2b). Cedar City exhibited the lowest soil respiration values among the three sites. At this site, the highest value was observed in the DT×NT×CC treatment at 50% irrigation (Figure 2c), while the lowest was under the conventional corn with tillage at 100% irrigation.

ACE protein concentrations differed significantly among treatments and showed significant site × irrigation and site × treatment interactions (Table 4). Across sites, the conventional alfalfa treatment showed the highest ACE protein concentrations (1.98 g kg⁻¹), while the NT (1.88 g kg⁻¹) and DT×NT×CC (1.83 g kg⁻¹) treatments also showed high ACE protein values (Figure 4). However, *post-hoc* comparisons indicated that only the alfalfa treatment differed significantly from other treatments. POXC did not show significant responses to treatment or interactions with site (Table 4). However, the irrigation × treatment interaction approached significance ($P = 0.0553$), suggesting a potential combined influence of irrigation and management practices on labile carbon pools (Figure 5). Aggregate stability did not respond significantly to treatment or

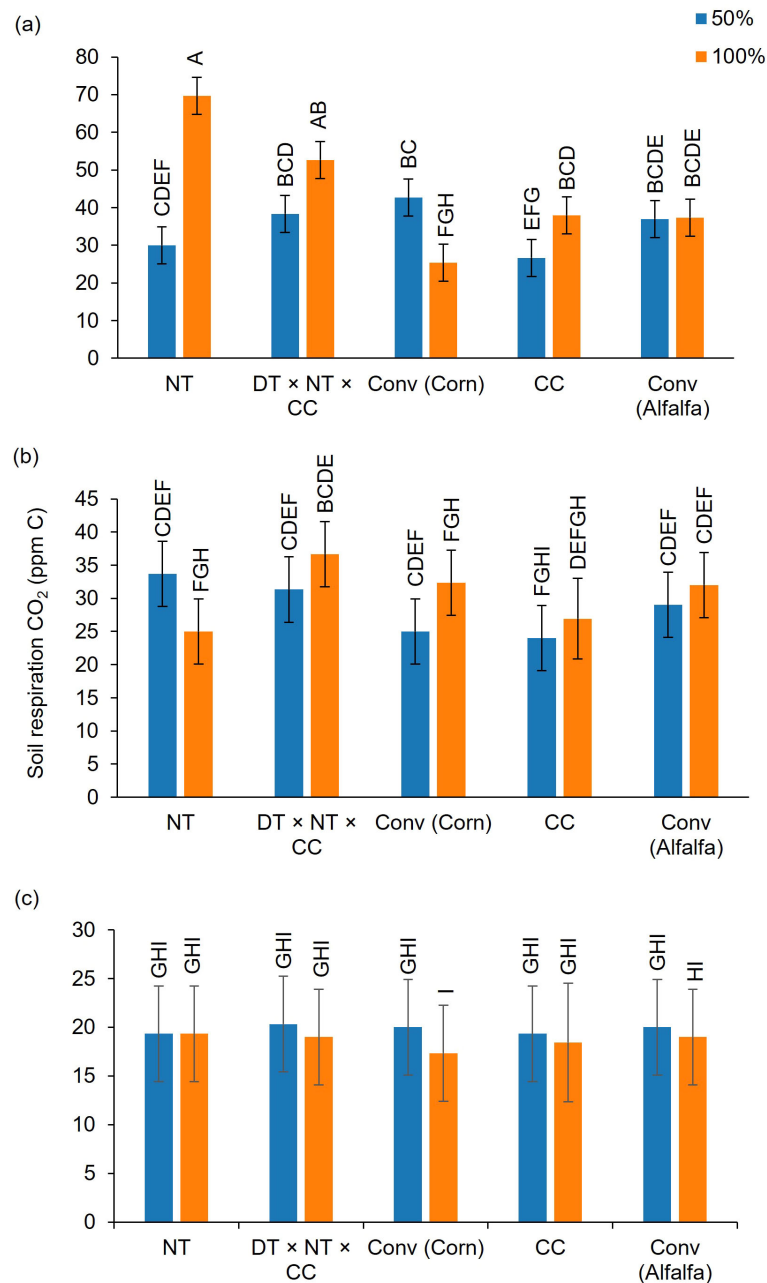


FIGURE 2

Effect of deficit irrigation (DI, 50% estimated evapotranspiration vs. 100%) and crop treatments [no-till (NT), cover crops (CC), and drought-tolerant genetics in corn, and in conventional (Conv) corn and alfalfa] on soil respiration (ppm C) during 2024 at Vernal (a), Wellsville (b), and Cedar City (c), UT, USA. Bars represent treatment means ($\pm$ SE), and letters denote significant differences among sites and treatments within each irrigation level according to LSD at $\alpha = 0.05$.

irrigation interactions and remained relatively similar across management systems (Table 4). These results indicate that the effects of irrigation and management cannot be interpreted independently, because treatment responses were moderated by site conditions and, for some variables, by their interaction.

3.5 Effect of soil management on field saturated hydraulic conductivity

Field saturated hydraulic conductivity (K_{fs}) responses to management practices varied across sites and years. Significant treatment

effects were detected only at the Vernal site in 2023, whereas no significant differences among treatments were observed at other sites or sampling periods. At Vernal, K_{fs} was measured twice, once in fall 2023 and again in spring 2024, providing an opportunity to compare seasonal dynamics. In fall 2023, CC in corn resulted in significantly higher K_{fs} (24.62 cm hr⁻¹), compared to conventional tillage (5.55 cm hr⁻¹) and NT (3.42 cm hr⁻¹) in corn. However, by spring 2024, treatment differences at Vernal did not differ significantly among treatments, and infiltration rates decreased in CC (13.15 cm hr⁻¹) but increased in NT (10.52 cm hr⁻¹). At Wellsville, K_{fs} did not differ statistically among management practices, but numerical differences

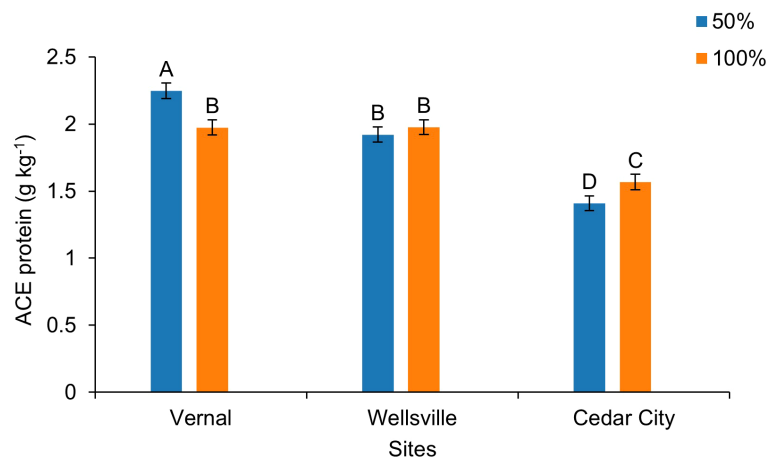


FIGURE 3

Effect of deficit irrigation (50% of estimated evapotranspiration vs. 100%) on ACE protein (g kg^{-1}) during 2024 at Vernal, Wellsville, and Cedar City, UT. Bars represent treatment means ($\pm$ SE), and letters denote significant differences among treatments within each irrigation level according to LSD at $\alpha=0.05$.

were observed among treatments. The CC treatment had the highest infiltration (33.73 cm hr^{-1}), followed by NT (24.20 cm hr^{-1}) and conventional tillage (12.63 cm hr^{-1}) in corn. Cedar City had the lowest K_{fs} values across all sites, with rates ranging from 0.87 to 3.92 cm hr^{-1} and no significant treatment differences. The results indicate that treatment effects were evident under specific conditions rather than consistently across environments.

4 Discussion

4.1 Soil organic matter responses to deficit irrigation and management

The SOM showed limited response to DI and conservation management practices during the study period. The lack of significant

treatment effects suggests that irrigation reductions and management changes may not immediately influence SOM. In semi-arid agroecosystems, SOM dynamics are often constrained by limited biomass production and residue inputs, which slow the rate of carbon accumulation in soils (36). However, DI and conservation practices also do not reduce SOM, suggesting that if severe drought conditions or limited available water periods prevail, soil will have enough OM to maintain crop production. The site $\times$ irrigation interaction observed for SOM indicates that the response of soil carbon to DI depends on local environmental conditions. At the Vernal site, higher SOM under DI suggests that moderate reductions in soil moisture may reduce microbial decomposition while maintaining residue inputs from crops. Reduced microbial mineralization under moderate water limitation has been reported in semi-arid cropping systems where soil carbon turnover becomes moisture-limited (37, 38). In contrast, irrigation levels had little influence on SOM at Wellsville and Cedar City, which highlights the importance of climate in regulating soil carbon dynamics. Higher

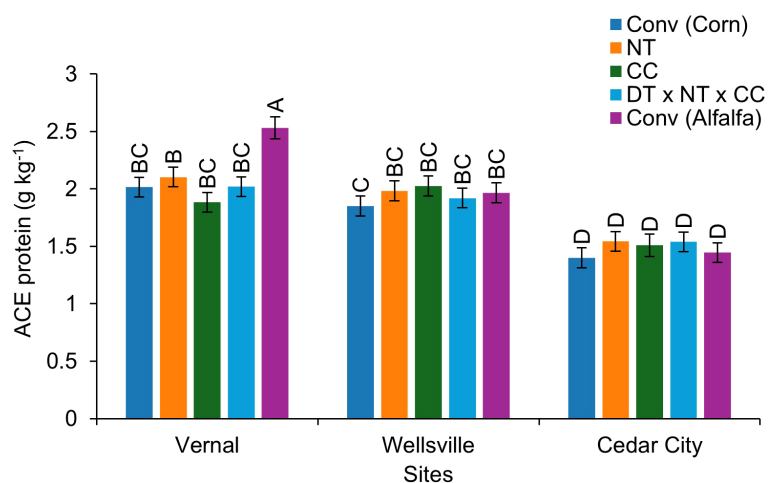


FIGURE 4

Effect of no-till (NT), cover crops (CC), drought-tolerant (DT) genetics, and conventional (Conv) management in corn and conventional alfalfa on ACE protein (g kg^{-1}) during 2024 at Vernal, Wellsville, and Cedar City, UT, USA. Bars represent treatment means ($\pm$ SE), and letters denote significant differences among treatments within each irrigation level according to LSD at $\alpha=0.05$.

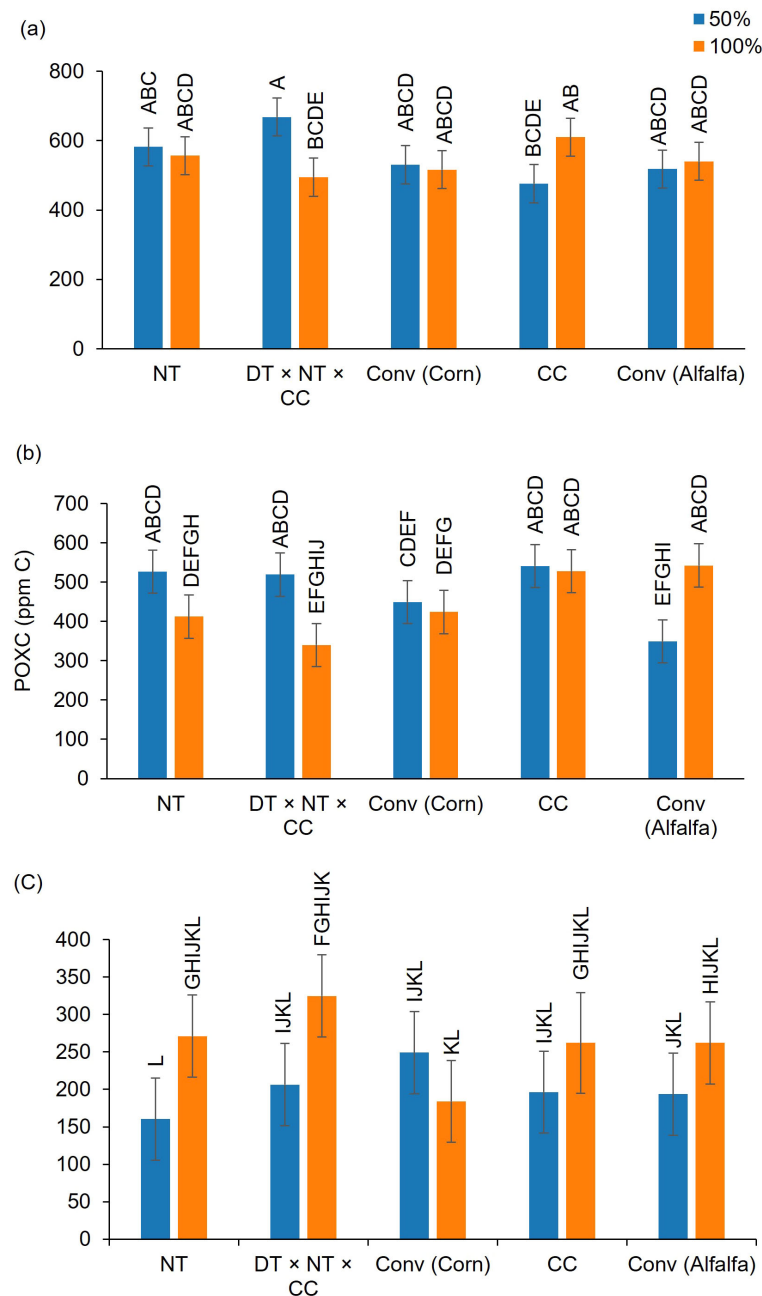


FIGURE 5

Effect of deficit irrigation (DI, 50% estimated evapotranspiration vs. 100%) and crop treatments [no-till (NT), cover crops (CC), and drought-tolerant genetics in corn, and in conventional (Conv) corn and alfalfa] on POX-C (ppm C) during 2024 at Vernal (a), Wellsville (b), and Cedar City (c), UT, USA. Bars represent treatment means ($\pm$ SE), and letters denote significant differences among treatments within each irrigation level according to LSD at $\alpha = 0.05$.

temperatures and lower soil moisture availability in arid environments can accelerate SOM oxidation and reduce long-term carbon storage (39). These results indicate that while DI can alter soil moisture regimes, its influence on SOM may remain limited unless combined with long-term residue inputs and favorable climatic conditions.

4.2 Soil respiration responses to deficit irrigation and management

Soil respiration was strongly influenced by the combined effect of irrigation and management practices, highlighting the sensitivity

of microbial activity to soil moisture conditions. The reduction in soil respiration under DI at Vernal suggests that reduced soil moisture limited microbial metabolism and carbon mineralization. Similar reductions in soil CO₂ efflux under drought or reduced irrigation have been widely reported in semi-arid systems where microbial activity is often constrained by water availability (40). However, soil respiration responses varied among treatments, indicating that management practices can influence microbial processes under different irrigation regimes. Higher respiration observed under NT and combined NT x CC systems reflects increased residue retention, improved soil structure, and enhanced

microbial habitat stability. Reduced soil disturbance in NT systems allows organic residues to accumulate at the surface, providing substrates that stimulate microbial decomposition and carbon cycling (41). In contrast, increases in respiration observed under conventional tillage in some treatments may be associated with soil disturbance that exposes previously protected organic matter to microbial decomposition. These results highlight that soil respiration is regulated by multiple interacting factors, including soil moisture, residue inputs, and soil disturbance. Overall, the significant interaction between site, irrigation, and management practices suggests that microbial responses to DI are highly dependent on environmental conditions and cropping systems. In semi-arid environments, even small changes in soil moisture can substantially influence microbial activity and carbon mineralization.

4.3 Microbial activity responses indicated by the ACE protein

ACE protein concentrations showed strong responses to both cropping systems and site conditions. The highest ACE protein levels were observed under the conventional alfalfa system, suggesting that perennial forage systems provide favorable conditions for microbial activity. Alfalfa contributes substantial root biomass and residue inputs and enhances soil nitrogen availability through biological nitrogen fixation, which can stimulate microbial growth and enzyme production (42, 43). Conservation practices such as NT or combined DT × NT × CC systems also produced relatively high ACE protein concentrations compared with conventional annual cropping systems of corn and small grain forages. Reduced soil disturbance and continuous residue inputs under conservation practices can improve microbial habitat stability and promote microbial biomass development (39). Site-specific climatic conditions also influenced ACE protein responses, as lower ACE protein values observed at Cedar City indicate that microbial activity may be constrained under hotter and drier conditions. Soil microorganisms are highly sensitive to soil moisture and temperature, and high evapotranspiration rates in arid environments can suppress microbial processes regardless of management practices (44). These results suggest that ACE protein was more strongly associated with cropping systems than with irrigation level alone, highlighting the importance of biological inputs and site conditions in regulating microbial functioning.

4.4 Labile carbon dynamics (POXC) under deficit irrigation and management

POXC, a labile fraction of organic soil carbon, did not show significant responses to irrigation or management treatments during the study period. This suggests that changes in irrigation and cropping practices may not immediately influence active carbon pools in semi-arid soils. However, the near-significant irrigation × treatment interaction indicates that labile carbon pools may respond to combined moisture and management effects. Labile carbon fractions are often more sensitive to environmental fluctuations than total SOM because they represent recently added or easily decomposable organic substrates (45). These findings

suggest that labile carbon pools were relatively insensitive to the imposed treatments during the study period, with responses likely governed by the combined influence of management and moisture regime over longer timescales.

4.5 Soil structural stability under deficit irrigation and management

Soil aggregate stability showed limited responses to irrigation and management treatments. Soil aggregation is controlled by multiple interacting factors, such as organic matter inputs, microbial activity, and soil mineral composition (46). In semi-arid environments where organic inputs are relatively low, structural changes may occur slowly and require longer periods of consistent management before measurable improvements become detectable. Although aggregate stability did not improve significantly among conservation management treatments, DI also did not reduce the stability of aggregates, highlighting the null effects of DI on aggregate stability under drought conditions.

4.6 Management effects on field-saturated hydraulic conductivity

Field saturated hydraulic conductivity (K_{fs}) responses to conservation practices were highly site- and season-dependent. Cooler temperatures and higher precipitation at Wellsville and Vernal supported more stable soil biological indicators and infiltration, whereas the hotter and drier environment at Cedar City corresponded with lower microbial activity, reduced active carbon pools, and the lowest infiltration rates across sites. Significant improvements in infiltration were observed only at the Vernal site during fall 2023, where cover cropping increased K_{fs} compared with conventional tillage and NT systems. Cover crops can improve infiltration by creating root-derived macropores, enhancing soil aggregation, and increasing pore connectivity within the soil profile (31). Similar improvements in infiltration under cover crop systems have been reported in other cropping systems where increased macroporosity facilitates water movement through the soil (21). However, treatment differences were not maintained in spring 2024, suggesting that seasonal factors such as residue decomposition, root decay, and antecedent soil moisture conditions influence infiltration dynamics. Variability in infiltration measurements has been documented in studies using double ring infiltrometers, where surface conditions and soil moisture history can strongly affect measured infiltration rates (47). The absence of significant treatment effects at Wellsville and Cedar City further indicates that infiltration responses are strongly influenced by inherent soil properties and climatic conditions. The consistently low K_{fs} values observed at Cedar City likely reflect structural limitations and lower organic matter inputs under arid conditions. In such environments, improvements in soil hydraulic properties may require long-term adoption of conservation practices before measurable changes occur (48). The weak and site-specific K_{fs} response shows that SOM alone is not a reliable predictor of saturated hydraulic conductivity; rather, hydraulic response depends on whether management-induced carbon inputs translate into stable aggregates, biologically

formed macropores, and connected flow pathways under prevailing soil and climate conditions (49). Overall, K_{fs} results showed the temporal and site-specific variability, indicating that hydraulic responses were governed less consistently by management alone and more by the interaction of soil structure, season, and local environmental conditions.

5 Conclusions

This study measured six soil health properties (SOM, ACE protein, soil respiration, POXC, aggregate stability, and field saturated hydraulic conductivity) at three sites in Utah, USA, following three to five years (depending on site) of deficit irrigation and soil and crop management treatments, including drought-tolerant genetics, NT, and cover crops practices. The results highlight that water optimization practices like DI had limited negative impacts on soil health in relatively cooler regions like Wellsville and Vernal, UT, USA, where biological activity and soil organic matter remained relatively stable. In contrast, Cedar City, with its hotter and drier conditions, has greater vulnerability to ACE protein and POXC, which declined under water stress. Among the soil and crop management treatments, NT in corn and small grain forage systems and conventional alfalfa consistently maintained or improved soil health indicators across sites and irrigation levels. The DT×NT×CC annual crop system also showed strong resilience under DI, especially at Vernal and Wellsville. These results suggest that site-specific management of irrigation and soil health is essential. Field saturated hydraulic conductivity responses were highly site-specific. Significant improvements under CC occurred only at Vernal in 2023, whereas other site-years showed numerical but non-significant differences, highlighting the seasonal and climatic variability of infiltration processes. Integrating NT, CC, and perennial forages with site-specific DI strategies offers a promising pathway for sustaining soil function under water-limited conditions.

Data availability statement

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

Author contributions

KD: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Validation. TS: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing, Methodology. MY: Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization. EC: Investigation, Supervision, Validation, Visualization, Writing – review & editing. GC: Investigation, Supervision, Validation,

Visualization, Writing – review & editing. CR: Data curation, Supervision, Validation, 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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