Agriculture, Ecosystems and Environment 347 (2023) 108392

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Changes in soil organic matter after conversion from irrigated to dryland cropping systems

Agustín Núñez [a,b,*], Meagan Schipanski [a]

[a] Department of Soil and Crop Sciences, Colorado State University, 307 University Ave., Fort Collins, CO 80523-1170, USA
[b] Instituto Nacional de Investigación Agropecuaria (INIA), Estación Experimental INIA La Estanzuela, Ruta 50 km 11, Colonia 70000, Uruguay

ARTICLE INFO

Keywords:
Agricultural soils
Conservation Reserve Program
Physical fractionation
Particulate organic matter
Mineral associated organic matter
Soil inorganic carbon

ABSTRACT

Global water resources are under increasing pressure, and some regions face the need to retire irrigation due to groundwater depletion or to meet governmental regulations. In arid and semiarid climates, irrigated lands tend to have more soil organic carbon (SOC) than non-irrigated croplands. However, little is known about how SOC might change following irrigation retirement. Our objective was to quantify changes in SOC and nitrogen stocks after irrigation retirement in semiarid agroecosystems of the High Plains. We sampled fields that stopped using irrigation and transitioned into either dryland crops or ungrazed perennial grasslands and compared SOC and nitrogen stocks in these fields with still irrigated and long-term dryland situations. Currently irrigated fields had more SOC (83.0 vs 73.3 Mg ha^{-1}) and nitrogen (10.2 vs 9.4 Mg ha^{-1}) at 0–80 cm depth than their dryland counterparts, confirming the reported positive impact of irrigation in semiarid agroecosystems. However, there was no legacy effect of irrigation on SOC and nitrogen topsoil stocks 7–10 years after transition to dryland crops as retired fields had lower stocks than still irrigated fields and did not differ from long-term dryland cropping zones of the same fields. This lack of a legacy effect was related to the preferential accumulation, during irrigation, of carbon and nitrogen in the less stable particulate organic matter pool at 0–10 cm soil depth. The transition from irrigated agriculture to perennial grasses resulted in intermediate SOC stocks, that did not differ from the still irrigated nor from the sites retired to dryland crops. Our results suggest that perennial systems are a viable option to mitigate, at least partially, the negative impact of irrigation retirement on SOC. However, the advantage of perennial grasses was explained by the accumulation of carbon and nitrogen in the particulate organic matter fraction, which poses some questions about the stability of SOC in these systems after changes in management.

1. Introduction

In semiarid agroecosystems, water is the main limiting factor for crop productivity (Nielsen et al., 2005; Peterson et al., 1993) and irrigation decreases the yield gap (Van Ittersum et al., 2013), increasing productivity and farmers' income. The higher biomass production under irrigation results in more carbon (C) inputs to the soil, which can increase soil organic carbon (SOC) (Emde et al., 2021; Trost et al., 2013). Due to its positive effect on SOC, irrigation has been proposed as a management practice with potential for SOC sequestration (Pan et al., 2009; Paustian et al., 2016). This is of particular relevance for climate change mitigation, as semiarid lands represent 20% of global terrestrial area (Bot et al., 2000) and have the potential to sequester a significant amount of C (Lal, 2004; Plaza-Bonilla et al., 2015). However, excessive water withdrawals, declining groundwater levels, and increased competition for water resources result in a need to decrease pumping rates for agriculture (FAO, 2011; Whittemore et al., 2016). This will result in an increase of irrigation retirement and the transition to dryland systems in key agricultural areas, especially in Asia and North America where groundwater is overexploited (Davis et al., 2018; Gleeson et al., 2012). Currently, the potential implication of irrigation retirement on SOC, a key soil property involved in most of the ecosystem services provided by soils (Milne et al., 2015), has received minimal attention.

The fate of SOC after irrigation retirement will depend on the relative changes in C inputs and outputs. Because the main effect of irrigation on SOC is due to an increase in C inputs (Denef et al., 2008), a loss of SOC during the transition from irrigated to dryland crops is expected. But, due to higher soil moisture, irrigation may also stimulate microbial

* Correspondence to: INIA La Estanzuela, Ruta 50 km 11, Colonia 70000, Uruguay.
E-mail address: anunez@inia.org.uy (A. Núñez).

https://doi.org/10.1016/j.agee.2023.108392
Received 19 September 2022; Received in revised form 10 January 2023; Accepted 1 February 2023
Available online 9 February 2023

activity, increasing SOC turnover and decomposition rates (Gillabel et al., 2007; Trost et al., 2013; Verma et al., 2005), so irrigation retirement may also decrease C outputs. In addition, residue accumulation and SOC gains during irrigation may have a positive impact on water dynamics (Franzluebbers, 2002; Rawls et al., 2003; Shaver et al., 2013) and on crop productivity and stability (Díaz-Zorita et al., 1999; Pan et al., 2009), especially under drought conditions (Kane et al., 2021). The highest positive yield response to SOC usually occurs when SOC concentration is below 2% (Oldfield et al., 2019), which is the case for many soils in dryland environments (Campbell et al., 2005; Oldfield et al., 2019). If the SOC gained during irrigation increases crop productivity after retirement, and if the decrease in C inputs is accompanied by a decrease in outputs, it may be possible that irrigation has a legacy effect on SOC after the transition to dryland cropping systems.

Alternatively, farmers may decide to transition from irrigated croplands to perennial grasslands or, where available, to enroll in programs that incentivize the retirement of environmentally sensible land from agricultural production. In the U.S., the Conservation Reserve Program (CRP) is an example of this latter option, as it funds the planting of perennial mixtures without grazing (Monger et al., 2018; Stubbs, 2015). There is evidence of an increase in SOC after the transition from non-irrigated croplands to grasslands (Conant et al., 2017) or to CRP (e.g., Baer et al., 2002; McLauchlan et al., 2006). Thus, transition from irrigated croplands to CRP may be a better strategy to maintain SOC than the transition to dryland crops. But the greater perennial grass residue inputs that contribute to this positive effect on SOC relative to dryland crops may not hold true when compared with irrigated croplands, which may have C inputs similar or even higher than native prairies (Denef et al., 2008; Gillabel et al., 2007). Thus, it is not clear if there would be a change in SOC after the transition from irrigation to CRP and the direction of this change. Compared to native vegetation, irrigation usually has a positive but variable effect on SOC (Trost et al., 2013) but, to our knowledge, no direct evaluation of the evolution of SOC after irrigation retirement and the transition to perennial grasslands has been done.

In addition to changes in C inputs and soil moisture, the fate of SOC after irrigation retirement may be influenced by the form in which SOC was accumulated during irrigation and the stability of the different pools. The size separation of soil organic matter (SOM) into particulate and mineral associated fractions allows to differentiate two pools with contrasting stability and response to management (Cambardella and Elliott, 1992). Particulate organic matter (POM) is mainly formed by plant material in various stages of decomposition and persists in the soil due to its inherent chemical recalcitrance or occlusion inside aggregates (Lavallee et al., 2020; Six et al., 2004). These mechanisms only provide transient protection against decomposition, and POM has low mean residence time (years to decades) and responds rapidly to changes in climate, land use, or management (Cambardella and Elliott, 1992; Lavallee et al., 2020; Rocci et al., 2021). On the other hand, mineral associated organic matter (MAOM) is formed by the sorption of plant- and microbial-derived molecules to the soil matrix (Cotrufo and Lavallee, 2022). These organo-mineral associations limit microbial access to SOM and results in MAOM being a more stable pool with higher mean residence time (decades to centuries) (Cotrufo and Lavallee, 2022; Salvo et al., 2014). Thus, fractionation of SOM into these different pools can increase the understanding of the impact of irrigation and its possible legacy effect on SOC.

Our objective was to quantify changes in soil C and nitrogen (N) stocks after irrigation retirement in semiarid agroecosystems of the U.S. High Plains. Irrigation retirement strongly decreases crop productivity, but it may also affect C outputs, and SOC gained during irrigation may have a positive impact on yields. Thus, we hypothesized that the loss of SOC gained during irrigation would not be complete and that there would be a legacy effect of irrigation on SOC. Based on the positive effect of perennial pastures on SOC, we also hypothesized that the transition to ungrazed CRP perennial grasslands would be able to maintain higher levels of SOC than the transition from irrigated to dryland cropping systems. To test these hypotheses, we used a space-for-time substitution to compare C and N stocks in fields with different irrigation history and used SOM fractions to understand the changes in the surface soil layer, where most of these changes are expected. With almost one third of the world's main aquifers under stress (Richey et al., 2015), our results demonstrating the potential fate of SOC after irrigation retirement are relevant to many environmentally sensitive areas of the world.

2. Materials and methods

2.1. Study area and site characteristics

Our study region was the Central High Plains of Colorado, USA. Irrigated systems of this area rely heavily on the Ogallala Aquifer, one of the biggest aquifers in the world where it is estimated that 24% of the currently irrigated area may need to transition to dryland systems by 2100 (Deines et al., 2020). To estimate the impact of irrigation retirement on agricultural systems, we searched for fields that had transitioned from irrigated to dryland systems. We consulted local extension agents and used irrigation maps (Deines et al., 2017) and Google Earth images (Google Earth v 7.1.2.26, Google Inc., Mountain View, CA) to identify candidate fields. We visited the sites and interviewed the farmers to confirm that the candidate fields had been retired for at least five years after long-term irrigation with center pivots. Sandy soils were not included, and we focused on silt loams and silty clay loams soils, representative of most cultivated soils in the region (Hansen et al., 2012). We also confirmed that the fields were managed mainly without tillage and that the transition from irrigated to dryland did not involve significant changes in tillage. Based on this process, we selected six farms for sampling that included five fields retired to dryland cropping systems and three fields retired to perennial grasses under the Conservation Reserve Program (CRP). Whenever available in the same farms, we also sampled long-term, currently irrigated fields (under center pivot irrigation for approx. 30 years) and long-term dryland fields (never irrigated) for comparison purposes (Table 1).

The selected farm sites were in Kit Carson County, eastern Colorado, all within 30 km of Burlington (Fig. 1). The climate of the area is cool semi-arid, with mean annual temperature of 10.9 °C and an annual precipitation of 489 mm (1999–2020 U.S. Climate Normals, National Oceanic and Atmospheric Administration NOAA, 2020). The dominant soils are Aridic Argiustolls, with minor presence of Aridic Ustorthents and Pachic Argiustolls (U.S. Department of Agriculture, N.R.C.S., 2019). In the retired sites, the last irrigation occurred seven to ten years before sampling. The presence of wheat was more frequent in dryland than irrigated rotations (Table 1), coincident with previous reports from the region (Hansen et al., 2012; Rosenzweig and Schipanski, 2019). Also, dryland rotations were longer and some included summer fallows, while irrigated rotations had a higher frequency of corn and did not use summer fallows.

To confirm the expected effect of irrigation on crop productivity, we analyzed normalized difference vegetation index data from satellite images. The analysis indicated that the amount of photosynthetically active radiation absorbed in irrigated systems was two times higher than in long-term drylands (see Supplemental materials for details on the analysis). The transition from irrigated to dryland cropping systems resulted in a significant decrease in the amount of energy absorption and fields that used to be irrigated had similar estimated productivity than long-term dryland fields (Fig. S1). On the other hand, the inclusion of perennial species after irrigation retirement resulted in intermediate productivity, with energy absorption values not different from irrigated or dryland cropping systems.

2.2. Sampling design

We defined three comparisons to estimate the changes in SOM after

Table 1
Characteristics of the 16 fields sampled across six farm sites representing four cropping histories: IRRI: currently irrigated fields; IRRI/DRY: fields that transitioned from irrigated to dryland crops; IRRI/CRP: fields that transitioned from irrigated crops to perennial grasslands without irrigation, DRY: long-term dryland fields. Year of retirement corresponds to the year the IRRI/DRY or IRRI/CRP field was transitioned from center pivot irrigation to dryland. Crop key is C: corn, W: wheat, S: soybean, F: summer fallow, cc: cover crop, CRP: perennial grasses under the Conservation Reserve Program, na: information not available.

		Current rotations per field type					
Farm	Soil Type	IRRI	IRRI/DRY	IRRI/CRP	DRY	Year of retirement	Year of sampling
1	Richfield, Rago Weld. Silty clay loam and silt loam	C-C	W-C-F	CRP	W-C-F	2007	2017
2	Richfield, Rago Weld. Silty clay loam and silt loam		W-C-F			2007	2017
3	Norka, Norka-Colby. Silt loam		W-C-F	CRP		2007	2017
4	Kuma-Keith. Silt loam	C-S-W-cc	W-W-cc-C-C-W		W-W-cc-C-C-W	2008	2017
5	Norka, Kuma-Keith. Silt loam	na	na		na	2012	2019
6	Norka, Weld. Silt loam	C-W		CRP	C-W-F-W	2011	2019

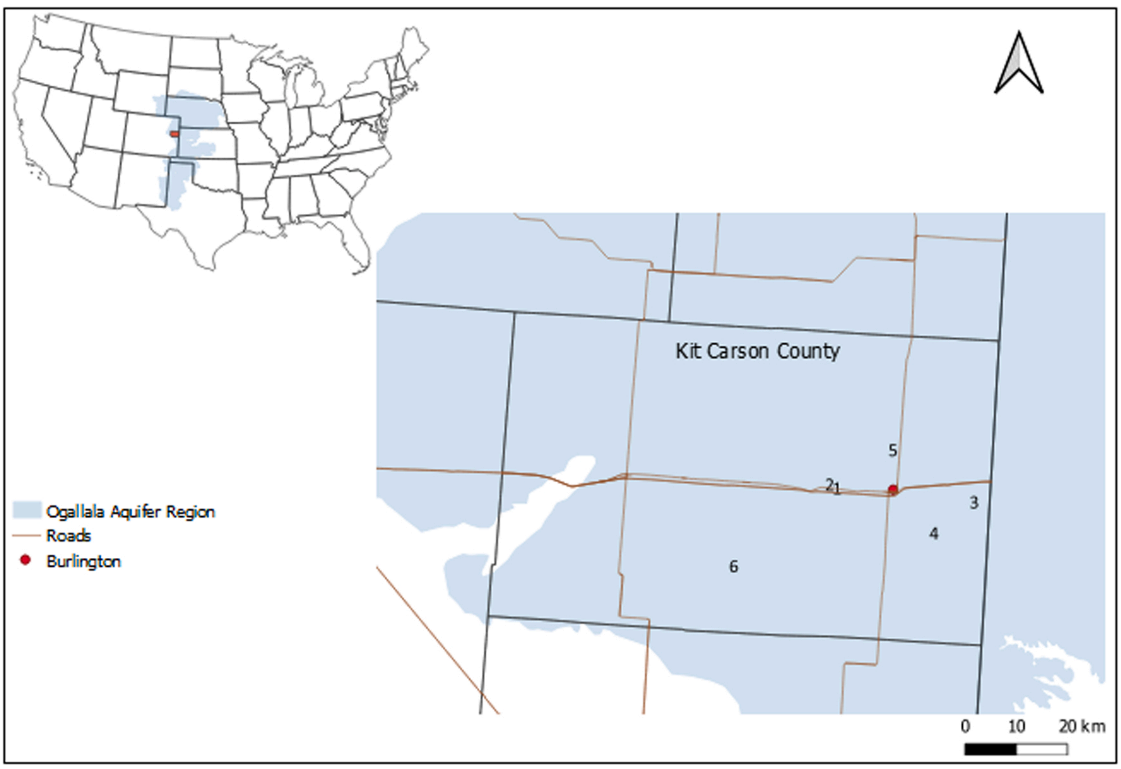

Fig. 1. Location of the sampled farms in the semiarid High Plains near Burlington, Colorado, USA. Multiple fields were sampled on each farm, see Table 1 for a description of each site. Location of the Ogallala Aquifer Region taken from Qi (2010).

the transition from irrigated to dryland systems: (i) currently irrigated fields (IRRI), (ii) formerly irrigated fields retired to dryland cropping systems (IRRI/DRY), and (iii) formerly irrigated fields retired to perennial grasses under the CRP program (IRRI/CRP). We used a paired sampling design and considered the field Corners outside the center pivot as long-term dryland controls of each field. In the case of the IRRI/CRP fields, the Corners represented the transition from dryland crops to perennial grasses, in comparison to the transition from irrigated to CRP that occurred in the Centers of the fields.

We divided each field in quadrants and defined two to four of these quadrants as sampling locations. In each location we sampled two zones, a Center zone inside the pivot as representative of the currently or formerly irrigated area and a Corner zone representative of long-term dryland management. In each zone we took four soil samples with a Giddings probe using a 4-cm diameter core to a depth of 80 cm. Each core was divided by depth (0–10, 10–20, 20–40, 40–60, and 60–80 cm), and the samples of the four cores combined per depth, bagged, and transported to the laboratory.

The selected zones in each field were inside the same soil unit and had similar topography and texture, with differences in surface clay content between Centers and Corners between ± 3%. Thus, we assumed similar soils in both zones and attributed the differences in the evaluated soil properties to management. This paired sampling approach has been useful to estimate the effect of irrigation on soil organic carbon (Denef et al., 2008; Mudge et al., 2017). But, because some fields had a history of flood irrigation and the Corners are a small proportion of the total field area, we wanted to test the validity of our assumption that the Corner zones were representative of long-term dryland management. To confirm that the Corners were representative long-term dryland controls, we also sampled fields under long-term dryland management

(DRY) that had no previous records of irrigation. In these fields we used the same sampling approach already described, but only sampled in the Center zones.

2.3. Soil analyses

Once in the laboratory, we recorded total sample mass and used a 10-g subsample to estimate gravimetric water content after oven-drying it for 48 h at 105 °C. We used the total dry mass and sampling core volume to estimate bulk density. Samples were air-dried, sieved to 8 mm for homogenization, and a subsample was sieved to 2-mm. Approximately 25 g of the 2-mm sieved sample was further ground on a rolling mill. We determined total C and N in the finely ground sample using a LECO Tru-SPEC elemental analyzer (Leco Corp., St. Joseph, MI). We also determined inorganic carbon with a modified pressure-calcimeter method (Sherrod et al., 2002), and calculated soil organic carbon (SOC) as the difference between total C and soil inorganic carbon. Soil texture and nutrient characterization analyses were measured on air-dried, 2-mm sieved soils by Ward Labs (Lincoln, Nebraska, US).

We used a size fractionation approach to understand the effect of irrigation on SOM dynamics (Cambardella and Elliott, 1992; Lavallee et al., 2020). We dispersed the surface soil (0–10 cm depth) by shaking a 10-g sample with 30 ml of 5 g L^{-1} sodium-hexametaphosphate for 18 h. Then, we sieved the samples on a 53 μm sieve to separate the particulate organic matter (POM, fraction bigger than 53 μm) from the mineral associated organic matter (MAOM). The collected slurries were oven-dried, weighed, and ground using mortar and pestle. All fractions were analyzed for SOC and N in the same way as explained above for the bulk samples.

2.4. Data analysis

We estimated carbon and nitrogen stocks on the same equivalent soil mass (ESM) for all the comparisons and considered the average of the IRRI/CRP fields, that had the lowest bulk density values (Table S1), as the reference soil mass. We then applied this reference bulk density values, equivalent to an accumulated soil mass in the profile (0–80 cm) of 10,264 Mg ha^{-1}, and used a cubic spline interpolation procedure (von Haden et al., 2020; Wendt and Hauser, 2013) to quantify the total stocks at each ESM-corrected sampled depth. The cubic spline method is not applicable to single-layer assessments (Wendt and Hauser, 2013). Therefore, to calculate ESM C and N stocks in SOM fractions (measured only at 0–10 cm) we adjusted the thickness of the sampled layer of the agricultural fields by the bulk density of the IRRI/CRP fields (Solomon et al., 2002; Veldkamp, 1994). The ESM corrections allowed a more accurate comparison of element stocks between fields without the confounding effect of differences in the soil mass sampled (Ellert and Bettany, 1995; Wendt and Hauser, 2013), but the main results were very similar when paired comparisons were done with fixed depth calculations or with element concentrations (Table S1).

We used a linear mixed model to estimate the effect of irrigation and irrigation retirement on the analyzed soil variables. Depending on the variable, the interactive effects of field type, zone (Center vs Corner), and depth were considered fixed, and a random term of sampling location nested in field was included to account for the sampling design. We conducted Type III analysis of variance and adjusted pairwise comparisons with Kenward-Roger's method to assess differences between zones within each field and between fields in the same zone. The analysis of zones within fields allowed us to estimate the effect of irrigation, or irrigation retirement, compared to its own long-term dryland reference. The comparisons between fields allowed us to estimate the change after irrigation retirement compared to the currently irrigated condition, the assumed starting point of the retired fields. We used R version 3.6.3 (R Core Team, 2020) with the packages *lme4* (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017), and *emmeans* (Lenth et al., 2018) for all statistical analyses.

3. Results

3.1. Evaluation of field homogeneity and of Corner zones as long-term dryland controls

The use of a space-for-time substitution approach requires a valid reference soil with similar characteristics for comparison. In addition to sampling the same soil type in each paired field, the comparison of soil texture and cation exchange capacity across fields confirmed that soils were similar across all field sites (Table 2). Thus, the observed differences can be attributed to management.

We also defined two references for the retired sites: the initial, long-term irrigated situation and the long-term dryland endpoint. The comparison between long-term dryland fields and the dryland Corners of irrigated or retired fields further supports the use of the field Corners as dryland references in each paired sampling (Table 2). There were some differences in soil bulk density, pH, and nutrient availability between long-term dryland fields and dryland Corners, but the effect was explained by the Corners that transitioned to perennial grasses (CRP) being different from the dryland cropping systems. Moreover, SOC at 0–10 cm in the long-term dryland fields (12.5 ± 0.4 g C kg^{-1}) was the same as observed in the Corners of the irrigated fields (12.5 ± 0.6 g C kg^{-1}). Besides the differences in soil fertility that are more likely to be influenced by management, textural analyses indicated that soils were similar for fields retired to perennial grasses or dryland crops.

3.2. Carbon and nitrogen stocks in currently irrigated fields

In the currently irrigated fields, the irrigated Center zones had more SOC and N than the dryland Corners in the surface layers, with a positive effect of irrigation on SOC at 0–10 and 10–20 cm, and on N content at 0–10 cm ($p < 0.05$, Fig. 2). This resulted in irrigated center pivots having more SOC and N stocks to 80 cm depth than their dryland counterparts (9.7 Mg ha^{-1} more SOC and 0.8 Mg ha^{-1} more N in the Center, Fig. 3). Related to the similar effects on SOC and N, there were no differences in C:N ratios due to irrigation, with average values at 0–10 cm of 9.0 ± 0.1 for irrigated Centers and 8.8 ± 0.1 for dryland Corners. The content of inorganic carbon increased with depth but was not affected by irrigation or by any of the irrigation retirement situations (Table S1).

3.3. Carbon and nitrogen stocks after irrigation retirement

When compared to the long-term dryland reference, the legacy effect of irrigation was largely undetectable 7–10 years after irrigation retirement (Fig. 2 and Fig. 3). In the fields that transitioned from irrigated to dryland cropping systems (IRRI/DRY), SOC stocks did not differ between Center and Corner zones in the surface layer ($p = 0.12$, Fig. 2) or in the profile ($p = 0.50$, Fig. 3), despite the higher concentration of SOC in the Center than in the Corner zone (Table S1). In the retired fields that transitioned to perennial grasses (IRRI/CRP) profile stocks did not differ between previously irrigated Centers and long-term dryland Corners (Fig. 3, $p = 0.12$), but the field Centers had lower SOC and N stocks at 40–60 cm depth than the Corners ($p < 0.01$, Fig. 2).

When compared with the currently irrigated center pivots (Fig. 4), the fields retired to dryland crops had lower SOC stocks at 0–10 cm (14.0 ± 0.1 vs 18.5 ± 0.3 Mg ha^{-1}, $p = 0.03$), while the sites retired to CRP showed intermediate contents (16.0 ± 0.2 Mg ha^{-1}, $p > 0.10$). However, there were no differences in SOC and N stocks between currently irrigated or retired Center fields when comparing stocks for the entire 0–80 cm profile (Fig. 3). In the long-term dryland Corners, the inclusion of perennial grasses increased SOC stocks at 0–80 cm (79.5 Mg ha^{-1} in the CRP corners vs 71.1 Mg ha^{-1} average of all corners with dryland crops, $p = 0.02$ for the contrast between corners under CRP and all corners with annual crops) but did not affect N stocks (Fig. 3).

Table 2
Soil physico-chemical characterization at 0–10 cm of long-term dryland fields and dryland Corners of irrigated and retired fields. DRY: long-term dryland fields, IRRI/DRY: dryland corners used as controls of pivots retired to dryland crops, IRRI/CRP: dryland corners used as controls of pivots retired to perennial grasslands, IRRI: dryland corners used as controls of currently irrigated pivots. Values correspond to mean ± SE, p-values correspond to type III anova with Kenward-Roger's method.

Field	n	Sand %	Silt %	Clay %	CEC $cmol_c\ kg^{-1}$	pH (H_2O)	bd $g\ cm^{-3}$	N-NO_3^- $\mu g\ g^{-1}$	P $\mu g\ g^{-1}$	EC $mS\ cm^{-1}$
DRY	12	36 ± 3	35 ± 3	29 ± 1	18.8 ± 1.3	7.3 ± 0.1 ab	1.27 ± 0.03 a	7.1 ± 2.3 a	53 ± 12 a	0.35 ± 0.02
IRRI/DRY Corner	17	31 ± 2	40 ± 2	29 ± 1	19.6 ± 1.2	7.2 ± 0.1 ab	1.26 ± 0.02 a	12.7 ± 2.3 a	50 ± 3 a	0.37 ± 0.02
IRRI/CRP Corner	11	34 ± 2	38 ± 2	28 ± 1	22.2 ± 1.8	7.6 ± 0.1 a	1.10 ± 0.03 b	1.0 ± 0.1 b	46 ± 9 a	0.29 ± 0.02
IRRI Corner	12	33 ± 2	38 ± 2	29 ± 1	20.0 ± 1.6	7.1 ± 0.2 b	1.23 ± 0.02 a	8.4 ± 1.7 a	68 ± 11 a	0.34 ± 0.02
p-value		0.26	0.11	0.98	0.53	0.01	< 0.01	< 0.01	0.05	0.08

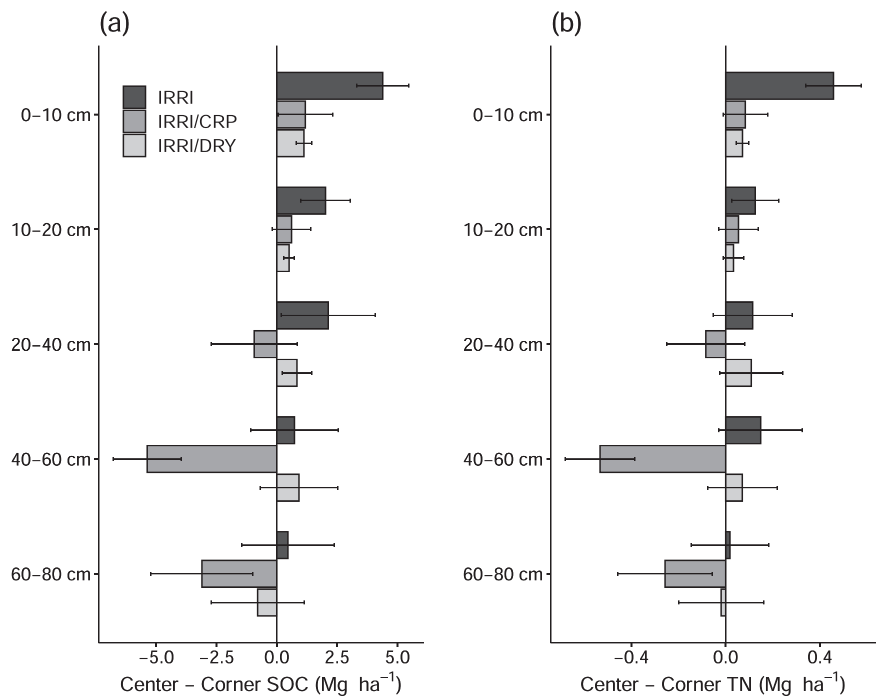

Fig. 2. Difference in soil organic carbon (a) and total nitrogen (b) stocks between paired Centers and Corners of currently irrigated fields (IRRI) and formerly irrigated fields that were retired to perennial grasslands (IRRI/CRP) or to dryland crops (IRRI/DRY) at different sampling depths. Corners are considered long-term dryland controls. Values correspond to mean ± SE.

3.4. Soil organic matter fractions

In the irrigated fields, the center pivots had more carbon and nitrogen contents both in the particulate (POM) and mineral associated (MAOM) organic matter fractions at 0–10 cm than the dryland Corners (Fig. 5), but the relative effect was higher in the POM than in the MAOM. There was almost 1.5 times as much POM-C in the irrigated Center fields than in the dryland Corners (5.4 ± 0.1 vs 3.7 ± 0.1 Mg ha^{-1}, $p < 0.01$), while the difference in MAOM-C was only 17% (11.9 ± 0.1 vs 10.2 ± 0.1 Mg ha^{-1}, $p < 0.01$). The relative proportion of N in each fraction was very similar (58% for POM, 17% for MAOM) between field Centers and Corners, although the C:N ratio of the POM was lower in the irrigated zones (C:N 12.9 ± 0.1 in POM of irrigated Centers vs 14.0 ± 0.2 in POM of dryland Corners, $p = 0.03$). The differential effect in each fraction resulted in a higher proportion of C found in the POM of irrigated Centers than in the POM of dryland Corners (30.2 ± 0.3% vs 26.7 ± 0.4%, $p = 0.05$).

In the fields that transitioned to dryland crops we found no differences between paired formerly irrigated Center and long-term dryland Corner zones in any of the SOM fractions evaluated. Moreover, the formerly irrigated Centers had lower C and N contents than the still irrigated center pivots in all the fractions (Fig. 5, IRRI Center vs IRRI/DRY Center). In the retired fields that transitioned to CRP, there was more POM-C in the Center than in the Corner zones (5.4 ± 0.1 vs 4.6 ± 0.1 Mg ha^{-1}, $p = 0.04$), but neither MAOM-C nor N in any fraction differed between paired zones ($p > 0.15$ in all the cases). Compared to the still irrigated center pivots, the Centers retired to CRP had the same amount of C and N in the POM but tended to have less in the MAOM (11.9 ± 0.1 vs 10.1 ± 0.1 Mg MAOM-C ha^{-1}, $p = 0.08$, and 1.33 ± 0.01 vs 1.14 ± 0.01 Mg MAOM-N ha^{-1}, $p = 0.07$, in IRRI vs IRRI/CRP Centers). In the long-term dryland corners, the inclusion of perennial grasses with CRP increased the POM contents but did not affect the MAOM.

4. Discussion

4.1. Irrigation increases soil organic matter

We found a positive effect of irrigation on SOM, as currently irrigated center pivots had 9.7 Mg ha^{-1} (i.e., 14%) more SOC and 0.8 Mg ha^{-1} (9.5%) more N stocks at 0–80 cm depth than their dryland counterparts. The differences, significant at the whole profile level, were caused by an accumulation of organic matter in the surface soil layers of the irrigated systems. These findings are in close agreement with other studies from the Great Plains and other semiarid agricultural regions of the world, that reported 11–35% more SOC with irrigation (Denef et al., 2008; Lueking and Schepers, 1985; Trost et al., 2013). The positive effect of irrigation in semiarid climates was also confirmed by a recent

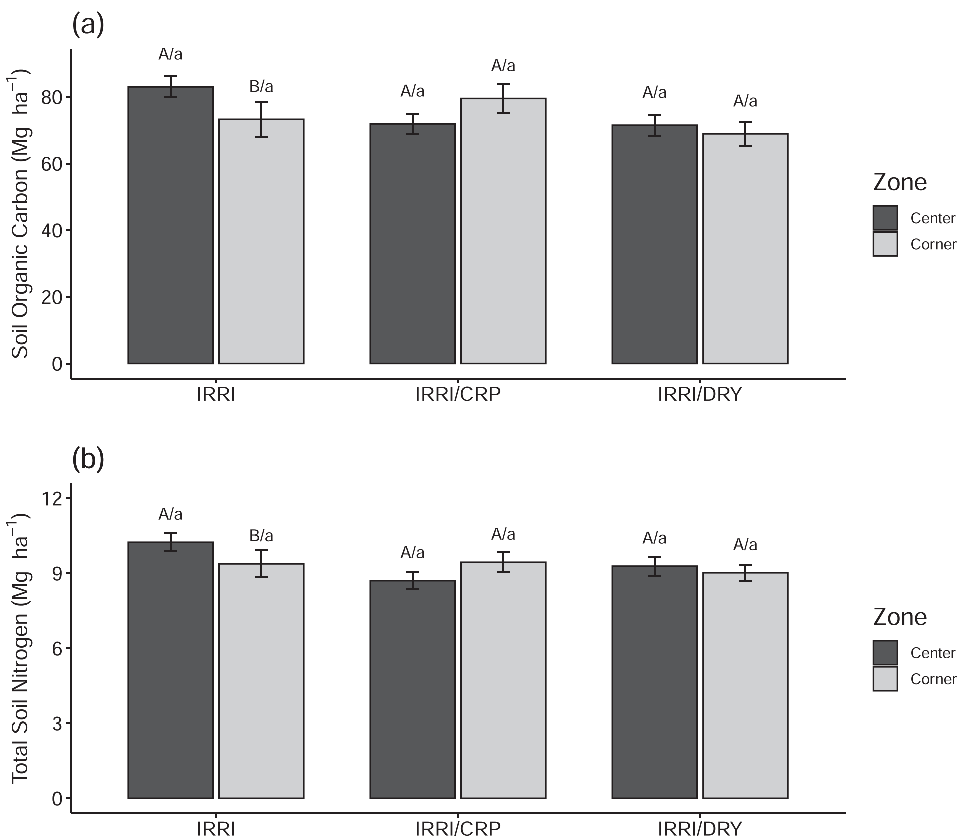

Fig. 3. Soil organic carbon (a) and total nitrogen (b) profile stocks at 0–80 cm depth in paired Center and Corner zones of currently irrigated fields (IRRI) and formerly irrigated fields that were retired to perennial grasslands (IRRI/CRP) or to dryland crops (IRRI/DRY). Corners are considered long-term dryland controls. Values correspond to mean ± SE. Uppercase letters indicate differences between paired zones (Center vs Corner) in the same fields, lowercase letters indicate differences between fields in the same zone ($p \leq 0.05$).

meta-analysis of experiments that followed the evolution of SOC through time and estimated a relative increase of 8% in the profile and of 15% at 0–10 cm depth (Emde et al., 2021). These differences in magnitude may be related to the different experimental approaches (Franca et al., 2016; Yanai et al., 2000), but all agree on the positive effect of irrigation on SOC in semiarid climates and on the stratification of the effect in surface soil layers.

Also in agreement with previous research (Denef et al., 2008; Phillips et al., 2015), soil inorganic carbon increased with depth and was more variable than SOC but it was not affected by irrigation or by the transition into dryland crops or CRP (Table S1). Moreover, the evaluation of total carbon stocks (data not shown) indicated a significant difference due to irrigation in the surface, explained by the effect on SOC, but no differences in total carbon stocks at 0–80 cm, as previously reported by Denef et al. (2008).

The close coincidence between our results and the literature about the effect of irrigation supports the representativeness of the selected sites. The use of a space-for-time substitution allowed us to estimate the effect of irrigation retirement after several years under common commercial management practices, which is usually hard to represent in controlled experiments. However, this approach has some limitations, mainly due to the comparison of different fields instead of directly measuring temporal changes in SOM during the transition from irrigated to dryland in a single field. We tried to minimize these limitations by checking field homogeneity, defining two references for the retired sites (Section 3.1), and by using SOM fractions to explore the possible causes of the changes.

4.2. *Small legacy effect of irrigation on soil organic matter*

Irrigation effects on SOM appear to be short-lived after the transition to dryland crops. The fields that transitioned to dryland crops had significantly less SOC at 0–10 cm than the currently irrigated fields, in close agreement with the observed decline in productivity (Fig. S1) due to the characteristic water limitation for crop production in semiarid climates (Stewart et al., 2006). Despite this expected loss of SOC after irrigation retirement, we hypothesized that SOC would be intermediate in a retired crop field. However, we did not find evidence to support this because there were very few differences between the fields retired to dryland crops and their long-term dryland controls. Moreover, SOC and N stocks were the same in the retired fields than in the long-term dryland corners of the irrigated fields, both in the profile and in the surface layer. Our results suggest that all the SOC and N gained during irrigation is lost approximately a decade after the transition to dryland cropping systems. Thus, any change in SOC turnover or a positive effect of SOC on crop yields were not enough to counterbalance the high impact of water stress on crop productivity and C inputs.

After irrigation retirement, the inclusion of perennial grasses appears as an option to mitigate, at least partially, the negative impacts on primary productivity and SOM. Surface SOC stocks in the sites that transitioned from irrigated agriculture to CRP did not differ from the stocks in the currently irrigated sites, indicating lower SOC losses compared to the transition to dryland crops. However, the sites retired to CRP had intermediate SOC stocks that did not differ from the sites retired to dryland crops either, coincident with the observation of intermediate productivity after irrigation retirement. Therefore, although CRP may be a better option than dryland crops, it may not be enough to retain all the SOC gained with irrigation. But CRP did have a positive effect on SOC stocks in the long-term dryland Corners, which represent almost a quarter of the total area in each field. In conclusion, the transition from irrigated agriculture to perennial grasses partially maintained SOC stocks in the formerly irrigated areas and increased them in the Corner zones, resulting in an overall advantage compared to the transition to dryland crops.

The transition from dryland crops to CRP usually increases SOC (Baer et al., 2002; Li et al., 2017; McLauchlan et al., 2006) and our

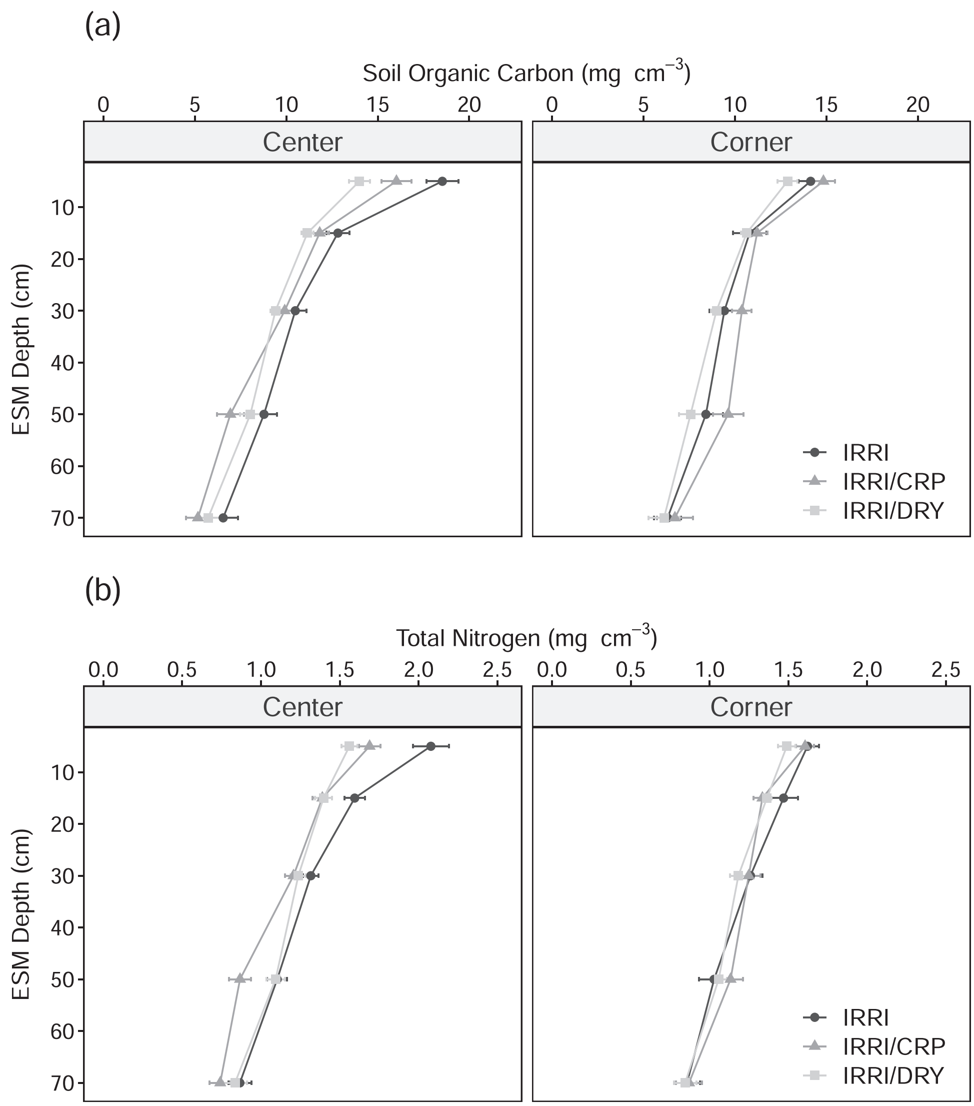

Fig. 4. Soil organic carbon (a) and total nitrogen (b) stock evolution with depth in Centers and Corners of currently irrigated fields (IRRI) and formerly irrigated fields that were retired to perennial grasslands (IRRI/CRP) or to dryland crops (IRRI/DRY). Corners are considered long-term dryland controls. Stocks were corrected to equivalent soil mass (ESM) using the bulk density of IRRI/CRP sites as reference. Values correspond to mean ± SE.

observations in the dryland corners coincide with these reports. However, in the center zones that used to be irrigated, SOC stocks in the sites retired to CRP did not differ from the sites retired to dryland crops. Because not all the area under irrigated agriculture is suitable for dryland cropping (Deines et al., 2020) it may have happened that soil quality in the sites retired to CRP was lower than in the sites retired to dryland crops. There were no differences in soil type or textural analyses between the retired sites that would suggest differences in initial SOC stocks, but the sampling design and low number of sites retired to CRP do not allow us to totally discard the possibility of previous differences between fields. Moreover, accumulation of SOC under CRP may take time (De et al., 2020), and the time needed to recover SOC stock levels similar to natural systems can vary from decades (Baer et al., 2010, 2002; McLauchlan et al., 2006) to centuries (Matamala et al., 2008). After 10 years or less, there were differences in other soil properties already reported to be affected by CRP, such as lower bulk density and nitrate concentrations (Baer et al., 2010; De et al., 2020), which may indicate that the restoration process is still under development. A longer time frame may be necessary to detect the effect of irrigation retirement to CRP and quantify SOC stocks under steady state conditions.

Interestingly, in the sites retired to CRP we found that the long-term dryland Corners, that also transitioned into CRP, had higher SOC and N stocks at depth than the formerly irrigated center pivots (Fig. 2). This difference reflected both a decrease and an accumulation in the Center and Corners of the CRP fields, respectively, as both zones tended to be different than the same zones of other fields at the 40–60 cm depth (Fig. 4). The mechanisms behind the differential effect of CRP due to irrigation history are not clear but may be associated to differences in biomass production. Perennial grasses have higher root production at depth than annual crops (Matamala et al., 2008; Phillips et al., 2015) and differences in soil moisture may affect root production and distribution in the soil profile (Flynn et al., 2021; Zhou et al., 2018). If lower soil moisture in the Corners during CRP installation stimulated root growth at depth, this may have resulted in higher C inputs in the corners than in the center of the fields.

Another plausible, but contrasting, explanation for the differences between zones in the CRP fields is a loss of SOC in the Center due to a positive priming effect. Together with a deeper root system, perennial mixtures produce roots of lower quality (higher C:N ratio, Baer et al., 2010, 2002; Matamala et al., 2008) and CRP sites have more microbial biomass per unit of SOC than croplands even at depth (Li et al., 2017; Matamala et al., 2008). In addition, during transitions to CRP, C stocks recover faster than N stocks (Matamala et al., 2008) and a decline in N availability may occur (Baer et al., 2010; McLauchlan et al., 2006). The

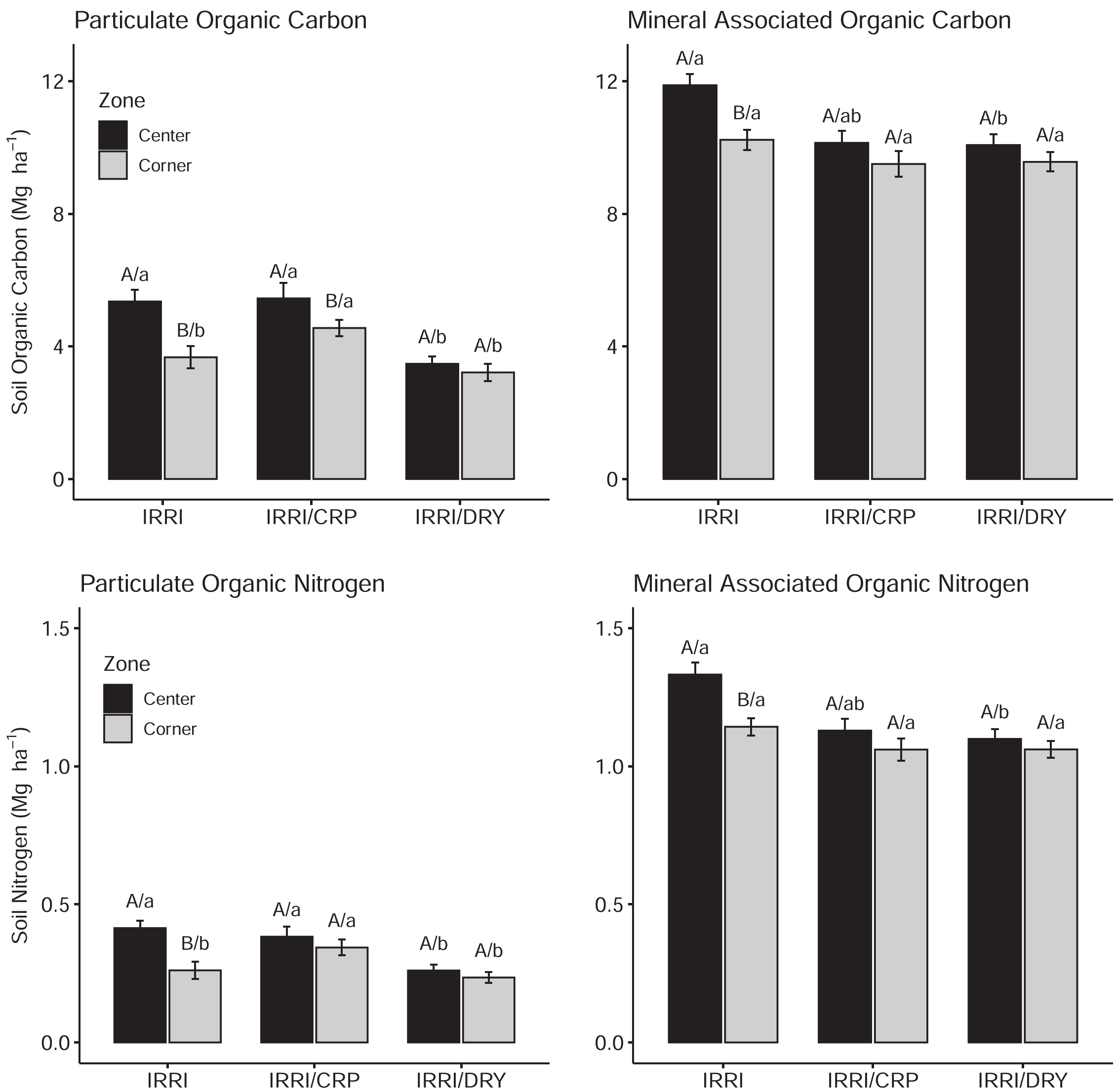

Fig. 5. Soil organic carbon and total nitrogen content in different soil organic matter fractions at 0–10 cm depth of paired Center and Corner zones of currently irrigated fields (IRRI) and formerly irrigated fields that were retired to perennial grasslands (IRRI/CRP) or to dryland crops (IRRI/DRY). Values correspond to mean ± SE. Uppercase letters indicate differences between paired zones of the same fields, lowercase letters indicate differences between fields in the same zone ($p < 0.05$).

CRP sites had very low nitrate concentrations but enough phosphorus availability (Table 2) which further supports the possibility of N limitations. In N-limited systems an increase in soil C inputs may stimulate microbial activity and result in a positive priming effect (Dijkstra et al., 2013; Diochon et al., 2016), increasing the microbial mineralization of deep, old SOC (Fontaine et al., 2007). If the grassland was more productive in the formerly irrigated center pivot than in the long-term dryland corners of the sites retired to CRP, more root growth may have resulted in a priming effect and in a loss of SOC. However, we do not have enough evidence to test these contrasting possibilities, and future studies that quantify root development and the evolution of C inputs and SOC stocks in depth are necessary.

4.3. Use of fractionation to understand changes in SOM dynamics due to irrigation

The analysis of SOM fractions provides more insights into the source of SOC gains and losses. The currently irrigated fields had more C and N in both POM and MAOM than their long-term dryland controls. This effect was bigger in the POM pool, which is mainly formed by plant-derived compounds (Grandy and Neff, 2008; Lavallee et al., 2020), further supporting changes in C inputs as the main driver of SOC responses to irrigation (Denef et al., 2008). The crop rotations in the irrigated fields were dominated by corn and wheat (Table 1). These crops produce low quality residues with a high C:N ratio (Mazzilli et al., 2015; St. Luce et al., 2014) that would contribute proportionally more to POM than to MAOM formation (Cotrufo et al., 2015, 2013). We did find that C:N ratio of the POM pool was lower under irrigation, probably related to differences in fertilization. Optimum N fertilization rates are higher under irrigation (Rudnick et al., 2016) which may increase POM-N (Divito et al., 2011) and decrease the C:N ratio of SOM (Jagadamma et al., 2008).

The high increase in litter inputs due to irrigation had the highest effect on the POM pool, which represented ~30% of total SOM in the irrigated fields. POM is not associated to the primary soil matrix and its persistence is mainly related to the chemical recalcitrance of its compounds (Cotrufo and Lavallee, 2022). Thus, C and N accumulated in the POM fraction can be rapidly lost after a decrease in litter inputs as expected during irrigation retirement. Indeed, we found a decrease in both the absorption of photosynthetically active radiation, an indicator of litter inputs, and POM after a decade of irrigation retirement and the transition to dryland cropping systems, coincident with the reported POM turnover times of years to decades (Lavallee et al., 2020; Salvo et al., 2014). We also found a decrease in MAOM after irrigation retirement, confirming that this pool is also vulnerable, especially in croplands where it represents most of the SOM (Lugato et al., 2021). Nevertheless, the impact of irrigation retirement on POM was much greater than the impact on MAOM, resulting in a higher proportion of SOM in the MAOM pool of dryland systems. The contribution of POM to total SOC of dryland fields (26%) was very similar to previous reports from the region (Cambardella and Elliott, 1992) and did not vary due to past irrigation management, indicating that all POM accumulated during irrigation was rapidly lost.

The transition from irrigated croplands to CRP maintained SOM stocks in the soil surface due to the preferential accumulation of POM. Perennial grasses from the CRP program have been shown to increase the pool of POM (Follett et al., 2015; Hurisso et al., 2014; Li et al., 2017) and our results suggest that they can maintain it at the same levels as irrigated systems due to the mitigation of productivity losses after irrigation retirement. Moreover, the inclusion of perennial grasses in the long-term dryland corners resulted in an increase in POM, coincident with the findings of previous authors. However, after the transition to CRP, POM contents were still higher in the formerly irrigated center pivots than in the dryland corners. Because POM protection against decomposition is low (Lavallee et al., 2020) this difference may be the result of a legacy effect of irrigation on grassland productivity but, as mentioned in the previous section, more evidence is needed to test this possibility.

The results of the fractionation analysis indicate that, although CRP can maintain SOM levels after irrigation retirement while dryland crops cannot, the majority of this effect is due to accumulation of POM. Given the low stability of POM already discussed, questions arise about its persistence in the long-term. This is particularly relevant under a global warming scenario (Rocci et al., 2021) and because it is expected that 30–40% of fields under CRP may eventually transition to dryland croplands (Barnes et al., 2020; Sullins et al., 2021). Our findings help explain and support previous findings that transitioning fields from CRP to dryland crops can rapidly lose the gained SOM (Abraha et al., 2018; Bowman and Anderson, 2002; Phillips et al., 2015). Soil aggregation is a mechanism of POM stabilization (Six et al., 2004) and irrigation can stimulate the accumulation of POM inside microaggregates (Gillabel et al., 2007). However, occlusion in aggregates provides short-term protection to decomposition (Lavallee et al., 2020) and, although we did not measure it, the similar POM content in fields retired to dryland crops compared to long-term dryland Corners suggests that aggregation was not an effective protection mechanism after irrigation retirement.

5. Summary and conclusions

We used a space-for-time substitution to estimate the legacy effect of irrigation on soil carbon and nitrogen stocks in agricultural systems of the Central High Plains. Our results confirmed the reported positive effect of irrigation on SOC and N stocks (Denef et al., 2008; Emde et al., 2021; Trost et al., 2013). However, the legacy effect of irrigation was limited, and after 7–10 years of irrigation retirement we did not find differences between zones that used to be irrigated (Center) and long-term dryland zones (Corner) of the same fields. This lack of a legacy effect after the transition to dryland cropping systems is related to the preferential accumulation, during irrigation, of C and N in the less stable particulate organic matter (POM) pool at 0–10 cm soil depth.

The transition to perennial grasses may provide an option to mitigate, at least partially, the negative impact of irrigation retirement on SOC. Sites retired to CRP had intermediate SOC stocks, that did not differ from the still irrigated nor from the sites retired to dryland crops. In addition, the long-term dryland Corners that went into CRP had higher stocks than the dryland cropping systems, further supporting the positive impact of perennial systems. Wider adoption of grasslands after irrigation retirement will likely require larger incentive payments as current payments are generally less than the net profits from dryland crop production. However, our results also suggest that the advantage of CRP over transitions to dryland crops is explained by the accumulation of C and N in the POM fraction, which poses some questions about the stability of SOM in these systems after changes in management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that support the findings of this study will be openly available following an embargo at the following URL/DOI: http://ogallalawater.colostate.edu/OWCAP/. Data will be available March 2023.

Acknowledgments

We thank Ron Meyer, Kristi Gay, Mike Slack, and Justin Stephen for help with site identification and selection, and Bruce Unruh, Dale Hansen, Jeremy Hansen, Barry Hinkhouse, and Tom May for allowing us to sample in their fields. We also thank Angie Moore, Dylan Casey, Kilian Guignot-Muffet and several Student Research Assistants at the CSU Agroecology lab for help with soil sampling and processing. We are grateful to José Paruelo and Pablo Baldassini for their help with the satellite data analysis. This work was supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2016-68007-25066, “Sustaining agriculture through adaptive management to preserve the Ogallala aquifer under a changing climate.”, and by a Fulbright Scholarship for graduate studies to Agustín Núñez.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108392.

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