DISSERTATION

THE EFFECT OF IRRIGATION AND CROPPING SYSTEMS ON SOIL CARBON AND NITROGEN STOCKS AND ORGANIC MATTER AGGREGATION IN SEMI-ARID LANDS

Submitted by

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ABSTRACT

THE EFFECT OF IRRIGATION AND CROPPING SYSTEMS ON SOIL CARBON AND NITROGEN STOCKS AND ORGANIC MATTER AGGREGATION IN SEMI-ARID LANDS

Demand for water is increasing as a result of population growth, economic activity and agricultural irrigation requirements. Thus, the balance between water demand and supply becomes unstable in countries suffering from water shortage. Therefore, overuse of non-rechargeable groundwater for irrigation in arid regions reduces the availability of water for other users. However, increasing drought periods, shortages of groundwater and urban competition for water have altered irrigated agriculture in Colorado. This may lead to changes in irrigated cropping practices such as alternative water conservation approaches from full irrigation to limited irrigation or dryland cropping systems to alleviate shortage. However, the risk of loss of soil C from dewatered cropland exists, because soil C levels may decline with reduced irrigation due to decreased C input into the soil.

The overall goal of the study is to evaluate the impact of conversion from full irrigation to no-till limited irrigation or dryland cropping systems on soil carbon and nitrogen stocks and organic matter aggregation in semi-arid lands. This goal was achieved in the context of three studies that are included in this dissertation. First, the impact of irrigation and cropping systems management on SOC and TN stocks in a semi-arid environment was evaluated for wheat (Triticum aestivum), corn (Zea mays), and alfalfa (Medicago sativa) managed under various treatments of full irrigation, limited irrigation and dryland cropping systems. Second, the effect of different

cropping systems with various irrigation levels and dryland cropping on soil aggregation and physical SOC stabilization in a semi-arid region was evaluated by measuring the aggregate size distribution, determining the C and N stocks in aggregate fractions and measuring the soil C mineralization rate in different cropping systems with various irrigation levels. Finally, the impact of conversion of irrigated farmland to limited irrigation or dryland cropping systems on SIC content was evaluated over a 3-yr period.

The SOC and TN were analyzed at different depths from 0 to 60 cm depth in 2007 and 2010. Aggregate size distribution, SOC and TN contents for the aggregate size fractions [macro (M) and micro (m) aggregates, and silt & clay fractions] and for the isolated fractions from macroaggregates [coarse particulate organic matter (cPOM), microaggregate into macroaggregate (mM) and Silt&Clay-M)] were measured in soils from full irrigation alfalfa (Full-A), full irrigation corn (Full-C), limited irrigation forage alfalfa (Ltd-fA), limited irrigation forage corn (Ltd-fC), limited irrigation grain wheat (Ltd-gW), limited irrigation grain corn (Ltd-gC), dryland wheat (Dry-W) and dryland corn (Dry-C) treatments. SIC was measured in 2007 and 2010 for all treatments, and in 2013 for limited irrigation grain wheat-corn sorghum cropping system (Ltd-gWCFs). Soil pH was measured for all treatments in 2010 and for Ltd-gWCFs in 2013 in the different depths.

The SOC and TN contents were significantly different among full irrigation and dryland treatments in the 0-20 cm layers of soil, but those differences were not significant below 20 cm depth. However, for all treatment comparisons, the differences remained significant throughout the soil profile in which crops rotated with alfalfa particularly limited irrigation systems (Ltd-fA and Ltd-fC) had higher SOC and TN stock compared with Ltd-gW. Our results showed the SOC and N stocks were significantly related to their concentrations not to bulk density for all depths.

The SOC and TN distribution throughout the soil profile were stratified, and the SOM accumulation under the treatments almost occurred at similar C/N ratios.

The amount of free microaggregates (m) under all treatments ranged from 69.4 to 75.6 % of the soil and the macroaggregates (M) comprised less than 18 % of the soil. The latter was higher under fully irrigated corn (Full-C), limited irrigation forage corn (Ltd-fC) and limited irrigation grain corn (Ltd-gC) compared to dryland corn (Dry-C). The SOC stock in the microaggregates occluded inside macroaggregates (mM) was higher under fully irrigated crops relative to dryland crops, especially in corn treatments. Conversion from full irrigation to dryland induced a reduction in macroaggregates. The Full-C treatment had higher SOC stocks in mM fraction relative to Dry-C. Our study indicates that irrigation and no-till management enhanced aggregate formation and increased C sequestration in mM fractions compared to dryland cropping systems.

The SIC stock was significantly higher under limited irrigation grain wheat (Ltd-gW) treatments compared to full irrigation cropping systems (Full-C and Full-A) and limited irrigation forage cropping systems (Ltd-fC and Ltd-fA). However, there were no significant differences between Ltd-gW and other treatments (Ltd-gC, Dry-C and Dry-W). The Ltd-gW treatment gained more SIC compared to other treatments which accounted 19.4 % of total SIC sequestered under all treatments over the entire profile (0-60 cm) through the period of the study. Our results showed that the most important factor controlling the process of SIC formation in the 0-30 cm depth was soil pH which explains the high variation of SIC among treatments (R^2 = 0.80, P <.01). This may be due to the effect of different cropping systems in which sunflower rotated into wheat-corn grain rotation (Ltd-gWCSf) consumed a greater amount of water than other summer crops and this may be effectively increasing soil pH in those crops rotated with sunflower.

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Thanks to my mother and my family for their support and encouragement, in particular, my wife for her support and patience throughout my program.

DEDICATION

To the souls of my brother and father, to their purified spirit I dedicate this simple work.

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CHAPTER 1. INTRODUCTION

This dissertation examines the potential effect of irrigated cropping systems on soil C contents and soil aggregation compared with dryland cropping systems. Specifically, this study explores the impact of conversion from fully irrigated cropping practices to limited irrigation or dryland cropping systems on soil C contents, and attempts to improve our knowledge of the C dynamics within the profile and how cropping system affects those dynamics under irrigated and water-stressed systems.

1.1 STATEMENT OF THE PROBLEM

Overuse of natural resources is increasing significantly all around the world because of population growth, economic development and demand for agriculture. The increased demand for water is causing an unstable balance between water demand and supply, in particular, in countries suffering from water shortage (Alghariani, 2007). (The CEO water mandate) indicated that the consumption of water worldwide has doubled since 1945 and is expected to increase another 25% by 2030. Thus, pressure on underground water exists especially in arid and semi-arid regions where agricultural production depends on irrigation. Water is the most important factor limiting agricultural production, which is the sector that consumes the most water (Figure 1-1). Therefore, increasing population will increase competition between agriculture and municipal use. Local concerns regarding reduced water availability increase the pressure on non-rechargeable groundwater and could grow to a global scale. Therefore, improving the efficiency of irrigation is an important management priority to conserve groundwater resources and produce food with less water.

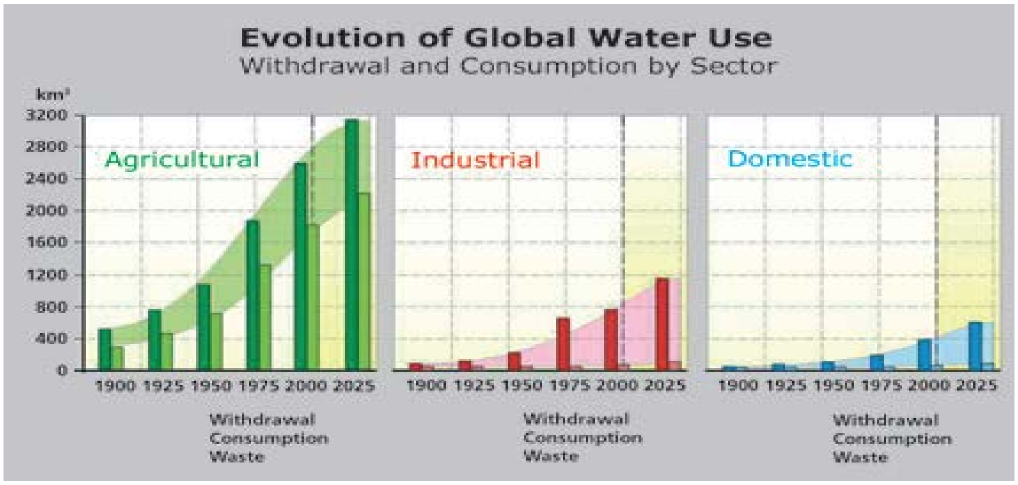

Fig. 1-1. Global water withdrawal and consumption by agricultural, industrial and domestic sectors.
Source: UNEP GRID-A 2002.

Libya is considered to be a country suffering from limited water resource availability because it is an arid country (Abdelrhem et al., 2008). Thus, surface water is not adequate for development and this limitation increases the pressures on underground water resources. Libya is facing increased water requirements from increasing population growth and huge demands from agricultural, domestic and industrial sectors. Algheriani (2007) reported that agriculture consumes the most water, using more than 80% of the total water consumed in Libya. The total demand of water use continues to increase yearly and causes an imbalance between water supply and water demand (water deficits) as indicated by Algheriani (2007). Another study done by Ghurbal and Ashour (2003) indicated that there is a water deficit in Libya, and it will increase as water demand increases up to 4202 Mm^3 by 2025 (Fig. 1-2). Libyan scientists indicate that agricultural water demand may be distorted by low irrigation efficiency in wheat and barley grown in Libya; those crops use much more water than the same crops grown in other countries with a similar climate (7,617 m^3/ha). However, the demand for water is rapidly increasing and the supply is limited; therefore, looking for other water sources is urgent, and water supply management is critically important in Libya (Algphariani, 2007). Increased competition for water has resulted in serious declines in water levels and quality, in particular in the coastal region of Libya (Abufayed and El-Ghuel, 2001) which puts the government in a challenging situation. There were only two options that the government considered to resolve the water shortage issue and meet its water demands: building sea water desalinization plants or transferring the groundwater from the southern region to the northern region (El-Geriani et al., 1989). Desalinization did not appear to be an economically efficient alternative to the groundwater system (El-Geriani et al., 1989). Therefore, the Libyan government decided to build a huge project called the Great Man-Made River Project (GMMRP) to transfer underground water from the Sahara Desert where the water existed under the sand to the coastal region where most people, agriculture, and industrial activities are located. The plan was developed to resolve the critical problems of water shortage, and the agricultural sector will be provided with supplemental irrigation instead of full irrigation.

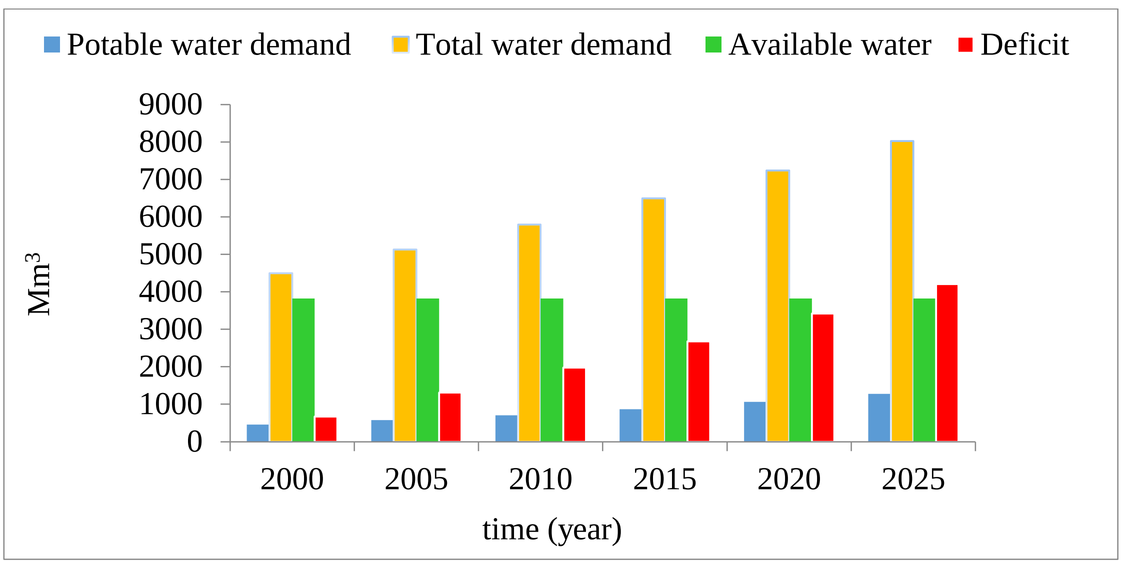

Fig. 1-2. Estimation of water demand and supply in Libya until 2025.
Source: Ghurbal and Ashour (2003).

In the state of Colorado in the USA, population is expected to double by 2050 (CDM, 2010). This will significantly increase additional water needed to meet agricultural, municipal and industrial demands. Agriculture is the largest consumptive user of water, accounting for 85% of the state's water use (CDM, 2007). However, the water shortage for irrigated agriculture in Colorado as a result of drought, groundwater depletion and increased urban competition emphasizes the need for improved water use efficiency (Hansen et al., 2011). Transferring water from the agriculture sector to other uses is an alternative option to meet other demands. Conversion to limited irrigation cropping systems (water conservation) other than dryland cropping systems is more effective because it has less potentially negative economic and environmental impact compared to the dryland option. In addition, limited irrigation cropping systems are an important approach to reducing water consumption which is conducted through supplemental irrigation instead of drying up irrigated land. However, there are concerns about the potential economic and ecological effects of dewatering irrigated farmland. One concern is the potential loss of soil C from de-watered cropland in which soil C levels may decline with reduced irrigation because of decreased biomass production and less biomass returned to the soil.

1.2 OBJECTIVES

This research project evaluated the effects of conversion from full irrigation to limited irrigation or dryland cropping systems. The field experiment and laboratory analyses were used to investigate and elucidate the influence of different irrigation and dryland cropping systems on soil organic and inorganic C storage. Furthermore, we aim to increase understanding and gain knowledge about mechanisms for C stabilization in different soil aggregate fractions under different treatments. The overall objective of this study was to increase knowledge about soil C content in water-conserving dryland systems compared with fully irrigated cropping systems. The specific objectives were to:

1) Evaluate soil organic carbon (SOC) and total nitrogen (TN) concentrations by depth under wheat, corn and alfalfa managed under various treatments of full irrigation, limited irrigation and dryland cropping systems.
2) Determine the vertical distribution of SOC and TN stocks throughout the soil profile (0-60 cm) under irrigated and dryland cropping systems.
3) Measure the aggregate size distribution in soils under various irrigated and dryland cropping systems.
4) Determine the C stocks found in the micro and macro aggregates, silt and clay fractions, cPOM and microaggregates within macroaggregtes, under different cropping systems with various irrigation levels.
5) Measure the soil C mineralization rate in different cropping systems with various irrigation levels.
6) Determine the effect of different irrigated and dryland cropping systems on soil inorganic C (SIC) content in a semi-arid soil at depths of 0-10, 10-20, 20-30, and 30-60 cm over a 3-yr period.

1.3 HYPOTHESES

Irrigation has an important impact on the soil C balance through several mechanisms. Thus, conversion to limited irrigation or dryland cropping systems as alternative water conserving approaches may have a negative impact on soil C content. Therefore, the hypotheses for this study were:

1) The irrigated cropping systems would store more C and N in the soil profile compared to dryland cropping systems due to higher biomass production and that the soil C:N ratio would change with depth.

2) The macro-aggregate proportion will be higher and the free micro-aggregate proportion will be lower under irrigation compared to dryland systems due to high C inputs stimulating macroaggregate formation.

3) SOC content in microaggregates within macroaggregates will be higher for irrigated systems than for dryland systems because they respire less C due to greater physical protection.

4) The SIC content under irrigated cropping systems will be both higher and deeper in the soil profile relative to limited and dryland cropping systems because of carbonate additions in the water and leaching of carbonates deeper into the soil profile.

1.4 DISSERTATION ORGANIZATION

This dissertation consists of three individual studies, each study covers separate objectives, but they all evaluate irrigated and dryland cropping systems. The first study in this dissertation was focused on the effect of irrigation regimes under different cropping systems on SOC and TN stocks in a semi-arid area over a 3-yr period. The results of this study's treatments were statistically compared to ascertain the effects of different irrigated cropping systems on SOC and N content within depth increment. The second study was conducted to evaluate the effect of irrigated and dryland cropping systems on C input and its effect on soil aggregation and physically protected SOC stocks in a semi-arid region. The third study evaluated the effect of conversion of irrigated farmland to limited irrigation or dryland cropping systems on SIC content and its change over the period of study in a semi-arid region.

CHAPTER 2. SOIL ORGANIC CARBON AND NITROGEN STOCKS AS AFFECTED BY IRRIGATION AND DRYLAND CROPPING SYSYEMS IN SEMI-ARID LANDS

2.1 INTRODUCTION

The balance between water demand and supply becomes unstable in countries suffering from water shortage (Alghariani, 2007). Therefore, increasing the use of non-rechargeable groundwater for irrigation in arid regions causes concern. Fallowing of formerly irrigated land is anticipated, and conversion to dryland cropping or limited irrigation is being explored as an alternative water conservation approach (Hansen et al., 2011).

Soils can serve as both a source and a sink for atmospheric CO_2 depending on land use and agricultural management practices (Lal et al., 2004). As a result, land use change and agricultural management practices may affect soil C pools and increase the concentration of greenhouse gases in the atmosphere (Lal et al., 2007).

The effect of irrigation on vertical SOC distribution is unknown. It is known in most cases that SOC concentration appears to be higher in upper layers (0-30 cm) in particular in no-till systems (Blanco-Canqui and Lal, 2008). Storage of SOC in deeper soil horizons is an important portion for long term SOC sequestration (Blanco-Canqui and Lal, 2008), since it is protected and has lower turnover rates (Lorenz and Lal, 2005), related to SOC in the surface layers which is rapidly decayed by microbial activity in the upper layer and high variability in soil temperature and moisture (Blanco-Canqui and Lal, 2008). Therefore, achieving SOC stocks stabilization by improving vertical distribution of SOC is an important strategy. Increasing C input into soil depth where the decomposition rate is slow, selecting cultivars that have higher root to shoot ratios and plants with large amounts of below-ground biomass enriched in biochemical recalcitrant compounds are important strategies to sequestes SOC in subsoil horizons (Lorenz and Lal, 2005).

Irrigation has an important impact on the soil C balance through several mechanisms. It increases crop productivity and plant residue inputs (Denef et al., 2008). High levels of crop residue under irrigated systems may be sufficient to increase SOC storage relative to rainfed systems. However, SOC may decline under irrigation due to direct enhancement of microbial activity that speeds SOM decomposition or indirectly through aggregate disruption or clay dispersion (Shrestha et al., 2004). Many studies have indicated that irrigation had a negative impact on soil physical properties (Shrestha et al., 2004). Other studies have shown that irrigation increased soil CO_2 flux even though it reduced soil temperatures (Wagai et al., 1998). Irrigation decreases soil temperature but increases soil water content, both of which influence CO_2 emissions.

Carbon and N in SOM are bound together, and their accumulations in the soil follow the same mechanism and their sequestration is assumed to be related (Gurmesa et al., 2013). Gärdenäs et al. (2011) stated that N availability is the main factor linked to active C of SOM and it cycling rate because it has a significant effect on decomposition processes. Crop residues with higher C/N ratios play an important role in C storage (Paustian et al., 1997). Recommended management practices enhance C storage by increasing C inputs and decreasing C outputs (Franzluebbers, 2005). Therefore, C and N stocks can be increased through management practices that add high amounts of biomass to the soil.

Previous studies have evaluated the impact of tillage, cropping system and N fertilization on soil C and N stocks. However, little is known about the effect of conversion of irrigated farmland to limited irrigation or dryland cropping systems on soil C and N stocks. Therefore, this study focused on the effect of irrigation regimes under different cropping systems on SOC and N stocks in a semi-arid area over a 3-yr period. Our hypotheses was: the irrigated cropping systems would store more C and N through soil profile zones related to dryland cropping systems due to high biomass produced, and that differences would influence the C:N ratio.

2.2 MATERIALS AND METHODS

2.2.1 Site description

This experiment was located at Colorado State University's Agricultural Research, Development, and Education Center (lat. 40^{o} 39'6" N, long. 104^{o} 59'57" W; 1535 m above sea level), located 8 km north of Fort Collins, CO. The experiment utilizes approximately one hectare under a linear-move sprinkler irrigation system, the soil is a Fort Collins loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalfs), and the climate is semi-arid with average annual precipitation of 26.4 cm and mean annual temperature from 8.4 to 9.1^{o}C. Prior to the experiment, the location had been used for irrigated crop production of wheat, corn, and dry beans using an annual plow-based tillage approach, providing a setting to evaluate the effects of converting irrigated land to limited irrigation or dryland crop production.

2.2.2 Experimental treatments

The experiment was initiated in 2005 with the establishment of four different cropping systems, which included eight treatments (Table 2-1). All of these cropping systems were managed with conservation tillage. The tillage system change was integrated to improve water capture and use in the limited irrigation and dryland systems and also to offset the potential for soil C loss. The irrigated alfalfa system is used as the fully irrigated reference system. The alfalfa stand was maintained for 5 years (2005-2010) and then rotated with the corresponding block of continuous corn. The experimental design was a randomized complete block with four replications. In addition, every phase of each crop rotation was present every year, making for a total of 32 individual plots. The irrigation system allowed for a maximum of one irrigation event per week and was controlled on an individual plot level by manually controlling drop nozzles. The amount of water and N application added to the treatments is presented in Table 2-1.

2.2.3 Soil sampling and analysis

Soil samples were collected at six different depths (0-5, 5-10, 10-15, 15-20, 20-30, and 30-60 cm). Twelve soil cores were taken from each plot at points randomly selected within a design stratified by position and composited by depth within each plot. Soil samples were taken at the end of the third (October 2007) and sixth (October 2010) cropping seasons.

Bulk density (BD) was measured in soil cores taken from each plot after harvest by using a sampling cylinder (5 cm diameter x 5 cm high). Soils were oven dried at 105^{o}C and weighed until a constant mass was achieved.

Total C (SOC+SIC) and TN content were measured using a LECO CHN-1000 elemental analyzer. SIC concentrations were determined by a modified pressure transducer method described by Sherrod et al. (2002). SOC was calculated by difference:

SOC = TC – SIC. [1]

The SOC stocks were calculated using the following equation (Shrestha et al., 2004):

Carbon stock (kg/m^2) = d (m) × BD (kg/m^3) × % SOC [2]

Nitrogen stock (kg/m^2) = d (m) × BD (kg/m^3) × % TN [3]

Where d is soil depth in meters, BD is bulk density in kilogram/cubic meter, SOC is the soil organic carbon (Percentage) and TN is the soil total nitrogen (Percentage).

Above and below-underground biomass for wheat and corn were calculated by using the following equations (Kong et al., 2005):

Winter wheat straw (Mg dry wt.ha^{-1}) = 1.06 x grain dry wt. (Mg dry wt. ha^{-1}) +0.39 [4]

Corn stover (Mg dry wt.ha^{-1}) = 1.06 x grain dry wt. (Mg dry wt. ha^{-1}) +0.50 [5]

Winter roots (Mg dry wt.ha^{-1}) = 0.22x aboveground biomass dry wt. (Mg dry wt. ha^{-1}) [6]

Corn roots (Mg dry wt.ha^{-1}) = 0.23 x aboveground biomass dry wt. (Mg dry wt. ha^{-1}) [7]

Where Mg is mega-gram, wt is weight and ha is hectare.

Below-ground biomass for alfalfa was calculated by using the root to shoot ratio from a previous study (Bolinder et al., 2002). The calculated biomass values are shown in Table 2-2.

2.2.4 Statistical analysis

Analysis of variance was completed using the PROC GLM procedure in SAS 9.1 (SAS Institute, 2009). Treatment means were compared using least significant differences (LSD) with 95% confidence in accordance with a randomized complete block experimental design to ascertain the effects of different irrigated cropping systems on SOC within depth increment, and C and N stocks over the entire sampling depth. Comparison over time was not done because it is only appropriate after all crop rotation sequences have completed one or more full cycles. However, in our study we have a two year rotation (WF), a three year rotation (WCFs), and a four year rotation (CA and AC) and the first time that all of these rotations will complete a full cycle is after 12 years. Therefore, I compared treatments in each year separately.

Estimate statements were used within PROC GLM to generalize effects of individual factors such as crop, irrigation level, or cropping system. Comparisons were: fully irrigated alfalfa- corn (Full-AC) vs. limited forage irrigated alfalfa- corn (Ltd-fAC), dry wheat-corn (Dry-WC) vs. fully irrigated alfalfa- corn (Full-AC), dry wheat-corn (Dry-WC) vs. limited forage irrigated alfalfa-corn (Ltd-fAC), fully irrigated alfalfa- corn (Full-AC) vs. limited grain irrigated wheat- corn (Ltd-gWC), and limited forage irrigated alfalfa- corn (Ltd-fAC) vs. limited grain irrigated wheat- corn (Ltd-gWC).

2.3 RESULTS

2.3.1 SOC and TN Concentrations

In 2007, the SOC and TN concentration in Full-C was higher than in Ltd-gC at the 30-60 cm depth. However, there were no significant differences among corn treatments at other depths (Figure 2-1A; Figure 2-2A). In 2010, the SOC concentration was significantly higher under Full-C and lower under Ltd-gC and Dry-C, in particular, at shallow depth increments (0-5, 5-10 cm), but at 10-15 and 15-20 cm depth increments, the concentrations were greater under Ltd-fC related to Ltd-gC and Dry-C. However, differences among corn treatments diminished by depth and no differences were observed below 20 cm (Figure 2-1B). The TN concentration in 2010 was significantly higher under full-C and Ltd-fC relative to other corn treatments (Ltd-gC and dry-C) in most depth increments (Figure 2-2B).

Treatments did not affect SOC and TN concentration in alfalfa and wheat crops at any depth with exception of the 30-60 depth in 2010 in which Dry-W was higher than Ltd-gW (Figure 2-1C and D, Figure 2-2E and F). For the whole treatment comparisons, in 2007 the Ltd-gW had the lowest concentration at all depths. The Full-A and Ltd-fA treatments had the highest SOC and TN concentrations at 0-30 cm depths. However, the full-C and Ltd-fC had higher SOC and TN concentrations compared to Ltd-gC at 30-60 cm. In 2010, the Ltd-gW treatment had the lowest SOC and TN concentrations at all depths, and the Full-C treatment had the greatest SOC and TN concentration at 0-10 cm. The Ltd-fC treatment had the greatest SOC and TN concentrations at the 10-20 cm depth. However, the Full-A had the highest concentration at 30-60 cm depth. In general, SOC and TN concentrations declined with depth in both years.

The comparison between different cropping systems (estimations) on SOC and TN concentrations were not significantly different at any depth in 2007, but in 2010, the differences in SOC concentrations were significant between Dry-WC vs Full-AC and Dry-WC vs. Ltd-fAC at 0-5 cm ($P = 0.002$ and 0.025), at 5-10 cm ($P = 0.007$, 0.0049) and at 15-20 cm ($P = 0.014$, 0.042). However, The TN was significantly different in the following estimations, Dry-WC vs Full-AC and Dry-WC vs. Ltd-fAC at 5-10 cm ($P = 0.003$ and 0.009) and Dry-WC vs Full-AC at 15-20 cm ($P = 0.014$, 0.04).

2.3.2 SOC and TN Stocks

The effects of treatment on SOC and TN Stocks by depth were inconsistent and varied in both years. In the entire soil profile (0-60 cm depth), all treatments stored an average of 324 Mg SOC ha^{-1} and 38.3 Mg N ha^{-1} in 2007 while the average were 359 Mg SOC ha^{-1} and 42.8 Mg N ha^{-1} in 2010. However, there were differences in SOC and TN stocks among treatments through the whole soil profile within either year (Table 2-3). The SOC and TN stocks were statistically greater under Full-A, Full-C, Ltd-fA and Ltd-fC treatments compared to Ltd-gW and Ltd-gC. However, there were no significant differences among fully irrigated treatment and dryland treatments (Table 2-3). In the 0-30 and 30-60 cm depth, differences among treatments occurred (Table 2-3). In 0-30 cm soil depth the SOC and TN Stocks ranged from 23.4 to 27.7 Mg ha^{-1} for SOC and from 2.81 to 3.37 Mg ha^{-1} for TN under Ltd-gW and Ltd-fC, respectively, in 2007. In 2010 the ranges were from 25.8 Mg ha^{-1} under Ltd-gW to 30.9 Mg ha^{-1} under Ltd-fA for SOC and from 3.16 Mg ha^{-1} under Ltd-gC to 3.72 Mg ha^{-1} under Ltd-fA (Table 2-3). However, both SOC and TN stocks decreased throughout the soil profile in which SOC ranged from 9.21 Mg ha^{-1} under Ltd-gW to 17.7 Mg ha^{-1} under Full-C and the TN was from 1.14 to 2.21 Mg ha^{-1} under Ltd-gW and Full-C, respectively, in 2007. In 2010, the SOC was from 12.8 to 17.7 Mg ha^{-1}, while the TN ranged from 1.34 to 2.30 Mg ha^{-1} under Ltd-gW and Full-C, respectively (Table 2-3).

Among the individual depths (0-10, 10-20 and 20-30 cm), the differences were varied and significant (table 2-4). In 2007, The SOC stocks were significantly higher under the Ltd-fA and Ltd-fC treatments at 0-10 and 20-30 cm depths and the lowest stocks were found under Ltd-gC and Dry-W at 0-10 cm and under Ltd-gW at the 20-30 cm depth. However, there were no significant differences at 10-20cm depth. The TN stocks in 2007 were significantly greater under Ltd-fC compared to Ltd-gC, Ltdg-W and Dry-W at 0-10 cm depth increments. The Full-C and Ltd-fC treatments had the highest TN stock relative to Ltd-gW and Dry-W at 10-20 cm depth increments (Table 2-4). Ltd-fA had significantly greater TN stocks compared to Ltd-gW at 20-30 cm.

In 2010, the SOC stocks were significantly higher under Full-A, Full-C, Ltd-fA and Ltd-fC treatments compared to Ltd-gW, Ltd-gC, Dry-W and Dry-C treatments at 0-10 cm depth (Table 2-4). The Ltd-fC and Full-A had the highest of SOC stock relative to Ltd-gC, Ltd-gW, Dry-w and Dry-C at 10-20 cm depth increment. At 20-30 cm depth increment there were no significant differences among treatments (Table 2-4). The differences in TN stocks were significant higher under Ltd-fA and lower under Ltd-gC treatments at 0-10 cm depth increment (Table 2-4), at 10-20 cm depth increment; the N stocks were higher under full-A, and lower under Ltd-gC (Table 2-4). However, there were no significant differences between all treatments at 20-30 cm depths (Table 2-4). In general, at most depths the Ltd-fA and Ltd-fC had the highest SOC stocks and the Ltd-gW, Ltd-gC, Dry-W and Dry-C had the lowest stocks particularly in 2010.

According to contrast statements there were no significant differences in any comparisons among cropping systems in 2007. In 2010, differences in SOC stocks during statements were significant between Dry-WC vs Full-AC and Dry-WC vs. Ltd-fAC cropping systems at 0-10 cm (P = 0.004 and 0.005), and at 10-20 cm (P = 0.048 and 0.038) respectively. However, the TN stocks were only significantly different between Dry-WC vs Full-AC statement at 10-20 cm where the P= 0.044.

2.3.3 C: N Ratio

In 2007, the C:N ratio was not significantly different among treatments at 0-30 cm depth. However, The Dry-W treatment had the highest ratio and Ltd-fA and Ltd-gC treatments had the lowest at 30-60 cm depth. Over the entire soil profile (0-60 cm) a significant difference was found for Dry-W treatment compared to Ltd-fC treatment (Table 2-3). In 2010, the C:N ratio among treatments was significantly lower under Ltd-fA and Ltd-fC treatments and higher under Ltd-gW, Ltd-gC, Dry-W and Dry-C treatments at the 30-60 cm depth. However, there were no significant differences in either the 0-30 cm or the 0-60 cm depths (Table 2-3).

2.3.4 Soil bulk density

Bulk density varied among treatments throughout the soil profile, ranging from 1.13 to 1.31 g cm^{-3}(Table 2-3). The significant lower density was found under Full-C treatment for all depths and for the entire soil profile (0-60 cm) (Table 2-3). The soil bulk density decreased with increased biomass rates returned to the soil, a significant negative regression relationship was found between the bulk density and biomass input rates (R^2=0.752, P < 0.005).

2.4 DISCUSSION

2.4.1 SOC and TN Concentrations

The concentrations of SOC and TN were significantly higher in fully irrigated and Limited irrigation forage treatments (full-A, full-C, Ltd-fA Ltd-fC) relative to the irrigated grain and dry treatments (Ltd-gW, Ltd-gC, Dry-W and Dry-C) in particular in the shallow depths in either year. The Ltd-gW had the lowest SOC and TN concentrations in most depths even though it had the highest TC concentration (data not shown). The results show that the differences were related to the amount of irrigation only in the 0-10 cm depth increment in 2010 (R^2 = 0.764). These results are in agreement with Blanco-Canqui et al. (2010) who found that that the SOC concentration increased with increased irrigation in the 0-10 cm depth. However, we did not find a relationship between the amount of crop biomass and SOC in either year (R^2 =0.355, p= 0.121 in 2007 and R^2 = 0.406, p = 0.073 in 2010). The accumulation of SOC does not only depend on the amount of plant residue, but there are other dynamic factors controlling the SOC accumulation process such as soil temperature, moisture and microbial activity that affect the dynamics of soil C storage (Blanco-Canqui et al., 2010). For example, rewetting of the soil could have enhanced the decomposition of SOM and reduced gains in residue-derived SOC.

Apparently both irrigation and cropping system had important effects or maybe there were factors other than irrigation and cropping system controlling the process of SOC accumulation. Our results show that SOC and TN concentration were different among cropping systems that have different crop rotations. Thus, these differences may were due to the combined factors (cropping systems) not to individual factors. For example, (Ltd-fC and Ltd-gC) received the same amount of irrigation and N application (Table 2-1) but they had different concentration of SOC in both years.

2.4.2 SOC and TN stocks

There were differences in SOC and TN stocks among fully irrigated and limited irrigation forage crops (full-A, Full-C, Ltd-fA and Ltd-fC) compared to limited irrigation grain crop (Ltd-gW and Ltd-gC) treatments throughout the soil profile. The results show that the differences among fully irrigated and dryland crop treatments were significant in the surface layers (0-20 cm) particularly in 2010, and no differences were observed below this depth. Our results are in accord with Denef et al. (2008) who found that under center pivot irrigation, C storage was higher compared with dryland cultivation, but this is in contradiction with Ricks et al. (2004) who sated that no difference in SOC stock under irrigated conditions was found compared to non-irrigated soils in the Central Great Plains.

The distribution of SOC and TN were stratified throughout the soil profile in which higher stocks were found in the 0-30 cm depths (64% of the total SOC and TN stocks) while these stocks declined with depth to be 36% in the deeper soil layer (30-60 cm). Similar distributions of SOC and TN with depth were reported by Puget and Lal (2005). However, throughout the soil profile (0-60 cm depth), the SOC and TN stocks remained significant different among treatments even decreased reduction of SOC and TN with depth was observed.

Differences in SOC and TN stocks for the entire profile (0-60 cm) were affected by treatments with Full-A, Full-C, Ltd-fA and Ltd-fC significantly higher compared to Ltd-gW and Ltd-gC. This is inconsistent with Blanco-Canqui and Lal (2008) who found that the stocks in the whole profile (0-60 cm) were not significantly different among treatments.

The BD were decreased with increased crop biomass rates ($P = 0.005$). This is in agreement with Blanco-Canqui and Lal (2007). However, the results showed that the difference in SOC and TN stocks was not related to BD but were influenced primarily by the SOC and TN concentrations ($P < 0.0001$). Denef et al. (2013) stated that the lower stocks of SOC and TN in cropland were not a result of differences in BD but because of low SOC and TN concentrations. The correlation between SOC and TN stocks under treatments were significant for the entire profile in both years ($R^2 = 0.98$, $P < 0.0001$ for 2007 and $R^2 = 0.99$, $P < 0.0001$ for 2010). We found that the C/N ratio throughout the soil profile was not significantly different. In addition, the differences in SOC and TN stocks under cropping systems rotated with alfalfa particularly under limited irrigation systems were significant higher than cropping systems rotated with sunflower but those variations were not larger. This may be due to lower amounts of biomass returned to the soil because of the removal of alfalfa hay which, in turn, reduced the input of C and N. Bell et al. (2012) found that alfalfa-crop rotation had less C sequestration compared to annual crops.

2.5 CONCLUSIONS

Different levels of SOC and TN were found among treatments throughout the soil profile in which fully irrigated and limited irrigation forage cropping systems had higher SOC and TN concentrations compared to the limited irrigation grain cropping systems in both years. The difference of SOC concentration between full irrigation and dryland cultivation was observed in the 0-20 cm depths. However, this variation diminished by depth, no significant differences was observed below that depth. With the exception of corn, the potential loss of SOC due to conversion of fully irrigated cropland to limited irrigation or dryland, was not observed during the study period especially when the conversion includes the use of conservation tillage. The results observed that differences in SOC and TN stocks among treatments were related to SOC and TN concentrations and not influenced by differences in BD. Distribution of SOC and TN were stratified with depth (64% of the total stocks under all treatments were found in the 0-30 cm depth compared to 30-60 cm depth with 36%). The differences in SOC and TN under cropping systems rotated with alfalfa were not higher as expected compared to other crop rotations; suggesting that removal of alfalfa hay decreased the C and N input or may be due to the short period of the experiment.

Consistent with our hypothesis, significant effects were observed in SOC and TN storage under fully irrigated corn compared to the dryland corn in the surface layer (0-20 cm) particularly in 2010. But the C:N ratio did not change throughout the soil profile, on average. For the 0-30 cm, treatments had no effect on C/N ratio, but from 30-60 cm, the Ltd-gWC and Dry-WC had higher C/N ratio.

Table 2-1. Irrigation, N application for 2007, 2008, 2009, 2010 and average of irrigation and average of N application from 2007-2010, for different cropping systems and treatments in a semi-arid climate.

Cropping Systems	Treatments	Irrigation					N fertilizer				
		2007	2008	2009	2010	Average	2007	2008	2009	2010	Average
		---------------------cm --------------------					----------------kg ha^{-1} ------------------				
Full AC	Full-A	35.6	40.6	29.2	38.9	36.1	0	0	0	0	0
	Full-C	34.3	40.6	34.3	40.0	37.3	157	157	168	168	163
Ltd f AC	Ltd-fA	22.4	20.3	1.30	38.9	20.7	0	0	0	0	0
	Ltd-fC	19.8	20.3	24.1	21.0	21.3	67.0	67.0	168	168	118
Ltd g WC	Ltd-gW	12.7	22.9	3.80	5.10	11.1	0	123	101	101	81.3
	Ltd-gC	19.8	20.3	24.1	21.0	21.3	67.0	112	168	168	129
Dry WF/WC	Dry-W	0	3.80	0	3.80	1.90	45.0	67.0	67.0	67.0	61.5
	Dry-F/C	†	3.81	1.27	0	1.69	†	168	168	168	168

† In 2007 the cropping system was wheat-fallow, but from 2008-2010 the cropping system was changed to wheat-dryland corn. Cropping systems are fully irrigated alfalfa-corn (Full AC), limited irrigation forage alfalfa-corn (Ltd f AC), limited irrigation wheat-corn (Ltd g WC), and dryland wheat-corn (Dry WF/WC). Treatments: fully irrigated-alfalfa (Full A), fully irrigated-corn (Full C), limited irrigation alfalfa (Ltd A), limited irrigation forage corn (Ltd f C), limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), and fallow or corn (Dry F/C).

Table 2-2. Aboveground biomass return to soil, belowground biomass by year and total biomass added to the soil throughout the years for different cropping systems and treatments in a semi-arid climate.

Cropping Systems	Treatments	Above biomass return to soil				Below biomass				Total Biomass added to soil
		2007	2008	2009	2010	2007	2008	2009	2010	2007-2010
		……………………………………………… Mg ha^{-1} ……………………………………………								
Full AC	Full-A	†††	†††	†††	†††	6.55	6.55	9.65	4.48	27.2
	Full-C	13.3	12.4	15.4	14	3.05	2.84	3.54	3.22	67.8
Ltd f AC	Ltd-fA	†††	†††	†††	†††	6.03	3.62	6.03	4.48	20.2
	Ltd-fC	9.65	11.9	13.2	11.5	2.22	2.73	3.04	2.65	56.9
Ltd g WC	Ltd-gW	2.51	††	4.82	4.01	0.553	††	1.06	0.882	13.8
	Ltd-gC	7.25	14.1	13.7	10.9	1.67	3.25	3.13	2.52	56.5
Dry WF/WC	Dry-W	1.72	2.06	3.69	3.35	0.378	0.454	0.811	0.737	13.2
	Dry-F/C	†	3.92	4.79	3.23	†	0.902	1.1	0.742	14.7

† In 2007 the cropping system was wheat-fallow, but from 2008-2010 the cropping system was changed to wheat-dryland corn.
†† In 2008 there were on biomass calculations for grain wheat because the crop was damaged by hail.
†† † No aboveground biomass returned to soil was calculated because the harvested alfalfa was taken out of the plots; only belowground biomass was calculated for alfalfa. Cropping systems are fully irrigated alfalfa-corn (Full AC), limited irrigation forage alfalfa-corn (Ltd f AC), limited irrigation wheat-corn (Ltd g WC), and dryland wheat-corn (Dry WF/WC). Treatments: fully irrigated-alfalfa (Full A), fully irrigated-corn (Full C), limited irrigation alfalfa (Ltd A), limited irrigation forage corn (Ltd f C), limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), and fallow or corn (Dry F/C).

Table 2-3. Bulk density, SOC, TN stocks and C/N ratio (0-30, 30-60, and 0-60 cm) under different cropping systems in a semi-arid region during a three-year period (2007-2010).

Depth	Cropping System	Treatments	Bulk density	SOC Stocks		N Stocks		C/N ratio	
				2007	2010	2007	2010	2007	2010
			g/cm^3	-------------------------Mg ha^{-1}		-----------------			
0-30 cm	Full AC	Full-A	1.20ab	26.0ab	30.38ab	3.07ab	3.62ab	8.80a	8.41a
		Full-C	1.14b	27.0ab	29.38ab	3.25a	3.55abc	8.54a	8.29a
	Ltd f AC	Ltd-fA	1.25a	27.3a	30.85a	3.25a	3.72a	8.72a	8.31a
		Ltd-fC	1.19ab	27.7a	30.75a	3.37a	3.61ab	8.27a	8.53a
	Ltd g WC	Ltd-gW	1.24a	23.4b	25.75b	2.81b	3.28bc	8.32a	7.90a
		Ltd-gC	1.15b	24.3ab	27.25ab	2.84b	3.16c	8.58a	8.63a
	Dry †WF/WC	Dry-W	1.21a	24.8ab	27.58ab	2.82b	3.4abc	8.99a	8.13a
		Dry-†F/C	1.23a	25.4ab	28.73ab	2.87b	3.44abc	9.04a	8.32a
30-60 cm	Full AC	Full-A	1.20ab	17.5a	17.4a	2.19a	2.20a	7.99ab	7.91ab
		Full-C	1.15b	17.7a	17.7a	2.21a	2.30a	8.01ab	7.70ab
	Ltd f AC	Ltd-fA	1.24ab	17.2a	15.9ab	2.18a	2.23a	7.89b	7.13b
		Ltd-fC	1.21ab	13.2ab	14.9ab	1.64ab	2.10ab	8.05ab	7.10b
	Ltd g WC	Ltd-gW	1.22ab	9.21b	12.8b	1.14b	1.34b	8.08ab	9.55a
		Ltd-gC	1.23ab	10.4b	15.8ab	1.32b	1.63b	7.88b	9.69a
	Dry †WF/WC	Dry-W	1.25ab	15.9ab	15.9ab	1.72ab	1.62b	9.24a	9.81a
		Dry-†F/C	1.31ab	16.5a	17.5ab	1.75ab	1.84ab	9.43a	9.51a
0-60 cm	Full AC	Full-A	1.20bc	43.5a	47.8a	5.26a	5.82a	8.27ab	8.21a
		Full-C	1.15b	44.7a	47.1a	5.34a	5.65a	8.19ab	7.05a
	Ltd f AC	Ltd-fA	1.24a	44.5a	46.8a	5.43a	5.95a	8.20ab	7.86a
		Ltd-fC	1.20ab	40.9a	45.7a	5.01a	5.71a	8.16b	7.99a
	Ltd g WC	Ltd-gW	1.23a	32.6b	38.6b	3.95b	4.62b	8.26ab	8.34a
		Ltd-gC	1.18ab	34.7b	43.1ab	4.12b	4.79b	8.42ab	8.99a
	Dry †WF/WC	Dry-W	1.23a	40.7a	43.5ab	4.54ab	5.02ab	8.96a	8.66a
		Dry-†F/C	1.27a	41.9a	46.2a	4.62ab	5.28ab	9.06a	8.76a

†In 2007 the cropping system was wheat-fallow, but from 2008-2010 the cropping system was changed to wheat-dryland corn. ropping systems: fully irrigated alfalfa-corn (Full AC), limited irrigation forage alfalfa-corn (Ltd f AC), limited irrigation grain wheat-corn (Ltd g WC), and dryland wheat-corn (Dry WC). Treatments: fully irrigated alfalfa (Full A), fully irrigated-corn (Full C), limited irrigation forage alfalfa (Ltd f A), limited irrigation forage corn (Ltd f C) limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), dryland fallow or corn (Dry F/C). Values followed by a common letter within a column are not significantly different ($p < 0.05$) between treatments based on Least Significant Differences.

Table 2-4. SOC and N stocks (0-10, 10-20 and 20-30 cm) under different cropping systems in a semi-arid region during a three-year period (2007-2010).

Depth	Cropping System	Treatments	SOC Stocks		N Stocks	
			2007	2010	2007	2010
			------------------ Mg ha $^{-1}$			------------------
0-10 cm	Full AC	Full-A	9.64ab	12.15a	1.12ab	1.35a
		Full-C	9.69ab	11.28a	1.10ab	1.32a
	Ltd f AC	Ltd-fA	9.99a	11.80a	1.09ab	1.38a
		Ltd-fC	9.90a	11.43a	1.20a	1.28ab
	Ltd g WC	Ltd-gW	8.74b	9.33b	1.01b	1.16b
		Ltd-gC	8.33b	9.83b	0.94b	1.13b
	Dry †WF/WC	Dry-W	8.34b	10.03b	0.94b	1.19b
		Dry-†F/C	9.16ab	9.53b	0.98b	1.20b
10-20 cm	Full AC	Full-A	8.63a	9.93a	1.02ab	1.23a
		Full-C	9.11a	9.65ab	1.13a	1.13ab
	Ltd f AC	Ltd-fA	9.09a	9.48ab	1.08ab	1.17ab
		Ltd-fC	9.04a	10.13a	1.13a	1.21ab
	Ltd g WC	Ltd-gW	8.21a	8.40b	0.95b	1.07b
		Ltd-gC	8.25a	8.35b	0.99ab	1.01b
	Dry †WF/WC	Dry-W	8.47a	8.80b	0.96b	1.12ab
		Dry-†F/C	8.76a	8.93b	1.01ab	1.12ab
20-30 cm	Full AC	Full-A	7.75ab	8.38a	0.92ab	1.04a
		Full-C	8.26a	8.48a	1.02ab	1.09a
	Ltd f AC	Ltd-fA	8.62a	9.60a	1.08a	1.18a
		Ltd-fC	8.34a	9.18a	1.04ab	1.12a
	Ltd g WC	Ltd-gW	6.47b	8.08a	0.84b	1.05a
		Ltd-gC	7.68ab	9.08a	0.92ab	1.02a
	Dry †WF/WC	Dry-W	7.98ab	8.78a	0.92ab	1.06a
		Dry-†F/C	7.47ab	10.25a	0.87ab	1.17a

† In 2007 the cropping system was wheat-fallow, but from 2008-2010 the cropping system was changed to wheat-dryland corn.
Cropping systems: fully irrigated alfalfa-corn (Full AC), limited irrigation forage alfalfa-corn (Ltd f AC), limited irrigation grain wheat-corn (Ltd g WC), and dryland wheat-corn (Dry WC). Treatments: fully irrigated alfalfa (Full A), fully irrigated-corn (Full C), limited irrigation forage alfalfa (Ltd f A), limited irrigation forage corn (Ltd f C) limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), dryland fallow or corn (Dry F/C). Values followed by a common letter within a column are not significantly different ($p < 0.05$) between treatments based on Least Significant Differences.

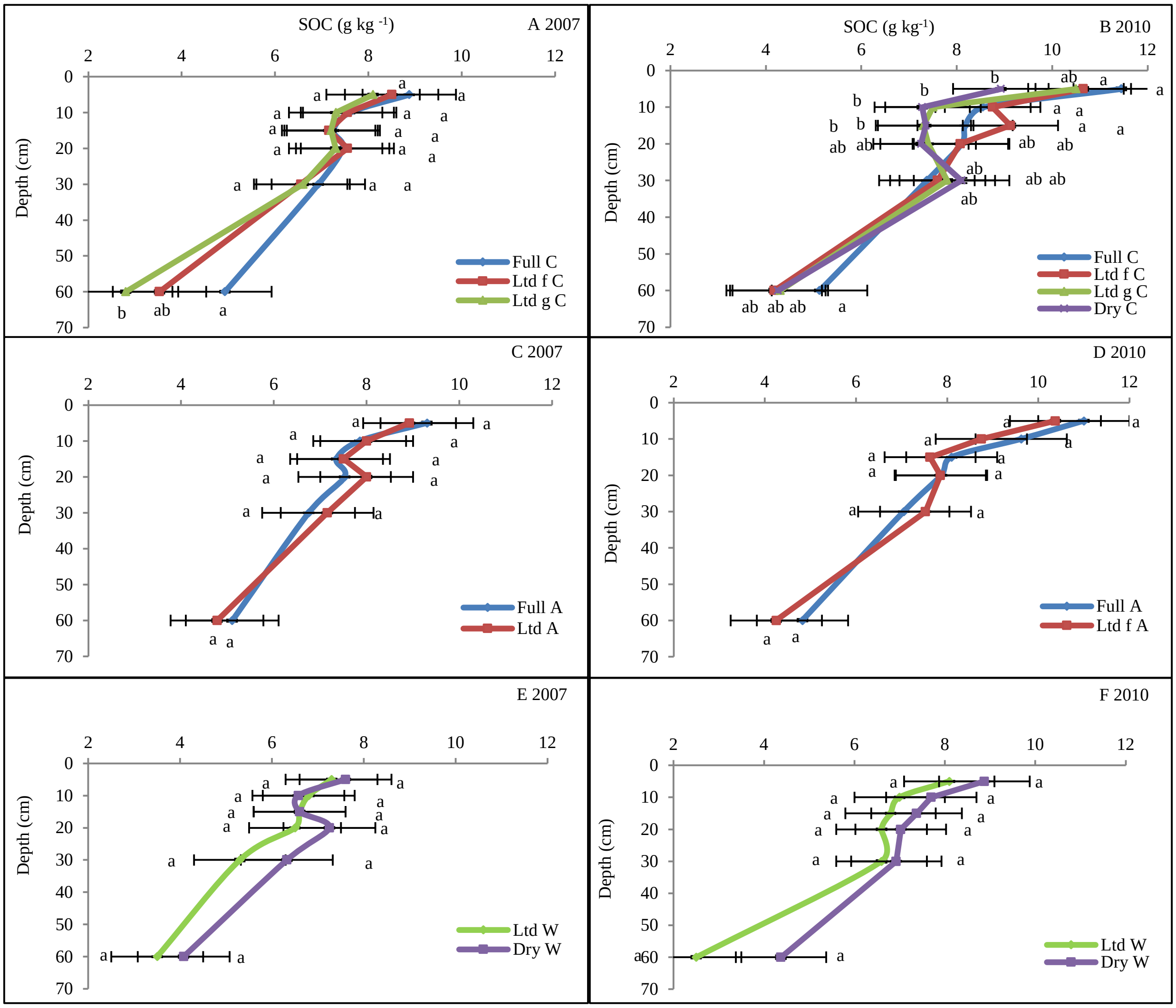

Fig.2-1. Concentration of SOC in the soil, in 2007 (A, C and E) and 2010 (B, D and F) for corn, alfalfa and wheat at six soil depths for different cropping systems in a semi-arid climate. Treatments: fully irrigated corn (Full C), Limited irrigation forage corn (Ltd f C), limited irrigation grain corn (Ltd g C), dry corn (Dry corn), full irrigation alfalfa (Full A), Limited irrigation alfalfa (Ltd A), limited irrigation wheat (Ltd W), and Dry wheat (Dry W). Values followed by different letters are significantly different at ($p < 0.05$) between management.

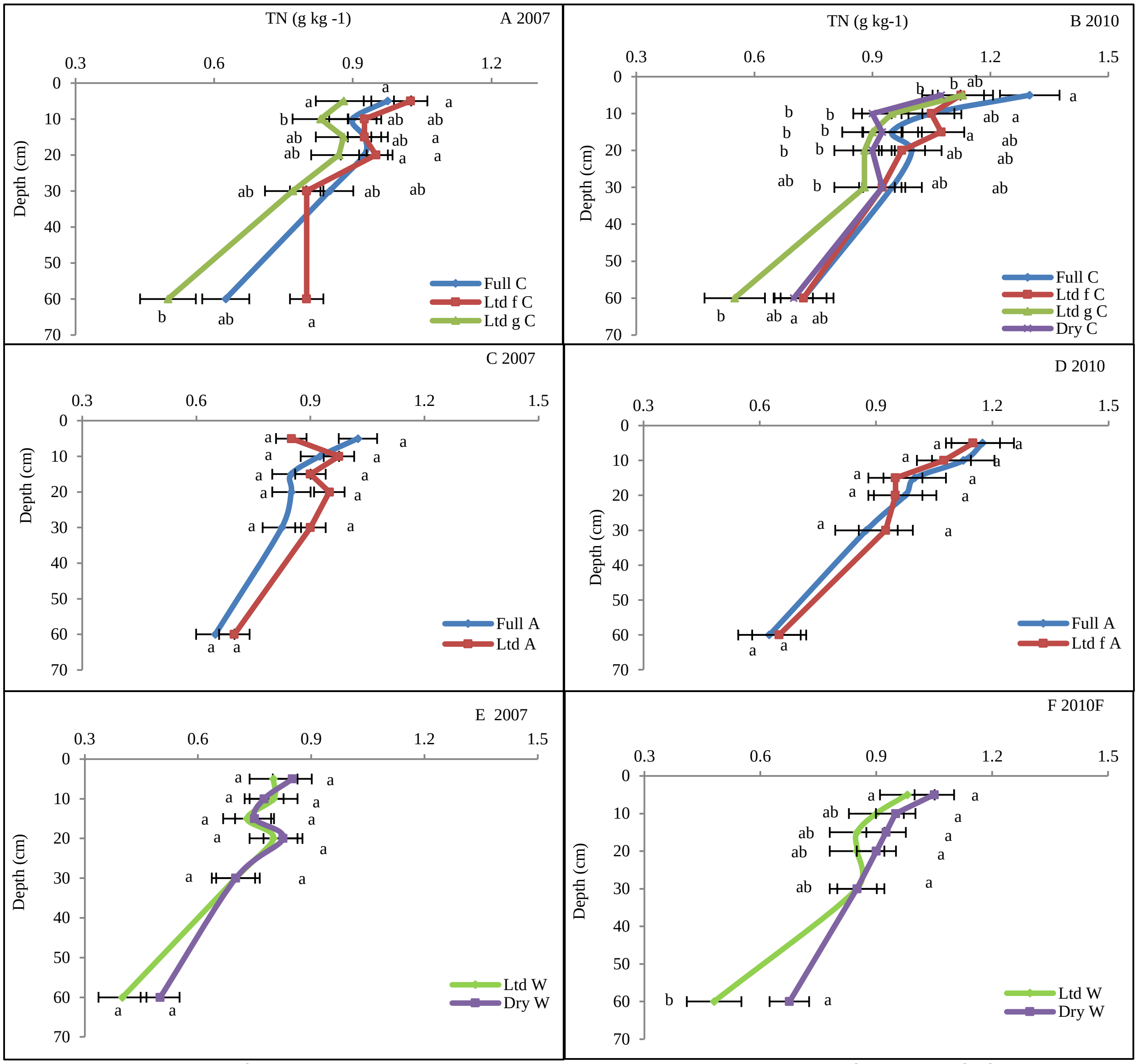

Fig.2-2. Concentration of TN in the soil, in 2007 (A, C and E) and 2010 (B, D and F) for corn, alfalfa and wheat at six soil depths for different cropping systems in a semi-arid climate. Treatments: fully irrigated corn (Full C), Limited irrigation forage corn (Ltd f C), limited irrigation grain corn (Ltd g C), dry corn (Dry corn), full irrigation alfalfa (Full A), Limited irrigation alfalfa (Ltd A), limited irrigation wheat (Ltd W), and Dry wheat (Dry W). Values followed by different letters are significantly different at ($p <0.05$) between management

CHAPTER 3. CARBON SEQUESTRATION IN SOIL AGGREGATES UNDER IRRIGATED AND DRYLAND CROPPING SYSTEMS IN A SEMI-ARID AREA

3.1 INTRODUCTION

Competition for limited water supplies has the potential to alter irrigated cropping systems as water transfers from agriculture to municipalities occur (Hansen et al., 2011). This leads to changes in irrigated cropping practices due to conversion to limited irrigation or dryland cropping systems as alternative water conserving approaches (CDM and GBSM, 2004; Hansen et al., 2011). However, the risk of loss of soil C from dewatered irrigated cropland exists (Hansen et al., 2011) since soil C levels may decline with reduced irrigation because of decreased C input to the soil (Hansen et al., 2011).

Soil organic matter (SOM) is an important component of soil quality (Ashagrie et al., 2007), due to its effect on C and nutrient storage (Hassink et al., 1997). SOM has multiple effects on soil physical, chemical and biological properties such as aggregation, plant water holding capacity, soil quality (Lal and Bruce, 1999), fertility (Pikul et al., 2009), and activity and species diversity of soil fauna (Lal, 2004a). Thus, increasing soil C storage is important for sustained agricultural production (Denef et al., 2001). Furthermore, SOM can act as a sink for atmospheric CO_2 when using recommended management practices (Lal, 2004a). Conversely decreased SOM stock leads to a decline in soil fertility, degraded soil quality, reduced biomass productivity and increased potential greenhouse gas emissions to the atmosphere (Lal, 2004a).

Increasing C input is an important strategy to enhance soil organic C (SOC) sequestration, but increasing the residence time of C in the soil (controlling the factors to limit the decomposition process) is more important to sequester C in the long-term (Jastrow et al., 2007). SOM may be protected from decomposition (stabilized) by many mechanisms that control residence time (Trumbore, 2009). SOC is transformed to chemical forms through biotic and abiotic processes to become more resistant to microbial utilization (biochemical alteration). SOC stabilization can also occur by physical protection through occlusion within aggregates and, therefore, inhibit the decomposition process (Jastrow et al., 2007). The inclusion of organic materials within aggregates reduces their decomposition rate thereby increasing C sequestration (Six et al., 2000; Pikul et al., 2009). Aggregate-associated C stabilizes and protects SOM from the attack of microbes and the impact of destructive forces. Overall, the amount and stability of macroaggregates are negatively affected by cultivation (Denef et al., 2004); however, microaggregate stability was found to be unimpacted (Denef et al., 2001). This may be due to the fact that dissociation of macroaggregates and associated C losses occur more rapidly under agricultural management because of their lower levels of stability relative to microaggregates (Jastrow and Miller, 1998).

Enhancing microaggregate formation and stabilization of C by utilizing best management practices to reduce macroaggregate turnover has become an important aspect of agroecosystem management strategy. Thus, understanding the effect of agroecosystem management on the distribution and form of SOC and the mechanisms of C storage into different soil aggregate size fractions is key to informing best management practices. Several studies have reported that improved management practices such as no-tillage and increased cropping intensity leads to enhanced aggregation and increased soil C stocks (Paustian et al., 2000). Irrigation is also an important management practice that may enhance soil structure and increase soil C sequestration through aggregation due to increased crop productivity and plant residue inputs. Increased SOM content due to high crop residue input as a result of irrigation, for example, can increase aggregate formation (Gillable et al., 2007). On the other hand, irrigation may have a negative impact on soil physical properties by accelerating decomposition processes through increased microbial activity (Blanco-Canqui et al., 2010) or by directly disrupting soil aggregates (Gillabel et al., 2007). Drying and wetting cycles also may influence aggregation; Denef et al. (2004) found that fast drying and wetting cycles causes significant reduction in soil aggregates, in particular the macroaggregate fractions. Therefore, irrigation combined with no-till has been advocated as a good management practice for C sequestration (Blanco-Canqui et al., 2010), since it can increase protection and stabilization for SOM in macroaggregate occluded microaggregates relative to irrigation alone (Gillable et al., 2007).

The C mineralization is an important indicator of OM availability to soil decomposers (Bremer et al., 1994). SOM quality, in particular C:N ratio also, affects the C mineralization rates; in general, SOM with a low C:N ratio respires more C compared to a high ratio. Agricultural management practices may increase the rate of mineralization by causing aggregate disruption (Mikha el at., 2005). Ashagrie et al. (2007) stated that cultivation caused the breakdown of aggregates and increased the loss of SOM. Agricultural management practices may also decrease the C mineralization by enhancing aggregate formation and increasing C sequestration within aggregate fractions. Therefore, soils with higher aggregation respire less C due to higher physical protection.

This study focused on the effect of irrigated and dryland cropping systems on soil aggregation and physical SOC stabilization in a semi-arid region. Our hypotheses were: (H1) the macro-aggregate proportion will be higher and the free micro-aggregate proportion will be lower under irrigation compared to dryland systems due to high C inputs stimulating macroaggregate formation and (H2) The SOC content in microaggregates within macroaggregates will be higher for irrigated systems than for dryland systems because they respire less C due to greater physical protection.

3.2 MATERIALS AND METHODS

3.2.1 The study site

The study was conducted at Colorado State University's Agricultural Research, Development, and Education Center (40^o 39'6" N and 104^o 59'57" W), located about 8 km north of Fort Collins, CO at an altitude of 1535 m. The area has a semi-arid climate with average annual precipitation of 26.4 cm and mean annual temperature from 8.40 to 9.10^{o}C. The soil is a Fort Collins loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalfs).

3.2.2 Description of the experiment

The experiment was started in 2005 and individual plots measured 9.14 by 24.91 m. The experiment included four replicates in a randomized complete block design with 8 treatments: fully irrigated alfalfa (Full-A), fully irrigated corn (Full-C), limited irrigation forage alfalfa (Ltd-fA), limited irrigation forage corn (Ltd-fC), limited irrigation grain wheat (Ltd-gW) limited irrigation grain corn (Ltd-gC), dryland wheat (Dry-W) and dryland corn (Dry-C), all of these cropping systems were managed with conservation tillage. The experiment utilizes approximately one hectare under a linear-move sprinkler irrigation system; in the past, the location had been used for irrigated crop production of wheat, corn, and dry beans using an annual plow-based tillage approach. Each phase of each crop rotation was present every year. The irrigation system allowed for a maximum of one irrigation event per week and was controlled on an individual plot level by manually controlling drop nozzles.

3.2.3 Soil sampling

Soil samples were collected at the end of the sixth (October 2010) cropping season, at 0-5 cm depth. Three soil cores were taken from each plot at points randomly selected. The soils from the three cores were combined, bagged, and transported to the laboratory. Field moist samples were passed through an 8 mm sieve and air dried. All organic material >8 mm was removed during sieving.

3.2.4 Aggregate separation

Size distribution of soil aggregates was determined by the wet sieving technique following the procedures of Elliott (1986). Briefly, 100 g of air dried soil sample was spread on a 250µm sieve submerged in deionized water. Soils were left immersed in the water for 5 min and then sieved by manually moving the sieve vertically 50 times in the water within a 2 min period. The material remaining on the sieve was backwashed into an aluminum pan. The soil and water that passed through the sieve was poured onto the next finer sieve (53µm), and the process was repeated. The different aggregate sizes (>250µm, 250- 53µm and < 53µm) were dried in the oven at 60°C, weighed and stored in glass jars at room temperature.

Mean weight diameter (MWD) of aggregates for each plot was determined as the sum of percentage of soil on each sieve multiplied by the mean diameter of each size fraction (mm) as follows:

$$\text{MWD} = \sum_{i=1}^{n} Xi \ {}^{*}\text{W}_{\text{i}} / 100 \qquad [8]$$

Where X is the mean diameter of each size fraction (*i*), W is the proportion of total sample weight recovered in size fraction after wet sieving (i) and n is the number of size fractions (Six et al., 2002; Lichter et al., 2008).

3.2.5 Microaggregate isolation

A micro-isolator shaking device developed by Six et al. (2000) was used to isolate the microaggregates occluded within the stable macroaggregates (>250 µm). A 10 g sub-sample of oven dried macroaggregates was immersed in deionized water on top of a 250 µm mesh screen and shaken with glass beads at a low speed for about 5 min; the water flowed continuously through the device to flush the microaggregates onto a 53 µm sieve. When all the macroaggregates were broken up, the material on the 53 µm sieve was manually sieved at a rate of 50 times in 2 min. The coarse particulate organic matter (cPOM, > 250 µm), microaggrgates within macraggregates (mM, 53-250 µm) and silt & clay fraction (S&C, <53 µm) were isolated from microaggregates. All fractions were transferred to aluminum pans, oven dried at 60°C, weighed and stored in glass jars at room temperature.

3.2.6 Carbon mineralization

An incubation-based method was used to determine potential C mineralization (C-min). A 30 g subsample of each soil sample was incubated at 30^{o}C and 50% water filled pore space in a 500 mL Wheaton serum bottle sealed with a rubber septum and closed with an aluminum ring. At the start of the incubation, the CO_2 level was measured at time 0 just before placing the bottles in the incubator at 30^{o}C in the dark. Respired CO_2 after 3 and 10 days were determined in four replications with a 1-mL syringe from the headspace gas and analyzed by Li-COR CO_2 gas analyzer using compressed N as a carrier gas.

3.2.7 Carbon input calculation

To determine the amount of C input for wheat and corn crops, we followed the method of Kong et al. (2005) who quantified cumulative C input by multiplying the total crop residues input by an average %C, which for wheat and corn was 43% C.

The C input (Wheat and Corn) = mass of total crop residues × 0.43 [9]

For alfalfa the % C input was calculated using the C/N ratio from a previous study (Rynk et al., 1992) which gave on average 40% C.

The C input (Alfalfa) = the total crop residues × 0.40 [10]

3.2.8 Carbon and Nitrogen analysis

The SOC and TN for the aggregate size fractions (macro, micro aggregates, and silt & clay fractions) and for the isolated fractions within macroaggregates (c-POM, mM and Silt&Clay-M) were measured using a LECO CHN-1000 analyzer. SIC concentrations were determined by a modified pressure transducer method described by Sherrod et al. (2002), and SOC was calculated by difference.

The SOC and N stocks were calculated using the following equations:

Carbon stock (kg/m^2) = d (m) × BD (kg/m^3) × % SOC [11]

Nitrogen stock (kg/m^2) = d (m) × BD (kg/m^3) × % TN [12]

C and N stock (kg/m^2) was converted to Mg ha^{-1}.

Where d is soil depth in meters, BD is bulk density in kilogram/cubic meter, SOC is the soil organic carbon (Percentage) and TN is the total soil nitrogen (Percentage).

3.2.9 Statistical analysis

The experiment was laid out in a randomized complete block design with different irrigated and dryland cropping systems in four replications. The data were analyzed using the PROC GLM procedure in SAS 9.1 (SAS Institute, 2009). Treatment means were compared using least significant differences (LSD) with a significance level of $p < 0.05$. Comparison over time was not done because it is only appropriate after all crop rotation sequences have completed one or more full cycles. However, in our study we have a two year rotation (WF), a three year rotation

(WCFs), and four year rotation (CA and AC) and the first time that all of these rotations will complete a full cycle is after 12 years. Therefore, treatments were compared by year. Estimate statements were used within PROC GLM to generalize effects of individual factors such as crop, irrigation level, or cropping system. Comparisons were: fully irrigated alfalfa- corn (Full-AC) vs. limited forage irrigated alfalfa- corn (Ltd-AC), dry wheat-corn (Dry-WC) vs. fully irrigated alfalfa- corn (Full-AC), dry wheat-corn (Dry-WC) vs. limited forage irrigated alfalfa- corn (Ltd-AC), fully irrigated alfalfa- corn (Full-AC) vs. limited grain irrigated wheat- corn (Ltd-WC), and limited forage irrigated alfalfa- corn (Ltd-AC) vs. limited grain irrigated wheat- corn (Ltd-WC).

3.3 RESULTS

3.3.1 Aggregation size distribution

Soil aggregation varied with treatments and aggregate size classes within corn treatments. Macroaggregate proportions were significantly lower under the Dry-C treatment compared to Full-C, Ltd-fC and Ltd-gC (Fig. 3-1 A). The Ltd-gC had a significantly lower microaggregate proportion (69.4 % of the total soil weight) than Full-C, Ltd-fC and Dry-C which were 73.7, 73.9 and 74.7 % of the total soil weight, respectively (Fig. 3-1 B). The silt and clay fraction (< 53µm) was higher under Dry-C compared to other corn treatments (Fig. 3-1 C).

The aggregate proportions under Full-A and Ltd-A were not statistically significant at any size fractions. Also the macroaggregate, microaggregate and silt and clay fraction proportions under Ltd-gW and Dry-W were not significantly different. The percentage of free microaggregates was higher compared to other sizes in all treatments; 69.4 to 75.6 % of soil was comprised of microaggregates, while less than 18 % of the soil of these treatments was found in the macroaggregate fraction. Overall, MWD of Ltd-gC treatment was significantly higher (0.23

mm) compared to Ltd-fA, Ltd-gW and Dry-C treatments (0.19, 0.19, and 0.17 mm) respectively (Table 3-1). However, the differences between the MWD of Ltd-gC and Full-A, Full-C, Ltd-fC and Dry-W were not significant. A significant regression relationship was found between the macroaggregate fraction and C input ($r^2 = 0.505$, $p = 0.0493$). However, no relationship was observed between C inputs and either the free microaggregate or silt & clay fractions among all treatments. According to the contrast statements (estimations), macroaggregate and free microaggregate percentages were not significantly different among all estimations. However, silt and clay fractions were significantly different among the following statements, Dry-WC vs. full-AC and Dry-WC vs. Ltd-fAC with $p = 0.001$ and 0.015 respectively.

3.3.2 Microaggregates Isolated

The percentage of macroaggregate as cPOM among all treatments ranged from 24.5 to 40.9% while the mM fraction accounted for 39.3 to 53.5% of macroaggregate fractions. In corn treatments, the proportion of cPOM fraction was higher under Dry-C relative to other corn treatments (Fig. 3-2 A), while the proportion of mM in Dry-C treatment was lower compared to other treatments (Full-C, Ltd-fC and Ltd-gC). However, in the alfalfa and wheat crops, the differences were not significant (Fig. 3-2 B and C).

3.3.3 C and N in Aggregation and Microaggregates Isolated

The C and N stocks in the fractions tended to be different among treatments, but as a result of the large spatial variability these differences were not statistically significant (Table 3-2).

The SOC and N stocks in cPOM were significantly higher in Full-C and Ltd-fC compared to Dry-C treatments (Table 3-3). However, the differences in SOC and N stocks in the cPOM under alfalfa treatments (Full-A and Ltd-fA) and wheat treatments (Ltd-gW and Dry-W) were not statistically significant. The mM had significantly higher SOC and N stocks under Full-C and Ltd-fC treatments compared to Ltd-gC and Dry-C treatments (Table 3-3). However, neither the effect of Full-A or Ltd-fA treatments on SOC or N content in mM, nor the Ltd-gW and Dry-W treatment were significant. In general, the SOC and N stocks in both cPOM and mM fractions were significantly greater under Full-C and Ltd-fC and lower in the Ltd-gW and Dry-W (Table 3-3). There was a significant positive linear relationship between the SOC in cPOM fractions and C input (r^2 =0.8106, p = 0.0023) and between N in cPOM and C input (r^2 = 0.763, p = 0.00460). The SOC and TN content in M, m, S&C, and the S&C-M aggregates fraction were not significantly different among all statements. However, in the POM and mM fractions the differences were significant between Dry-WC vs Full-AC and Dry-WC vs. Ltd-fAC with p> 0.05 for SOC and TN content.

3.3.4 Carbon mineralization

Carbon mineralization rates in different treatments ranged from 76.0_{3d} and 163_{10d} ug C g^{-1} soil under Ltd-gW to 156_{3d} and 321_{10d} ug C g^{-1} soil under full-A. Within the same crop treatments, the differences in C mineralization rates were not significant either after three or ten days of incubation. Overall, the alfalfa treatments (Full-A and Ltd-fA) had the highest rate of C mineralization, and the wheat treatments (Ltd-gW and Dry-W) had the lowest rate (Table 3-1). A significant positive regression relationship was found between the C mineralization rates and C/N (r^2 = 0.865, p > 0.005). However, no significant regression relationship was found between the fractions isolated from macroaggregates and C mineralization rates. There was no relation between the SOC in mM fraction and C output (C-min). Furthermore, we did not find any significant relationship between C inputs and C output, but the C mineralization was significantly affected by the residues quality (C/N).

3.4 DISCUSSION

Macroaggregate formation occurs around fresh residue (Six et al., 2000), and macroaggregates are stabilized by fresh residue (Angers and Giroux, 1996). The soil microbes use the residue as a source of C and drive the aggregate binding agents (Six et al., 1999). Consistent with our hypothesis, significant effects were observed on macroaggregate percentage under corn treatments in which irrigated treatments (Full-C, Ltd-fC and Ltd-gC) stimulated a higher input compared to the dryland treatment (Dry-C) (Table 3-1, Fig. 3-1). Irrigation did not affect residue input or macro-aggregate percentage in alfalfa or wheat crops. Aggregate stability increases with management practices that induce high residue-C to be returned to the soil (Kong et al., 2005; Blanco-Canqui et al., 2010). The addition of available C to the soil may have stimulated microbial activity and in turn, induced binding of aggregates (Six et al., 1999; De Gryze et al., 2005; Gillabel et al., 2007) compared to Dry-C with low C input. Many studies have indicated that macroaggregates increased in proportion to the amount of residue added (Denef et al., 2002; De Gryze et al., 2005). This is consistent with our finding that the difference among corn treatments was directly related to the differences in the amount of C input under those treatments. On the contrary, others found the relation between increased C input and stable aggregates to be a non-linear either in laboratory incubation (Degens, 1997) or field experiments (Diaz et al., 1994).

The only significant difference observed in free microaggregate percentage was under Ltd-gC which had a lower microaggregate percentage compared to other corn treatments (Fig. 3-1B). Since we found no relationship between the amount of the microaggregates and C input added to the soil, the high proportion of free microaggregates under fully irrigated cropping systems may be due to breaking of bonds that bind the microaggregates to build macroaggregates because these bonds are very sensitive to cultivation and land use (Ashagrie et al., 2007). Boix-Fayos et al. (2001) found the high microaggregate proportion was related to soil fauna (earthworms) that breakdown the OM which in turn becomes nuclei for new microaggregates. Another possibility may be related to the continuous breakdown of macroaggregates by water drops (Saha et al., 2011). However, the high proportion of microaggregates under the dryland cropping system may be due to lower SOM returned to the soil because of low C input (Saha et al., 2011) inducing a low amount of disrupted macroaggregates under that treatment.

Overall, our results found a high amount of microaggregates compared to macroaggregates under all treatments. This higher percentage may be due to the previous tillage management (the location had been used for irrigated crop production of wheat, corn, and dry beans using an annual plow-based tillage approach, before 2005 when the experiment was initiated) that increased the fragmentation of the macroaggregates into microaggregates. Cultivation and agricultural management practices such as tillage for example, result in reduced macroaggregates due to physical disruption (Paul et al., 2013). Six et al. (2000) built a conceptual model explaining the turnover of macroaggregates under conventional tillage (CT) and no tillage (NT). They stated that the macroaggregate turnover induced by tillage led to formation of stable microaggregates. Therefore, our results confirm earlier observations that microaggregates are more stable than macroaggregates (Beare et al., 1994; Six et al., 2000).

Our results show a higher proportion of cPOM in Dry-C treatment than in Full-C, Ltd-fC and Ltd-gC (Fig. 3-2A). However, the opposite effect was observed for the mM under these treaments. In contrast we did not observe a significant difference among either alfalfa or wheat treatments.

We assumed that the low percentage of cPOM under irrigated treatments (Full-C, Ltd-fC and Ltd-gC) was due to fast decomposition by microorganisms, resulting in formation of mM as compared to Dry-C, because decomposition decreases the size of cPOM to become fine iPOM within macroaggregates, and the fine iPOM is encrusted with clay and microbial production to form mM (Six et al., 2000). Denef et al. (2001) indicated that in undisturbed macroaggregates, the turnover of cPOM to fine iPOM occurs rapidly to induce mM formation. However, we found that the cPOM levels under those treatments were not related to either C input or C mineralization. Therefore, we assume that factors other than C input and C mineralization were responsible for the low cPOM amount under the irrigated cropping system.

The mM fraction is an important indicator ofC sequestration in sustainable agroecosystems in no-till systems (Denef et al., 2004). The mM fractions are less dynamic and actually responsible for the longer-term stabilization and protection of soil C, alongside with mineral stabilization in silt and clay (von Lützow et al., 2007); therefore, mM is a longer term pool for C sequestration.

No significant treatment effect on SOC and N content in the aggregate fractions was found, although there was large spatial variability among treatments. However, the significant difference in the aggregate size distribution among treatments was not consistent with the C and N concentration in these fractions. This may be due to C loss as CO_2 to the atmosphere as a result of soil aggregate disruption which increased respiration (Six et al., 2000).

Our data showed that the Full-C treatment resulted in considerably higher SOC and N stocks in the mM fraction relative to Dry-C (Table 3-3). However, there were no differences observed under either alfalfa or wheat treatments. We found that the difference in SOC and N stocks in mM fractions under corn treatments was consistent with the difference in proportion of those fractions (mM) among treatments. However, the difference in C in mM was not always related to the proportion of mM (Six et al., 2002; Denef et al., 2007). This difference could be due to the difference in the quality of the crop residue added (De Gryze et al., 2005), although we did not find a relationship between SOC or N content in mM and C mineralization. In addition, we did not find any significant relationship between C inputs and C output, but the carbon mineralization was significantly affected by C/N ratio ($p > 0.005$).

The results showed that the SOC and TN in cPOM was positively correlated with C input ($p = 0.00230$ and $p = 0.00460$) and the higher amount of SOC and TN in mM were related to the amount of SOC and TN in cPOM under those treatments ($R^2 = 0.682$, $p < 0.005$ and $R^2 = 0.882$, $p < 0.001$) respectively. Thus, the higher C and N storage in mM fraction under Full-C treatment may have been induced as a result of high turnover of the cPOM under these treatments allowing a greater stabilization of bound C in the mM fraction. Results suggest that macroaggregates under Dry-C were less disturbed related to Full-C although the differences in C mineralization during 3 and 10 days incubation under corn treatments were not significant. Therefore, the amount of SOC in mM fractions under Full-C versus Dry-C could be linked to differences in quantity, stability and decomposition of cPOM. Apparently the high C input with no-till management improved SOM conservation and may also have reduced the loss of carbon as CO_2.

3.5 CONCLUSIONS

As we predicted, macroaggregate percentage was higher under irrigated treatments (Full-C, Ltd-fC and Ltd-gC) due to a higher C input in the form of crop residue compared to the dryland treatment (Dry-C). Therefore, conversion from full irrigation to limited irrigation cropping systems had no effect on macroaggregate formation, but the effect was significant when converted to dryland cropping systems. However, the irrigation did not affect the free microaggregate percentage.

The proportion of free microaggregates was higher under all treatments (comprised 69.4 to 75.6 % of soil) compared to macroaggregates (less than 18 % of the soil). This suggests that the previous (before 2005 when the experiment was initiated) tillage management may be increased the fragmentation of macroaggregates into micraggregates. Although there was a significant difference in the aggregate size distribution among treatments that was not consistent with the C and N stocks in these aggregate fractions.

Full-C treatment had a considerably higher SOC and N stock in the mM fraction relative to Dry-C but the difference in respiration rates was not significant. These data suggest that macroaggregates under Dry-C are less exposed to decomposition compared to Full-C. Irrigation with no-till can enhance the aggregate formation and reduce the turnover rate of macroaggregates, therefore, increasing C stock in the mM fractions.

Table. 3-1. Total biomass (above and below), carbon input from (2007-2010), mean weight diameter (MWD mm) of soil aggregates and Carbon Mineralization (3 and 10 day) for different cropping systems and treatments in a semi-arid climate.

Cropping Systems	Treatments	Total biomass	C-input	MWD	C- Mineralization 3 days	C- Mineralization 10 days
		----------Mg ha^{-1} ------		---mm---	----ug C g^{-1} soil ----	
Full AC	Full A	27.2	10.9	0.20abc	156a	321a
	Full C	70.3	30.2	0.21ab	117b	259b
Ltd f AC	Ltd f A	20.1	8.04	0.19bc	154a	312a
	Ltd f C	59.3	25.5	0.21ab	115b	267b
Ltd g WC	Ltd g W	15.2	6.54	0.19bc	76.0c	163c
	Ltd g C	58.9	25.3	0.23a	121b	256bc
Dry WC	Dry W	15.1	6.49	0.20abc	92.0bc	213bc
	Dry C	16.5	7.10	0.17c	106bc	221bc

Cropping systems are fully irrigated alfalfa-corn (Full AC), limited irrigation forage alfalfa-corn (Ltd f AC), limited irrigation wheat-corn (Ltd g WC), and dryland wheat-corn (Dry WF/WC). Treatments: fully irrigated-corn (Full C), fully irrigated-alfalfa (Full A), limited irrigation forage corn (Ltd f C), limited irrigation alfalfa (Ltd A), limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), and dryland corn (Dry C). Values followed by a common letter within a column are not significantly different ($p < 0.05$) based on Least Significant Differences.

Table. 3-2. Soil organic carbon (SOC) and total nitrogen (TN) stocks of aggregate size classes to the depth of 0-5 cm as affected by different irrigated and dryland cropping systems in a semi-arid climate.

Cropping Systems	Treatments	Macro-aggregates		Micro-aggregates		Silt and Clay fraction	
		SOC Stock	N Stock	SOC Stock	N Stock	SOC Stock	N Stock
		---------------------------------------Mg ha $^{-1}$---------------------------------					
Full AC	Full A	7.74a	0.84a	9.82a	1.02a	9.04a	0.935a
	Full C	8.75a	0.93a	8.11a	0.863a	7.23a	0.728a
Ltd f AC	Ltd f A	7.66a	0.83a	7.73a	0.823a	8.05a	0.885a
	Ltd f C	7.26a	0.81a	9.07a	0.958a	8.67a	0.855a
Ltd g WC	Ltd g W	7.98a	0.897a	7.93a	0.910a	7.81a	0.915a
	Ltd g C	7.54a	0.812a	5.72a	0.667a	6.52a	0.705a
Dry WC	Dry W	8.68a	0.979a	8.14a	0.939a	8.82a	0.937a
	Dry C	7.12a	0.873a	8.38a	0.884a	8.41a	0.987a

Cropping systems are fully irrigated alfalfa-corn (Full AC), limited irrigation forage alfalfa-corn (Ltd f AC), limited irrigation wheat-corn (Ltd g WC), and dryland wheat-corn (Dry WC). Treatments: fully irrigated-alfalfa (Full A), fully irrigated- corn (Full C), limited irrigation forage corn (Ltd f C), limited irrigation forage alfalfa (Ltd f A), limited irrigation grain corn (Ltd g C), limited irrigation grain wheat (Ltd g W), dryland wheat (Dry W), and dryland corn (Dry C). Values followed by a common letter within a column are not significantly different ($p < 0.05$) by Least Significant Differences.

Table. 3-3. Soil organic carbon (SOC) and total nitrogen (TN) stocks for coarse particulate organic matter (cPOM), microaggregates within macroaggregates (mM) and silt and clay within macroagregates (S&C-M) size fractions after isolation of macroaggregates for different cropping systems and treatments at 0-5 cm depth in a semi-arid climate.

Cropping Systems	Treatments	cPOM		mM		S&C-M	
		SOC Stock	N Stock	SOC Stock	N Stock	SOC Stock	N Stock
		--------------------------------Mg ha^{-1}--------------------------------					
Full AC	Full A	8.84bcd	0.497bc	13.7b	1.16b	11.4cd	1.21cd
	Full C	13.5a	0.915a	15.4a	1.42a	13.2abc	1.41ab
Ltd f AC	Ltd f A	10.5ab	0.597b	12.7b	1.11b	11.4cd	1.31bc
	Ltd f C	14. 6a	0.976a	16.8a	1.52a	15.0a	1.53a
Ltd g WC	Ltd g W	5.76cd	0.312c	8.88c	0.788c	10.8d	1.09d
	Ltd g C	10.2abc	0.543bc	9.72c	0.838c	11.6bcd	1.18cd
Dry WC	Dry W	5.56d	0.295c	9.01c	0.827c	11.0d	1.12d
	Dry C	7.81bcd	0.453bc	13.7b	1.124b	13.4abc	1.37b

Cropping systems are fully irrigated alfalfa-corn (Full AC), limited irrigation forage alfalfa-corn (Ltd f AC), limited irrigation wheat-corn (Ltd g WC), and dryland wheat-corn (Dry WC). Treatments: fully irrigated-alfalfa (Full A), fully irrigated- corn (Full C), limited irrigation forage corn (Ltd f C), limited irrigation forage alfalfa (Ltd f A), limited irrigation grain corn (Ltd g C), limited irrigation grain wheat (Ltd g W), dryland wheat (Dry W), and dryland corn (Dry C). Values followed by a common letter within a column are not significantly different ($p < 0.05$) based on Least Significant Differences.

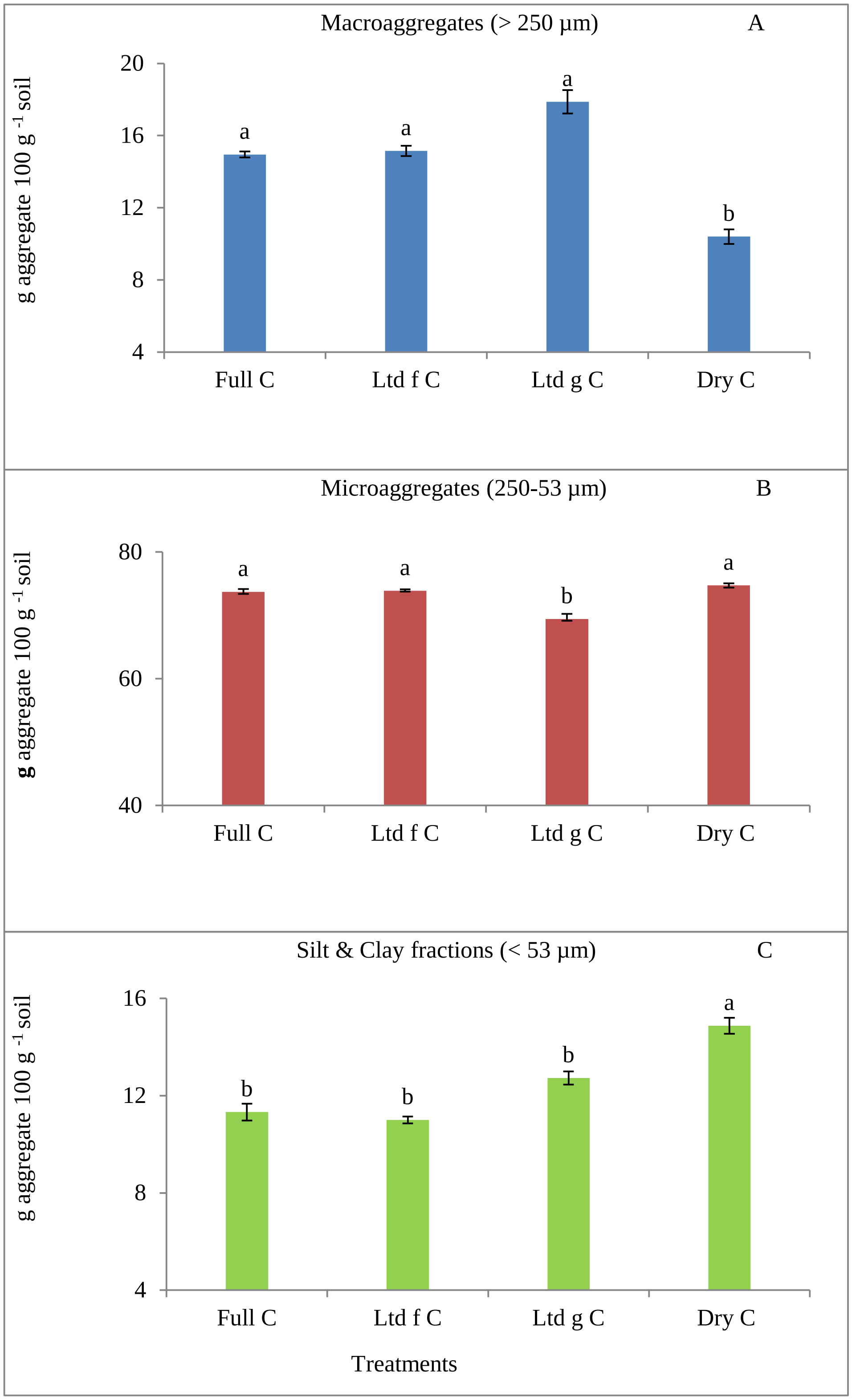

Fig. 3-1. Aggregate size distribution as determined by wet sieving method: macroaggregates (A), microaggregates (B) and silt & clay fraction (C) for different irrigated corn and dryland corn treatments at 0-5 cm depth in a semi-arid climate. Treatments: fully irrigated corn (Full C), limited irrigation forage corn (Ltd f C), limited irrigation grain corn (Ltd g C), and dryland corn (Dry C). Values followed by a common letter are not significantly different ($p < 0.05$) by Least Significant Differences.

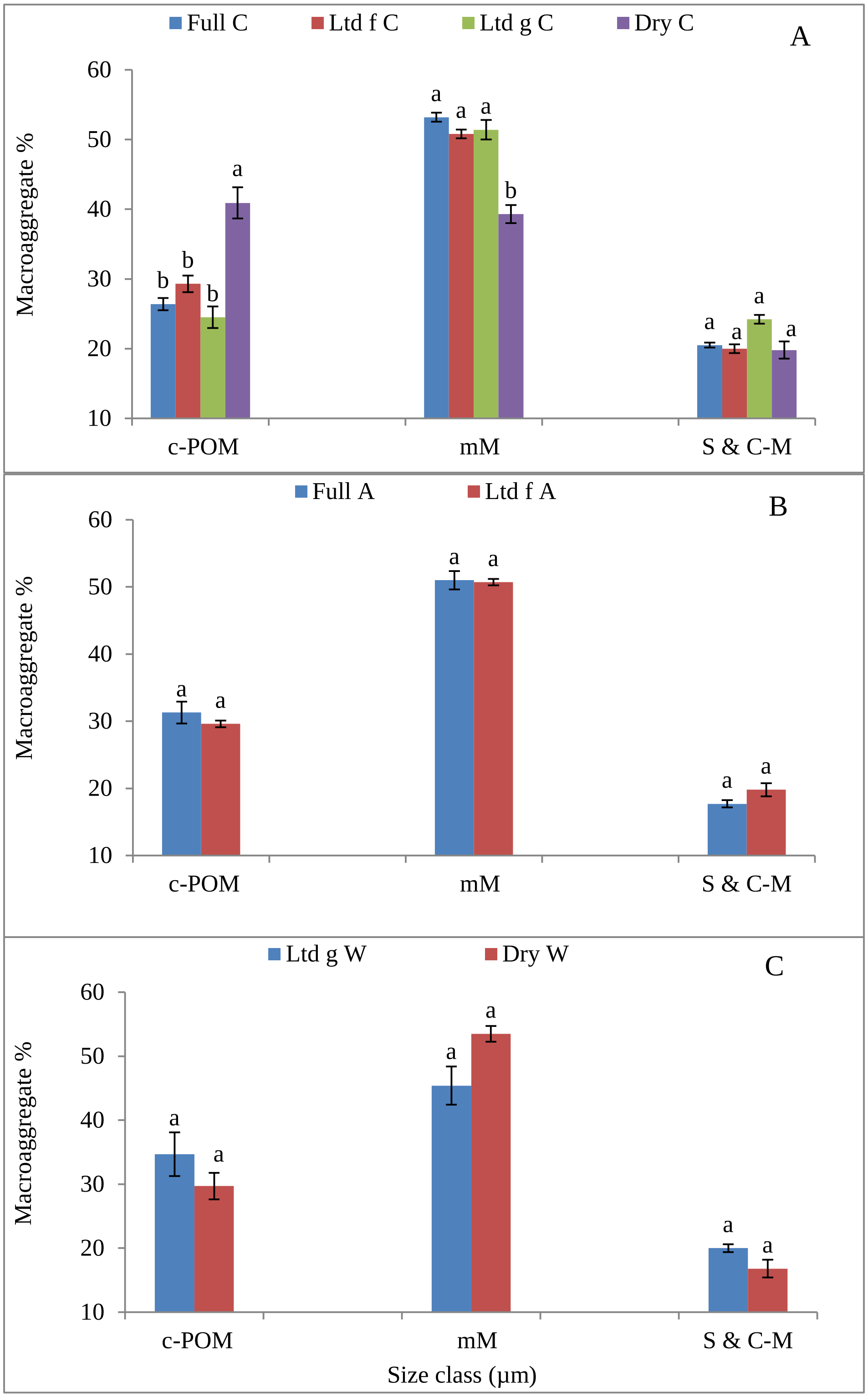

Fig.3-2. The percentage of macroaggregates (%): C-POM coarse particulate organic matter, mM micro into macro-aggregates, S& C silt and clay fraction of macroaggregates for irrigated corn and dryland corn (A), different irrigated alfalfa treatments (B) and limited irrigation grain wheat and dryland wheat (C) at 0-5 cm depth in a semi-arid climate. Treatments: fully irrigated-alfalfa (Full A), fully irrigated- corn (Full C), limited irrigation forage corn (Ltd f C), limited irrigation forage alfalfa (Ltd f A), limited irrigation grain corn (Ltd g C), fully irrigated- alfalfa (Full A), limited irrigation forage alfalfa (Ltd f A) limited irrigation grain wheat (Ltd g W) and dryland wheat (Dry W). Values followed by a common letter are not significantly different ($p < 0.05$) by Least Significant Differences.

CHAPTER 4. IRRIGATION EFFECTS ON SOIL INORGANIC CARBON CONTENT IN SEMI-ARID CROPPING SYSTEMS

4.1 INTRODUCTION

Water demand is increasing as a result of population growth, economic activity and demand for agricultural irrigation. However, increasing drought periods, shortages of groundwater, and urban competition for water has reduced the availability of water for irrigated agriculture in Colorado (CDM and GBSM, 2004; Hansen et al., 2011). Converting land to limited irrigation or dryland cropping systems is a potential water conserving method to alleviate shortage (Hansen et al., 2011).

Dryland soils around the world are estimated to cover 4.9 x 10^9 ha distributed 43.5% in semi-arid, 44.6% in arid and 11.9% in highly arid regions (Lal and Kimble, 2000). These soils contain more soil inorganic carbon (SIC) in the form of Ca and Mg carbonates than soil organic carbon (SOC) because the evapotranspiration (ET) exceeds the precipitation (less than 500 mm per year; Lal and Kimble, 2000). Schlesinger (1982) suggested that in arid regions, SIC concentration is typically higher than SOC concentration by a factor of 10. The SIC pool is less amenable to loss by agricultural practices compared to SOC because of its presence deeper in the profile which may, in turn, have potential as a long-term sink for atmospheric CO_2 (Lal, 2004b).

Irrigation water quality in arid and semiarid regions can impact SIC; water with high dissolved CO_3^{2-} and HCO_3^- concentrations can increase the reaction with Ca^{2+} resulting in $CaCO_3$ precipitation and effectively increasing SIC sequestration. High pH as a result of Ca^{2+} concentration combined with elevated temperatures in low rainfall areas also impacts the reaction with Ca^{2+} and Mg^{2+}, resulting in precipitation of carbonates (Blanco-Canqui et al., 2010). Soil pH may be affected by root exudation; plant roots can release either H^+ or OH^- to offset unbalanced cation-anion absorption by plants, which can increase or decrease the rhizosphere pH (Hinsinger et al., 2003).

Irrigation of arid and semiarid soils can increase SIC content (Entry et al., 2004) by increasing the biomass production (Lal and Kimble, 2000; Wu et al., 2009), and in turn increasing C deposition into soil. However, addition of water to those soils may affect the SIC by enhancing the dissolution of carbonates and increasing CO_2 emissions into the atmosphere (Eswaran et al., 2000). This is dependent on soil type and climate (Blanco-Canqui et al., 2010).

Most studies have focused on the impact of agricultural practices on soil organic carbon (SOC) in the soil surface and ignored the soil inorganic carbon (SIC) pool which is the most important C form (carbonates) in arid and semi-arid soils (Lal and Kimble, 2000; Denef et al., 2008). Therefore, this study focused on the effect of conversion of irrigated farmland to limited irrigation or dryland cropping systems on SIC content in a semi-arid environment over a 3-yr period. In addition, more analys were taken for Ltd-gWCFs cropping systems in 2013 to determine whether there was a difference in SIC concentration after three years of changing from sunflower to forage sorghum. Our hypotheses was: the SIC content under irrigated cropping systems will be both higher and deeper in the soil profile relative to limited and dryland cropping systems because of carbonate additions in the water and leaching of carbonates deeper into the soil profile.

4.2 MATERIALS AND METHODS

4.2.1 Site description

This experiment was located at Colorado State University's Agricultural Research, Development and Education Center (lat. 40^o 39'6" N, long. 104^o 59'57" W; 1535 m above sea level), located 8 km north of Fort Collins, CO. The experiment utilizes approximately one hectare under a linear-move sprinkler irrigation system, the soil is a Fort Collins loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalfs), and the climate is semi-arid with average annual precipitation of 26.4 cm and mean annual temperature from 8.4 to 9.1^{o}C. Prior to the experiment, the location had been used for irrigated crop production of wheat, corn, and dry beans using an annual plow-based tillage approach, providing a setting to evaluate the effects of converting irrigated conventionally tilled land to limited irrigation or dryland crop production under conservation tillage.

4.2.2 Experimental treatments

The experiment was initiated in 2005 with the establishment of four different cropping systems (Table 4-1). All of these cropping systems were managed with conservation tillage. This tillage system was integrated to improve water capture and use in the limited irrigation and dryland systems and also to offset the potential for soil C loss (Hansen et al., 2011). The irrigated alfalfa system is used as the fully irrigated reference system. The alfalfa stand was maintained for 5 years (2005-2010) and then rotated with the corresponding block of continuous corn. The experimental design was a randomized complete block with four replications. In addition, every phase of each crop rotation was present every year. The irrigation system allowed for a maximum of one irrigation event per week and was controlled on an individual plot level by manually controlling drop nozzles. The amount of water added to the treatments is shown in Table 4-1.

The average of irrigation was 36.1 cm for full alfalfa (Full-A), 37.3 cm for full corn (Full-C), 20.7 cm for limited irrigation forage alfalfa (Ltd-fA), 21.3 cm for limited irrigation forage corn (Ltd-fC), 11.1 cm for limited irrigation grain wheat (Ltd-gW), 21.3 cm for limited irrigation grain corn Ltd-gC, 1.90 cm for dry wheat (Dry-W) and 1.69 cm for dry corn (Dry-C).

4.2.3 Soil sampling and analysis

Soil samples were collected by hydraulic soil sampling equipment (soil probe truck, with cylinder of 5 cm diameter x 5 cm high) to a 60 cm depth. Twelve soil cores were taken from each plot at points randomly selected within a design stratified by position. Each soil core was then separated into four different depths (0-10, 10-20, 20-30, and 30-60 cm), and samples were composited by depth within each plot. Soil samples were taken at the end of the third (October 2007) and sixth (October 2010) cropping seasons from the establishment of the experiment. Additional soil samples from limited irrigation grain crops (Ltd-gW, Ltd-gC and Ltd-Fs) were collected in April 2013 for subsequent SIC analysis.

Soil inorganic carbon (SIC) concentrations were determined on all soil samples by a modified pressure transducer method described by Sherrod et al. (2002). Ground soil samples (1.0 g each) and calibration standards (0.25, 0.50, 1, 2, 4, 5, 10 percent of $CaCO_3$ by weight using powder-ground and oven-dried laboratory sand) were transferred to reaction vessels (20 mL Wheaton serum vials), and 2 mL of 6 *M* HCl was dropped into each reaction vessel. The bottle was sealed with a rubber stopper and closed with an aluminum cap. The reaction vessel was vigorously shaken to spill out all the acid into the vial to have contact with the soil sample. After a set reaction time (2 hours), CO_2 evolution was measured by inserting a needle attached to a pressure transducer and voltage meter and recording the output after approximately 3 to 5 seconds (Figure 4-1).

Soil pH was measured on all soil samples collected in 2010 and in 2013 by using 1:1 soil to water ratio method with Orion 420A pH meter.

Irrigation water was analyzed to determine the amounts of Ca^{2+}, Mg^{2+} and HCO_3^- that were added to the soil via irrigation (Table 4-1). The exchangeable Ca^{2+} and Mg^{2+} contents in the soil profile in 2010 samples were determined in ammonium acetate extracts as described by Sumner and Miller (1996). Ground soil samples (5.0 g) were transferred to beakers and 25 ml of 1 N ammonium acetate (pH 7) was added, shaken for 15 minutes and then filtered through a medium porosity p5 paper filter (Fisher p5 paper). The extracts were analyzed by inductively coupled plasma source optical emission spectroscopy (ICP-OES) (PerkinElmer Optima 7300). The Ca^{2+} and Mg^{2+} concentrations were analyzed to determine whether there was any difference among the treatments as a result of crop rotation or irrigation that could affect the formation or weathering of SIC in the soil profile.

Bulk density (BD) was measured in soil cores taken from each plot after harvest by using a sampling cylinder (5 cm diameter x 5 cm high). Soils were oven dried at 105°C and weighed.

The Bd (g/cm^3) = weight of oven dried soil (g) / total volume of soil (cm^3) [13]

The SIC stocks were calculated using the following equation (Shrestha et al., 2004):

Carbon stock (kg/m^2) = d (m) × BD (kg/m^3) × % SIC. [14]

The SIC stock was then converted to Mg/ha.

Where d is soil depth in meters, BD is bulk density in kilogram/cubic meter and SIC is the soil inorganic carbon (Percentage). The annual SIC Stocks change rates were calculated by using the following equation:

The annual ΔSIC stocks = (SIC $stocks_{2010}$- SIC $stocks_{2007}$ / 3years) [15]

4.2.4 Statistical analysis

Analysis of variance was completed using the PROC GLM procedure in SAS 9.1 (SAS Institute, 2009). Treatment means were compared using least significant differences (LSD) with 95% confidence in accordance with a randomized complete block design to ascertain the effects of different irrigated and dryland cropping systems on SIC within depth increment. Estimate statements were used within PROC GLM to generalize effects of individual factors such as crop, irrigation level, or cropping system. Comparisons were: fully irrigated alfalfa- corn (Full-AC) vs. limited forage irrigated alfalfa- corn (Ltd-AC), dry wheat-corn (DryWC) vs. fully irrigated alfalfa- corn (Full-AC), dry wheat-corn (Dry-WC) vs. limited forage irrigated alfalfa- corn (Ltd-AC), fully irrigated alfalfa- corn (Full-AC) vs. limited grain irrigated wheat- corn (Ltd-WC), and limited forage irrigated alfalfa- corn (Ltd-AC) vs. limited grain irrigated wheat- corn (Ltd-WC).

4.3 RESULTS

4.3.1 Concentration of Soil Inorganic Carbon

The SIC concentration was significantly higher under Ltd-gC than Full-C or Ltd-fC in the 0-30 cm depth in both years (Fig. 4-2 A and B). In addition, the concentration under Dry-C was higher than the concentration under Full-C in the 0-20 cm depth in 2010. There were no significant differences among treatments below 30 cm depth.

The SIC concentration under Full-A and Ltd-fA were not significantly different at any depth in either year, even though there were differences in the amounts of irrigation supplied (Table 4-1) and biomass production (data not shown) of the alfalfa cropping systems (Fig. 4-2 C and D).

The concentration of SIC under Ltd-gW was significantly higher than Dry-W at the 30 cm depth in both years (Fig. 4-2 E and F). However, there were no significant differences among treatments at other depths in either year. Overall, the Ltd-gW treatment had the highest concentration of SIC at most depths in both years compared to other treatments (Table 4-2).

The SIC concentrations under the limited irrigation grain wheat, corn, sunflower and sorghum (Ltd-gWCSf/Fs) cropping system during a period of six years (2007, 2010 and 2013) are shown in Fig.4-3 and 4-4. The SIC concentration was higher in Ltd-gW, and lower in Ltd-gSf and Ltd-gFs at depths (0-20 cm) in 2007 and 2013. However, there were no significant differences among treatments at other depths (30-60 cm) in 2007 and 2013 (Fig. 4-3 A and D). In 2010, the SIC concentration was higher under Ltd-gW compared to Ltd-gFs at 20 and 30 cm, but there were no significant differences among the treatments at other depths (Fig. 4-3 B). According to the contrast statements (estimations), SIC concentrations were significantly different among Full-AC vs. Ltd-gWC and Ltd-fAC vs. Ltd-gWC at 0-10, 10-20 and 20-30 cm depths in either year with $p < 0.05$.

4.3.2 Soil profile pH

Soil pH was analyzed for 2010 and 2013 but was not available for 2007. The differences in soil pH among treatments during 2010 were significant at all depth increments (Table 4-2). In general, pH was higher under Ltd-gW and lower in Full-C. At 0-10 cm the pH was higher under Ltd-gW and Ltd-gC treatments compared to other treatments (Full-C, Full-A, Ltd-fC, Ltd-fA, Dry-W and Dry-C). At other depths, the pH appeared to be higher in Ltd-gW and Ltd-gC treatments and lower in Full-C, Full-A, Ltd-fC, and Ltd-fA (Table 4-2). The soil pH in the 0-30 and 30-60 cm depth increments was significantly different among treatments in 2010 (Table 4-2). The Soil pH (0-30 cm) was higher under Ltd-gW compared to Full-C, Full-A, Ltd-fC, Ltd-fA, Dry-W and Dry-C. Soil pH (30-60 cm) was highest in Ltd-gW and lowest in Full-A, Full-C, Ltd-fA, and Ltd-fC (Table 4-2). The pH values were significantly different in the following estimations Dry-WC vs Full-AC, Full-AC vs. Ltd-gWC and Ltd-fAC vs. Ltd-gWC at all depth increments with $p < 0.001$.

In the limited irrigation grain cropping system (Ltd-gWCFs), the pH in 2010 tended to be higher in Ltd-gW compared to Ltd-gC and Ltd Fs, but there were no significant differences among treatments at any depth (Fig. 4-3 C). In contrast, there were significant differences in soil pH among treatments from 0 to 30 cm depth in the same cropping system (Ltd-gWCFs) in 2013. The Ltd-gW had the highest pH value compared to Ltd-gFs. However, there was no significant difference at the 30-60 cm depth (Fig. 4-3 E).

4.3.3 Concentration of Ca^{2+} and Mg^{2+} in soil profile

The concentration of Ca^{2+} in the 0-30 cm increment was higher under Full- A and Full-C relative to the Ltd-gW, Ltd-gC, Ltd-gFs, Dry-W and Dry-C treatments. In the 30-60 cm depth, the concentration was higher under Full-C than Ltd-fA, Ltd-gW, Ltd-gC, Ltd-gFs, Dry-C and Dry-W treatments (Fig. 4-5A).

The differences in the Mg^{2+} content in the soil profile were statistically significant among the treatments by depth (Fig. 4-5B). In the 0-30 cm increment the highest concentration was under Full-A and Full-C, and the lowest was under Dry-C and Dry-W treatments. In the 30-60 cm depth, the concentration was higher under Full-C then Ltd-fA and Ltd-gFs treatments.

4.3.4 Soil Inorganic Carbon stocks and changes

The SIC stock 0 to 30 cm depth was significantly different among treatments in both years (Table 4-2). The SIC stock at 0 to 30 cm was higher under Ltd-gW relative to fully irrigated treatments (Full-A and Full-C) and limited irrigated forage treatments (Ltd-fA and Ltd-fC) but the differences between Ltd-gW and other treatments (Ltd-gC, Dry-C and Dry-W) were not significant. However, there were no significant differences among treatments in the 30-60 cm depth in either year. Within the whole profile (60 cm) depth, the highest SIC stock was under Ltd-gW and Ltd-gC, and the lowest was under Full-C and Full-A treatment in both years.

The ΔSIC between 2007 and 2010 ranged from -0.60 Mg ha^{-1} to 2.48 Mg ha^{-1} for the 0-30 cm depth and 0.20 Mg ha^{-1} to 3.42 Mg ha^{-1} for the 30-60 cm depth (Table 4-2). The ΔSIC rate ranged from -0.20 Mg ha $^{-1}$ Y^{-1} to 0.83 Mg ha $^{-1}$ Y^{-1} for the 0-30 cm depth and 0.07 Mg ha^{-1} to 1.14 Mg ha^{-1} in the 30-60 cm depth increment. The highest gain of SIC during the study period of 3 years (2007-2010) within the whole profile (60 cm) depth was under Ltd-gW with 5.32 Mg ha^{-1}, and the lowest was under Full-A treatment with an average of -0.40 Mg ha^{-1}. Overall, the ΔSIC was not significant (Table 4-2), although the SIC stocks did show significant differences.

4.4 DISCUSSION

4.4.1 Concentration of soil inorganic carbon

At our study site SIC values were higher with depth under all the treatments, which is common in arid and semiarid regions, because soils in these regions are expected to contain more SIC (Schlesinger, 1982; Lal and Kimble, 2000). The reaction of high concentration of CO_3^{2-} and HCO_3^- in irrigation water with Ca^{2+} and Mg^{2+}, resulting in carbonates formation (Blanco-Canqui et al., 2010). Therefore, irrigation such are regions resulting in deeper precipitation of carbonates due to water percolation (Lal and Kimble, 2000). Our results show significantly higher SIC concentration in the Ltd-gW and Ltd-gC than for the fully irrigated crops (full-C and full-A) and for limited irrigation forage crops (Ltd-fC, Ltd-fA) from 0 to 30 cm depth increments, but the difference was not significant deeper in the profile (Table 4-2).

The SIC is affected by climate and physical and chemical factors such as soil pH, evapotranspiration, temperature, precipitation and soil moisture (Lal and Kimble, 2000).

It can be inferred from the results of SIC concentration under limited irrigation systems (Ltd-gWCSf/Fs) during a period of six years that changing from sunflower to forage sorghum in 2010 affected SIC under Ltd-gFs in 2013.

The SIC increased from 2007 to 2010 at the 20 cm and 60 cm depths. However, after sunflower was changed to forage sorghum in rotation in 2010, and SIC was measured again in 2013, the 20 cm and 60 cm SIC values had returned to 2007 levels. This may be a result of more C input added to the soil due to high productivity of forage sorghum from 2010-2013, thus, increasing the soil microbial activity and potentially speeding up the decomposition process and increasing CO_2 concentration. Increased CO_2 concentration in calcareous soils can considerably decrease soil pH (Hinsinger et al., 2003). Alternatively, the availability of N as a result of OM decay may have increased soil acidity which in turn reduced the pH (Shi et al., 2012) and prevented formation of carbonates.

Soil pH and SIC were positively correlated particularly in the 0-30 cm depth increments, with an $R^2 = 0.80$, and $P < 0.0001$ for 2010 (Fig. 4-6 A). This suggested that, the high SIC under limited irrigation grain crops (Ltd-gW and Ltd-gC) may be due to the decreased soil water content (Lal and Kimble, 2000) or CO_2 partial pressure in the soil air (Nordt et al., 2000; Blanco-Canqui et al., 2010), and with rising pH (Lal and Kimble, 2000), which is a favorable condition for carbonate precipitation. This is in accordance with Shi et al. (2012) who built linear regression models for SIC and found that SIC was correlated positively with soil pH ($p < 0.01$).

4.4.2 The value of soil pH and its influence on carbonate

The prevalent fraction of the carbonate ion depends on solution pH in which non-reactive H_2CO_3 is prevalent at pH 4-6, the more reactive HCO_3^{-2} is prevalent at pH 7-9, and the very reactive CO_3^{2-} is prevalent at pH 10-12. This activity increases as pH value increases; the dissolved HCO_3^{-1} increases 10 times, and the dissolved CO_3^{2-} increases 100 times for each unit increase in pH (Lindsay, 1979; Entry et al., 2004). Our results indicate that there were higher pH values under limited grain crops (Ltd-gW and Ltd-gC) compared with other treatments at most depths (Table 4-2), even though the concentration of Ca and Mg was higher under fully irrigated crops (Full-A and Full-C) compared to Ltd-gW and Ltd-gC (Fig. 4-5). Also, the irrigation water added more HCO_3^-, Ca^{2+} and Mg^{2+} to Full-A and Full-C compared to Ltd-gW, Ltd-gC, Dry-W and Dry-C, but we found negative correlations (not significant) between soil pH and soil concentration of Ca^{2+} [($p = 0.0657$) and Mg^{2+} ($p = 0.262$); Fig. 4-7 A and B]. Also there were negative correlations (not significant) between soil pH and the amount applied of HCO_3^- [($p = 0.192$), Ca^{2+} ($p = 0.152$) and Mg^{2+} ($p = 0.150$); Fig. 4-7 C, D and E]. Therefore, the difference in soil pH was not related to the irrigation amount or to Ca^{2+} and Mg^{2+} concentrations and amount of HCO_3^-, Ca^{2+} and Mg^{2+} applied by irrigation water; there may be other factors influencing the process. This may be due to the effect of different cropping systems in which sunflower rotated into wheat-corn grain rotation (Ltd-gWCSf) from 2005 to 2009, and consumed soil moisture (Hansen et al., 2011), leaving very little water available for subsequent crops. Nielsen et al (1999) stated that sunflower consumed a greater amount of water than other summer crops, and the soil water content at wheat planting (rotated with sunflower) was low compared to wheat in other rotation. This may be effectively increasing soil pH and providing a good environment for carbonate precipitation. Bowman et al, (2000) reported that biomass production by wheat rotated with sunflower was significantly lower compared to rotation without sunflower. This is consistent with our results and may explain the differences in pH and SIC concentration under Ltd-gW rotated with sunflower compared to other crops including wheat in rotations without sunflower.

4.4.3 Soil Inorganic Carbon Stocks and Changes

The SIC stock was lower under fully irrigated crops (Full-A and Full-C) and limited irrigation forage crops (Ltd-fA and Ltd-fC) as a result of low pH under these treatments although more HCO_3^-, Ca^{2+} and Mg^{2+} were added to the soil in the fully irrigated treatments (Table 4-2). However, the difference in SIC content between full irrigation and dryland cropping systems was not significant, consistent with Denef et al. (2008) who found that the SIC content was not different among dryland and irrigated sites. Thus, the lower amount of SIC under full irrigated cropping systems in our study may be due to the high biomass produced (above and below ground) returned to the soil and / or fertilizer application. For example, the fully irrigated corn had more C input and more N fertilizer (data not shown), and the fully irrigated alfalfa had high C input and is a nitrogen-fixing crop. Therefore, higher N concentrations under these crops may have increased the soil acidity, thus generally decreasing SIC formation (Lal and Kimble, 2000; Suarez, 2000; Mi et al., 2008; Shi et al., 2012). In addition, irrigation water may have reduced soil temperatures under these treatments which could also contribute to decreased formation of SIC (Wagai et al., 1998; Shi et al., 2012).

The SIC stock was higher at the 30-60 cm depth compared to the 0-30 cm depth, but there was no significant difference among treatments in this depth although the soil pH was significantly different; the correlation between SIC and soil pH in the 30-60 cm depth was not significant ($R^2 = 0.22$ and $p = 0.19$; Fig. 4-6 B). This higher concentration in deeper depths may be due to water percolation that transported the Ca^{2+} and HCO_3^- deeper into the profile and precipitated in the form of $CaCO_3$ (Lal and Kimble, 2000).

The SIC stocks were only significant in one estimation, Dry-WC vs Full-AC at 0-10 cm depth in both years with $p < 0.05$.

The ΔSIC was not significant difference among treatments in any depth increment (Table 4-2). Our results indicate that the amount of inorganic C gained under Ltd-gW treatment comprised a 19.4% of the total SIC sequestered under all treatments over the entire profile (0-60 cm) during the period of the study. The low inorganic C sequestered under the Full-C treatment may be due to the high productivity and N fertilizer that induced acid synthesis and inhibited carbonate formation (Entry et al., 2004; Mi et al., 2008). Irrigation also may stimulate microbial activity leading to more C and N mineralization (Sparling and Ros, 1988; Denef et al., 2008), which in turn increase the acidity and may result in SIC release from the soil (Yang et al., 2010).

4.5 CONCLUSIONS

SIC stocks were significantly different among treatments. Specifically, in the Ltd-gW SIC stocks were higher than in the fully irrigated crops (Full-C and Full-A) and limited forage crops (Ltd-f C, Ltd-f A) in either year. The most important factor controlling the process of SIC formation was soil pH which resulted in high variation of SIC among treatments. We found negative correlation (not significant) between soil pH and concentration of exchangeable Ca^{2+} and Mg^{2+}. This suggests that root activity may have led to soil pH change due to root exudation of either H^+ or OH^- (Hinsinger et al., 2003). The Ltd-gW and Ltd-gC that rotated with sunflower treatment gained the highest percentages of SIC sequestrated under all treatments over the entire profile (0-60 cm) through the period of the study. This may be due to effect of sunflower that consumed soil moisture and leaved very little water available for subsequent crops and may be effectively increased soil pH which is increased SIC formation. It can be inferred from the results that more inorganic C sequestration accrued deeper in the soil profile possibly due to water percolation that transported bicarbonate deeper into the profile resulting in precipitation of $CaCO_3$. Overall irrigation did not affect SIC content but the difference was due to the soil pH.

Table 4-1. Irrigation quantity and application of HCO_3^-, Ca^{2+} and Mg^{2+} in irrigation water from 2007 to 2010 under different cropping systems in a semi-arid climate.

Cropping Systems	Treatments	Irrigation				HCO_3^-				Ca^{2+}				Mg^{2+}			
		2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010
		---------------cm-------------				------------------------------------- Mg ha $^{-1}$ -------------------------------------											
Full AC	Full-A	35.6	40.6	29.2	38.9	0.953	1.09	0.782	1.04	0.546	0.622	0.447	0.596	0.179	0.204	0.147	0.196
	Full-C	34.3	40.6	34.3	40	0.918	1.09	0.918	1.07	0.526	0.622	0.526	0.613	0.173	0.204	0.173	0.201
Ltd f AC	Ltd-fA	22.4	20.3	1.3	38.9	0.600	0.543	0.035	1.041	0.343	0.311	0.020	0.596	0.113	0.102	0.007	0.196
	Ltd-fC	19.8	20.3	24.1	21	0.530	0.543	0.645	0.562	0.303	0.311	0.369	0.322	0.100	0.102	0.121	0.106
Ltd g WC	Ltd-gW	12.7	22.9	3.8	5.1	0.340	0.613	0.102	0.137	0.195	0.351	0.058	0.078	0.064	0.115	0.019	0.026
	Ltd-gC	19.8	20.3	24.1	21	0.530	0.543	0.645	0.562	0.303	0.311	0.369	0.322	0.100	0.102	0.121	0.106
Dry WF/WC	Dry-W	0	3.8	0	3.8	0.000	0.102	0.000	0.102	0.000	0.058	0.000	0.058	0.000	0.019	0.000	0.019
	Dry-F/C	†	3.81	1.27	0	†	0.102	0.034	0.000	†	0.058	0.019	0.000	†	0.019	0.006	0.000

† In 2007 the cropping system was wheat-fallow, but from 2008-2010 the cropping system was changed to wheat-dryland corn. Treatments: fully irrigated-corn (Full C), fully irrigated-alfalfa (Full A), limited irrigation forage corn (Ltd f C), limited irrigation forage alfalfa (Ltd f A), limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), fallow (F) and dry corn (Dry C).

Table 4-2. SIC Stocks in 2007, 2010 and soil pH in 2010, difference of SIC stocks during 2007 to 2010 and the rate of change by depth under different systems in a semi-arid climate.

Depth	Cropping System	Treatments	SIC Stocks		pH 2010	ΔSIC Stock	Change rate
			2007	2010			
			------Mg ha $^{-1}$-----			Mg ha $^{-1}$	Mg ha $^{-1}$ yr^{-1}
0 - 10 cm	Full AC	FullA	4.88bc	4.43c	7.68b	-0.45a	-0.15a
		Full C	3.80c	4.88bc	7.62b	1.08a	0.36a
	Ltd f AC	Ltd f A	5.20bc	5.48bc	7.68b	0.28a	0.09a
		Ltd f C	5.73bc	5.85bc	7.62b	0.12a	0.04a
	Ltd g WC	Ltd g W	9.80a	10.43a	7.87a	0.60a	0.20a
		Ltd g C	8.55ab	9.45ab	7.84a	0.90a	0.30a
	Dry-F/C	Dry W	7.60abc	8.10abc	7.68b	0.50a	0.17a
		Dry F/C	7.15abc	7.75abc	7.70b	0.60a	0.20a
10-20 cm	Full AC	Full A	4.93bc	4.38c	7.67cd	-0.55a	-0.18a
		Full C	4.18c	5.18bc	7.64d	1.00a	0.33a
	Ltd f AC	Ltd f A	5.30bc	6.30bc	7.71cd	1.00a	0.33a
		Ltd f C	5.33bc	6.15bc	7.72cd	0.82a	0.27a
	Ltd g WC	Ltd g W	9.80a	11.00a	7.89a	1.20a	0.40a
		Ltd g C	9.23ab	9.75ab	7.85ab	0.52a	0.17a
	Dry WC	Dry W	7.70abc	8.48abc	7.73bcd	0.78a	0.26a
		Dry F/C	6.83abc	7.35abc	7.79abc	0.52a	0.17a
20-30 cm	Full AC	Full A	4.58c	4.98b	7.72cd	0.40a	0.13a
		Full C	4.65c	4.88b	7.66d	0.23a	0.08a
	Ltd f AC	Ltd f A	5.80bc	6.58b	7.75cd	0.78a	0.26a
		Ltd f C	5.18bc	5.95ab	7.75cd	0.77a	0.26a
	Ltd g WC	Ltd g W	11.4a	12.1a	7.92a	0.68a	0.23a
		Ltd g C	9.90ab	10.0ab	7.88ab	0.13a	0.04a
	Dry-F/C	Dry W	7.73abc	8.15ab	7.76bcd	0.42a	0.14a
		Dry F/C	7.60abc	7.33ab	7.83abc	-0.27a	-0.09a
0-30 cm	Full AC	Full A	14.4c	13.8c	7.69cd	-0.60a	-0.20a
		Full C	12.6c	14.9c	7.64d	2.31a	0.77a
	Ltd f AC	Ltd f A	16.3bc	18.4bc	7.71cd	2.06a	0.69a
		Ltd f C	16.2bc	17.9bc	7.70cd	1.71a	0.57a
	Ltd g WC	Ltd g W	31.0a	33.5a	7.89a	2.48a	0.83a
		Ltd g C	27.7ab	29.2ab	7.86ab	1.55a	0.52a
	Dry WC	Dry W	23.0abc	24.7abc	7.72cd	1.70a	0.57a
		Dry C/F	21.6abc	22.4abc	7.77bc	0.85a	0.28a
30-60 cm	Full AC	Full A	32.8a	33.0a	7.69cd	0.20a	0.07a
		Full C	34.1a	36.4a	7.66d	2.30a	0.77a
	Ltd f AC	Ltd f A	40.3a	42.3a	7.77bcd	2.05a	0.68a
		Ltd f C	37.5a	40.9a	7.74bcd	3.42a	1.14a
	Ltd g WC	Ltd g W	41.4a	44.3a	7.93a	2.84a	0.95a
		Ltd g C	40.7a	43.7a	7.90ab	3.00a	1.00a
	Dry-F/C	Dry W	34.1a	35.0a	7.84abc	0.83a	0.28a
		Dry C/F	34.1a	34.8a	7.84abc	0.70a	0.23a
0-60 cm	Full AC	Full A	47.2c	46.8c	7.69de	-0.40a	-0.13a
		Full C	46.7c	51.3c	7.65e	4.61a	1.54a
	Ltd f AC	Ltd f A	56.6bc	60.7abc	7.74cde	4.11a	1.37a
		Ltd f C	53.7bc	58.8abc	7.72cde	5.13a	1.71a
	Ltd g WC	Ltd g W	72.4a	77.8a	7.91a	5.32a	1.77a
		Ltd g C	68.4ab	72.9a	7.88ab	4.55a	1.52a
	Dry-F/C	Dry W	57.2bc	59.7bc	7.78bcd	2.53a	0.84a
		Dry C/F	55.6bc	57.2bc	7.81bc	1.55a	0.52a

Values followed by a common letter within a column are not significantly different ($p < 0.05$) by Least Significant Differences. Treatments: fully irrigated-corn (Full C), fully irrigated-alfalfa (Full A), limited irrigation forage corn (Ltd f C), limited irrigation forage alfalfa (Ltd f A), limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), dry fallow (dry F) and dry corn (Dry C).

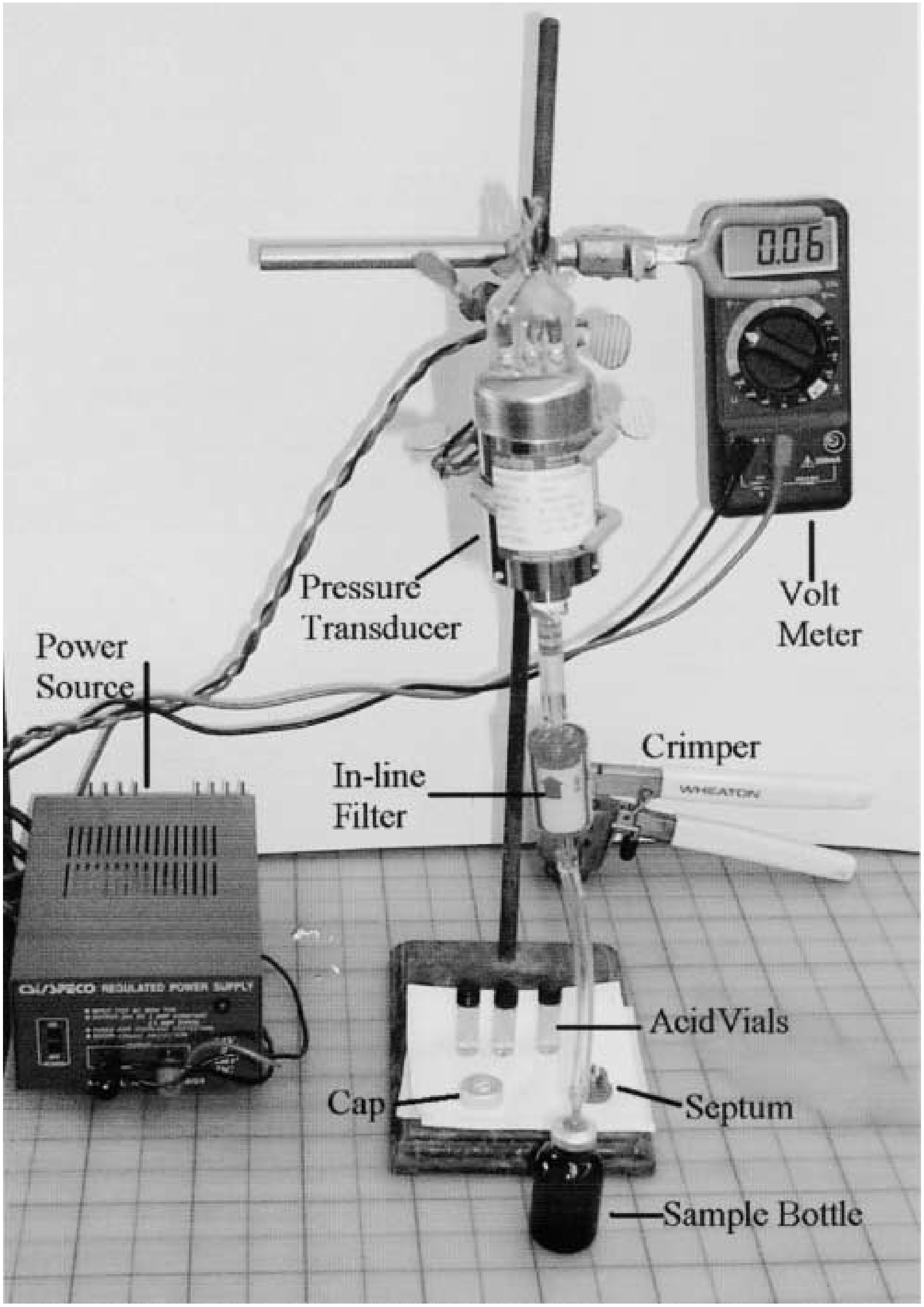

Fig. 4-1. Modified pressure calcimeter method for soil inorganic carbon analysis using Wheaton serum bottles (Wheaton Science Products, Millville, NJ) as the reaction vessel.
Source; Sherrod et al. (2002).

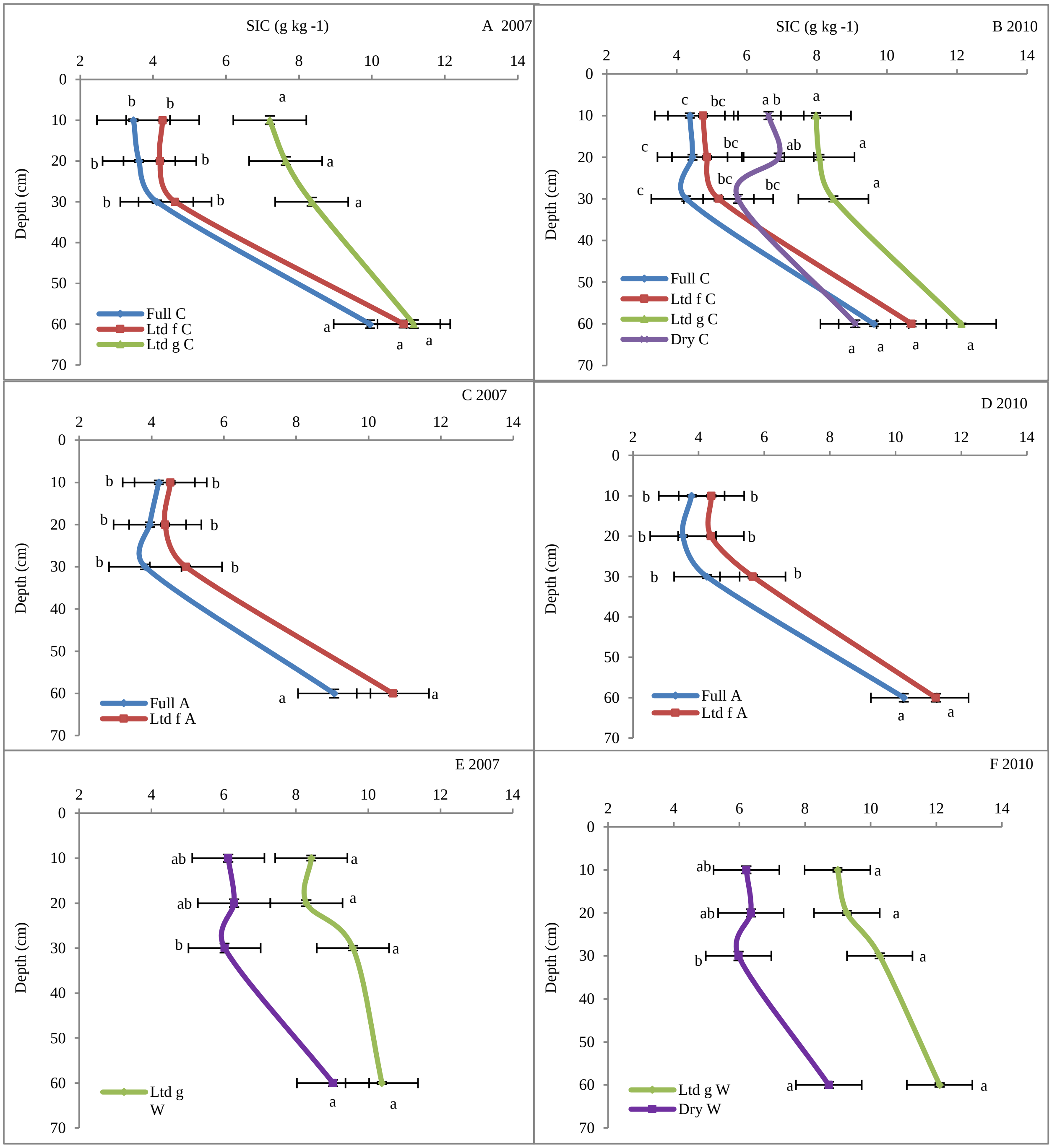

Fig.4-2. Concentration of SIC in 2007 (A, C and E) and 2010 (B, D and F) for corn (A and B), alfalfa (C and D) and wheat (E and F) at four soil depths for different cropping systems in a semi-arid climate. Treatments: full irrigation alfalfa (Full A), Limited irrigation alfalfa (Ltd A), fully irrigated corn (Full C), Limited irrigation forage corn (Ltd f C), limited irrigation grain corn (Ltd g C), dry corn (Dry corn), limited irrigation wheat (Ltd W), and Dry wheat (Dry W). Averages with a common latter at the same depth are not significantly different ($p<0.05$).

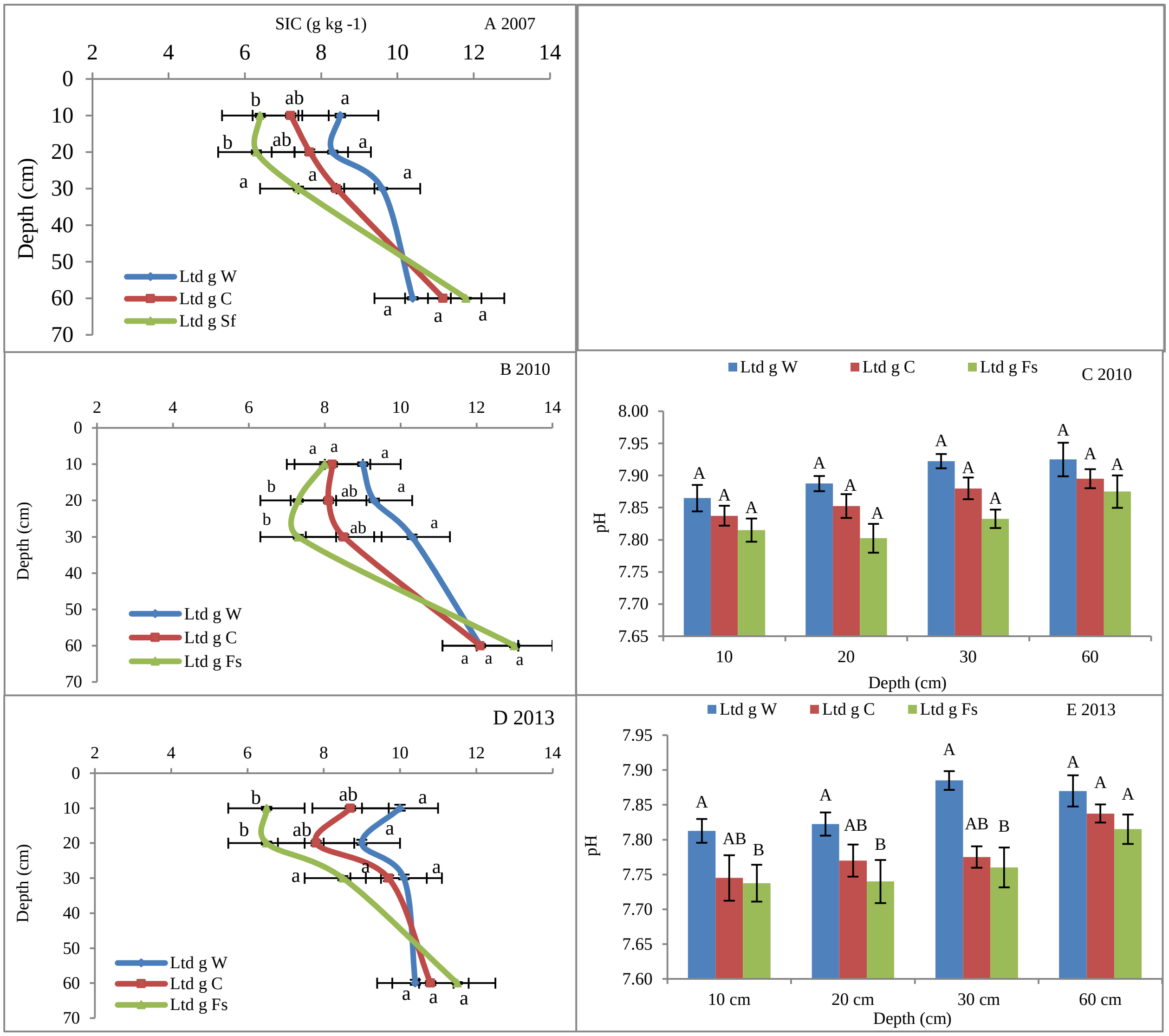

Fig.4-3. Concentration of SIC in 2007 (A), 2010 (B) 2013 (D), pH in 2010 (C) and 2013 (E) for limited irrigation grain corn wheat and sunflower/forage sorghum systems at four soil depths in a semi-arid climate. Treatments: limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), limited irrigation grain sunflower / forage sorghum (Ltd g Sf / Fs). Values followed by different letters are significantly different at ($p < 0.05$) between management treatments.

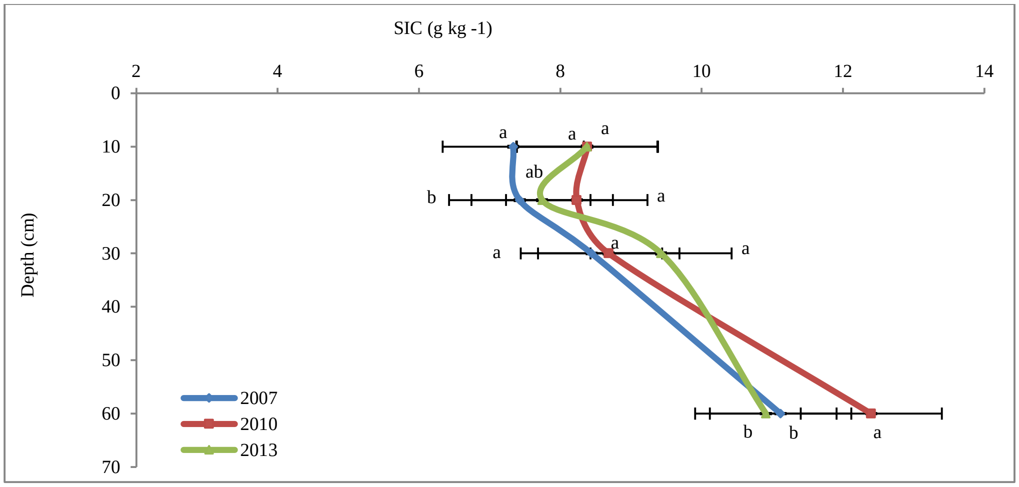

Fig.4-4. The average of SIC concentration during 2007, 2010 and 2013 for limited irrigation grain corn, wheat and sunflower/forage sorghum systems at four soil depths in a semi-arid climate. Values followed by different letters are significantly different at (p <0.05) between management treatments.

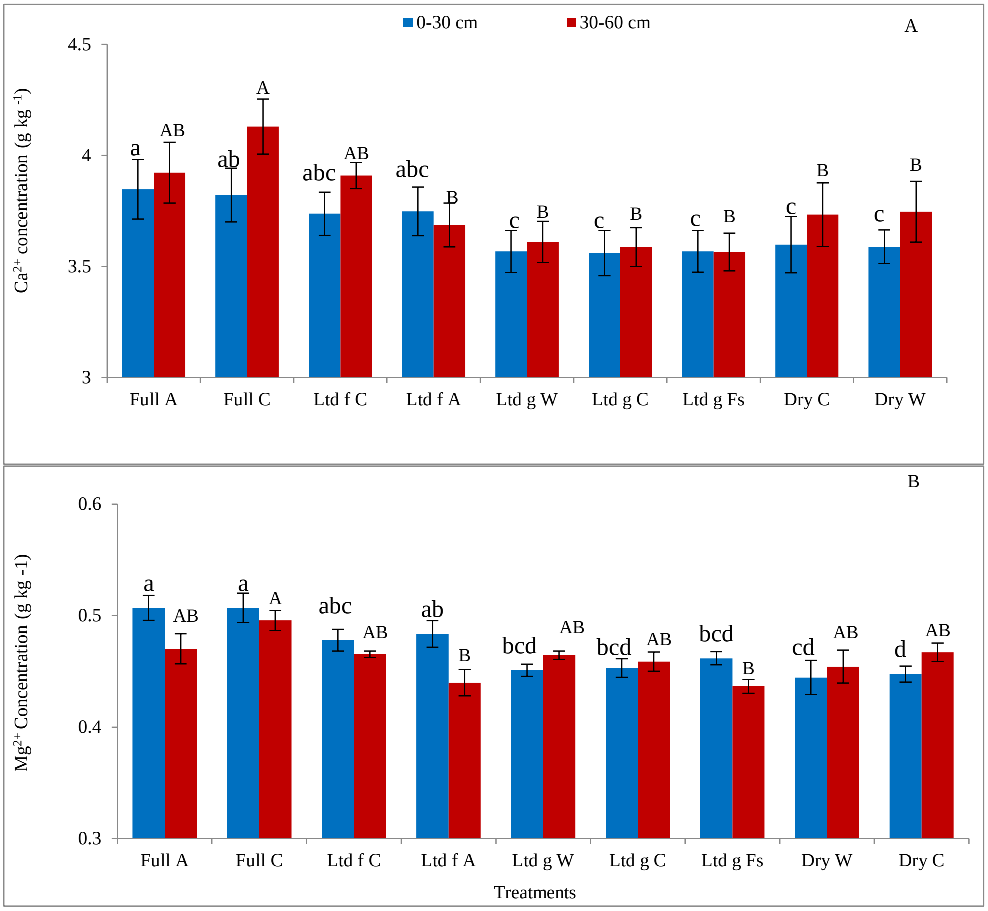

Fig. 4-5. Soil Ca^{2+} (A) and Mg^{2+} (B) concentration (0-30 and 30-60 cm), under different cropping systems in a semi-arid region (2010). Treatments: fully irrigated-corn (Full C), fully irrigated-alfalfa (Full A), limited irrigation forage corn (Ltd f C), limited irrigation forage alfalfa (Ltd f A), limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), limited irrigation forage sorghum (Ltd Fs), dryland wheat (Dry W), dryland corn (Dry C). Values followed by different lowercase letters at (0-30) cm and highercase letters at (30-60) cm depth are significantly different among treatments.

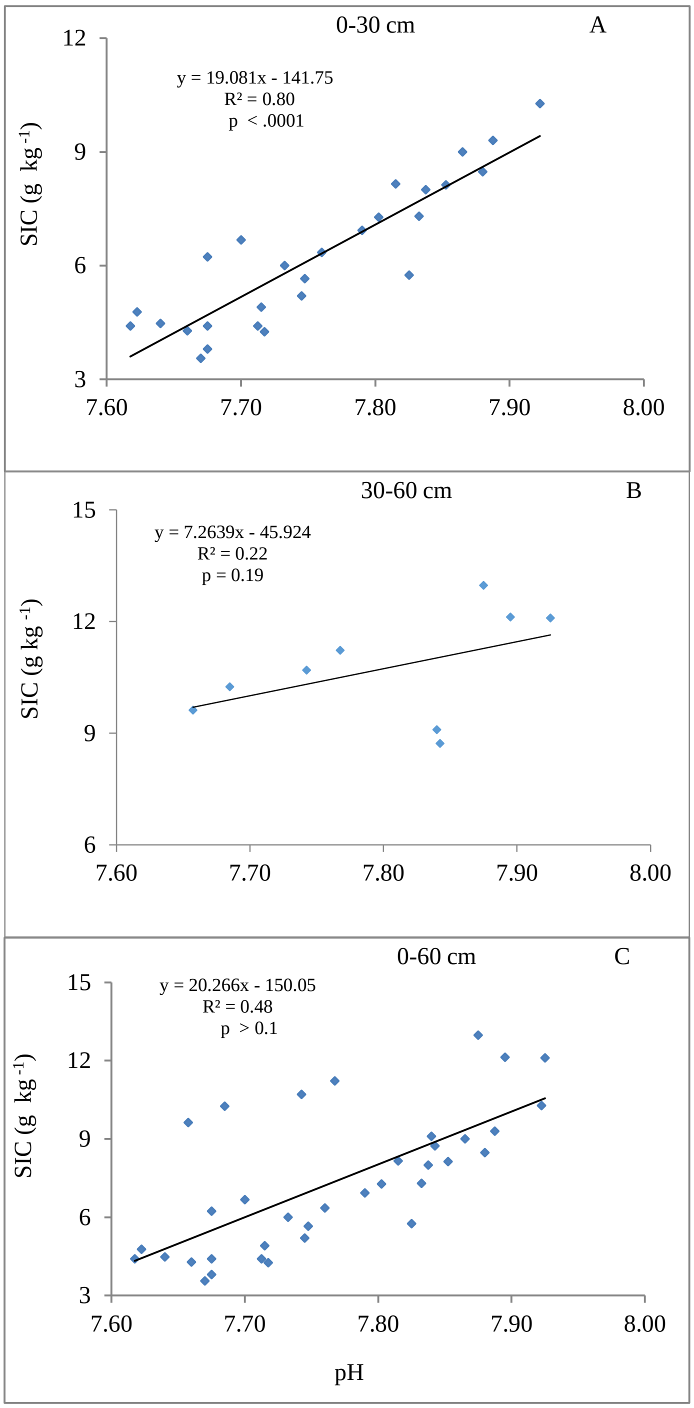

Fig.4-6. Relationship between SIC concentration and soil pH in 2010 at 0-30 cm (A), 30-60 cm (B), and 0-60 cm depth (C) under different cropping systems in a semi-arid region.

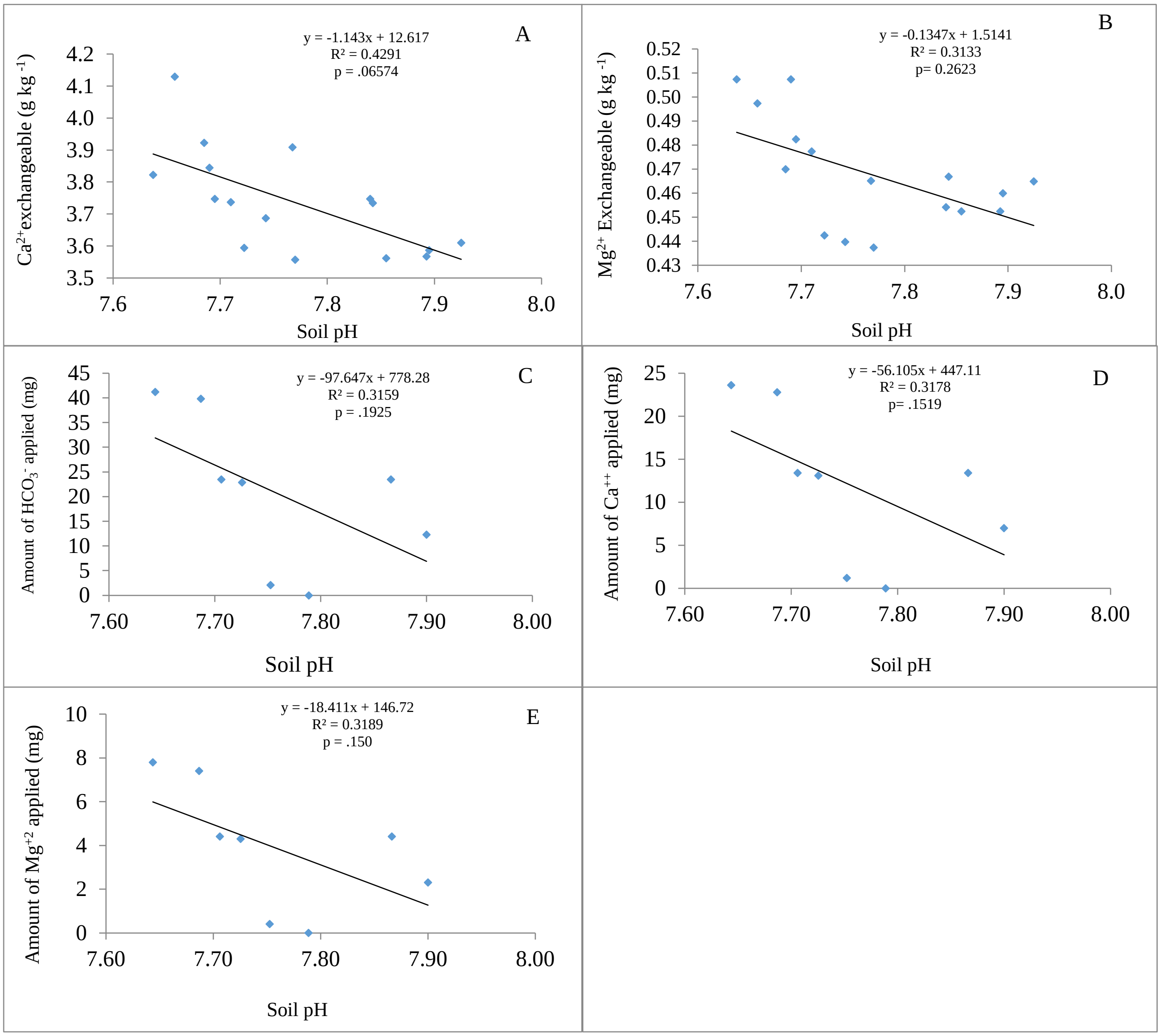

Fig.4-7. Relationship between soil pH and Ca^{2+} (A), Mg^{2+} (B) concentrations, amount of HCO^{-3} (C), Ca^{2+} (D) and Mg^{2+} (E) applied by Irrigation water in 2010 at the 0-60 cm depth under different cropping systems in a semi-arid region.

CHAPTER 5. SUMMARY, CONCLUSION, AND RECOMMENDATIONS

Conversion from full irrigation to limited or dryland crop cultivation are alternative water conservation approaches as Colorado adapts to population growth and increasing demand for water. Therefore, this research was conducted to evaluate the effect of irrigated and dryland cropping systems on soil C and N stocks, soil aggregation and physically protected SOC, and on SIC content in a semi-arid environment over a short-term (3 years).

The first study observed different levels of SOC and TN under full irrigation compared to dryland cropping systems at the 0-20 cm depths. However, below 20 cm SOC and TN contents declined, and no significant differences were found. The fully irrigated and limited irrigation forage cropping systems had the highest SOC and TN concentrations compared to the irrigated grain cropping systems throughout the soil profile (0-60 cm). We found a relationship between the SOC or TN and the amount of irrigation only in the 0-10 cm depth in 2010, but there was no relationship between the SOC or TN and the crop biomass in both years. This suggested that crop rotation may be more important than irrigation level; for example, crops rotated with sunflower had lower SOC and TN concentrations compared to crops rotated with non-sunflower crops even though they got the same amount of irrigation water. These differences were due to combined factors (whole cropping system) not to individual (irrigation or crop) factors. The differences in SOC and TN stocks among the treatments were attributed to changes in concentration of SOC and TN not due to differences in bulk density alone. The distribution of SOC and TN was higher in the surface layers (0-30 cm) compared to subsoil layers (30-60 cm), but the differences among treatments occurred throughout the soil profile (0-60 cm). However, the relationship between SOC and TN (C/N ratio) was observed to be significantly positive ($P < 0.0001$). This suggested that the accumulation of SOM occurred at the same C/N ratio and followed the same mechanism of sequestration under all treatments. On the other hand, the crops rotated with alfalfa had more SOC and TN compared to other crop rotations; however, the C/N ratio was similar to other crops.

In the second study we found a higher percentage of macroaggregates under irrigated treatments compared to dryland treatments, particularly under corn. The significant difference between those treatments was due to the amount of residue added to the soil; a positive relationship was found between the macroaggregate fraction and C inputs. The differences in microaggregate percentage between fully irrigated and dryland treatments were not significant, suggesting that the high percentage of free microaggregates under fully irrigated cropping systems may be due to breaking of bonds that bind the microaggregates to build macroaggregates or due to water droplets causing breakdown of macroaggregates. However, the high percentage of microaggregates under dryland cropping systems may be due to macroaggregates being more susceptible to breakdown as a result of low C input. In general, we found high levels of microaggregates related to macroaggregates under all treatments which may be due to fragmentation of the macroaggregates into microaggregates caused by previous management (plow-based tillage). In contrast, the cPOM under full irrigation was lower than under dryland treatments which may be due to faster decomposition under irrigated treatments decreasing the size of cPOM to induce mM formation. The SOC and TN stocks in the mM fraction under full irrigation were significantly higher relative to dryland crops, particularly in corn treatments. This may be due to the difference in the quality of the crop residue added because there was no relationship between SOC or TN content in mM and the amount of C inputs. It can be inferred from the results that irrigation with no-till management can enhance aggregate formation and increase C sequestration in mM fractions.

The final study showed that the SIC concentration under limited irrigation grain crops was significantly higher than under fully irrigated crops in the 0-30 cm depth. However, the difference was not significant below 30 cm. The difference in soil pH values was the main factor in SIC formation. Accordingly, the cropping systems may have different effects on soil pH. For example, sunflower rotated with grain crop treatments consumed a greater amount of water leaving low soil water content for the following crop. This may effectively have increased soil pH and provided a good environment for carbonate precipitation. Another possibility could be root exudation of either H^+ or OH^- leading to soil pH change. On the other hand, after forage sorghum replaced sunflower in the rotation beginning in 2010, the 2013 SIC values returned to 2007 levels, particularly at the 20 and 60 cm depths. The results show that the SIC stock was higher at the 30-60 cm depth compared to shallower depths, but the difference among treatments was not significant deeper in the soil profile. The high SIC sequestered deeper in the soil profile may be due to percolating water transporting bicarbonate which, in turn, precipitated as $CaCO_3$ or $MgCO_3$.

In addition, we found that the TC stocks were significantly different among different cropping systems in particular, in corn treatments in which Ltd-gC > Full-C at all depths in both years, with an exception of the depth 30-60 cm in 2007 (Table 5-1). However, the effect of treatments on TC stocks in alfalfa and wheat crops were not significant in any depth with the exception of the 30-60 depth in 2010 in which Ltd-gW was higher than Dry-W, and Ltd-fA was higher than Full-A. For the whole treatment comparison, we found that Ltd-gW and Ltd-gC tended to have greater TC stocks compared to Full-C and Full-A at all depths. These differences among treatments may be due to the variation in crop rotation systems that may have differently influenced C accumulation among the treatments. Most of the TC was found in SIC form under all treatments at the 0-30 and 30-60 cm depth in both years (Fig. 5-1 A, B, C and D). Accordingly, the Ltd-gW had the lowest SOC at both depths and had the highest SIC at 0-30 cm. However, there were no significant differences in SIC contents among treatments at 30-60 cm in either year (Fig. 5-1 C and D).

The overall conclusion of this work is that conversion of full irrigation to limited irrigation or dryland cultivation may not pose a large risk in terms of SOC loss, especially when the conversion includes the application of conservation tillage. Macroaggregate formation was not affected by conversion from full irrigation to limited irrigation cropping systems, but the effect was significant when converted to dryland cropping systems. The most important factor controlling the process of SIC formation was soil pH which resulted in high variation in SIC among treatments.

According to our results we recommend that farms in the region with inadequate water supplies to convert from full irrigation to limited irrigation systems with conservation tillage to reduce the risk of SOC loss because limited irrigation cropping systems have less potentially negative impact on soil C and soil aggregates compared to dryland systems. In addition, limited irrigation cropping systems are an important approach to reducing water consumption because they utilize supplemental irrigation instead of full irrigation, and at the same time, they did not affect formation of macroaggregates as long as no-till was utilized. Furthermore, following this approach limited irrigation increased the microaggregate within macroaggregate (mM) fraction that contains stabilized carbon which serves as a sink and source for nutrients. We also recommend farms to avoid planting sunflower in this region with limited available water because it consumes a greater amount of water and leaves very little water available for subsequent crops which, in turn, reduces the SOC content in the soil profile.

For future study we recommend further research including more soil sampling from deeper depths to elucidate the influence of irrigation and cropping systems on C and N storage deeper in the soil profile, because SOC can be transported throughout the soil profile and contribute to subsoil C sequestration. Also, more experimentation on the impact of legumes in rotation is needed to determine their influence on soil microbes and soil C compared to other crops under different irrigation water applications. In this study we had different lengths of rotation cycles, and the comparisons over time are only appropriate after all of these rotations have been completed. Therefore, more soil sample analyses are required after 12 years from the start date to determine the effect of rotations over time.

Table 5-1. TC Stocks in soil (0-10, 10-20, 20-30, and 30-60 cm) under different cropping systems in a semi-arid region during a three-year period (2007-2010).

Depth	Cropping System	Treatments	TC Stocks 2007	TC Stocks 2010
			--------------Mg ha $^{-1}$-----------	
0 - 10 cm	Full AC	Full A	14.5ab	16.6b
		Full C	13.5b	16.2b
	Ltd f AC	Ltd f A	15.2ab	17.3ab
		Ltd f C	15.6ab	17.3ab
	Ltd g WC	Ltd g W	18.5a	19.8a
		Ltd g C	16.9a	19.3a
	Dry-F/C	Dry W	15.9ab	18.1ab
		Dry C/F	16.3ab	17.3ab
10-20 cm	Full AC	Full A	13.6b	14.3b
		Full C	13.3b	14.8b
	Ltd f AC	Ltd f A	14.4ab	15.8ab
		Ltd f C	14.4ab	16.3ab
	Ltd g WC	Ltd g W	18.0a	19.4a
		Ltd g C	17.5a	18.1a
	Dry-F/C	Dry W	16.2ab	17.3ab
		Dry C/F	15.6ab	16.3ab
20-30 cm	Full AC	Full A	12.3b	13.5b
		Full C	12.9b	13.4b
	Ltd f AC	Ltd f A	14.4ab	16.2ab
		Ltd f C	13.5b	15.1b
	Ltd g WC	Ltd g W	17.9a	20.2a
		Ltd g C	17.6a	19.1a
	Dry-F/C	Dry W	15.7ab	16.9ab
		Dry C/F	15.1ab	17.6ab
30-60 cm	Full AC	Full A	50.3a	50.4b
		Full C	51.8a	54.1b
	Ltd f AC	Ltd f A	57.5a	58.2a
		Ltd f C	50.7a	55.8ab
	Ltd g WC	Ltd g W	50.6a	57.1a
		Ltd g C	51.1a	59.5a
	Dry-F/C	Dry W	50.0a	50.9b
		Dry C/F	50.6a	52.3b

Cropping systems: fully irrigated alfalfa-corn (Full AC), limited irrigation forage alfalfa-corn (Ltd f AC), limited irrigation grain wheat-corn (Ltd g WC), and dryland wheat-corn (Dry WC). Treatments: fully irrigated alfalfa (Full A), fully irrigated-corn (Full C), limited irrigation forage alfalfa (Ltd f A), limited irrigation forage corn (Ltd f C) limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), dryland fallow or corn (Dry F/C). Values followed by a common letter within a column are not significantly different ($p < 0.05$) between treatments based on Least Significant Differences.

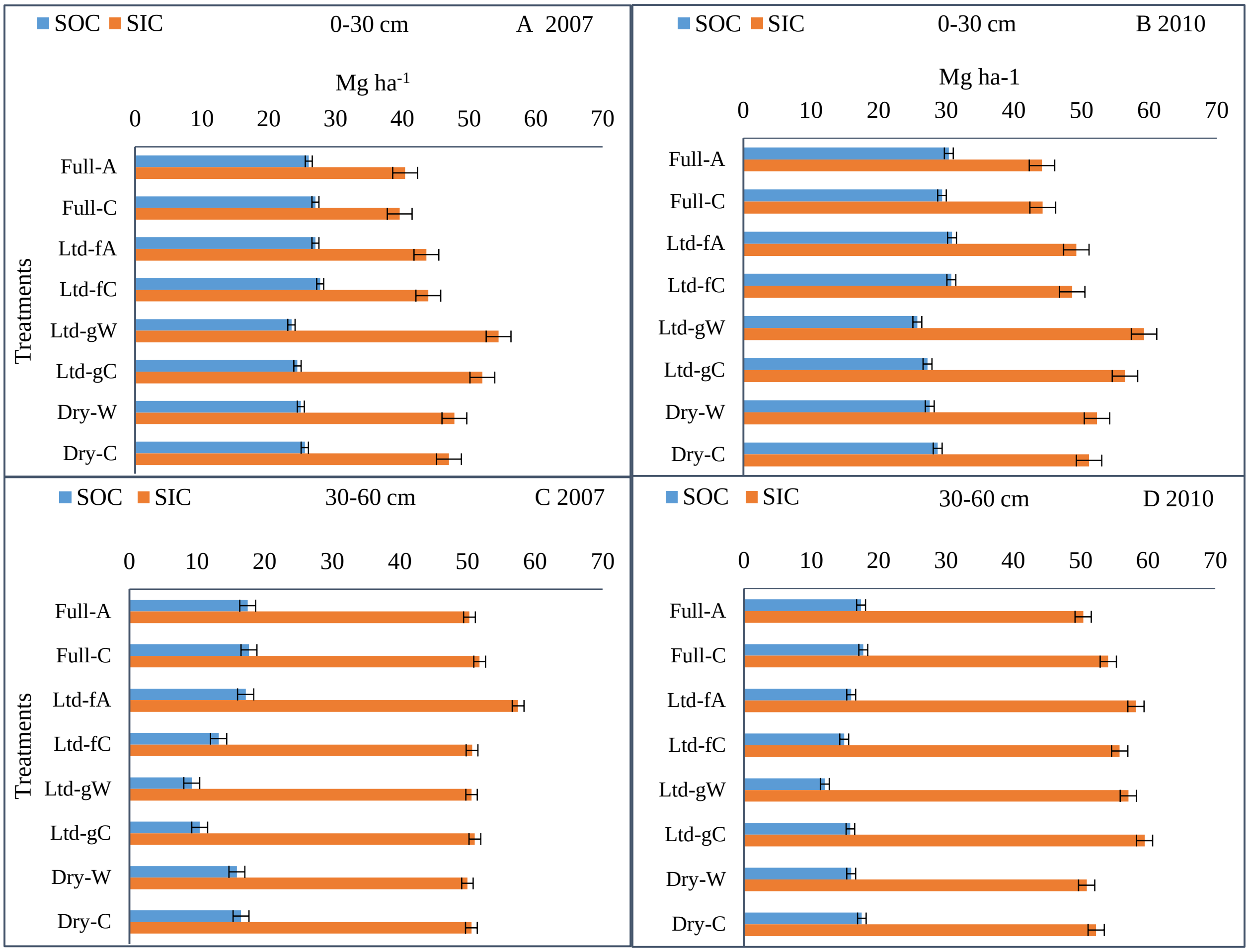

Fig. 5-1. The SOC and SIC Stocks at 0-30 cm (A and B) and at 30-60 cm (C and D) in 200 and 2010, under different cropping systems in a semi-arid region. Treatments:), fully irrigated-alfalfa (Full A), fully irrigated-corn (Full), limited irrigation forage alfalfa (Ltd f A), limited irrigation forage corn (Ltd f C), limited irrigation grain wheat (Ltd g W), limited irrigation grain corn (Ltd g C), dryland wheat (Dry W), dryland corn (Dry C).

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