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# Effects of Irrigation and Nitrogen Fertilizer on Soil Carbon Leaching in Cotton Fields in Arid Areas

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**Abstract:** In order to formulate a reasonable water input model for cotton fields in southern Xinjiang for scientific and rational fertilization, to reduce soil carbon leaching, and to improve soil carbon sequestration capacity, an undisturbed soil column leaching test was used to simulate the current field management method in the study area. Two methods, drip irrigation and flood irrigation, were set up, and three irrigation and three nitrogen fertilizer levels were used to carry out the undisturbed soil column leaching test. The results showed that the amount and mode of water and nitrogen input affected the distribution and leaching loss of organic carbon and inorganic carbon in the soil. When the nitrogen application rate increased from 270 kg·hm$^{-2}$ to 450 kg·hm$^{-2}$, the leaching loss of soluble organic carbon and soluble inorganic carbon increased significantly. When the water input increased from 6000 m$^3$·hm$^{-2}$ to 9000 m$^3$·hm$^{-2}$, the leaching loss of DOC and DIC increased significantly. The carbon leaching loss under drip irrigation was higher than that under flood irrigation. The leaching rates of DOC and DIC were fastest under the conditions of high water (9000 m$^3$·hm$^{-2}$) and high fertilizer (450 kg·hm$^{-2}$). This shows that water and nitrogen input and irrigation methods are important factors affecting soil carbon leaching. In the case of excessive water input, long-term high-frequency irrigation is the main factor affecting carbon leaching.

**Keywords:** arid area; water nitrogen input; DIC; DOC

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## 1. Introduction

The carbon cycle is crucial to the impact of global climate change. The study of the global carbon cycle is one of the important concerns of scholars at home and abroad [1–3]. Dissolved carbon is an important and active chemical component in terrestrial and aquatic ecosystems [4,5], including dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC), which have different ecological and environmental effects. DOC has a high degree of fluidity and is a key link in the biogeology chemical cycle. It plays an important role in the carbon cycle and its distribution in the ecosystem. It can complex with pollutants such as pesticides and heavy metals and become a carrier for the migration of organic and inorganic pollutants [6]. DIC is an important part of the carbon budget, which is crucial in regulating the carbon flux between the three major carbon pools and is a rich carbon pool in inland waters [7]. The migration of DOC from terrestrial ecosystems to aquatic ecosystems will aggravate water pollution and soil carbon pool loss. Therefore, it is of great significance to strengthen the research on the leaching processes of DOC and DIC in farmland soil and their regulatory pathways for the prevention and control of water environment pollution and soil carbon management from the source, and effective soil carbon leaching data can increase the accuracy of estimating the carbon balance of terrestrial ecosystems. This is the basis for further evaluation of carbon transport through soil between aquifer water and inland water [8,9].

The cotton area in the upper reaches of Tarim is the main high-quality cotton producing area in China. With the innovation in the cotton planting mode, the irrigation mode has changed from flood irrigation to drip irrigation, with there previously being four irrigations in the whole growth period, to there now being 8–12 drip irrigations. The cotton area is mainly reclaimed from wasteland, and increasing nitrogen fertilizer is an important crop yield increase measure in this area. The irrigation amount and fertilizer amount are the main factors affecting soil carbon migration in this area, but the effects of different water and nitrogen inputs and water input methods on soil carbon migration in this area have been rarely reported, and the surface soil organic carbon content in this area (generally less than 10 g/kg) is lower than in other soils in China. In addition to the climate, soil properties, and farmland management measures in this area, whether soluble carbon leaching is also an important factor is still unclear. At present, a lot of studies have been performed on the influencing factors of DOC leaching in forest soils (such as soil thickness, soil temperature, soil physical and chemical properties, soil hydrological conditions, etc.) and the chemical structure of DOC in leaching water [10–12]. For DIC, many studies have focused on karst or arid saline areas [13,14], but there is still a lack of research on the leaching of carbon directly from soil water [15]. Overall, there are relatively few studies on the leaching of soluble carbon in farmland ecosystems in arid areas [16–18]. Due to frequent human disturbances such as fertilization in farmland ecosystems, the input of exogenous substances (quantity and quality) and soils' physical and chemical properties are quite different, so the characteristics of soil carbon migration are closely related to fertilization [19]. In this region, most of the related studies have focused on the effects of long-term fertilization on the morphology, structural characteristics, and occurrence mechanism of soil organic carbon [20]. There are few studies on the leaching of soluble carbon from soil under long-term irrigation and fertilization, especially from the perspective of soil DOC and DIC.

Therefore, this study was designed to investigate the leaching of soil DOC and DIC under long-term irrigation and fertilization management of cotton fields in the upper reaches of Tarim. It aimed to provide a theoretical basis for the sustainable development of agricultural planting, such as preventing soil carbon leaching from the source, rationally applying water and fertilizer, and improving soil carbon sequestration.

## 2. Materials and Methods

### *2.1. Test Materials*

The soil texture of the test was sand loam and soil from a depth of 0 to 60 cm was selected. The soil column leaching test (undisturbed soil column) was carried out using a PVC pipe with a diameter of 20 cm and a height of 60 cm. The PVC pipe bottom was connected to a plastic funnel that was vertically fixed on an iron frame platform. A closed bottle was placed under the funnel to collect the leaching solution. In order to prevent the loss of the bottom soil, the soil particles are discharged with water. First, three layers of nylon net are laid at the bottom of the PVC pipe, and then, an iron plate with a high density and small gap is placed in the funnel. To prevent the edge effect, the soil at the edge of the pipe wall is compacted as much as possible, and the gap between the PVC pipe and the funnel is filled with plastic bags and foam glue. Due to the high temperature in Xinjiang in summer, a shading net was set up above the leaching device.

### *2.2. Experimental Design*

The experiment was a three-factor experiment, including the irrigation method, irrigation amount, and nitrogen level. The irrigation method was set to drip irrigation and flood irrigation, and the nitrogen application rate was set to three nitrogen levels (as urea): low N fertilizer 270 kg·hm$^{-2}$, medium N fertilizer 360 kg·hm$^{-2}$, high N fertilizer 450 kg·hm$^{-2}$ (F1, F2, F3). The irrigation amount was set at three levels: low water 6000 m$^3$·hm$^{-2}$, medium water 7500 $m^3 \cdot hm^{-2}$, high water 9000 $m^3 \cdot hm^{-2}$. that is, drip irrigation: D1, D2, D3, and flood irrigation: M1, M2, M3. The phosphate fertilizer application rate was 510 $kg \cdot hm^{-2}$ (potassium dihydrogen phosphate). The experiment used a full combination design, each treatment was repeated three times, a total of 54 treatments.

Cotton sowing: Four holes were dug at 5 cm from the center of the circle in each soil column, and 3–4 seeds were sown in each hole. When the cotton seedlings were 5 cm higher than the horizontal plane of the PVC tube, the seedlings were set. One cotton seedling with good growth was retained in each hole, and four plants were retained in each soil column.

Irrigation: No base fertilizer was applied before irrigation; the water was filled every 8 days for 10 times. Under drip irrigation, nitrogen fertilizer was mixed with water, and poured in ten times. It was dissolved and dripped into the soil with a drip irrigation bottle (the drip irrigation bottle mouth has a rotary knob to control the rate of drip irrigation). The amount of fertilizer applied in each treatment was the same. Under diffuse irrigation conditions, nitrogen fertilizer was applied to the soil five times, and the amount of fertilizer applied in each flood irrigation was twice that of drip irrigation. The fertilizer was dissolved with part of the irrigation water and dumped directly onto the surface of the soil column through the irrigation mouth, and then, the remaining irrigation water was poured onto the soil column to facilitate the fertilizer to be carried into the deep soil. No leakage occurred during the test. The basic physical and chemical properties of the soil are shown in Tables 1 and 2.

**Table 1.** Particle size composition of tested soil.

| Texture | Proportion of Coarse Sand and Gravel 0.2–1 mm | Proportion of Fine Sand Particles 0.02–0.2 mm | Proportion of Silk 0.002–0.02 mm | Proportion of Clay <0.002 |
|---|---|---|---|---|
| sand loam | 5.11 | 65.50 | 24.88 | 4.51 |

**Table 2.** Physical and chemical properties of basic soil.

| Soil Depth (cm) | pH | Electrical Conductivity ($ms \cdot cm^{-1}$) | Available Phosphorus ($mg \cdot kg^{-1}$) | Quick Available Potassium ($mg \cdot kg^{-1}$) | Organic Matter ($g \cdot kg^{-1}$) | Alkaline Hydrolysis Nitrogen ($mg \cdot kg^{-1}$) |
|---|---|---|---|---|---|---|
| 0~20 | 7.52 ± 0.12 | 0.78 ± 0.06 | 49.7 ± 2.97 | 258.5 ± 2.15 | 11.96 ± 1.33 | 20.65 ± 0.82 |
| 20~40 | 7.59 ± 0.21 | 0.94 ± 0.09 | 14.1 ± 1.12 | 168.0 ± 2.03 | 7.38 ± 0.52 | 11.2 ± 1.02 |
| 40~60 | 7.55 ± 0.18 | 0.82 ± 0.03 | 6.6 ± 0.32 | 143.0 ± 1.98 | 5.62 ± 0.32 | 3.15 ± 0.66 |

### *2.3. Determination Items and Methods*

After irrigation, the leachate was collected once a day for the first two days, and then every two days thereafter. Then, the volume of the leaching solution was measured. The leaching solution was stored at 4 °C until determination (<1 week). The leaching solution was pressure-filtered through a 0.45 μm membrane filter, and subsequently, the soluble organic and inorganic carbon was determined using a total organic carbon analyzer (Shimadzu, Kyoto, Japan).

$$\text{Soluble carbon content (mg)} = \text{soluble carbon concentration } (mg \cdot L^{-1}) \times \text{leaching solution volume (L)}$$

$$\text{Leaching rate } (mg \cdot d^{-1}) = \text{leaching amount (mg)/leaching solution collection time (d)}$$

### *2.4. Data Processing and Analysis*

SPSS 26.0 (PSS, Chicago, IL, USA) was used for the statistical analysis. Tukey-HSD analysis of variance was employed to compare the effects on the responses of the total soluble inorganic carbon leaching, total soluble organic carbon leaching, and total soluble carbon leaching rates under different treatments. The Origin 2018 software was used for plotting.

## 3. Results and Analysis

### 3.1. Effect of Different Water and Nitrogen Input on Soluble Carbon Content in Leaching Solution

Some studies have shown that only a very small amount of carbon is leached in the topsoil, and dissolved carbon (DIC, DOC) in the leachate is the main leaching form of carbon [21]. It can be seen from Figure 1 that the content of dissolved organic carbon (DOC) in the leaching solution increased first and then decreased with the increase in the leaching time.

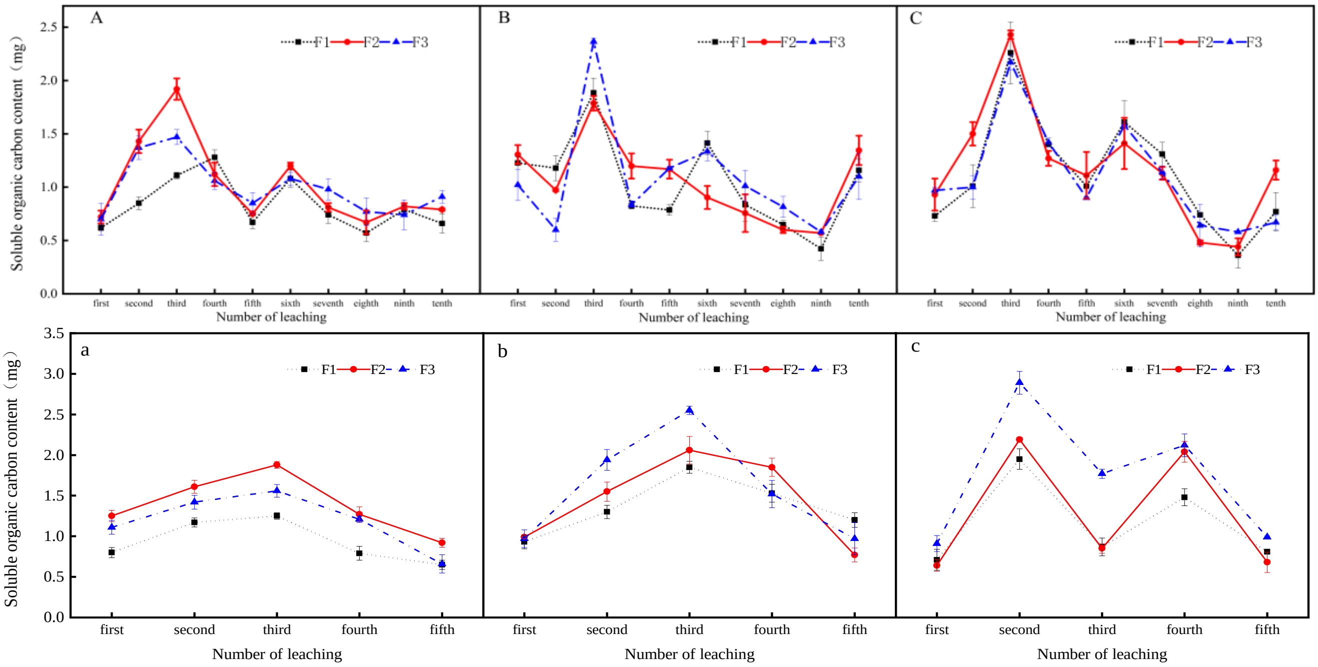


**Figure 1.** Effects of different water and nitrogen levels on DOC content in soil leaching. Note: (**A**–**C**) refer to three irrigation amounts under drip irrigation, namely, D1: 6000 $m^3$ $hm^{-2}$; D2: 7500 $m^3$ $hm^{-2}$; and D3: 9000 $m^3$ $hm^{-2}$. (**a**–**c**) The three irrigation amounts under the conditions of flood irrigation, namely, M1: 6000 $m^3$ $hm^{-2}$; M2: 7500 $m^3$ $hm^{-2}$; and M3: 9000 $m^3$ $hm^{-2}$.

The DOC content under drip irrigation was higher than that under flood irrigation, and the DOC content under each treatment ranged from 0.62 to 1.92 mg under the D1 condition. The DOC content ranged from 0.43 to 2.41 mg under the D2 condition. The DOC content ranged from 0.46 to 2.43 mg under the D3 condition. The DOC content ranged from 0.66 to 1.88 mg under the M1 condition. Under the M2 condition, the DOC content ranged from 0.77 to 2.55 mg. Under the condition of M3, the DOC content ranged from 0.64 to 2.89 mg, indicating that the DOC content in the leaching solution increased with the increase in the irrigation amount. The content of dissolved organic carbon in the third leaching was the largest under the three irrigation amounts, indicating that DOC may move from the surface to the deep layer at the initial stage of leaching. Under the condition of M3, the maximum leaching appeared only at the second leaching, indicating that the increase in the irrigation amount accelerated the migration of DOC to the lower layer and accelerated the leaching rate. The DOC contents in the F2 and F3 treatments were generally higher than that in the F1 treatment under the three drip irrigation amounts, indicating that increasing the amount of nitrogen will lead to an increase in the leaching loss of organic carbon.

Under the condition of drip irrigation, the content of soluble inorganic carbon (DIC) increased first, then decreased, and then increased during the ten leaching processes (Figure 2). The content of DIC under the D1 condition ranged from 0.69 to 3.11 mg; under the condition of D2, the DIC content ranged from 1.12 to 3.73 mg. The DIC content ranged from 0.94 to 3.67 mg under the D3 condition. The peaks of the DIC leaching content under the three drip irrigation amounts all appeared in the third leaching, and the second peak appeared in the sixth or seventh. This may be because for flood irrigation, when the soil is dry, the increase in water content in the soil leads to an increase in the DIC concentration, and an increase in DIC content in the later period due to the weak respiration of root activity in the early stages of crop growth. The DIC leaching losses under the D2 and D3 conditions were higher than that under D1, indicating that the greater the amount of crop irrigation, the greater the leaching loss of inorganic carbon.

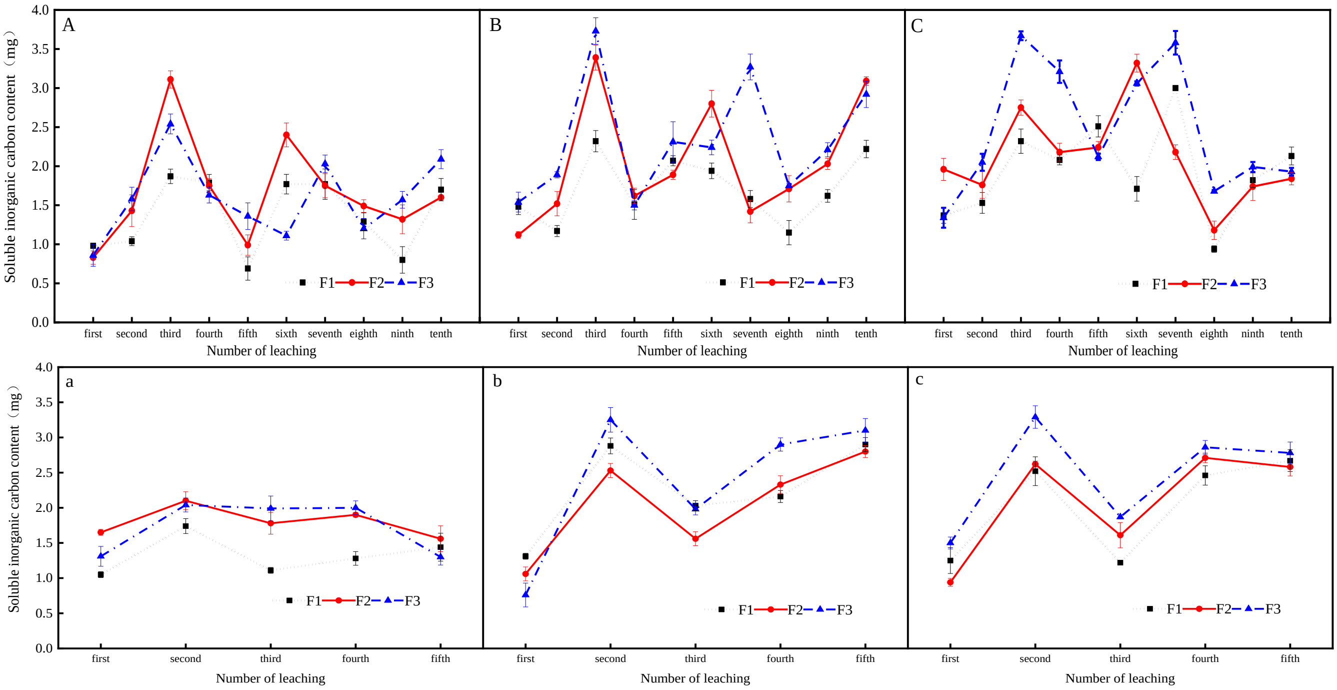


**Figure 2.** Effects of different water and nitrogen levels on DIC content in soil leaching. Note: (**A**–**C**) refer to three irrigation amounts under drip irrigation, namely, D1: 6000 m$^3$ hm$^{-2}$; D2: 7500 m$^3$ hm$^{-2}$; and D3: 9000 m$^3$ hm$^{-2}$. (**a**–**c**) The three irrigation amounts under the conditions of flood irrigation, namely, M1: 6000 m$^3$ hm$^{-2}$; M2: 7500 m$^3$ hm$^{-2}$; and M3: 9000 m$^3$ hm$^{-2}$, respectively.

Under the condition of M1, the DIC content ranged from 1.05 to 2.04 mg; under the condition of M2, the DIC content ranged from 0.76 to 3.25 mg; under the condition of M3, the DIC content ranged from 0.94 to 3.29 mg. The maximum value of DIC leaching content under the three flood irrigation amounts all appeared in the second leaching, and the DIC contents in the leaching solutions in the M3 treatment and the M2 treatment were higher than that in M1, indicating that the first flood irrigation was due to the drought of the soil. The DIC leaching was not complete, the DIC migration distance was short, and the deep soil DIC interception was high, so the leaching loss was small. When the irrigation amount was increased, the DIC leaching amount also increased and the DIC content increased. Under the three flood irrigation conditions, the DIC contents of the F2 and F3 treatments were higher than that of the F1 treatment, indicating that after the increase in nitrogen fertilizer application, nitrification may aggravate the dissolution and release of soil carbonate and increase the DIC leaching content.

### *3.2. Effects of Different Water and Nitrogen Inputs on the Total Amount of Soil Soluble Carbon Leaching*

From Figure 3, it can be seen that different drip irrigation amounts and different nitrogen application rates have different effects on the total amount of soil dissolved organic carbon DOC leaching. The D3F2 treatment had the highest DOC leaching amount of 11.86 mg, significantly higher than the D1F1, D1F2, and D1F3 treatments; the minimum leaching loss, in the D1F1 treatment, was 8.37 mg. Under the same nitrogen level, F1, the D3 treatment was 33.8% higher than the D1 treatment and 6% higher than the D2 treatment, indicating that increasing the amount of drip irrigation will increase the leaching loss of DOC when the nitrogen application rate is low. Under the F2 condition, there was no significant difference between the D1 and D2 treatments, and the leaching loss of the D3 treatment was significantly higher than that of the D1 treatment, by 15.93%. Under the F3 condition, there was no significant difference between the treatments. This indicates that the increase in drip irrigation amount leads to an increase in DOC leaching amount, which is related to an increase in soil column water content during drip irrigation, which leads to the rapid leaching of DOC in the leaching process after the soil water content reaches saturation. Under the same drip irrigation amount, D1, the DOC leaching loss in the F1 treatment was significantly lower than those in the F2 and F3 treatments. Under the condition of D2, there was no significant difference between the treatments, but F3 had the highest leaching loss. Under the condition of D3, the leaching loss in the F2 treatment was higher than those in the F1 and F3 treatments.

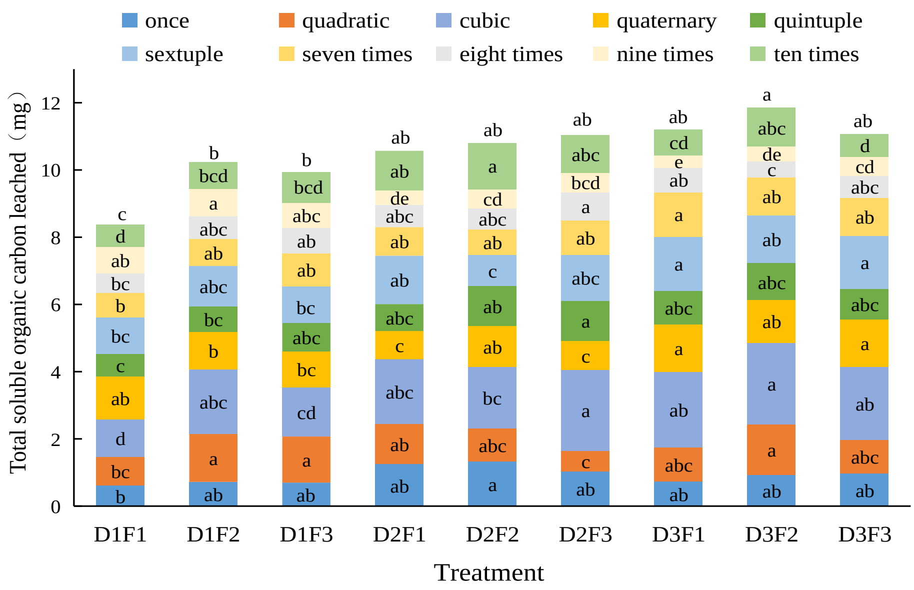


**Figure 3.** Effects of different water and nitrogen inputs on total soil soluble organic carbon (DOC) leaching under drip irrigation. Note: lowercase letters indicate the difference between nitrogen application and irrigation at the same leaching times ($p$ < 0.05).

The total amount of DOC leaching in the M3F3 treatment was 8.68 mg, which was significantly higher than that in other combinations (Figure 4). The total leaching amount of the M1F1 treatment was 4.66 mg. Under the same nitrogen level, F1, the M2 treatment was significantly higher than the M1 treatment, by 46.1% ($p$ < 0.05). There was no significant difference between the treatments under the F2 condition. Under the F3 condition, the M3 and M2 treatments were significantly higher than the M1 treatment, by 45.63% ($p$ < 0.05) and 33.39% ($p$ < 0.05), respectively. This shows that the increase in flood irrigation amount increases the total amount of DOC leaching, which may be due to the large amount of irrigation water leaching and migration of surface soil organic carbon, resulting in an increase in loss, while the decrease in irrigation amount leads to a slower migration rate and a smaller loss of DOC. Under the same flood irrigation condition, the leaching loss of the F2 treatment under the M1 condition was significantly higher than that of other treatments, and the total leaching amount was 6.93 mg. Under the condition of M2, the F3 treatment was significantly higher than the F1 treatment, by 16.74% ($p$ < 0.05); under the condition of M3, the F3 treatment was significantly higher than the F1 and F2 treatments, by 49.14% and 35.63%, respectively ($p$ < 0.05). This shows that the leaching loss of soluble organic carbon increases with the increase in nitrogen application rate under flood irrigation.

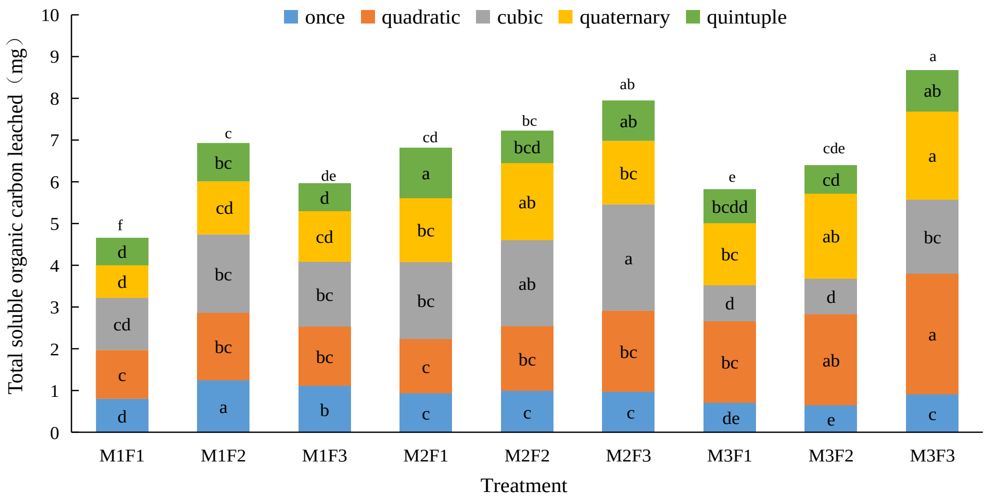


**Figure 4.** Effects of different water and nitrogen inputs on total leaching of soil soluble organic carbon (DOC) under flood irrigation. Note: lowercase letters indicate the difference between nitrogen application and irrigation at the same leaching times ($p < 0.05$).

The total amount of soil DIC leaching under drip irrigation was significantly different due to different water and nitrogen inputs (Figure 5). The total leaching amount of DIC in the D3F3 treatment was 24.63 mg, which was significantly higher than that in other combinations. The total amount of DIC leaching in the D1F1 treatment was 13.7 mg, which was significantly lower than in other treatments. Under the same nitrogen levels, F1 and F2, the total amount of DIC leaching in the D3 treatment was significantly higher than that in the D1 treatment. Under the condition of F3, the D3 treatment was significantly higher than the D1 treatment (54.23%), and higher than the D2 treatment (5.43%) ($p < 0.05$). The results showed that under the same nitrogen level, the DIC leaching loss increased with the increase in drip irrigation amount. This is because when the irrigation amount increases, the soil moisture exceeds the field capacity, resulting in an increase in DIC concentration, resulting in an increase in soil DIC leaching. Under the same drip irrigation condition, the total leaching amount of DIC in the F2 treatment was significantly higher than that in the F1 treatment, by 21.68% under the D1 condition ($p < 0.05$). When the irrigation amount was D2, the total leaching amount in the F3 treatment was significantly higher than that of the F1 treatment, by 6.3 mg, and higher than that in the F2 treatment by 2.77 mg. Under the condition of D3, the total leaching amount in the F3 treatment was higher than those in the F1 and F2 treatments by 26.89% and 16.45%, respectively. This shows that the increase in nitrogen application will increase the leaching loss of DIC, which may be due to the increase in carbonate dissolution caused by a large amount of nitrogen fertilizer input, which accelerates the loss of soil carbonate.

The effects of different water and nitrogen inputs on the total amount of soil DIC leaching under flood irrigation were significantly different (Figure 6). Under the same nitrogen level, the total amount of soil soluble inorganic carbon leaching under the F1 treatment was 11.28 mg. Under the F2 and F3 conditions, the greater the irrigation amount, the higher the total amount of soluble inorganic carbon leaching. This shows that when the nitrogen application rate is constant, the greater the amount of crop flooding, the more the DIC leaching loss. This may be related to the increase in the irrigation method and irrigation amount, which leads to the strengthening of water gravity and accelerates the migration of DIC in soil. Under the condition of M1, the total amount of DIC leaching in the F1 treatment was the least; under the condition of M2, the leaching amount in the F3 treatment was significantly higher than that in the F2 treatment, by 16.63% ($p < 0.05$); under the condition of M3, the DIC leaching loss in the F3 treatment was significantly higher than those in the F1 and F2 treatments, by 21.54% and 17.59% ($p < 0.05$). This shows that an increase in fertilizer application may promote the leaching of DIC.

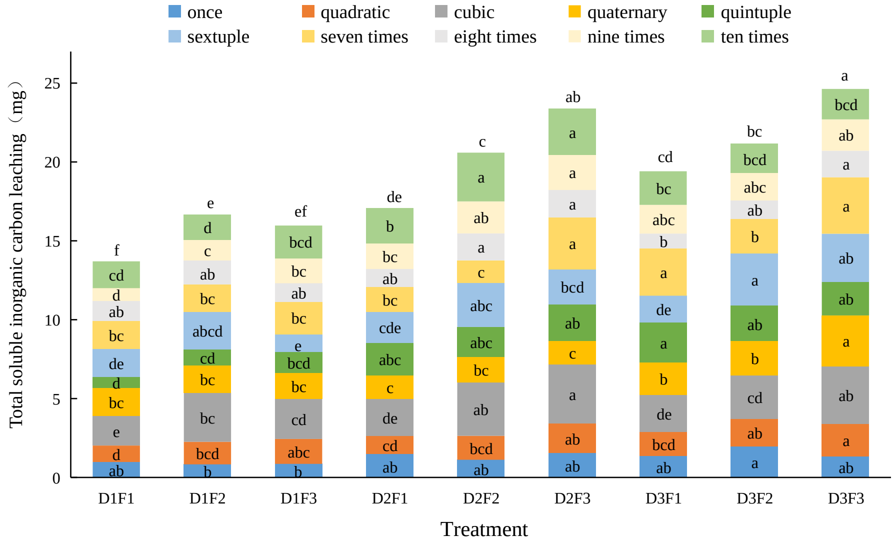


**Figure 5.** Effects of different water and nitrogen inputs on total soil soluble inorganic carbon (DIC) leaching under drip irrigation. Note: lowercase letters indicate the difference between nitrogen application and irrigation at the same leaching times ($p < 0.05$).

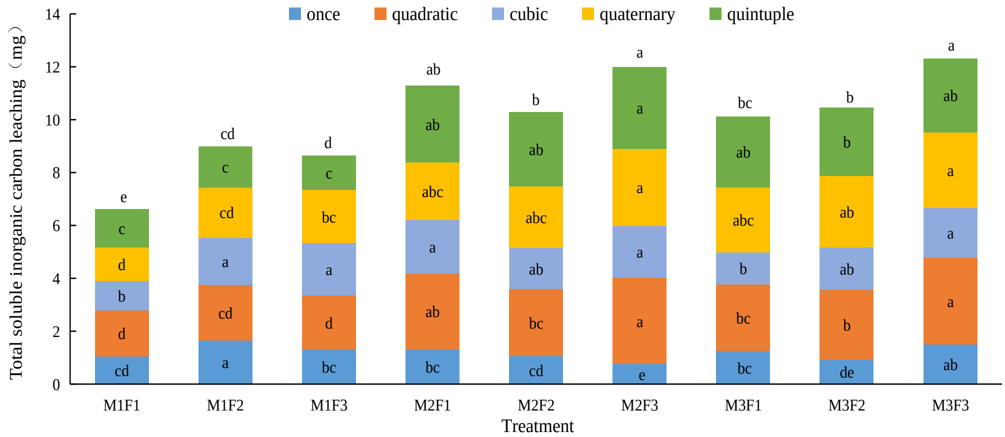


**Figure 6.** Effects of different water and nitrogen inputs on total leaching of soil soluble inorganic carbon (DIC) under flood irrigation. Note: lowercase letters indicate the difference between nitrogen application and irrigation at the same leaching times ($p < 0.05$).

### *3.3. Effects of Different Water and Nitrogen Inputs on the Leaching Rate of Soluble Carbon*

From Table 3, it can be seen that the leaching loss rate of soluble organic carbon is the highest under the M3F3 treatment, which is 0.58 mg·d$^{-1}$, and the DOC leaching rate under the D1F1 treatment is the lowest, which is 0.28 mg·d$^{-1}$. Under the conditions of D2, M2, and M3, the leaching rate of soluble organic carbon in the F3 treatment was higher than those in the F1 and F2 treatments. This indicates that the leaching loss rate of soluble organic carbon increased with the increase in the nitrogen fertilizer application rate under a large irrigation amount. The DOC leaching loss rates in F2 under the D1, D3, and M1 treatments were higher than those in the F1 and F3 treatments. Under the same amount of nitrogen fertilizer, the leaching loss rate of soluble organic carbon increased with the increase in the drip irrigation amount, which may be related to the increase in irrigation amount, which accelerated the migration of soluble organic carbon in soil. Under the F1 and F2 conditions, the DOC leaching rate in the M2 treatment was higher than those in the M1 and M3 treatments. The leaching rate of soluble organic carbon in the M3 treatment was the highest under the F3 condition. This shows that the increase in irrigation amount during flood irrigation may increase the DOC content in the soil and accelerate the DOC leaching rate. Under the same nitrogen application rate, the DOC leaching loss rate under drip irrigation was lower than that under flood irrigation.

**Table 3.** Effects of different water and nitrogen inputs on soluble carbon leaching rates (mg·d$^{-1}$).

| Item | N-Rate | Irrigation Regime | | | | | |
|---|---|---|---|---|---|---|---|
| | | D1 | D2 | D3 | M1 | M2 | M3 |
| DOC | F1 | 0.28 ± 0.012 bC | 0.35 ± 0.004 aB | 0.37 ± 0.015 aB | 0.31 ± 0.003 cC | 0.45 ± 0.014 bA | 0.39 ± 0.01 cB |
| | F2 | 0.34 ± 0.004 aD | 0.36 ± 0.025 aCD | 0.40 ± 0.010 aBCD | 0.46 ± 0.021 aAB | 0.48 ± 0.055 bA | 0.43 ± 0.01 b ABC |
| | F3 | 0.33 ± 0.013 aC | 0.37 ± 0.015 aB | 0.37 ± 0.001 aBC | 0.40 ± 0.004 bB | 0.53 ± 0.032 aA | 0.58 ± 0.02 aA |
| DIC | F1 | 0.46 ± 0.039 bD | 0.57 ± 0.050 cC | 0.65 ± 0.012 cB | 0.44 ± 0.011 bD | 0.75 ± 0.009 abA | 0.67 ± 0.00 cB |
| | F2 | 0.56 ± 0.008 aC | 0.69 ± 0.017 bA | 0.71 ± 0.014 bA | 0.60 ± 0.006 aB | 0.69 ± 0.007 bA | 0.70 ± 0.00 bA |
| | F3 | 0.53 ± 0.015 aE | 0.78 ± 0.022 aC | 0.85 ± 0.001 aA | 0.58 ± 0.026 aD | 0.80 ± 0.072 aBC | 0.82 ± 0.01 aAB |

Note: Capital letters indicate the difference between different irrigation methods and irrigation amounts ($p < 0.05$); lowercase letters represent the difference between different nitrogen application rates under the same irrigation method and irrigation amount ($p < 0.05$).

The leaching loss rate of soluble inorganic carbon in the D3F3 treatment was significantly higher than that in other combinations ($p < 0.05$). Under the conditions of 0.82 mg·d$^{-1}$, D2, D3, M1, and M3, the leaching loss rate of soluble inorganic carbon in the F3 treatment was significantly higher than those in the F1 and F2 treatments ($p < 0.05$). Under the condition of D1, the DIC leaching loss in the F2 treatment was significantly higher than that in the F1 treatment ($p < 0.05$). Under the condition of M2, the DIC leaching loss rate in the F3 treatment was significantly higher than those in the F1 and F2 treatments. This shows that the leaching loss rate of soluble inorganic carbon in soil increases with an increase in the nitrogen application rate. Under the same nitrogen application rate, the leaching loss rate of soluble inorganic carbon increased with the increase in drip irrigation amount. The DIC leaching loss rate in the M2 treatment was significantly higher than those in the M1 and M3 treatments under the F1 condition. the loss rate of DIC in M3 in F2 and F3 was higher than that of M1 and M2. Suggesting that the increased perfusion volume enhances the leaching rate of the DIC.

## 4. Discussion

The amount of water and nitrogen input and the irrigation method are the main influencing factors of carbon leaching in soil. The results of this study showed that when the nitrogen application rate was the same, the soil soluble organic carbon and soluble inorganic carbon dissolution rate increased with an increase in the irrigation amount, and the leaching loss increased significantly. This is mainly because irrigation significantly affects the soil solute transport process [22]. The amount of organic carbon leaching obtained under different leaching times was different. Under the three drip irrigation amounts, the F1, F2, and F3 treatments all reached the maximum DOC leaching amount at the third leaching, and the DOC leaching loss increased with the increase in the drip irrigation amount. In flood irrigation, the maximum leaching loss of DOC appeared in the third leaching under the M1 and M2 conditions, while the maximum leaching loss appeared only in the second leaching under the M3 condition, indicating that the increase in irrigation amount accelerated the migration of DOC to the lower layer and accelerated the leaching rate. Consistent with the results of this study, Wang Hongxia [21] found that the amount of DOC leached in the third leaching was higher than that in the first leaching through soil column simulation experiments. This is because the soil has a strong adsorption of DOC during the initial leaching, and the DOC is desorbed with the increase in leaching times. The amount of irrigation has a certain effect on the leaching of inorganic carbon [23]. This study shows that the greater the amount of crop irrigation under the same nitrogen level, the faster the leaching rate, and the higher the DIC content in the leaching solution. This is because vertical carbon loss will accelerate with increased precipitation [24]. Through this experiment, it was found that the amount of DIC leaching by agricultural irrigation in arid areas was very considerable, significantly higher than that of DIC leaching, which was consistent with the view of Schulze [25], that the increase in water content in soil increased the concentration of DIC, and DIC was difficult to maintain the easier the leaching in the soil. In addition, this study showed that the carbon leaching loss of drip irrigation was significantly higher than that of flood irrigation under high water input (irrigation amount 9000 $m^3 \cdot hm^{-2}$) and two irrigation methods.

Excessive use of fertilizers is the main factor causing the loss of soluble carbon and nitrogen in soil [26]. At present, most of the common fertilizers on the market are instant fertilizers, which have a fast dissolution rate and high concentration after application. However, they are easy to leach, affecting the absorption of nutrients by crops [27]. The results of this study showed that when the flood irrigation amount was the same, the leaching loss of soluble carbon and nitrogen increased with an increase in nitrogen application rate (from F1 to F3). This shows that the increase in nitrogen input will promote the leaching rate of soluble carbon and nitrogen and increase the leaching loss. Consistent with the results of this study, Lu et al. [28] showed that nitrogen addition caused an increase in soil DOC concentration, because nitrogen input promoted crop growth, increased low-molecular-weight carbon-containing organic secretions in litter and roots, and increased soil soluble organic carbon concentration. Studies have shown that fertilization promotes DIC leaching [29], which is caused by a large amount of nitrogen fertilizer input that increases the amount of carbonate dissolution and accelerates soil carbonate loss. Cui Jiaojiao [30] also concluded that the application of nitrogen fertilizer significantly increased the content of water-soluble calcium and magnesium ions in soil and accelerated the leaching loss of calcium and magnesium ions, which was consistent with the conclusions of this experiment. It may also be because fertilization increased the crop growth rate, and increased root respiration and inorganic carbon leaching [31].

Through this study, it was found that the risk of soil carbon leaching increased after the long-term high-frequency input of water and fertilizer. In the future, the environmental risk caused by carbon leaching should be fully considered in the process of crop cultivation.

## 5. Conclusions

The leaching loss of soluble carbon in cotton fields in the experimental area was not high. The total leaching loss of soluble organic carbon was 4.66–11.86 mg, and the total leaching loss of soluble inorganic carbon was 6.62–24.63 mg. The amount of carbon leaching under drip irrigation was higher than that under flood irrigation. The amount of water and nitrogen input and irrigation methods were the factors affecting the leaching of soil carbon. Under the conditions of drip irrigation and high water (D3), the leaching loss of DOC and DIC was the highest. Under the conditions of high water (9000 $m^3 \cdot hm^{-2}$) and high fertilizer (450 $kg \cdot hm^{-2}$), the leaching rate of DOC and DIC was the fastest, indicating that under the condition of excessive water input, long-term high-frequency irrigation was the main factor affecting carbon leaching. Long-term application of nitrogen fertilizer increased the leaching risk of DOC and DIC in the soil profile. Therefore, in order to reduce carbon leaching loss in cotton production, the irrigation amount should be controlled. Drip irrigation, medium nitrogen (nitrogen application rate of 360 $kg \cdot hm^{-2}$) and medium water (irrigation amount of 7500 $m^3 \cdot hm^{-2}$) can be used as the recommended water and nitrogen input methods and inputs for cotton in the experimental area. The leaching of DOC and DIC in soil mainly occurred in the whole profile of 0~60 cm. From the results of this study, it is of great significance to understand the transport process of soluble carbon in farmland soil during the water cycle in arid areas, and to provide effective data support for further estimating the leaching effect of agricultural irrigation in arid areas. In addition, attention should be paid to the risk of organic and inorganic compound pollution and carbon pool loss caused by carbon leaching in regional water bodies.

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