

Article

Effects of Dissolved Organic Carbon Leaching and Soil Carbon Fractions Under Intercropping *Dactylis glomerata* L.–*Medicago sativa* L. in Response to Extreme Rainfall

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Abstract: Climate change aggravates the frequency of extreme rainfall events, resulting in carbon (C) loss. For the special climate of the highlands, cultivating the land underneath orchards increases C reservation. Systematic research on the impact of extreme rainfall on soil organic carbon compositions and (dissolved organic carbon) DOC leaching is limited, especially regarding the response to different cropping patterns underneath orchards, requiring a deeper understanding. The results showed that the DOC-leaching fluxes for the cropping patterns under rainstorms and heavy rainstorms were in the order *Dactylis glomerata* L. monocropping (13.5, 4.4 kg/hm²) > *Medicago sativa* L. monocropping (11.2, 3.8 kg/hm²) ≥ *D. glomerata*. + *M. sativa*. (10.4, 3.6 kg/hm²). The DOC-leaching fluxes during heavy rainstorms were reduced with D + M, and the root morphology showed a significant correlation with DOC concentration. Compared to the D, SOC in layers 40–60 cm of the M and the D + M increased by 68.36% and 64.24%, respectively. TP and POC of the D + M increased with soil depth. Relationships between cropping pattern and rainfall intensity for particulate organic carbon (POC) and mineral-associated organic carbon (MOC) were observed. Heavy rainstorms reduced MOC, including the decomposition of substances related to the MOC, such as ROC and DOC, then POC in layers 40–60 cm increased; compared with 0–20 cm of D and M, the content of readily oxidizable carbon (ROC) in layers 40–60 cm reduced by 56.90~77.64%, and the POC increased by 38.38~87.00% in the D + M. Therefore, it was suggested that the decomposition of deeper MOC due to heavy rainstorms is the main source of soil POC and leaching DOC. This will provide a reference basis for research on assessing soil carbon-leaching fluxes and carbon stocks under extreme rainfall events.

Keywords: orchard cultivating; cropping pattern; mineral-associated organic carbon; readily oxidizable carbon



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1. Introduction

The production, accumulation, and flux export of dissolved organic matter (DOM) in soil determines the balance of the carbon cycle and the sustainability of ecosystems [1,2]. Soil carbon is exported in particulate form, such as particulate organic carbon (POC) and particulate inorganic carbon (PIC), or dissolved form, such as dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) [3]. The sources of organic carbon in lakes are either native DOC produced by the lake's own biological activities or exogenous DOC imported from the land. The rainfall erosion processes have become the main driver of

DOC release and transport from land to lakes [4,5]. At the slope or watershed scale, the SOC is regulated by a combination of horizontal transport (downslope transport), mineralization release, and underground leaching during the water erosion period [6]. In the vertical direction, SOC is leached from the surface layer to the subsoil, and the leaching degree in each soil layer is different due to the influence of the rainfall intensity, soil structure, and vegetation type. The surface layer has the highest content of organic carbon, which is generally manifested as leaching from the surface layer (0–10 cm) to the deep layer, and the erosion makes the DOC migrate vertically along with the water infiltration. DOC is more sensitive to environmental changes. Its migration at the soil–water interface is not only an important cause of soil carbon pool loss but also a carrier of pollutants flowing from the land to the aquatic ecosystem [7], which leads to an increase in pollutants such as chemical oxygen and DOC in lakes. These will result in deterioration of the water quality.

As one of the five major forest resources, the economic forest plays an important role in the world forest industry. In the subtropical hilly area of China, the cultivation area of fruit trees is more than 8.7 million hm², which is a prime part of agricultural production [8]. At present, cultivation is commonly used to clear grass under economic trees, which leads to large lands in the orchard being exposed. As the rainfall intensity increases, the nutrient substances in the soil are accelerated from the surface runoff and subsurface leaching. The cultivation practice on the sloping cropland is a major contributor to organic carbon loss, but the terrace planting will prevent soil erosion from surface runoff and keep more organic carbon [9]. However, this process may ignore leaching from subsurface runoff of DOC. Although conserving cultivation is a common method, such as the contour tillage practice and artificial digging tillage practice, these delay the initiation of surface runoff, promote infiltration, and improve the water-storage capacity on the surface, so the proportion of subsurface seepage becomes high. Due to sufficient contact time with soil particles, the DOC concentration in subsurface flow is approximately 7 to 18 times higher than in surface runoff [5]. This means carbon leaching may increase with subsurface flow. Through artificially planting herbs in the orchard, the surface source pollution will be effectively controlled, thus alleviating the water eutrophication in the mountainous areas [10,11]. Existing studies have confirmed the positive role of cropping in decreasing non-point source pollution in orchards [12,13]. These are focused on the comparison between ecological cultivation mode and clean planting treatment, while studies in reclaimed cropping patterns are scarce, which limits the optimization measures of different cultivation modes, fruit trees, and climate types.

Yilong Lake has the highest water temperature and precipitation among the nine plateau shallow lakes in Yunnan Province. There are more than 100 hm² of *Morella rubra* L. cultivation area around the Yilong Lake, accounting for 1/3 of the mountainous area, and there arises a great risk of non-point source pollution. Until April 2022, the monthly report on the water quality testing status of nine plateau lakes in Yunnan Province showed that the water quality of Yilong Lake was in a moderately nutrient-rich state. The exceedance indicators are chemical oxygen demand (COD) and permanganate index. These indicators are generally used as water environmental quality parameters to describe organic carbon pollution [14]. The DOC can be used as an alternative index of water quality instead of COD to reflect the pollution [15].

The effect of runoff reduction showed in order is poaceae > compositae ≥ fabaceae, and intercepting sediment is poaceae > fabaceae > compositae [16]. *Medicago sativa* L. (fabaceae) is a deep-rooted herb, and *Dactylis glomerata* L. (poaceae) is shallow-rooted; however, there are few studies on preventing the soil DOC leaching by cropping patterns of *M. sativa*. and *D. glomerata*. Leaching loss is also one of the main ways of soil nutrient

loss [17], and it generally occurs under heavy rainfall and irrational cultivation [18]. When the rainfall intensity is higher than 50 mm for 24 h, it can generate leaching [19].

According to the statistics of 2009–2024 data from the Meteorological Bureau of Honghe Prefecture (Yunnan Province, China), the annual rainstorm in Yilong Lake mostly occurs in July and August, with a monthly average rainfall of 145 mm and 200 mm, respectively. The daily average rainfall during the rainstorm process is 37–93 mm [20,21]; this may cause larger leaching losses. As dissolved substances are high mobility [22], this leads to the alteration of unstable carbon fractions, including the transport and formation of DOC, readily oxidizable carbon (ROC), and particulate organic carbon (POC) in the soil profile. However, the contribution of unstable carbon fractions to the leaching of DOC under extreme rainfall events is not clear. We hypothesized that the decomposition of MOC was the main factor leading to DOC leaching. *D. glomerata*–*M. sativa* intercropping increased the SOC in subsoil after extreme rainfall, and root morphology reduced the risk of DOC leaching. The simulation experiments of leaching columns were used to investigate the effects of rainfall intensity of rainstorms and heavy rainstorms on carbon leaching from soils with different cropping patterns. The response characteristics of soil carbon components to rainfall intensity under different cropping patterns were discussed to provide a theoretical basis for the practical application of reducing lake water eutrophication in the ecological fallow area and orchard vegetation restoration.

2. Materials and Methods

2.1. Soil and Plant Sources

The soil was collected from the ecological restoration forest of *M. rubra* in the southern area of Yilong Lake (Yunnan Province, China; 102°28' E, 23°35' N), the soil type is mainly red soil, and the physicochemical properties are shown in Table 1. Humus was removed from the top layer, and samples were collected every 20 cm at a depth of 60. One part was kept in the original state as far as possible and filled into the leaching device, and the other part was dried and passed through a mesh sieve. The crops were *Dactylis glomerata* L. cv. Amba and *Medicago sativa* L. WL525HQ, the seeds of which were purchased from Beijing Zhengdao Co., Ltd. (Beijing, China), and *Morella rubra* cv. Dongkui, the annual seedlings of which were purchased from the Zhengxin Seedling Base in Kunming (Kunming, China).

Table 1. Soil physicochemical properties.

Soil Depth (cm)	pH	CEC (c mol/kg)	Soc (g/kg)	Total N (g/kg)	Total P (g/kg)	AN (mg/kg)	AP (mg/kg)	Bulk Density (g/cm)	Soil Moisture (%)
0–20	5.37	4.27	25.59	1.42	0.29	109.67	37.25	1.12	34.07
20–40	4.51	4.70	20.65	1.29	0.18	88.67	28.13	1.26	35.52
40–60	4.35	1.15	7.41	1.00	0.13	74.67	22.12	1.46	25.01

2.2. Leaching Device

A total of 18 leaching devices were designed, which were made of PVC cylinders with a height of 0.8 m and an inner diameter of 160 mm. The bottom of the column was first filled with a 5 cm thick layer of coarse-grained quartz sand (3–10 mesh, national medicine), which served as a cushion and prevented the outlet from being blocked, and a nylon mesh (200 mesh) with an inner diameter of 160 mm was laid over the quartz sand layer to prevent soil particles from being washed into the lower quartz sand layer (Figure 1). The soil was filled into the column in equal layers (0–20 cm, 20–40 cm, 40–60 cm). While filling the soil column, the water samplers (Rhizon MOM, Rhizosphere) of A1 and A2 were inserted and a switchgear of A3 installed at the bottom of column. The sample of A1 and A2 was pore water, and A3 was leaching water. The natural soil was settled for 2 weeks in the column.

After sampling, the water sampler was emptied and evacuated with a syringe to <80 kPa (adjusted for local atmospheric pressure).

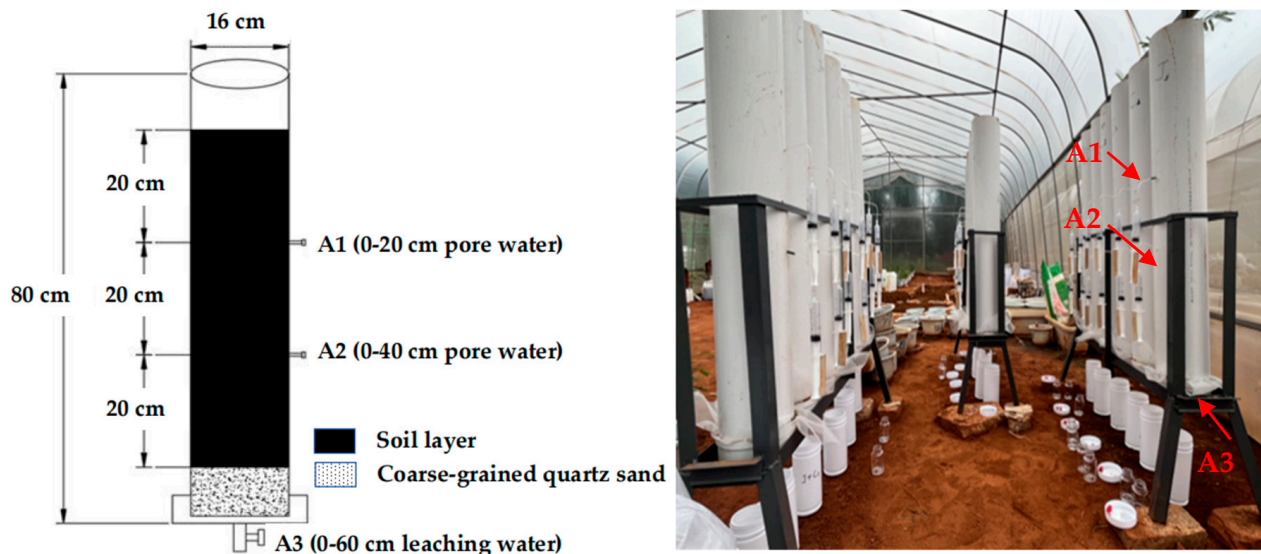


Figure 1. Design of the leaching device. The (left) is a leaching device, the (right) figure is sampling site. A1, A2, and A3 are for collecting leachate water of the soil layers 0–20 cm, 0–40 cm, and 0–60 cm, respectively, at the positions of 30 cm, 50 cm, and the bottom of the column from the top.

2.3. Cropping and Rainfall Patterns

Three vegetation patterns were designed as follows: *M. rubra.* + *M. sativa.* (M), *M. rubra.* + *D. glomerata.* (D), and *M. rubra.* + *D. glomerata.* + *M. sativa.* (D + M). Each pattern was repeated 3 times. The same seedlings of *M. rubra.* were transported in the column and watered normally. One month later, *D. glomerata.* and *M. sativa.* seeds were spread evenly on the topsoil. The sowing ratio of *D. glomerata.* and *M. sativa.* is 6:4, based on the area of the column cutout, and the seed amount was 0.18 and 0.12 g, respectively. During the growth period, 100 mL of deionized water was poured into each column every day at 6:00 p.m. to maintain the soil humidity. After 60 days of plant cropping, plant samples were collected to determine plant root morphology.

Rainstorms and heavy rainstorms were designed in this experiment; the rainfall times were 5 and 1. Concerning the Grade of Precipitation (GB/T28592-2012) [23], 50–99.9 mm/24 h was classified as a rainstorm, 100.0–249.9 mm/24 h was classified as a heavy rainstorm, and combined with actual local rainfall, the rainfall intensity was classified as 50 mm/24 h and 121 mm/24 h (Figure 2). Each of the 2 rainfall intensities was replicated 3 times, combined with 3 replications for each of the 3 planting patterns, and the experiment was designed as a 9 + 9 = 18 experiment. Surface runoff and evaporation losses (40%) were deducted from leaching. Rainstorm leaching took place every 10 d, according to Equation (1), and the rainstorm was converted to a single leaching volume of 1.0 L and 200 mL/15 min, while the heavy rainstorm was 2.4 L and 400 mL/15 min. After a leaching event was completed, pore water and leaching water were collected after 24 h to determine the content of dissolved organic carbon.

$$V = \text{precipitation} \times 3.14 \times R^2 \quad (1)$$

The “V” is the volume of leaching sample (L), and “R” is the inner diameter of leaching column (m²).

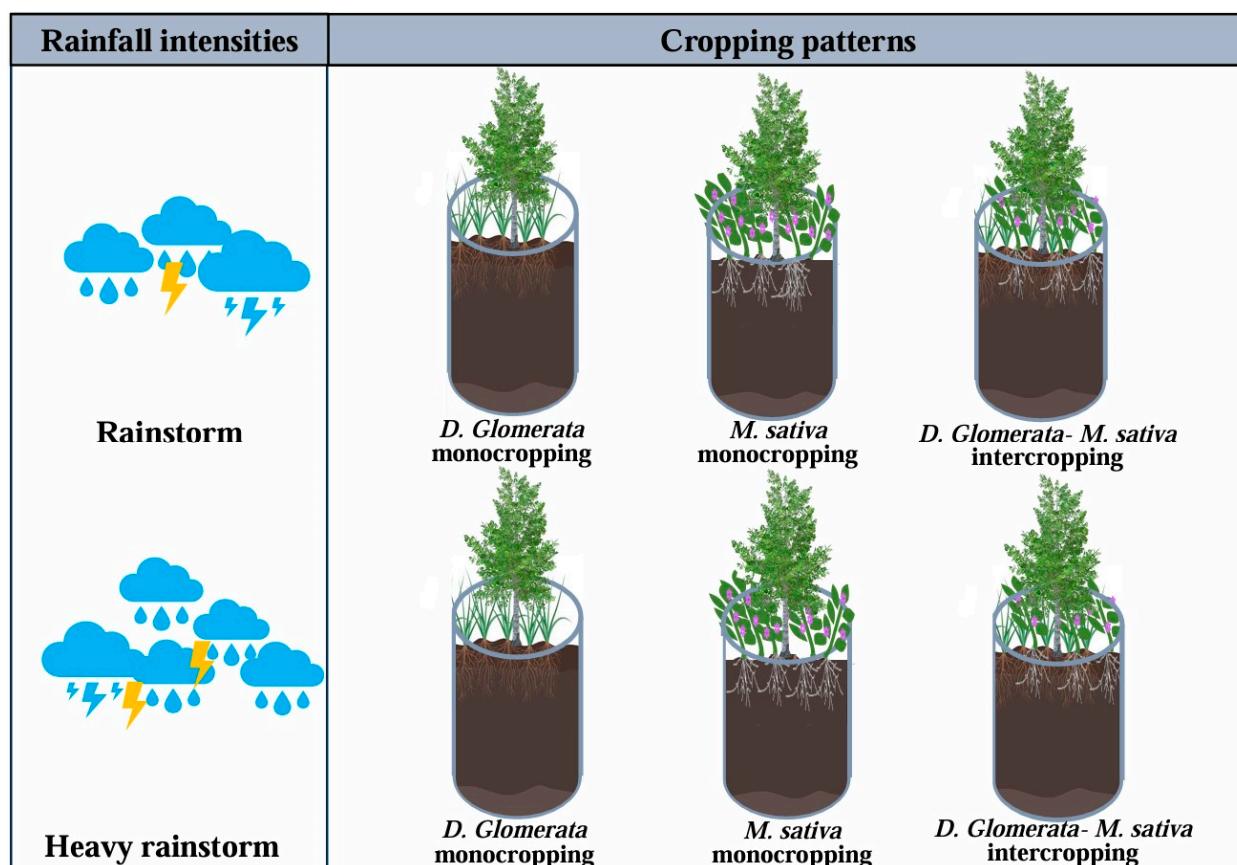


Figure 2. Design of cropping and rainfall patterns. Cropping patterns are *Dactylis glomerata* L. monocropping, *Medicago sativa* L. monocropping, and *D. glomerata*–*M. sativa*. intercropping; the two rainfall intensities are rainstorm (50, 121 mm/24 h) and heavy rainstorm (121 mm/24 h).

2.4. Sample Collection

The pore and leaching water were collected three times in 100 mL and 1000 mL polyethylene bottles after 24 h leaching. Water samples were passed through a 0.45 µm membrane filter, stored at 4 °C, and determined in 10 days. After 60 days of plant growth, the column was gently scratched vertically from all sides. The plant was taken out and the root system was washed with deionized water 5 times to determine the root morphology. Soil samples were collected on the 10th day after the end of the leaching. The leaching column was taken in three layers, from top to bottom: 0–20 cm (top soil), 20–40 cm (middle soil), and 40–60 cm (subsoil). The soil samples were dried naturally and then passed through the 20 and 100-mesh sieve for use later.

2.5. Indicator Determination

DOC in water was determined by combustion oxidation nondispersive infrared absorption method using a TOC analyzer (Multi N/C 2100S/1, Analytik Jena Co., Ltd., Beijing, China) [24]. A soil/water mixture with a pH at 1:2.5 (*m/v*) was shaken for 30 min before determination with a digital pH meter (ATARTER 3100, OHAUS Instruments Co., Ltd., Shanghai, China); TN was determined by automatic nitrogen determination; TP was determined by the Mo-Sb Anti-spectrophotometer method (700 nm); and SOC was determined by the potassium dichromate ($K_2Cr_2O_7$) method, in which 0.5 g soil was soaked with 5 mL of 0.8 mol/L $K_2Cr_2O_7$ solution, 5 mL H_2SO_4 (concentration 98%) was added and boiled in an oil bath at 180 °C for 5 min, and 2–3 drops of ph-phenanthroline indicator were added after cooling. Lastly, the organic carbon content was calculated by consuming 0.2 mol/L $FeSO_4$ volume [25]; fresh soil samples were mixed at a ratio of 1:5 (*m/v*) soil/water, shaken,

centrifuged, and filtered by 0.45 µm membrane, then the soil dissolved organic carbon (DOC) was determined by the $K_2Cr_2O_7$ method (same as above). Readily oxidizable carbon (ROC) was determined by the potassium permanganate oxidation ($KMnO_4$) method, where 5 g soil was soaked with 25 mL of 33 mol/L $KMnO_4$ solution, shaken for 1 h, and centrifuged for 5 min; after diluting, the change in $KMnO_4$ concentration was calculated by colorimetric spectrophotometer. Particulate organic carbon (POC) and mineral-associated organic carbon (MOC) were separated by sodium iodide density, where 10 g soil was shaken with 5 g/L $(NaPO_3)_6$ for 16 h, the soil suspension was poured into a 53 µm sieve and washed with distilled water to ensure separation, so the above is POC and the below is MOC, then it was dried at 60 °C for 48 h and passed through a 0.053 µm sieve after cooling. POC and MOC were determined by the $K_2Cr_2O_7$ method [26]. Plant roots were scanned using a scanner (Perfection V700, Epson, Jakarta Selatan, Indonesia), and then the data was analyzed by WinRHIZO software (2013e) for total root length, average root diameter, total root surface area, and total root volume.

2.6. Statistical Analysis

The data were analyzed by Microsoft Excel 2010 for the data collation, SPSS 23.0 for one-way ANOVA, Origin 2023b for data processing and graph plotting, and R studio packages dplyr, linkET, and ggplot2 for Pearson correlation and Mantel test correlation. DOC loss flux was calculated according to Equation (2):

$$Q_i = \frac{\sum_{j=1}^n c_{ij} V_{ij}}{S} \times \frac{1}{100} \quad (2)$$

The “ Q_i ” indicates the cumulative loss of a form as DOC in the “ith” treatment (kg/hm^2); “ c_{ij} ” indicates the concentration of a form as carbon in the “jth” experiment in the ith treatment (mg/L); “ V_{ij} ” indicates the volume of leachate in the “jth” experiment in the ith treatment (L); and “ S ” indicates the cross-sectional area of the soil column (m^2), which was 0.02 m^2 .

3. Results

3.1. Effect of Vegetation Pattern and Rainfall Intensity on Leaching DOC Content and Flux Characteristics

As measured by the DOC of the pore water after 24 h (Figure 3A,B), the DOC concentration in the pore water at the 20 cm soil layer gradually decreased with the increasing numbers of rainstorms under different cropping patterns. With increasing soil depth (Figure 3C), the pore water at 40 cm after the D + M reached 6.44 g/kg at the last leaching, while the concentration in the leaching solution at 60 cm was 4.24 g/kg, decreased by 34%, and the M and D increased by 35% and 7% from 40 cm to 60 cm. Under heavy rainstorm conditions (Figure 3D), the pore water DOC concentrations in the layers at 20 cm and 60 cm did not change ($p > 0.05$) among the different cropping patterns, ranging from 5.24 to 5.73 k/kg and 3.78 to 3.98 k/kg, respectively, and the DOC concentration of the M decreased by 36% from 40 cm to 60 cm.

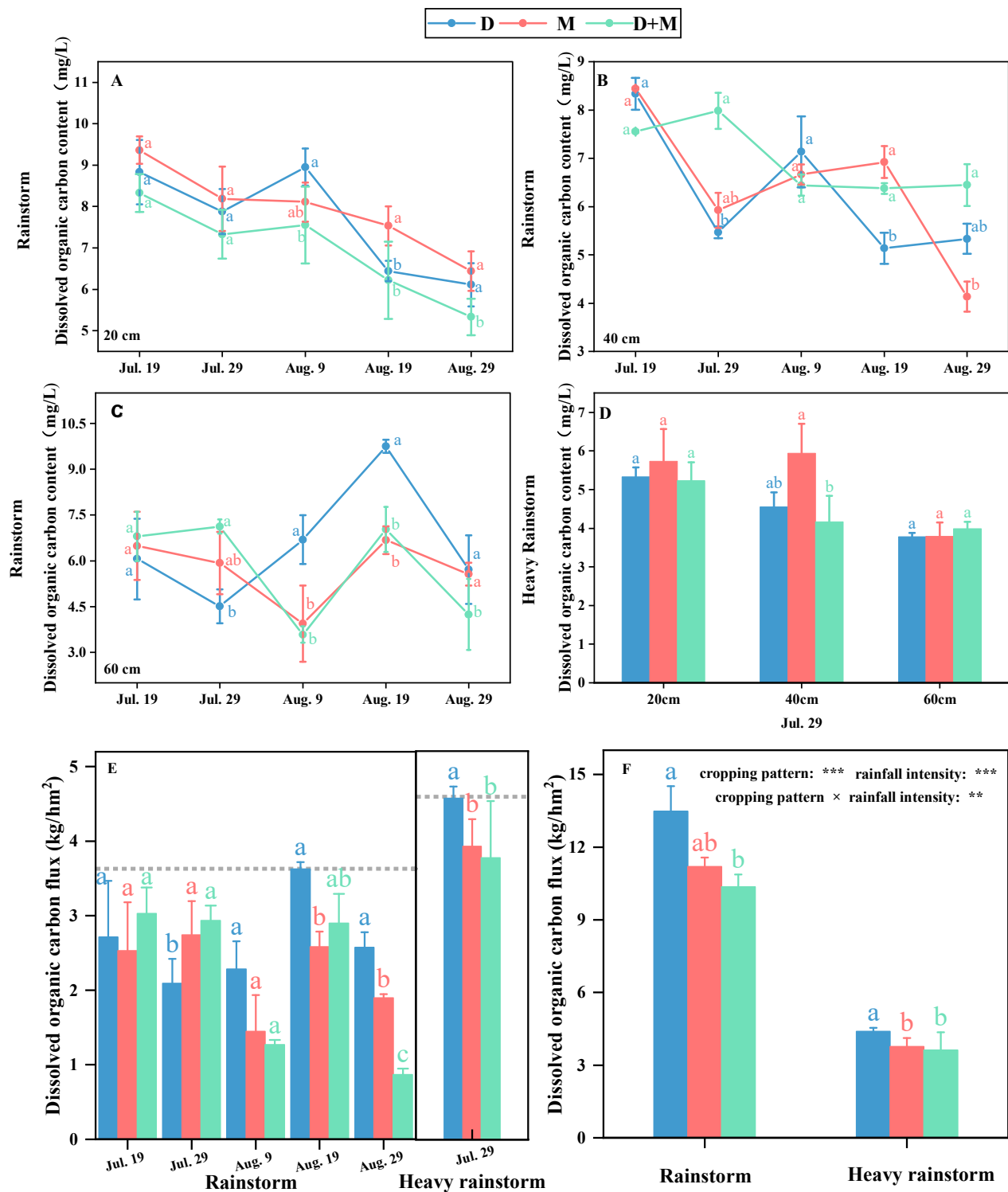


Figure 3. Leaching concentration and loss flux of organic carbon under different cropping patterns and rainfall intensity. “D” indicates *D. glomerata*. monocropping, “M” indicates *M. sativa*. monocropping, “D + M” indicates *D. glomerata*. and *M. sativa*. intercropping. Different lowercase letters indicate significant differences between different patterns in the same soil layer, and the data in the figure show the mean $\pm$ standard deviation of three replicates. “***” and “**” indicated that the significance levels reached $p < 0.001$ and $p < 0.01$, respectively. Dissolved organic carbon (DOC) content in the pore samples at 20 cm (A), 40 cm (B), and 60 cm (C) of rainstorm. The DOC content in the pore samples at 20 cm, 40 cm, and 60 cm of heavy rainstorm (D). DOC flux in water sample after each rainfall event (E) and in water sample after total rainfall (F).

As shown in Figure 3E, there was no significant difference ($p < 0.05$) in DOC flow among the different cropping patterns in the first three rainstorm intensities. In the last two rainfalls, the DOC loss from D reached a maximum value of 2.62 kg/hm^2 , compared with the D monocropping. D + M intercropping was the most effective in controlling the DOC loss, with a reduction of 20% and 66%, respectively, then the DOC control effect in M monocropping was reduced by 29% and 27%. Under the heavy rainstorm intensity, the DOC loss of single rainfall was higher than that of the rainstorm intensity, and the DOC loss of D was the highest (4.39 kg/hm^2). These results showed that vegetation patterns and rainfall intensity had a significant effect on DOC leaching flux ($p < 0.001$). After five times of rainstorm leaching or one time of heavy rainstorm leaching, the DOC leaching flux with D + M significantly reduced, which was 18–23% lower than that of the D (Figure 3F).

3.2. Effects of Cropping Patterns and Rainfall Intensity on Soil Carbon Fractions and Soil Properties

As the SOC content increased, most of the DOC was preserved at 20–40 cm in the D + M, and the highest DOC was in the 20–40 cm soil layer of the D under the heavy rainstorm (Figure 4). Compared to 0–20 cm, ROC content in soil at 40–60 cm with M and the D + M reduced by 77.64% and 56.90% under heavy rainstorm. Rainstorm and heavy rainstorm leaching promoted the downward migration of POC substances in intercropping patterns, and the POC content at 40–60 cm increased by 2.54 and 0.5 times higher than 0–20 cm. The D + M intercropping promoted the formation of MOC in the top soil layer, and with the increase of soil depth, the MOC content in the 0–20 cm layer was increased by 52.95% and 48.18%, compared to the 40–60 cm.

As shown in Figure 5A,E, the soil pH in the three cropping patterns gradually decreased with the increase of soil depth. After rainstorm and heavy rainstorm, the pH of 40–60 cm soil in the D was the smallest, both at 4.37. The SOC of the D and the D + M were similarly trended after leaching by rainstorm, and SOC was 27–28 g/kg at 40–60 cm after leaching by heavy rainstorms. The intercropping was better than the D at retaining SOC at 40–60 cm under different rainfall intensities ($p < 0.05$). The highest ($p < 0.05$) TN was in the layer 0–60 cm after the M under heavy rainstorm intensity, ranging from 1.27–1.48 g/kg. With the increase in rainstorm leaching, the migration of TP was promoted to the soil depth in D + M intercropping, and the TP content in 40–60 cm soil layer was 0.21 g/kg, which was increased by 48% and 38% compared with the D and the M. Heavy rainstorm reduced the TP content in the intercropping pattern to 0.14 g/kg at layer 40–60 cm, 14% lower than the monocropping pattern.

The three factors either individually or interactively had highly significant ($p < 0.05$) soil DOC and MOC content, but the interaction of rainfall intensity and soil depth had a significant effect on DOC and MOC content (Table 2). That indicated that rainfall intensity promotes material transformation of DOC and MOC between different soil layers.

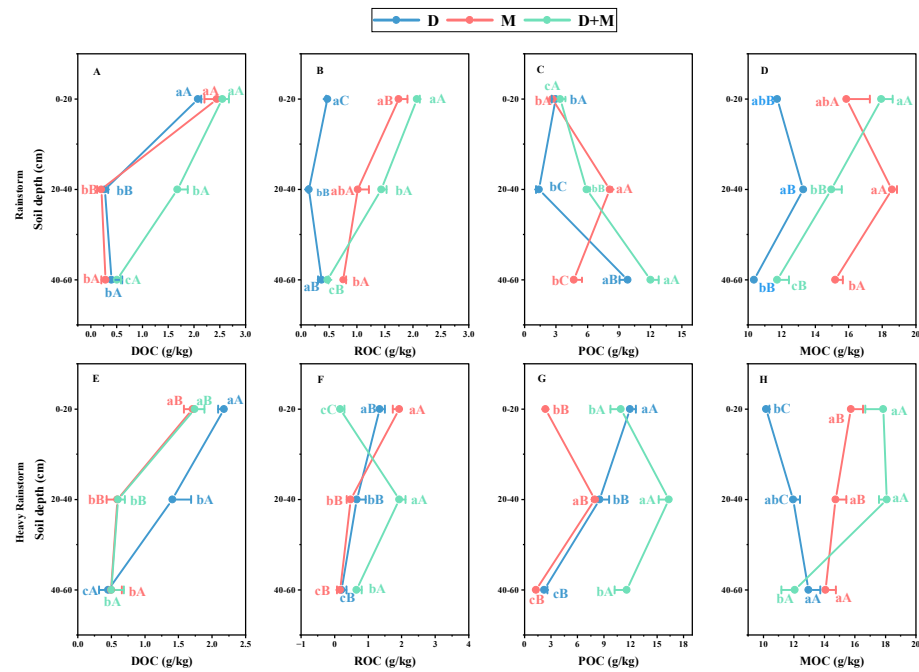


Figure 4. Soil carbon fraction content under different cropping patterns and rainfall intensities. Under rainstorm intensity, DOC (A), ROC (B), POC (C), and MOC (D) content in soil layers of 0~20 cm, 20~40 cm, and 40~60 cm. Under heavy rainstorm intensity, DOC (E), ROC (F), POC (G), and MOC (H) content in soil layers of 0~20 cm, 20~40 cm, and 40~60 cm. Different lowercase letters indicate significant differences between different soil layers for the same planting pattern ($p < 0.05$), and different capital letters indicate significant differences between different planting patterns in the same soil layer ($p < 0.05$).

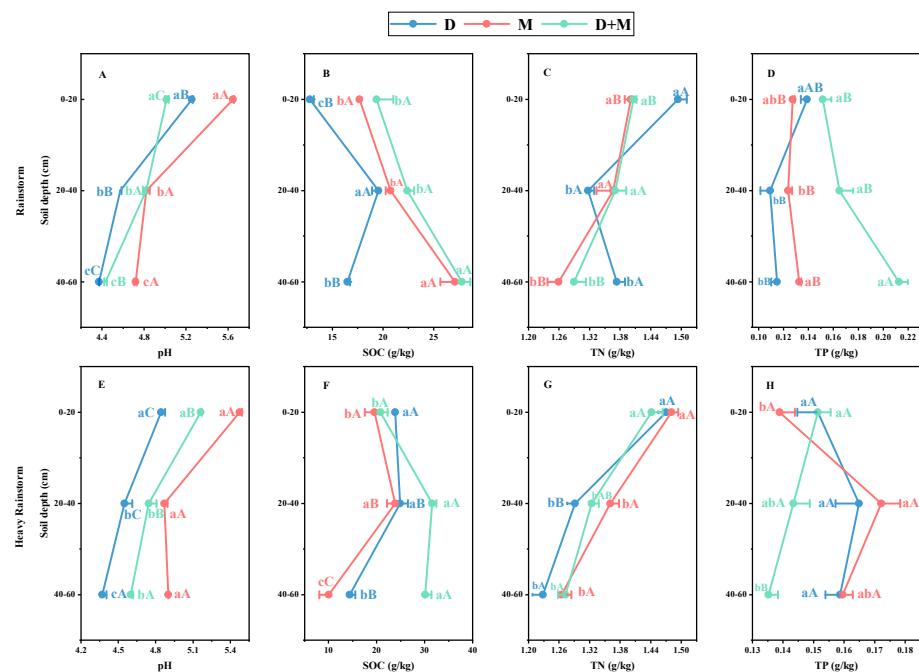


Figure 5. Physicochemical properties of soil under different cropping patterns and rainfall intensities. Under rainstorm intensity, pH (A), organic carbon (B), total nitrogen (C), and total phosphorus (D) content in soil layers of 0~20 cm, 20~40 cm, and 40~60 cm. Under heavy rainstorm intensity, pH (E), organic carbon (F), total nitrogen (G), and total phosphorus (H) content in soil layers of 0~20 cm, 20~40 cm, and 40~60 cm. Different lowercase letters indicate significant differences between different soil layers for the same planting pattern ($p < 0.05$), and different capital letters indicate significant differences between different planting patterns in the same soil layer ($p < 0.05$).

Table 2. Analysis of variance (ANOVA) of the interaction effects of different soil layers, cropping patterns, and rainfall intensities on soil carbon fractions.

Source of Variation	SOC g/kg		DOC g/kg		ROC g/kg		POC g/kg		MOC g/kg	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Soil depth	20.932	0.000	177.845	0.000	535.623	0.000	19.404	0.000	28.426	0.000
Vegetation pattern	116.32	0.000	13.607	0.000	1811.459	0.000	134.097	0.000	74.277	0.000
Rainfall intensity	41.884	0.000	0.033	0.858	1330.777	0.000	70.452	0.000	0.533	0.470
Cropping pattern × Soil depth	3.843	0.000	3.407	0.018	577.099	0.000	33.056	0.000	15.173	0.000
Rainfall intensity × Soil depth	67.164	0.000	12.766	0.000	492.331	0.000	70.477	0.000	1.943	0.038
Cropping pattern × Rainfall intensity	55.625	0.000	9.648	0.000	5328.886	0.000	44.960	0.000	7.561	0.002
Soil depth × Cropping pattern × Rainfall intensity	4.648	0.004	13.586	0.000	757.489	0.000	19.924	0.000	6.732	0.000

“Sig.” < 0.05 means a significant difference between different sources of variation.

3.3. Effect of Vegetation Pattern and Rainfall Intensity on Plant Growth and Root Morphology

As shown in Figure 6, rainfall intensity had no effect ($p > 0.05$) on the biomass of the *M. sativa*., but the cropping pattern had a significant effect on the root morphology. The shoot biomass, root biomass, and the total root length of the D were 1–3 times higher than those in the intercropping pattern. The intercropping pattern promoted the root surface area, root average diameter, and total root volume of *M. sativa*. under rainstorm conditions by monocropping pattern. Rainstorm or heavy rainstorm had no significant effect ($p > 0.05$) on the biomass, total root length, and total root surface area of *D. glomerata*., and the intercropping pattern increased the average root diameter and total root volume from 41% to 76% in *D. glomerata*. after heavy rainstorm compared with the monocropping pattern.

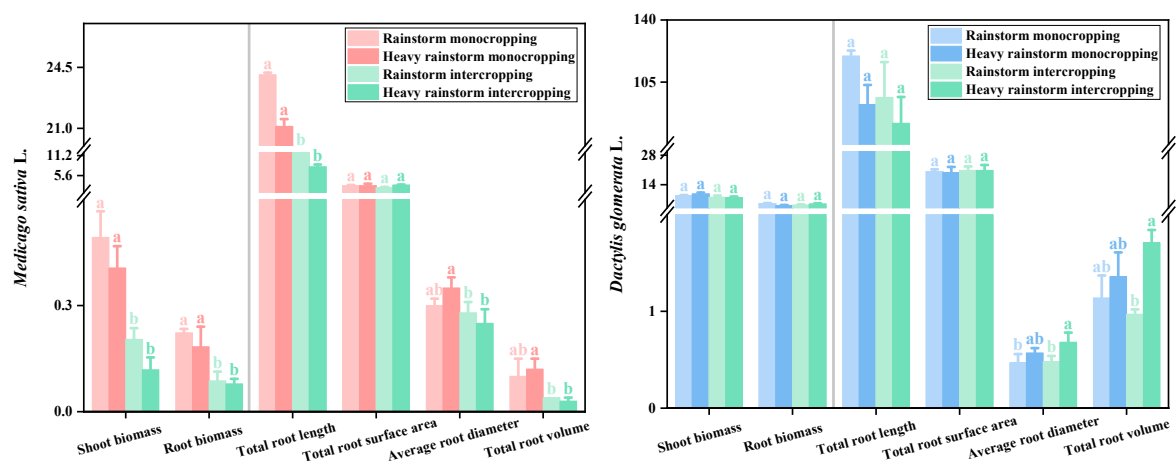


Figure 6. Growth and root morphology of plants under different cropping patterns and rainfall intensities. Different lowercase letters indicate significant differences between each pattern, and the data in the figure show the mean $\pm$ standard deviation of three replicates. The horizontal coordinates indicate the indicators of plant biomass and root morphology. The unit of “shoot biomass” is “g”, “Root biomass” is “g”, “total root length” is “cm”, “Total root surface area” is “cm²”, “Average root diameter” is “mm”, and “Total root volume” is “cm³”.

Based on the carbon loss flux, plant biomass, and root morphology, Pearson and Mantel analyses are shown in Figure 7. Carbon loss flux in the leachate was significantly correlated with soil SOC content, and plant biomass (shoot biomass, root biomass) and plant root morphology altered the DOC flux in the leaching, the ROC, and MOC in the soil. The DOC content in the leachate varied with TP, SOC, and POC in the soil, the POC had a significant positive correlation with TP and SOC, and the pH altered the content of ROC and MOC and was significantly positively correlated ($p < 0.05$).

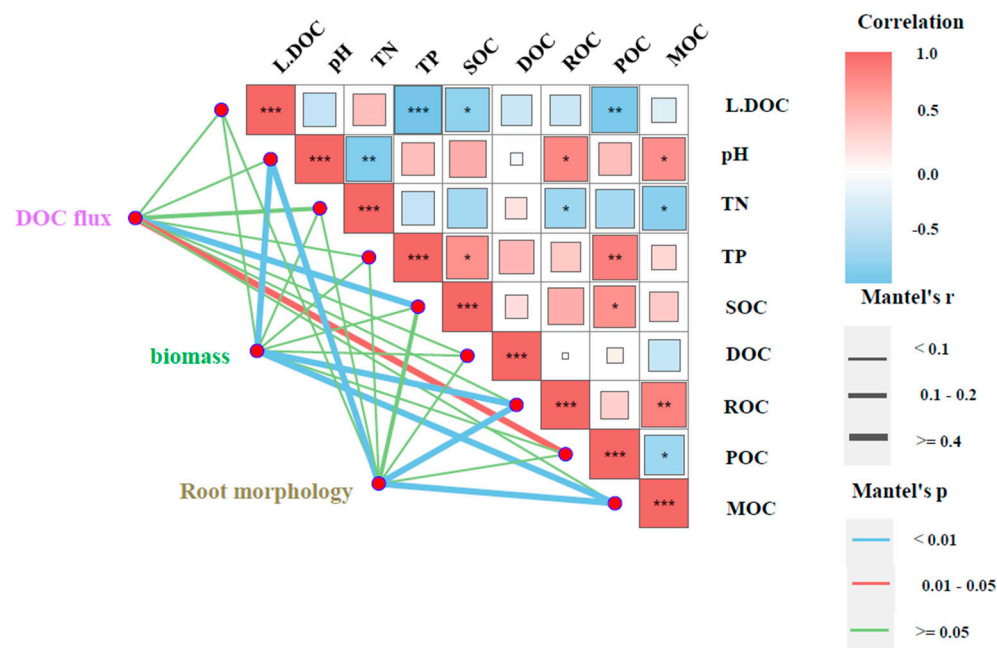


Figure 7. Correlation analysis of DOC loss fluxes and plant root morphology with soil carbon fractions. “***”, “**”, and “*” indicated that the relevance level of the two indicators reached $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively. The “L.DOC” indicates the sample is from leaching water, and the “DOC” indicates the sample is from soil. Color gradients indicate Pearson’s correlation coefficients. The dissolved organic carbon fluxes, plant biomass, and plant root morphology were correlated with dissolved organic carbon of leaching water and environmental factors by Mantel tests analysis. Plant root morphology in the figure includes total root length, total root surface area, average root diameter, and total root volume.

4. Discussion

4.1. Vegetation Pattern and Rainfall Intensity Effects on DOC Loss

Vegetation is an important functional layer to reduce the potential energy of rainfall, and differences in cropping patterns affect the transport of SOC. Compared with D, D + M intercropping reduced DOC loss fluxes, especially as the frequency of rainstorms increased, and the intercropping pattern was more effective in reducing DOC concentrations, which may be influenced by plant species and root morphology. The D + M intercropping provided the best control of DOC loss compared to the D or M monocropping, reducing DOC loss fluxes by 20~66%. On the one hand, the existence of intercropping plants underneath orchards enhances rainfall retention and evaporation and reduces the volume of water in contact with the soil, influencing hydrological and soil erosion processes by intercepting raindrops and reducing the kinetic energy [27,28]. Due to the superiority of *M. Sativa*. in promoting the vertical movement in soil resources [29], *M. Sativa*. intercropping increased the POC content in the 20–60 cm layer in the deeper soils. This suggests that intercropping promotes the decomposition and transformation of soil organic matter [30]. In the deep-rooted *M. Sativa*., through carbon deposition in the primary roots [31], the MOC content of layers 0–60 cm increased, which is beneficial to stabilize carbon fraction formation [32]. In addition, the consistency in the root surface area of *M. Sativa*. under the M or the D + M intercropping conditions (2.27–2.93 cm²) ensured slower DOC infiltration, especially after heavy rainstorms. The M and D + M were equally effective in reducing DOC leaching, which indicated that the root morphology of *M. Sativa*. plays a key role in the control of DOC loss. The retention of DOC leaching relies on the root system of a plant in contact with the soil contact area. The maximum root system in the soil is a direct way to prolong the residence time of assimilated carbon in the soil, and a larger root surface area

can absorb more soil water and nutrients [33,34]. In addition, roots with faster RER (Root elongation rate) and greater RLP (Root length production) facilitated the accumulation of C to the carbon pool, as smaller root diameters and lower contents of active compounds (hemicellulose and water-soluble compounds) increased the accumulation of C to the C_{POM} pool [32]. In summary, the intercropping pattern of *M. sativa* and *D. glomerata* can reduce the leaching output of DOC under extreme rainfall events, and the root morphology is a key factor in DOC retention. Compared to the fibrous roots of *D. glomerata*, *M. sativa* is a taproot type, and it may be able to control leaching losses of DOC deeper into the soil.

4.2. Vegetation Pattern and Rainfall Intensity Effects on Soil Organic Fractions

Higher plant diversity can alter soil carbon fractions by increasing carbon inputs from the root system, including root residues and root deposition pathways [29,35]. The average SOC in different soil layers under intercropping patterns (23.18, 24.50 g/kg) was higher than that of monocropping, but the soil location of the highest SOC content in the storm intensity is inconsistent with the heavy storm intensity. It suggests that there may be differences in SOC transport pathways between different rainfall intensities. Firstly, it is affected by the alteration of organic carbon fractions. POC was the main export form of carbon leaching during rainfall, with 89% of C loss being mainly POC [36], mainly concentrated at 40–60 cm under rainstorm, and mainly concentrated at 20–40 cm under heavy rainstorm. This showed that the frequency of rainstorm may be more influential than the intensity of heavy rainstorm in causing the formation and transport of unstable organic carbon fractions in the soil leaching [37]. Secondly, the cropping pattern alternated the soil's physicochemical characteristics, such as pH, nitrogen, and phosphorus content. In normal conditions, lower phosphorus content and phosphorus utilization were shown in organic matter-poor soils [38]. In this experiment, the POC content increased with the increase in TP, which indicated that the soil of TP and POC had a strong correlation [39]. However, there was no correlation between soil TP and MOC content, which was inconsistent with Spohn (2020) [40], who argued that the mineral soil is *p*-rich, and therefore organic carbon storage in mineral soils leads to sequestration of large amounts of organic phosphorus (OP). This may be caused by cropping patterns, and rainfall can carry away many nitrogen and phosphorus nutrients in the soil that are not absorbed by the crop or fixed in the soil [41], including the inorganic and organic phosphorus fractions. The fabaceae can secrete large organic acids through the root system and have a higher phosphorus absorption than non-fabaceae crops [42]. With the intercropping of the fabaceae and poaceae, phosphorus limitation in the root system of the poaceae could be alleviated by altering the phosphorus fractions [43]. Therefore, most of the inorganic phosphorus in the soil may be absorbed by plants. OP is not easy to decompose, resulting in TP not following the change of MOC. It is worth noting that the intensity and the frequency of heavy rainstorm promote the accumulation of TP in the deeper soil, while phosphate and dissolved organic phosphorus (DOP) are the main pollutants in the lake [44], so the supervision of OP in the process of infiltration and leaching should be enhanced.

4.3. Relationship Between Soil Carbon Fractions and Carbon Loss Fluxes in Extreme Rainfall Processes

The SOC and POC contents increase with soil depth under heavy rainstorms, and both are affected by cropping patterns. The POCs mainly originate from inputs of fresh plant carbon and the decomposition of carbon already present in the soil [43], but Li et al. reported that oxygen depletion processes in the water during heavy rainfalls lead to the rapid mineralization of DOM [45]. A portion of the mineralized DOM is supplied to plants for growth or to generate greenhouse gases (CO_2 , CH_4), and another part potentially is resolved to the POC fraction. Generally, SOC in subsurface flow has higher molecular

weights, lower H/C and S/C ratios, higher O/C ratios, higher unsaturated structures, and more aromatic structures compared to surface flow [5]. Combined with the present experiment, the MOC content in the layer 40–60 cm decreased with the depth and plant diversity, and the MOC showed a negative correlation with the POC ($p < 0.05$), which suggests that the mineralization of DOM in the subsoil layer should be caused by the extreme rainstorm and be the main reason for increasing POC in the subsoil. ROC functions as an oxidizable fraction of organic carbon; ROC and DOC are both the mechanisms for mineral soil carbon sequestration, transport, and stabilization [46]. MOC has a similar trend with DOC and ROC under rainstorms. This suggests that with the loss of DOC and ROC by soil leaching at rainstorm intensity, there is a corresponding decrease in MOC, and the soil pH was decreased by the oxygen-consuming behavior of MOC decomposition. It is necessary and meaningful to increase MOC for carbon sequestration, and MOC can reach saturation while POC cannot [47]. It indicates that reducing MOC leaching is more beneficial to reduce DOC-leaching loss fluxes under extreme storms. The results may be affected by soil properties, plant community diversity, and soil microbial diversity, and it is worthwhile to further investigate the influence of multiple factors on DOC-leaching characteristics under long-term monitoring conditions in the field.

5. Conclusions

The D + M (*D. glomerata*–*M. sativa*.) intercropping significantly reduced DOC-leaching loss under rainstorm and heavy rainstorm intensities compared to D and M monocropping, reducing DOC by 7.17~22.96% and 5.26~18.18%, respectively. The root morphology, especially the increased total root surface area of *M. sativa*, can contribute to reduced DOC leaching. POC was mainly concentrated in the 40–60 cm soil layer in the D + M treatment under rainstorm and in the 20–40 cm layer under heavy rainstorm intensity. Under heavy rainstorm, the MOC decomposition leads to decreased ROC and DOC fractions, reduced DOC leaching with the D + M intercropping, and by increased POC content in the subsoil. Our results are not only useful to identify suitable planting species in the orchard but also contribute to understanding the mechanisms of soil carbon cycling and plant action in extreme climates. Future investigations may delve deeper into elucidating the impacts of soil type on the DOC leaching. Such endeavors are imperative to fully tap into the cultivation underneath orchards, thus promoting environmental protection of water bodies.

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