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Intercropping Gramineae Herbage in Semiarid Jujube Cultivar 'LingwuChangzao' (*Ziziphus jujuba* Mill. *cv*. LingwuChangzao) Orchard Improves Productivity, Plant Nutritional Quality, and Soil Quality

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Abstract: Forest-grass intercropping has great advantages in exploiting the potential of biological resources, improving the productivity of agriculture. Nevertheless, research on intercropping of 'LingwuChangzao' (*Ziziphus jujuba* Mill. *cv*. LingwuChangzao) with Gramineae herbage is less frequently reported. In this study, we measured the land equivalent ratio (LER), the nutritional quality of fruit and forage, and soil properties when 'LingwuChangzao' jujube was intercropped with Gramineae herbage compared to when grown in a corresponding monoculture, using clean tillage as a control. The results indicated that 'LingwuChangzao' jujube/Gramineae herbage intercropping significantly improved the LER in the system, the appearance traits, and the quality of jujube fruit (e.g., the total soluble solids, soluble sugar, vitamin C, anthocyanin, and flavonoids). Conversely, some nutritional quality indicators, such as dry matter, crude protein, crude fat, and neutral detergent fiber of forage, were lower than the corresponding monoculture. The physical properties in the soil improved with increased soil water content, electrical conductivity, total nitrogen, available phosphorus, etc. Further, intercropping systems had significant effects on soil organic carbon fractions and most of the C-N cycling enzyme activities. Redundancy analyses (RDA) revealed that electrical conductivity and total nitrogen were the dominant soil factors that influenced the C-N cycling enzyme activities and four soil organic carbon fractions correlated with C-N cycling soil enzyme activities. In conclusion, these results demonstrated that 'LingwuChangzao' jujube/Gramineae herbage intercropping significantly altered C-N cycling enzyme activities by driving the soil physicochemical properties and soil organic carbon fractions. Our findings show how to improve the productivity of 'LingwuChangzao' jujube and they provide insights into the mechanisms underlying healthy, biodiverse soils in agroecosystems.

Keywords: fruit quality; land equivalent ratio; soil enzyme activity; soil organic carbon fractions; soil properties

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1. Introduction

Jujube (*Ziziphus jujuba* Mill.) is one of the oldest fruit trees in China and it has been cultivated for over 3000 years [1]. This fruit tree is growing in popularity globally for its strong stress resistance, rich nutrition, and remarkable economic and ecological benefits. The commercial production of 'LingwuChangzao' (*Ziziphus jujuba* Mill. *cv*. LingwuChangzao) is concentrated in the Yellow River Basin in the Ningxia Hui Autonomous Region where agricultural practices that improve production are being promoted to farmers. 'LingwuChangzao' jujube has been cultivated traditionally using clean tillage, monoculture, and crop residue removal, whereby it has caused soil erosion [2], surface runoff [3], poor soil quality, and loss of soil biodiversity [4]. In addition, the area of vacant land inter-rows, which accounts for roughly 60% of the total orchard, is a waste of land resources. Consequently, it is urgently recommended that the transition to 'nature-based solutions' (NBS) practices as an alternative to traditional agriculture [5].

Intercropping is the practice of growing two or more crops simultaneously in the same field, to gain the greatest benefits of it on a sustainable basis [6]. It is recognized as a potential cropping system that is environmentally benign and may resolve the difficulties in greater yield from less or equivalent land. Intercropping is becoming common in India and African countries, such as beans, wheat, maize, sorghum, and cassava [7]. Since the 1960s, intercropping areas have expanded rapidly around the world and different intercropping patterns have emerged, such as legume–cereal [8], grain–grass [9], shrub–tea [10], and orchard intercropping [11].

Intercropping utilizes resources more sufficiently due to niche differentiation and complementarity. Reiss and Drinkwater [12] conducted a meta-analysis of 91 studies on the relationship between intraspecific diversity and yield in cultivar mixtures and found that the yield increased by 2.2% overall in cultivar mixtures compared to their monoculture components. The many benefits of intercropping mulch include utilizing the resources (e.g., light, heat, water, and nutrients) efficiently [13], reducing soil surface temperature, pesticide, and fertilizer inputs, controlling pests, diseases, and weeds [14] and increasing soil organic carbon (SOC) content [15]. Previous studies revealed that Gramineae plants have a high C/N ratio and their litter residues contain a large amount of cellulose and hemicellulose, leading to a relatively slow degradation, which is conducive to the accumulation of soil carbon. Moreover, its dense fibrous root system favors the formation and stability of soil aggregates [16,17]. As common cover crops in orchards, perennial ryegrass (*Lolium perenne* L.) and rattan grass (*Vulpia myuros* L.) have the characteristics of high yield, good palatability, and strong adaptability. Qin et al. [18] found that cover crop of *Lolium perenne* L. was more conducive to changing the microbial community structure than red clover (*Trifolium pratense* L.). Intercropping with *Lolium perenne* L. increased the proportions of Nitrospirae, Chloroflexi, and Basidiomycota, whereas it reduced that of Acidobacteria. In addition, *Lolium perenne* L. is slowly degraded in soil, which is conducive to soil C accumulation. Thus, it can be considered that microbial sole-carbon-source utilisation is changed by intercropping with *Lolium perenne* L. Ma et al. [19] reported that *Vulpia myuros* L. functions as conservation grass in deciduous orchards. During this species decomposition, the decomposing materials are mostly water-soluble substances that can inhibit the growth of other weeds and there is no need to mow grass in summer, saving labor. In addition, living cover with *Vulpia myuros* L. has a favorable regulating effect on soil properties, microbial communities, and microbial function in hazelnut orchards and caused great changes to the soil microbial diversity, community composition, and ecological functions, especially in the fungal community, which reduced the OTUs of pathotrophs and increased that of symbiotrophs. Moreover, the living cover treatments with *Vulpia myuros* L. in hazelnut orchards could have more beneficial and diverse microecological environments than the no-cover treatment.

Intercropping influences the growth of succeeding plants because of interspecific competition and complementation, which may induce changes in the accumulation of secondary plant metabolites and mineral content, thus, altering nutritional qualities [20]. Wen et al. [21] found that loquat-tea, waxberry-tea (*Camellia sinensis* L.), and citrus-tea intercropping patterns had relatively high free amino acid contents and lower catechin contents, which is beneficial to the formation of green tea quality. Zaeem et al. [22] revealed that intercropping between corn and soybean significantly increased nutritional quality, such as the crude protein, total digestible nutrients, and dry matter intake. Simultaneously, intercropping also increased the activity of rhizo-microbiota, which can potentially help improve the nutritional quality of forage due to the soil microbial community composition demonstrated significant association with soluble sugars and soluble proteins contents.

Soil enzymes are proteinaceous substances with high catalytic capability produced by soil microorganisms and are usually considered a vital indicator for predicting soil quality [23]. Studies have revealed that the activities of protease, sucrase, and alkaline phosphatase were all increased by covering the white clover of an apple orchard for one month and six months [24]. Wang et al. [16] found that mulching with orchard grass (*Dactylis glomerata* L.) and white clover (*Trifolium repens* L.) significantly increased the activities of β-1,4-xylosidase (20.65%, 26.07%) and cellobiohydrolase (61.57%, 69.48%) compared to clean tillage. In fact, the use of cover crops increases enzyme activities related to carbon and nitrogen cycles because the plant residues and root exudates containing carbon and nitrogen return to the soils, stimulating the activities of many of these enzymes [25].

The objective of this study was to determine the influence of Gramineae plants in concert with 'LingwuChangzao' jujube on (1) yield and LER; (2) the nutritional quality of fruit and forage; (3) soil properties, soil organic carbon fractions, and C-N cycling enzyme activities; and (4) to assess the relationships between enzyme activities and soil properties and soil organic carbon fractions under different cropping systems.

2. Materials and Methods

2.1. Experiment Site Description and Design

This field experiment was conducted at Yinhu agrosilvopastoral technological development Co., Ltd. 'LingwuChangzao' jujube production base (37°53′ N, 106°23′ E, 1180 m in altitude), Lingwu City, Ningxia Province, China (Figure 1). This area has a temperate continental climate, with average annual temperature and rainfall being about 8.8 °C and 206.2–255.2 mm, respectively. The soil in the study area was mainly sandy soil. Soil physicochemical properties were determined and analyzed according to the standard methods in China (Agricultural Chemistry Committee of China 1983). The physical and chemical characteristics of topsoil (0–20 cm) before the experiment were as follows: bulk density (BD) of 1.35 g cm^{-3}, pH of 8.44, EC of 108.35 μS cm^{-1}, organic matter (SOM) of 12.04 g kg^{-1}, total nitrogen (TN) of 0.45 g kg^{-1}, total phosphorus (TP) of 0.39 g kg^{-1}, total potassium (TK) of 17.23 g kg^{-1}, available phosphorous (AP) of 32.57 mg kg^{-1}, available potassium (AK) of 172.17 mg kg^{-1}, nitrate nitrogen (NO_3^--N) of 14.14 mg kg^{-1}, and ammonium nitrogen (NH_4^+-N) of 3.32 mg kg^{-1}.

'LingwuChangzao' fruit trees were planted in 2008 with a spacing of 2 m × 6 m. The experiment followed a randomized complete block design in jujube orchard, which consisted of six treatments: (1) 'LingwuChangzao' jujube monoculture, MJ; (2) perennial ryegrass (*Lolium perenne* L.) monoculture, MR; (3) rattan grass (*Vulpia myuros* L.) monoculture, MF; (4) jujube-nature grass intercropping, NG; (5) jujube-perennial ryegrass intercropping, IR; and (6) jujube-rattan grass intercropping, IF. Each treatment was repeated three times and each intercropping treatment replicate contained 2 rows with 9 trees. For the MJ treatment, the residues need to be removed from the plot after monthly manual weeding to keep the ground clean. The Gramineous plant seeds were bought from Ningxia Fenglv Forest and Grass Co., Ltd (Yinchuan, China). and sown in April 2021 at a depth of 2.5 cm and 3.0 m wide with the sowing volumes of perennial ryegrass and rattan grass being 23 and 12 kg per ha, respectively. The disc of jujube trees was covered with black film 1.0 m wide and the intercropping grass was kept 1 m away from the jujube trees (Figure 2a,c,e). The field management by manual mowing in July, August, and September 2021 and the residues were mulched on the soil surface or as food for herbivores. The method of fertilization was digging a ring trench from the center of 30 cm whose depth and width were about 20 cm per jujube tree. The fertilizer types of 'LingwuChangzao' jujube are humic acid bio-organic fertilizer (3000 kg ha^{-1}), N, P, K water soluble fertilizer (N 57%, P_2O_5 46%, and K_2O 50%; 200–230 kg ha^{-1}), and trace element water soluble fertilizer (6–10 kg ha^{-1}). A topdressing was applied with jujube trees 5–9 times during the growth stages of budding stage, flowering stage, fruit setting stage, fruit enlargement period, and fruit coloring stage. No fertilizer was applied between jujube rows and no fertilizer was applied to Gramineous plant's monoculture system. During the growth stages of plants, the micro-sprinkler irrigation system was arranged between rows with the irrigation quota ranging from 2250 m^3 ha^{-1} $year^{-1}$ to 3250 m^3 ha^{-1} $year^{-1}$. The meteorological conditions from January to December 2021 are in Figure S1 (Supplementary Materials).

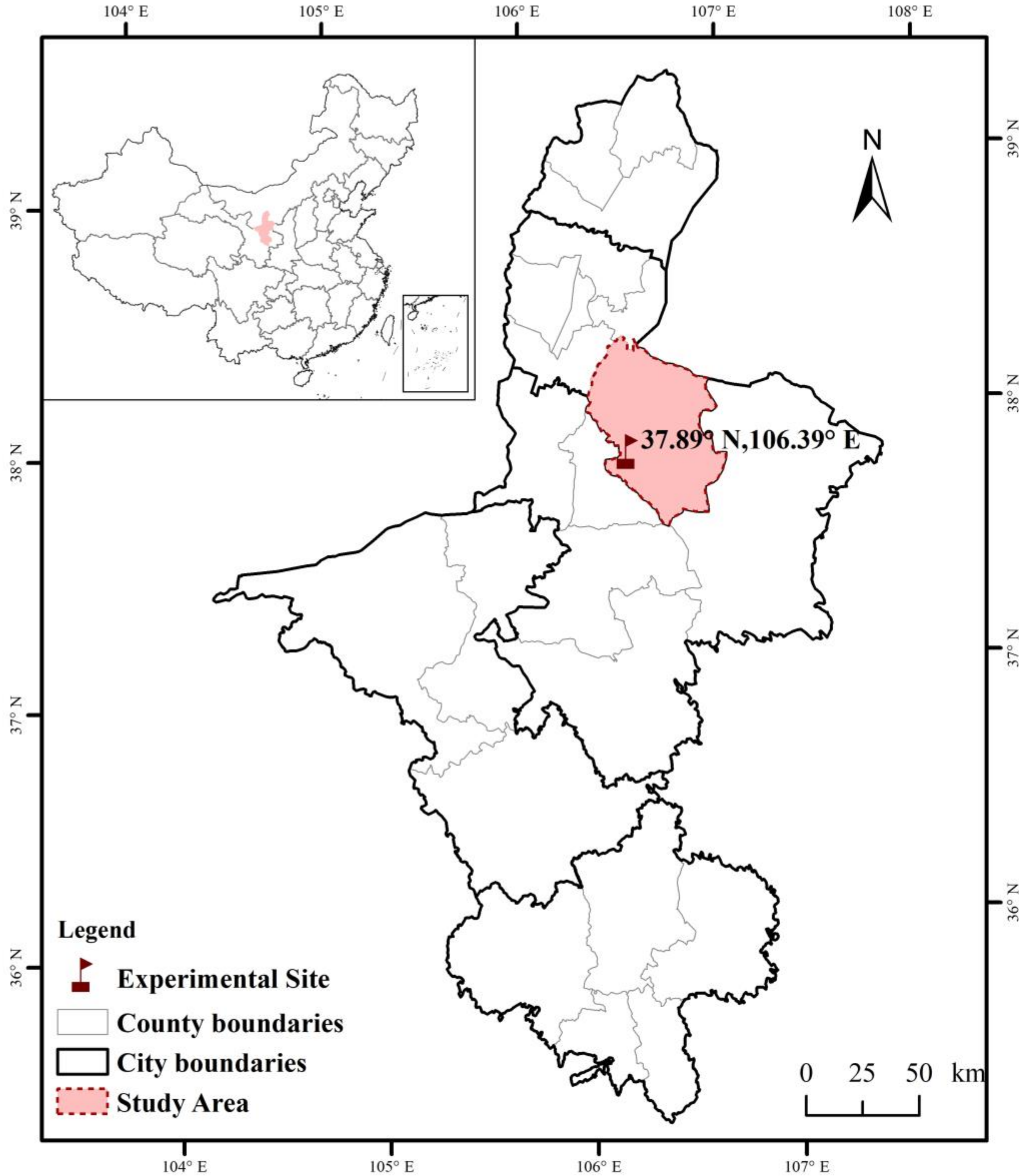

Figure 1. Study area and sampling site in Lingwu City, Ningxia Province, China.

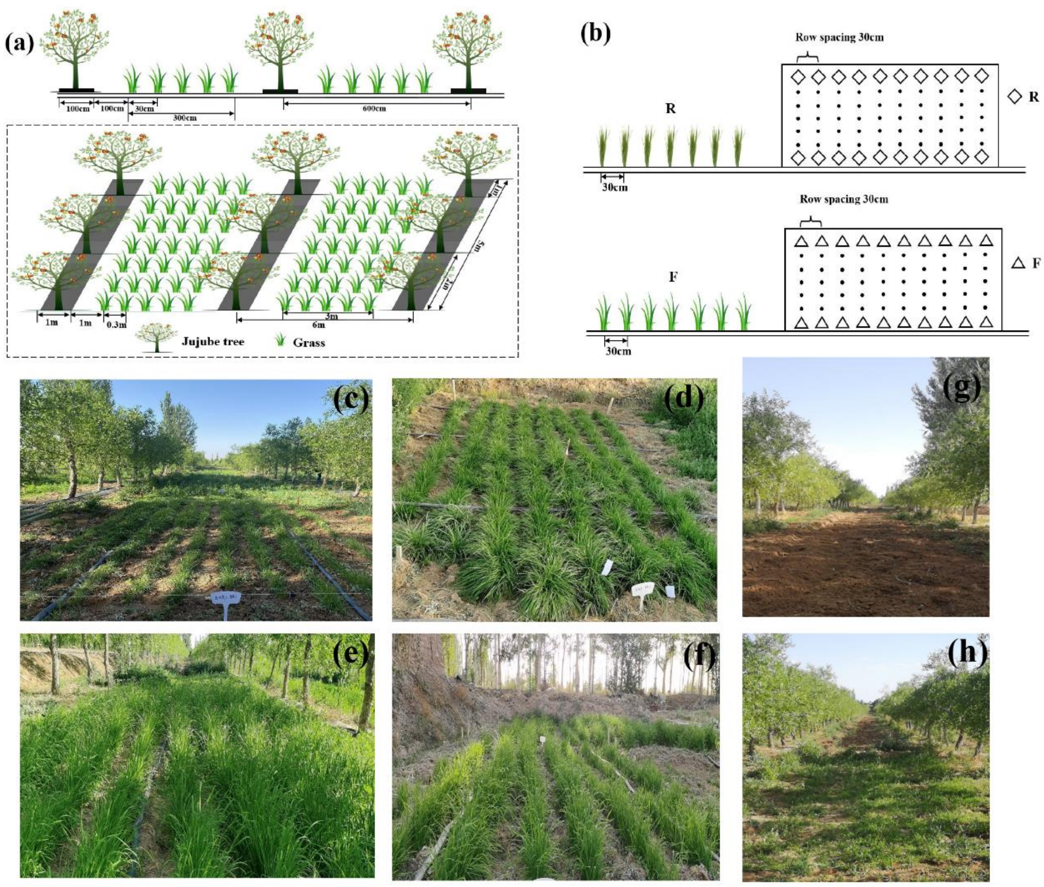

Figure 2. Schematic diagram of experimental design (**a**) intercropping and (**b**) monoculture, photos of experiment on the Yinhu agrosilvopastoral technological development Co., Ltd. 'LingwuChangzao' jujube production base at Lingwu in northwest China (**c**) jujube-perennial ryegrass intercropping and (**d**) perennial ryegrass monoculture, (**e**) jujube-rattan grass intercropping, and (**f**) rattan grass monoculture, (**g**) 'LingwuChangzao' jujube monoculture, (**h**) jujube-nature grass intercropping (R represents perennial ryegrass, F represents rattan grass in subfigure **b**).

2.2. Soil and Plant Sampling

In mid-September 2021, a 5 cm diameter soil auger was used to sample layers (0–20, 20–40 cm) according to the diagonal 5-point method (four points were selected at both ends of an "X" with one point selected at the intersection) [26] in each plot. For the intercropping system, the soils near the forage strip between rows were sampled. For the MJ treatment, the soils near the bare soil between rows were sampled. For the Gramineous plant's monoculture system, the soils near the forage strip were sampled. Five soil samples of the same soil layer homogenously mixed to obtain one composite sample. Then we removed coarse debris, plant roots, and stones before laboratory analysis. In total, 36 soil samples (six treatments $\times$ three replicates $\times$ two soil layers) were obtained. Each soil sample was passed through a 2 mm mesh sieve and separated into two parts. One half was air dried for the determination of soil physicochemical properties, the other part was stored at 4 °C for the determination of the microbial biomass carbon (MBC) and enzyme activities. For each treatment, a sample of 30 jujube fruits was randomly collected from 9 trees during the complete ripening stage to determine fruit quality. Three sample plots of 1 m^2 were randomly selected for each treatment in the early bloom stage to determine forage yield. Eighteen plants were selected randomly within each replication (sample plots) to determine forage nutritional qualities

2.3. Soil Physicochemical Property and Enzymatic Activity Analysis

Briefly, soil water content (SWC) was measured by temperature and humidity tester (TZS-2X-G). Soil BD was determined using the cutting ring method [27]. The Kjeldahl method [28] was used to measure the soil TN. Soil TP was measured using acid-soluble aluminium antimony resistance colorimetry (China HJ 632-2011). Soil AP was determined through Bray-1 extraction followed by molybdenum blue colorimetry and soil AK was determined using flame photometry [29]. NO_3^--N and NH_4^+-N were extracted by 2 mol L^{-1} KCl solution (soil/KCl, 1:5) and measured using a continuous flow analyzer (AA3, SEAL Company, Germany). Soil pH and EC were determined using a glass electrode and a conductivity meter during soil–water suspension (1:2.5 volume/volume). SOC was determined by the potassium dichromate oxidation at 170–180 °C followed by titration with $FeSO_4$. Dissolved organic carbon (DOC) was measured by a total organic carbon analyzer (Shimadzu TOC-L, Kyoto, Japan) [11]. Easily oxidized organic carbon (EOC) was measured via oxidation with $KMnO_4$ [30]. The content of MBC was analyzed by the chloroform fumigation extraction method [31] and was calculated as E_C/k_{EC}, where E_C = (organic C extracted from fumigated soils) − (organic C extracted from non-fumigated soils) and k_{EC} = 0.4551.

The β-glucosidase (BG), cellobiohydrolase (CBH), L-Leucine amino peptidase (LAP), β-1,4-N-acetylglucosaminidase (NAG), and alkaline phosphatase (AKP) activities of soils were determined using the microplate fluorometric assay method [32]. Fluorescence was determined at 365 nm excitation and 450 nm emission by ELIASA (Infinite 200 PRO, Tecan, Mannedorf, Switzerland). Urease (UR) activity was determined using indophenol blue colorimetry as described by Vlek et al. [33].

2.4. Determination of the Growth Parameters and Quality of 'LingwuChangzao' Jujube Fruits and Gramineous Herbage

Jujube fruit transverse diameter and longitudinal diameter were measured using a digital caliper of 0.01 mm resolution. The single fruit weight was measured with digital balance with an accuracy of 0.001 g. The total soluble solids were assessed by a digital hand-held refractometer (Zhejiang Tuopuyunnong Technology Co. Ltd., Hangzhou, China). The firmness of flesh fruit was determined using a GY-4 digital penetrometer (Zhejiang Top Instrument Co. Ltd., Hangzhou, China) with a 3 mm diameter probe. The soluble sugar content was determined using the anthrone-sulfuric acid colorimetric method. Organic acids were assayed using the acid-base titration method. Vitamin C content was determined using the Molybdenum blue colorimetry method. The anthocyanin and flavonoid contents were assayed according to the method described by Wang and Hu [34].

Near-Infrared Spectroscopy (FOSS-NIRS DS 2500, Hillerød, Denmark) was applied to measure the Gramineous herbage quality, including dry matter (DM), crude ash (Ash), crude protein (CP), crude fat (EE), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Dry matter intake (DMI), dry matter digestibility (DDM), and relative feed value (RFV) were based on the reference model as described by Weiss et al. [35].

2.5. 'LingwuChangzao' Jujube and Gramineous Herbage Yield and LER

LER is an indicator to evaluate the land productivity of monocropping and intercropping [36], which was calculated by utilizing the following formula: LER = $(Y_{ia}/Y_a) + (Y_{ib}/Y_b)$. Monocropping weighting is an expression of assessing land productivity, which is commonly used for comparison with intercropping productivity. Weighted mean = $Y_a \times O_a + Y_b \times O_b$, where Y_{ia} is jujube yield in the intercropping system; Y_{ib} is Gramineous herbage yield in the intercropping system; Y_a is jujube yield in the monoculture system; Y_b is Gramineous herbage yield in the monoculture system; O_a is the proportion of the area occupied by jujube in the intercropping system; and O_b is the proportion of the area occupied by Gramineous herbage in intercropping system. When LER > 1, it means that intercropping system favors the crop growth and yield of intercropped species, while if LER $\leq$ 1, the intercropping system reduces resource use efficiency and has no productive advantage.

2.6. Data Analysis and Statistics

A one-way analysis of variance (ANOVA), followed by the least significant difference (LSD) ($p < 0.05$), was conducted to analyze the differences in yield, jujube fruit appearance and nutritional quality, Gramineae herbage nutritional quality, soil physicochemical properties, soil organic carbon fractions, and enzyme activities. Statistical analyses were conducted using SPSS (Version 26, IBM, Chicago, IL, USA). All data were checked for homogeneity and normality of variances by Levene and Shapiro–Wilk's tests. Data of transverse diameter were normalized using lg10 × cos/sqrt transformation. Data of neutral detergent fiber was normalized using sqrt × cos × sin transformation and relative feed value was normalized using lg10 × sin transformation. All figures were generated using Origin 2022 (Version 9.1, Origin Lab Corporation, Northampton, MA, USA). In addition, principal component analysis and redundancy analysis were performed using CANOCO 5.0 (Ithaca, NY, USA). Redundancy analysis (RDA) was to determine the relationships among soil enzyme activities and soil physicochemical properties and soil organic carbon fractions in different cropping systems. Principal component analysis (PCA) of soil enzyme activities, soil physicochemical properties and soil organic carbon fractions based on the Monte Carlo test was performed by considering 499 random permutations, resulting in estimates of significance and weight of each correlation.

3. Results

3.1. Yield and LER

The values of yield, weighted mean yield, and LER of 'LingwuChangzao' jujube and Gramineae plants for every harvest season under different cropping systems in 2021 are presented in Table 1. Specifically, IF and IR treatments significantly ($p < 0.05$) increased the 'LingwuChangzao' jujube yields compared to NG treatment (by 266.58% and 189.48%). Herbage yields under intercropping were significantly lower than under monocropping in the first three mowings ($p < 0.05$). Simultaneously, the yield of the first mowing was significantly higher than that of others. Total yields of ryegrass under intercropping were significantly higher than under monocropping (by 69.3%) ($p < 0.05$), whereas total yields of rattan grass under intercropping were significantly lower than under monocropping (by 31.4%) ($p < 0.05$). To evaluate interspecies interaction contribution to the yield, the yield of the intercropping system was compared with the weighted average of its corresponding monoculture systems. Weighted mean yield of IF treatment significantly higher than IR treatment (by 39.8%) ($p < 0.05$). The values of LER ranged from 2.74 to 2.99 and showed a significant productivity advantage of intercropping over monocropping. LER of IF treatment showed no significant difference with IR treatment ($p > 0.05$).

Table 1. Yield, weighted means yield, and LER of 'LingwuChangzao' jujube and Gramineae plants in different cropping systems in 2021.

Treatments	Yield (kg ha^{-1})					Weighted Mean Yield	LER ^{y}
	Jujube	Ryegrass ^{m}/Rattan Grass ^{n}/Nature Grass ^{x}					
		First Mowing	Second Mowing	Third Mowing	Total Yield		
MJ	6595.46 ± 181.81 c	–	–	–	–	–	–
MR	–	5944.12 ± 190.87 d	3892.18 ± 6.05 d	3112.06 ± 36.36 d	12,948.36 ± 213.67 d	–	–
MF	–	10,799.43 ± 440.73 a	7199.72 ± 66.97 a	5442.57 ± 16.00 a	23,441.72 ± 499.61 a	–	–
NG	4320.45 ± 81.41 d	7500.37 ± 56.14 c	3632.18 ± 33.33 e	2928.60 ± 63.92 e	12,415.09 ± 321.43 d	–	–
IR	12,507.01 ± 272.62 b	5854.31 ± 283.69 d	6824.17 ± 105.65 b	5267.84 ± 33.43 b	21,917.51 ± 397.05 b	14.66 ± 0.09 b	2.99 ± 0.11 a
IF	15,838.03 ± 450.73 a	9825.49 ± 281.00 b	4744.29 ± 15.87 c	3828.09 ± 10.74 c	16,072.75 ± 58.15 c	24.36 ± 1.46 a	2.74 ± 0.08 a

Note: MJ: 'LingwuChangzao' jujube monoculture; MR: perennial ryegrass monoculture; MF: rattan grass monoculture; NG: jujube-nature grass intercropping; IR: jujube-ryegrass intercropping; IF: jujube-rattan grass intercropping. Different letters (a–d) indicate statistical differences analyzed by one-way ANOVA and LSD post hoc test ($p < 0.05$). Values are means of three replicates ± SE. The difference analysis between monocropping and intercropping was carried out for the same index. ^{m} Ryegrass corresponded to the forage yield of MR and IR treatments, respectively; ^{n} Rattan grass corresponded to the forage yield of MF and IF treatments, respectively; ^{x} Nature grass corresponded to the forage yield of NG treatment; ^{y} LER is defined as the relative land area required in monoculture to produce the same yield as in an intercropping production system.

3.2. Fruit Appearance Traits and Nutritional Quality

The overall fruit appearance traits and nutritional quality of 'LingwuChangzao' jujube increased significantly under the intercropping systems compared to monoculture systems, especially in IR treatment (Table 2). The transverse diameter, longitudinal diameter, and single-fruit weight of jujube fruit under intercropping were significantly higher than under monocropping ($p < 0.05$). Compared to MJ treatment, IR and IF treatments increased the longitudinal diameter (by 27.25%, 10.71%) and single-fruit weight (by 35.22%, 17.17%). Firmness of flesh fruit and flavonoids of jujube fruit were not significantly different between intercropping and monoculture cultivation systems ($p > 0.05$). The total soluble solids, soluble sugar, vitamin C, and anthocyanin of jujube fruit increased, but the organic acids decreased under the intercropping systems compared to monoculture systems. For the total soluble solids, the effect of NG treatment was slightly increased compared with that of IR (by 1.2%), MJ (by 4.7%), and IF (by 7.7%) treatments, respectively. We observed that IF treatment produced the highest vitamin C content (49.02 mg·100 g^{-1}) compared to all other treatments. The highest soluble sugar and anthocyanin contents were measured in IF (31.64%) and IR (1.68 mg·100 g^{-1} FW) treatments, while the lowest value was recorded in the MJ treatment (22.04%, 1.39 mg·100 g^{-1} FW).

Table 2. Fruit appearance traits and nutritional quality of 'LingwuChangzao' jujube in different cropping systems in 2021.

Treatment	Transverse Diameter (mm)	Longitudinal Diameter (mm)	Single-fruit weight (g)	Total Soluble Solids (%)	Firmness of Flesh Fruit (kg cm^{-3})	Soluble Sugar (%)	Organic Acids (%)	Vitamin C (mg·100 g^{-1})	Anthocyanin (mg·100 g^{-1} FW)	Flavonoids (mg·100 g^{-1} FW)
MJ	28.90 ± 0.03 ab	42.49 ± 1.21 c	14.85 ± 0.48 c	27.18 ± 0.46 bc	2.83 ± 0.06 b	22.04 ± 0.24 c	8.12 ± 0.95 a	34.39 ± 2.52 b	1.38 ± 0.11 ab	6.31 ± 0.35 c
NG	26.06 ± 0.03 a	44.37 ± 0.89 bc	13.08 ± 0.32 d	28.47 ± 0.45 a	3.03 ± 0.07 ab	27.35 ± 0.17 b	6.08 ± 0.68 b	28.24 ± 2.48 b	1.31 ± 0.15 b	8.25 ± 0.37 b
IR	29.32 ± 0.04 ab	54.07 ± 0.84 a	20.08 ± 0.44 a	28.14 ± 0.42 ab	3.00 ± 0.08 ab	26.65 ± 0.43 b	5.91 ± 0.15 b	28.1 ± 1.47 b	1.68 ± 0.04 a	10.63 ± 0.12 a
IF	27.85 ± 0.03 b	47.04 ± 1.03 b	17.40 ± 0.54 b	26.43 ± 0.43 c	3.21 ± 0.08 a	31.64 ± 0.05 a	3.60 ± 0.26 c	49.02 ± 0.90 a	1.49 ± 0.03 ab	8.15 ± 0.20 b

Note: MJ: 'LingwuChangzao' jujube monoculture; NG: jujube-nature grass intercropping; IR: jujube-ryegrass intercropping; IF: jujube-rattan grass intercropping. Different letters (a–c) indicate statistical differences analyzed by one-way ANOVA and LSD post hoc test ($p < 0.05$). The size, weight, total soluble solids, and firmness of jujube are means of thirty replicates ± SE and the fruit quality is means of three replicates ± SE.

3.3. Gramineae Herbage Nutritional Quality

The differences in the nutritional quality of Gramineae herbage between intercropping and monocropping systems were significant ($p < 0.05$, Table 3). The DM, CP, EE, NDF, and ADF concentration was significantly higher in ryegrass cultivated compared to rattan grass. For the DM, MR treatment was significantly higher than IR, MF, NG, and IF treatments by 2.6%, 3.3%, 4.6%, and 4.3%, respectively ($p < 0.05$). The highest ash concentration was observed in MF treatment (15.94% DM) and the lowest in NG treatment (10.09% DM). The effect on CP of MR treatment was slightly increased compared with that of IR (by 8.4%), MF (by 9.4%), IF (by 17.2%), and NG (by 46.4%) treatments, respectively. We observed that MR treatment produced the highest NDF (67.06% DM) compared to all other treatments; the lowest NDF and ADF were observed in IF and MF treatments (53.13% DM, 29.51% DM). Conversely, the DDM in MF treatment was significantly higher than in IF (by 0.6%), MR (by 4.4%), IR (by 4.7%), and NG (by 22.3%) treatments. The RFV in MF treatment was significantly higher than in IF (by 4.7%), IR (by 17.4%), MR (by 22.1%), and NG (by 37.2%) treatments. The highest DMI content was measured in IF (2.26) treatment, while the lowest value was recorded in the MR treatment (1.79).

Table 3. The nutritional quality of Gramineae herbage in different cropping systems in 2021.

Treatments	DM (%)	Ash (% DM)	CP (% DM)	EE (% DM)	NDF (% DM)	ADF (% DM)	DMI	DDM (%)	RFV (%)
MR	97.99 ± 0.11 a	14.20 ± 0.18 b	14.61 ± 0.38 a	2.60 ± 0.05 a	67.06 ± 0.69 a	31.08 ± 0.25 b	1.79 ± 0.02 c	64.76 ± 0.83 bc	121.17 ± 0.40 bc
MF	94.72 ± 0.09 c	15.49 ± 0.09 a	13.24 ± 0.35 bc	1.94 ± 0.02 c	59.63 ± 0.64 b	29.51 ± 0.23 b	2.01 ± 0.02 b	67.73 ± 0.87 a	147.91 ± 0.27 a
NG	93.72 ± 0.18 d	10.09 ± 0.41 c	9.98 ± 0.47 d	1.33 ± 0.05 e	62.64 ± 0.71 ab	43.04 ± 0.23 a	1.94 ± 0.05 b	55.37 ± 1.26 d	107.80 ± 0.29 c
IR	95.41 ± 0.11 b	13.78 ± 0.09 b	13.38 ± 0.40 b	2.30 ± 0.04 b	60.90 ± 0.67 ab	31.04 ± 0.18 b	1.97 ± 0.01 b	64.55 ± 0.62 c	125.97 ± 0.36 ab
IF	93.72 ± 0.08 d	14.26 ± 0.14 b	12.10 ± 0.50 c	1.75 ± 0.03 d	53.13 ± 0.46 b	30.22 ± 0.27 b	2.26 ± 0.02 a	67.35 ± 1.02 ab	141.32 ± 0.35 bc

Note: MR: ryegrass monoculture; MF: rattan grass monoculture; NG: jujube-nature grass intercropping; IR: jujube-ryegrass intercropping; IF: jujube-rattan grass intercropping. DM: dry matter; Ash: crude ash; CP: crude protein; EE: crude fat; NDF: neutral detergent fiber; ADF: acid detergent fiber; DMI: dry matter intake; DDM: dry matter digestibility; RFV: relative feed value. Different letters (a–d) indicate statistical differences analyzed by one-way ANOVA and LSD post-hoc test ($p < 0.05$). Values are means of eighteen replicates ± SE.

3.4. Soil Physicochemical Properties and Soil Organic Carbon Fractions

Different cropping systems have different effects on the soil physicochemical properties and soil organic carbon fractions of each soil layer (Table 4, Figure 3). Compared with monocropping, intercropped treatments significantly increased the contents of the SWC, EC, TN, AP, AK, NO_3^--N, and NH_4^+-N at 0–20 cm soil depth, but the values of BD and pH in MJ treatment were significantly higher than MR, MF, NG, IR, and IF treatments ($p < 0.05$). For the SWC and EC, IF treatment was significantly higher than MF (by 0.2%, 8.7%), IR (by 19.1%, 14.2%), NG (by 28.02%, 48.5%), MR (by 24.8%, 30.7%), and MJ (by 34.7%, 27.3%) treatments ($p < 0.05$) at 0–20 cm soil depth. Compared to MF treatment, IR and IF treatments increased the TN (by 100%, 90.9%) and AP (by 199.56%, 167.59%) at 0–20 cm soil depth. The highest NO_3^--N and NH_4^+-N were observed in IR treatment (8.47 mg kg^{-1}, 2.88 mg kg^{-1}) and the lowest in MF (4.51 mg kg^{-1}) and MJ treatment (2.42 mg kg^{-1}) at 0–20 cm soil depth. Furthermore, intercropped treatments significantly increased the content of the SWC, TN, TP, NO_3^--N, and NH_4^+-N compared to monoculture treatments, but the values of BD, EC, AP, and AK in MJ treatment were significantly higher than other treatments at 20–40 cm soil depth ($p < 0.05$). Additionally, these soil parameters decreased with increasing soil depth. For the SWC, IF treatment was significantly higher than MF, IR, MR, MJ, and NG treatments by 11%, 45.2%, 46.9%, 61%, and 129.6%, respectively, at 20–40 cm soil depth ($p < 0.05$). The values of BD, pH, TP, and AK had no significant difference at the depth of 20–40 cm levels. The highest NO_3^--N and NH_4^+-N were observed in IR treatment (6.85 mg kg^{-1} and 2.28 mg kg^{-1}) and the lowest in MF (4.95 mg kg^{-1}) and MJ treatment (1.77 mg kg^{-1}) at 20–40 cm soil depth. The EC in MF was significantly higher than IF (by 8.4%), NG (by 21.46%), MR (by 22.5%), MJ (by 28.8%), and IR (by 34.2%) ($p < 0.05$). For TN and AP, the lowest value was found in MJ (0.11 g kg^{-1}) and MF (7.2 mg kg^{-1}) and the highest value was found in IF (0.32 g kg^{-1}) and MJ (23.93 mg kg^{-1}) ($p < 0.05$).

Table 4. Soil physicochemical properties at different soil depths in different cropping systems in 2021.

Soil Depths (cm)	Treatments	SWC (%)	BD (g cm^{-3})	EC (μS cm^{-1})	pH	TN (g kg^{-1})	TP (g kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})
0–20	MJ	7.97 ± 0.86 b	1.44 ± 0.01 a	107.03 ± 0.66 bc	8.65 ± 0.02 a	0.40 ± 0.05 a	0.43 ± 0.03 bc	27.53 ± 4.00 a	78.41± 1.16 b	4.91 ± 0.26 b	2.42 ± 0.06 b
	MR	9.17 ± 0.55 ab	1.26 ± 0.06 b	102.1 ± 6.44 c	8.48 ± 0.06 ab	0.26 ± 0.03 b	0.40 ± 0.07 c	11.27 ± 2.89 b	95.61 ± 3.07 a	5.62 ± 0.74 b	2.61 ± 0.09 ab
	MF	12.17 ± 1.30 a	1.35 ± 0.01 ab	134.43 ± 13.69 ab	8.23 ± 0.19 ab	0.22 ± 0.04 b	0.55 ± 0.02 a	9.07 ± 4.24 b	80.40 ± 7.00 b	4.51 ± 0.20 b	2.50 ± 0.06 b
	NG	9.53 ± 0.88 ab	1.34 ± 0.10 ab	99.17 ± 6.71 c	8.54 ± 0.04 ab	0.34 ± 0.02 ab	0.34 ± 0.02 c	32.13 ± 1.44 a	92.09± 1.83 ab	5.12 ± 0.42 b	2.88 ± 0.17 a
	IR	9.87 ± 0.59 ab	1.21 ± 0.02 b	126.33 ± 11.08 abc	8.22 ± 0.13 ab	0.44 ± 0.06 a	0.36 ± 0.03 c	27.17 ± 1.25 a	97.86 ± 5.32 a	8.47 ± 0.56 a	2.88 ± 0.07 a
	IF	12.2 ± 1.27 a	1.29 ± 0.01 ab	147.27 ± 11.24 a	8.1 ± 0.23 b	0.42 ± 0.00 a	0.53 ± 0.03 ab	24.27 ± 0.84 a	89.06 ± 4.42 ab	5.89 ± 0.77 b	2.56 ± 0.03 b
20–40	MJ	6.27 ± 0.23 e	1.50 ± 0.02 a	89.90 ± 0.49 d	8.69 ± 0.03 a	0.11± 0.00 e	0.19 ± 0.00 b	23.93 ± 1.21 a	67.18 ± 11.45 ab	5.12 ± 6.77 cd	1.77 ± 0.03 c
	MR	8.53 ± 0.09 d	1.41 ± 0.05 b	97.80 ± 0.25 c	8.63 ± 0.05 ab	0.19 ± 0.01 c	0.38 ± 0.02 a	12.33 ± 0.26 b	39.92 ± 3.11 d	5.84 ± 6.77 bc	2.03 ± 0.03 b
	MF	14.3 ± 0.46 b	1.43 ± 0.02 ab	126.20 ± 2.16 a	8.14 ± 0.04 c	0.21 ± 0.00 bc	0.37 ± 0.04 a	7.20 ± 0.51 c	47.92 ± 0.52 cd	4.95 ± 6.77 d	1.86 ± 0.06 c
	NG	7.0 ± 0.06 e	1.40 ± 0.01 b	103.9 ± 3.05 c	8.49 ± 0.10 b	0.17 ± 0.01 d	0.26 ± 0.01 b	27.4 ± 3.01 a	73.29 ± 3.02 a	5.34 ± 0.41 cd	2.22 ± 0.09 a
	IR	9.6 ± 0.46 c	1.35 ± 0.01 b	83.07 ± 2.95 d	8.57 ± 0.08 ab	0.22 ± 0.01 b	0.26 ± 0.05 b	14.63 ± 1.30 b	64.92 ± 0.70 abc	6.85 ± 6.77 a	2.28 ± 0.03 a
	IF	16.07 ± 0.22 a	1.41 ± 0.00 b	115.60 ± 3.03 b	8.08 ± 0.00 c	0.32 ± 0.00 a	0.43 ± 0.01 a	12.20 ± 1.10 b	53.94 ± 6.77 bcd	6.39 ± 6.77 ab	1.92 ± 0.03 bc

Note: MJ: 'LingwuChangzao' jujube monoculture; MR: ryegrass monoculture; MF: rattan grass monoculture; NG: jujube-nature grass intercropping; IR: jujube-ryegrass intercropping; IF: jujube-rattan grass intercropping. SWC: soil water content; BD: bulk density; EC: electrical conductivity; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; AK: available potassium; NO_3^--N: nitrate nitrogen; NH_4^+-N: ammonium nitrogen. Different letters (a–e) indicate statistical differences analyzed by one-way ANOVA and LSD post hoc test ($p < 0.05$). Values are means of three replicates ± SE.

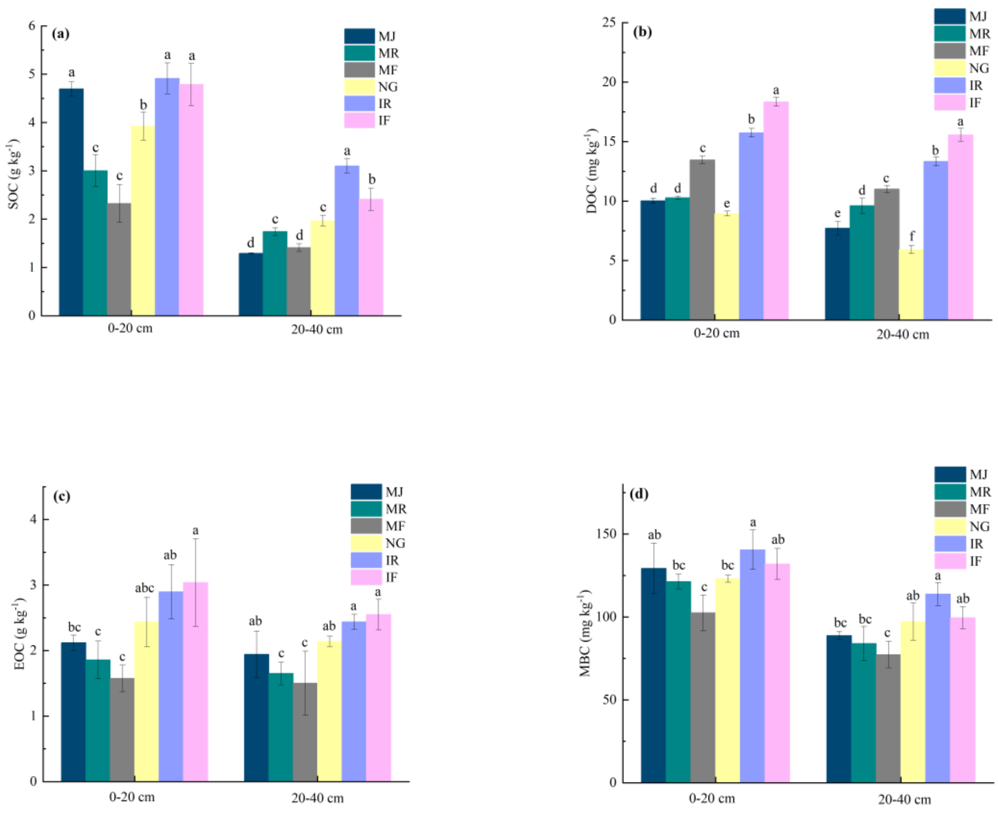

Figure 3. The content of soil organic carbon (SOC) (**a**), dissolved organic carbon (DOC) (**b**), easily oxidizable carbon (EOC) (**c**), and microbial biomass carbon (MBC) (**d**) at the level of 0–20 cm and 20–40 cm depth of soil under intercropping or monocropping treatments. MJ: 'LingwuChangzao' jujube monoculture; MR: ryegrass monoculture; MF: rattan grass monoculture; NG: jujube-nature grass intercropping; IR: jujube-ryegrass intercropping; IF: jujube-rattan grass intercropping. Different letters show significant differences determined by LSD's test ($p < 0.05$, $n = 3$).

The SOC, DOC, EOC, and MBC concentrations significantly differed with intercropping and monoculture systems ($p < 0.05$, Figure 3). Intercropped treatments significantly increased the content of the SOC, DOC, EOC, and MBC compared to monoculture treatments at the overall soil depth ($p < 0.05$). For the SOC, IR treatment was significantly higher than IF, MJ, NG, MR, and MF treatments by 2.4%, 4.3%, 25.23%, 38.9%, and 52.5% at the 0–20 cm soil depth, respectively. Furthermore, IR treatment was significantly higher than IF, NG, MR, MF, and MJ treatments by 28.45%, 57.62%, 77.82%, 120.37%, and 140.31% at the 20–40 cm soil depth, respectively ($p < 0.05$, Figure 3a). IF and IR treatments significantly ($p < 0.05$) increased the DOC concentrations compared to NG treatment (by 133.96%, 100.52%) at the overall soil depth (Figure 3b). Moreover, the highest EOC was observed in IF treatment (3.64 g kg^{-1}, 2.55 g kg^{-1}) and the lowest in MF (1.57 g kg^{-1}, 1.50 g kg^{-1}) at the overall soil depth, respectively ($p < 0.05$, Figure 3c). We observed that the MBC concentrations in IR and IF were significantly higher than MJ, NG, MR, and MF at the overall soil depth ($p < 0.05$, Figure 3d).

3.5. Soil Enzyme Activities

Six soil enzyme activities related to the soil C-N cycles were evaluated in different cropping systems (Figure 4). Intercropped treatments significantly increased the activities of the BG, CBH, LAP, UR, NAG, and AKP compared to monoculture treatments at the overall soil depth ($p < 0.05$). Simultaneously, these soil enzyme activities decreased with increasing soil depth. IF and IR treatments significantly ($p < 0.05$) increased the activities of BG (by 120.11%, 101.33%), LAP (by 113.84%, 81.78%), and AKP (by 70%, 48.73%) compared to MJ treatment at the overall soil depth (Figure 4a,c,f). For the CBH, IF treatment was significantly higher than IR (by 2.8%, 7.1%), MJ (by 25.6%, 24.1%), MF (by 39.3%, 37.6%), MR (by 43.4%, 41.9%), and NG (by 98.4%, 103.7%) treatments at 0–40 cm soil depth, respectively ($p < 0.05$) (Figure 4b). Compared to monocropping treatments, the activities of UR were significantly enhanced by intercropping treatments at the overall soil depth. The highest NAG was observed in NG treatment (5.5 nmol g^{-1} h^{-1}, 4.03 nmol g^{-1} h^{-1}) and the lowest in MJ (2.72 nmol g^{-1} h^{-1}, 1.96 nmol g^{-1} h^{-1}) treatment at 0–40 cm soil depth, respectively ($p < 0.05$) (Figure 4e).

3.6. Relationship among Soil Physicochemical Properties, Soil Organic Carbon Fractions, and Soil Enzyme Activities Affected by Soil Depth and Different Cropping Systems

The PCA analysis of soil physicochemical properties, soil organic carbon fractions, and soil enzyme activities performed that the soils from the same cropping system were clustered together and there was a clear separation of the different systems (Figure 5). The principal component (PC1) and the second principal component (PC2) accounted for 38.93% and 19.22% of the explained variance at 0–20 cm soil depth and 46.01% and 22.67% of the explained variation at 20–40 cm depth, respectively (Figure 5). This showed that there are significant differences in the effects of different cropping systems on the soil parameters. The soil physicochemical properties (SWC, EC, TN, TP, AP, AK, NO_3^--N, and NH_4^+-N), soil organic carbon fractions (SOC, DOC, EOC, and MBC), and soil enzyme activities (BG, CBH, LAP, UR, NAG, and AKP) were enhanced at sites under IR and IF treatments.

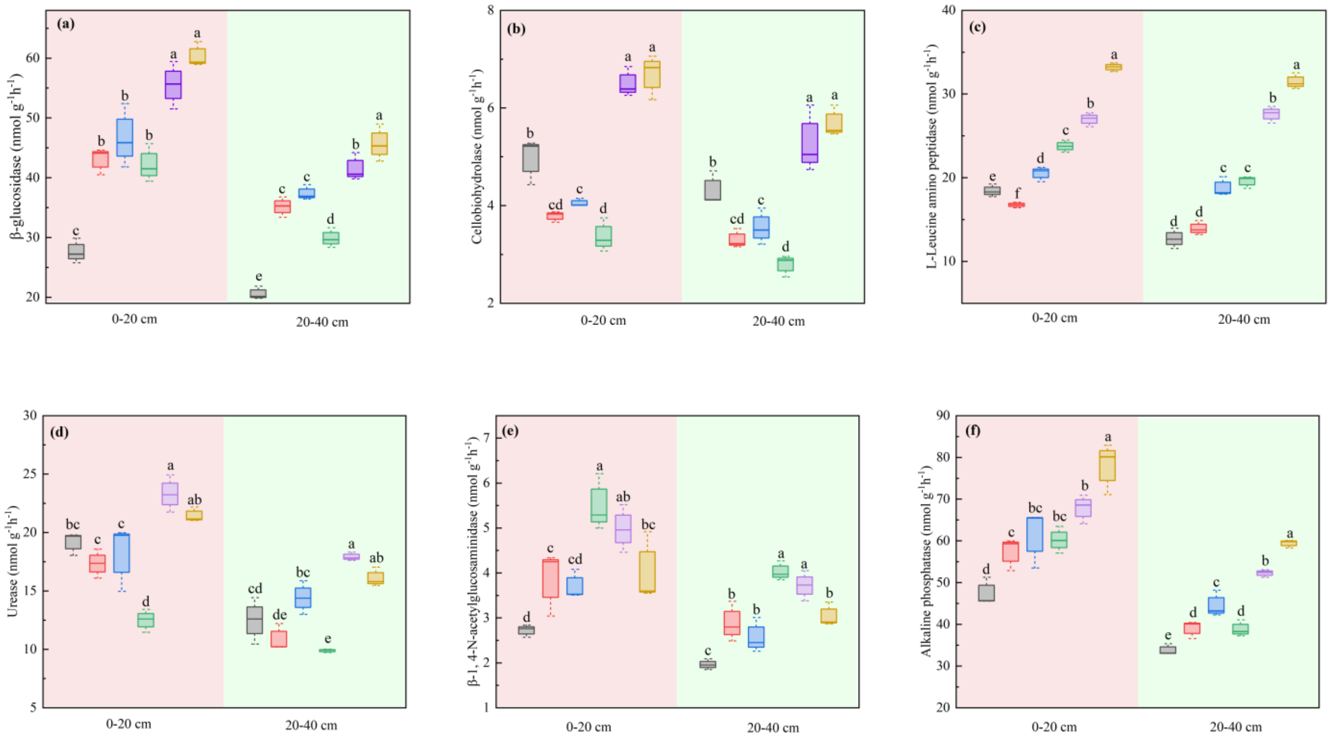

Figure 4. The activities of β−glucosidase (BG), (**a**), cellobiohydrolase (CBH), (**b**), L−Leucine amino peptidase (LAP), (**c**), urease (UR), (**d**), β−1, 4−N−acetylglucosaminidase (NAG), (**e**) and alkaline phosphatase (AKP), (**f**) at different soil depth (cm) under intercropping or monocropping treatments. MJ: 'LingwuChangzao' jujube monoculture; MR: ryegrass monoculture; MF: rattan grass monoculture; NG: jujube−nature grass intercropping; IR: jujube−ryegrass intercropping; IF: jujube−rattan grass intercropping. Different letters show significant differences determined by LSD's test ($p < 0.05$, n = 3).

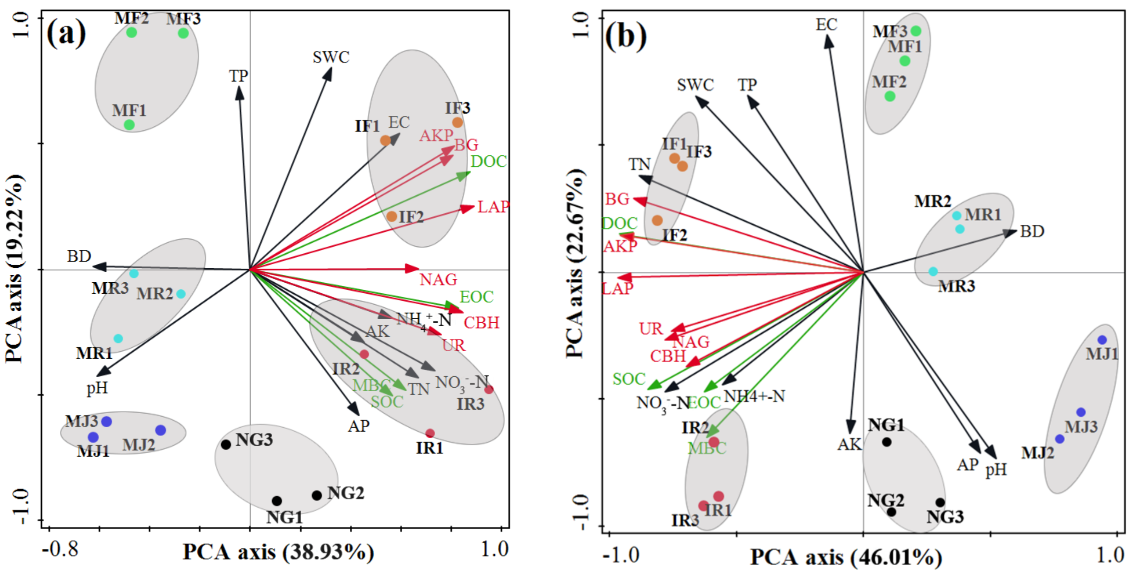

Figure 5. Principal component analysis (PCA) of soil enzyme activities (red arrows) and soil physicochemical properties (black arrows) and soil organic carbon fractions (green arrows) in different cropping systems based on the Monte Carlo permutation test (499 random permutations). MJ: 'LingwuChangzao' jujube monoculture (denoted by purple circle dots); MR: ryegrass monoculture (denoted by arctic circle dots); MF: rattan grass monoculture (denoted by green circle dots); NG: jujube−nature grass intercropping (denoted by black circle dots); IR: jujube−ryegrass intercropping (denoted by red circle dots); IF: jujube−rattan grass intercropping

(denoted by orange circle dots). (**a**) 0−20 cm depth of soil, (**b**) 20–40 cm depth of soil; *n* = 3. BG: β−glucosidase; CBH: cellobiohydrolase; LAP: L−Leucine amino peptidase; UR: urease; NAG: β−1,4−N−acetylglucosaminidase; AKP: alkaline phosphatase; SWC: soil water content; BD: bulk density; EC: electrical conductivity; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; AK: available potassium; NO_3^--N: nitrate nitrogen; NH_4^+-N: ammonium nitrogen; SOC: soil organic carbon; DOC: dissolved organic carbon; EOC: easily oxidizable carbon; MBC: microbial biomass carbon.

Redundancy analysis (RDA) was used to analyze the soil enzyme activities that responded differently to changes in the soil physicochemical properties and soil organic carbon fractions in different cropping systems (Figure 6). At 0–20 cm soil depth, explanatory variables (SWC, BD, pH, EC, TN, TP, AP, AK, NO_3^--N, and NH_4^+-N) accounted for 89.9% of the total variation in the model, with the first axis and the second axis explaining 71.56% and 15.03%, respectively. We found that six soil physiochemical properties factors were significantly affected by soil enzyme activities based on forward selection in RDA (TN, $p < 0.05$; BD, $p < 0.05$; NH_4^+-N, $p < 0.05$; EC, $p < 0.05$; SWC, $p < 0.05$; AK, $p < 0.05$; pH, $p < 0.05$; NO_3^--N, $p < 0.05$; and TP, $p < 0.05$) (Figure 6a). At 20–40 cm soil depth, the first two RDAs axes explained 91.5% of the total variation and Axis 1 and Axis 2 accounted for 72.37% and 17.4% variation in soil enzyme activities, respectively. Among these soil properties variables, TN explained most of the variations in soil enzyme activities (55.5%, $p < 0.01$), followed by SWC (39%, $p < 0.01$), NO_3^--N (36.4%, $p < 0.01$), pH (22.4%, $p < 0.05$), AP (20.6%, $p < 0.05$), and BD (18.8%, $p < 0.05$) (Figure 6b).

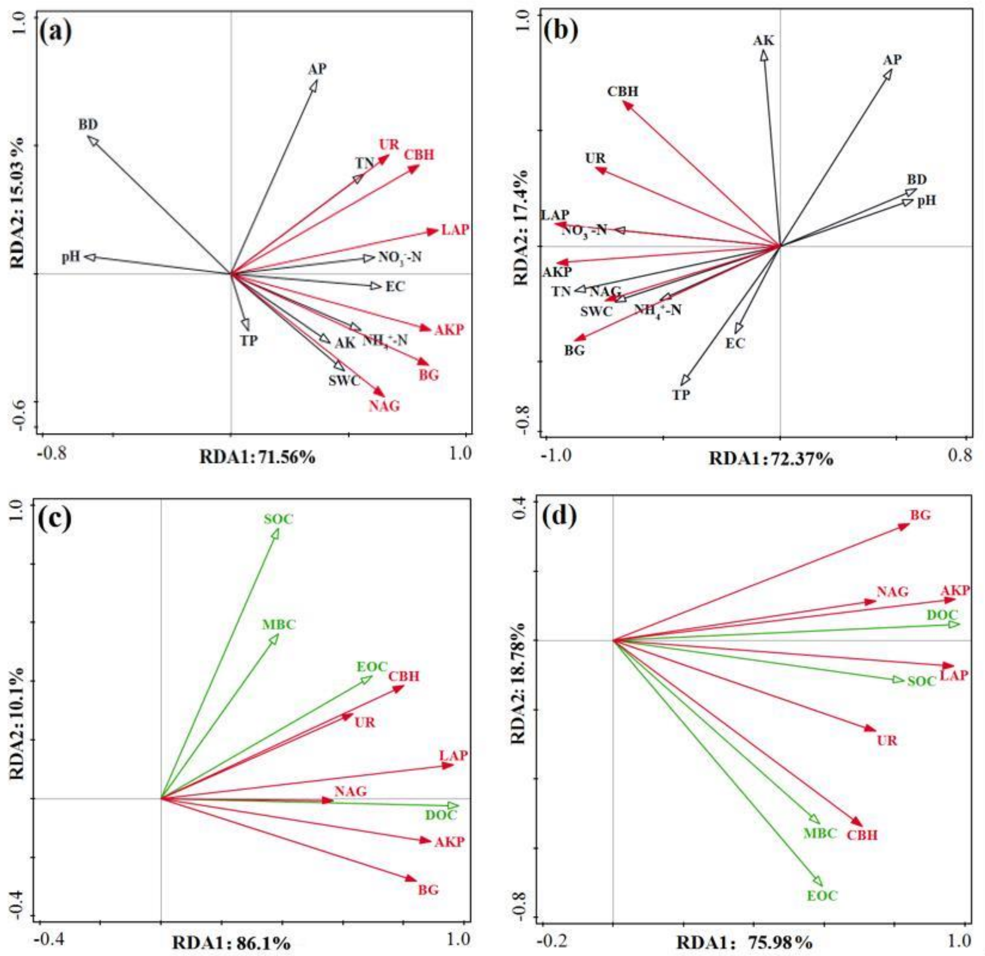

Figure 6. Ordination plots of the redundancy analysis (RDA) were to determine the relationships among soil enzyme activities (red arrows) and soil physicochemical properties (black arrows) and

soil organic carbon fractions (green arrows) in different cropping systems. Associations between soil enzyme activities and the soil physiochemical properties at the level of 0–20 cm (**a**) and 20–40 cm (**b**) depth of soil, respectively. Associations between soil enzyme activities and soil organic carbon fractions at the level of 0–20 cm (**c**) and 20–40 cm (**d**) depth of soil, respectively, $n = 3$. BG: β−glucosidase; CBH: cellobiohydrolase; LAP: L−Leucine amino peptidase; UR: urease; NAG: β−1,4−N−acetylglucosaminidase; AKP: alkaline phosphatase; SWC: soil water content; BD: bulk density; EC: electrical conductivity; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; AK: available potassium; NO_3^--N: nitrate nitrogen; NH_4^+-N: ammonium nitrogen; SOC: soil organic carbon; DOC: dissolved organic carbon; EOC: easily oxidizable carbon; MBC: microbial biomass carbon.

At 0–20 cm soil depth, explanatory variables (SOC, DOC, EOC and MBC) accounted for 78.9% of the total variation and the first two axes explained 86.1% and 10.1% variation in soil enzyme activities, respectively. According to the forward selection, soil enzyme activities driven by DOC and MBC explained 82.3% ($p < 0.01$) and 46.8% ($p < 0.01$) of the variation, respectively, showing that DOC and MBC were two significant factors affecting soil enzymatic activity (Figure 6c). At 20–40 cm soil depth, RDA analysis demonstrated that the first two axes explained 75.98% and 18.78% of the total variation, respectively. There were four factors significantly correlated with the variations in soil enzyme activity based on the forward selection in RDA. In these soil organic carbon fraction variables, DOC explained most of the variations in soil enzyme activities (68%, $p < 0.01$), followed by SOC (51.2%, $p < 0.01$), MBC (34.4%, $p < 0.01$), and EOC (28.5%, $p < 0.01$) (Figure 6d).

4. Discussion

4.1. Effect of Cropping System on Yield and Productivity

The development of intercropping has attracted worldwide attention as it can use available resources more effectively and obtain higher yields compared with monoculture [37]. In this study, yield, weighted mean yield, and LER of 'LingwuChangzao' jujube and Gramineae plants for every harvest season differed between cropping systems (Table 1). Overall, the results support our hypothesis that intercropping Gramineae herbage in jujube orchards could improve land productivity. The primary limitation in the technology of intercropping mulch involves the competition for soil water and fertilizers between the intercropping forage and fruit trees, which adversely affects the growth of fruit trees [19,38]. In the present study, perennial ryegrass has a well-developed root system and grows upright, generally concentrated in shallower soil horizons. The time for germination and mulching is faster than that of other grass species. It can survive the winter safely under the low temperature of −30 °C and has strong water and soil conservation performance. Rattan grass with a plant height of ~50 cm fell naturally in early May, forming a natural organic mulch on the soil surface. During decomposition, it mainly releases water-soluble chemicals, which can inhibit the growth of other weeds. Additionally, rattan grass with fibrous root systems can maintain soil moisture, prevent soil erosion, and stabilize the soil structure [19,39]. Yang et al. [40] reported that July to October is the main period of rattan grass decomposition; this decomposition can provide nutrients for the growth of fruit trees, rather than grass and fruit trees competing for nutrients. Wang et al. [41] found that the comprehensive fruit quality of ryegrass planted in kyoho vineyard in arid area was the best. This may be because intercropping mulch on the inter-row makes the distribution of grape roots in the 20–40 cm soil layer higher than 0–20 cm, indicating that the intercropping mulch on inter-row promotes the development of plant roots in deep soil, which is conducive to the absorption of water and nutrients. Motosugi et al. [42] found that the infection rate of arbuscular mycorrhizae (AM) fungi was very high when the grapevines cover-cropped rat-tail fescue by using isotope tracer techniques. AM fungi could regulate the transport of nitrogen between the grapevines and rat-tail fescue, promoting the transport of nitrogen from rat-tail fescue to grapevines, which favors the growth of grapevines and improves the quality of the grape. Our study utilized crop species with different canopy structures, collocated with different rooting depths, physiological structures, and growth periods and showed advantages of intercropping sufficiently.

4.2. Effect of Cropping System on 'LingwuChangzao' Jujube Quality and Gramineous Herbage Nutritional Quality

Our study has shown varying effects on jujube fruits: the fruit size increased under the intercropping system compared with the monoculture system (Table 2). Combined with Table 1, intercropping Gramineae herbage had a significant influence on the yield of 'LingwuChangzao' jujube. Simultaneously, we compared the quality of jujube fruits between intercropping and monoculture systems and identified that intercropping systems can significantly improve fruit quality, including total soluble solids, firmness of flesh fruit, soluble sugar, vitamin C, anthocyanin, and flavonoids, while organic acid content was decreased. Zhu et al. [43] reported that intercropping increased the carotenoid, flavonoid, total sugar, and ascorbic acid content of Chinese Wolfberry. This indicates that intercropping could change fruit quality and nutritional quality by affecting the content of metabolites. A meta-analysis of 62 studies published between 1990 and 2020 revealed that planting grasses (natural or artificial) in orchards significantly improved fruit yield and quality compared with non-grass orchards [44]. This is probably because cover crops can improve the metabolic function of the tree itself and prolong the photosynthesis time of the leaves, thereby providing more nutrients for the growth and development of the fruit tree, and promoting the formation and development of aboveground organs [45].

Forage nutritional quality was improved under the monoculture systems compared with under the intercropping systems (Table 3). In addition, ryegrass intercropped with jujube can improve the herbage nutritional quality better than that of rattan grass, especially concerning the crude protein concentration increasing to 13.38 % DM. Crude protein of forages is reportedly influenced by nitrogen availability, which demonstrated that nitrogen contribution from jujube-ryegrass intercropping system leads to increased crude protein content. Moreover, nature grass reduced forage quality by decreasing protein, crude fat, ash contents, and increasing fiber content, as fiber is considered to be an anti-nutritional factor [14].

4.3. Effect of 'LingwuChangzao' Jujube/Gramineous Herbage Intercropping Systems on Soil Physicochemical Properties, Soil Organic Carbon Fractions, and Soil Enzyme Activities

In this study, 'LingwuChangzao' jujube/Gramineous herbage intercropping systems significantly increased SWC, EC, TN, AP, TP, AK, NO_3^--N, and NH_4^+-N, while BD and pH values decreased slightly (Table 4). Soil bulk density is a sensitive indicator of soil tightness and lower number often suggests that the soil is loose with good permeability and high fertility. Soil particles are entangled by the roots of intercropping crops and the exudates cause the soil particles to bind and rearrange, resulting in changes in soil structure, hence, promoting the formation of soil aggregates, which may be the reason for the observed decrease in soil bulk density [44]. Studies have shown that organic matter decomposes, with the most rapid rate occurring at neutral pH. Therefore, the pH of the soil under grass intercrop in our study was closer to neutral than in the clear tillage and natural grass treatments, which may accelerate the decomposition of SOM [46]. The use of intercropping crops increases the supply of organic carbon in the soil, which is conducive to the formation of loose and porous soil aggregate structure and promotes the decomposition and utilization of organic carbon by microorganisms [44]. The absorption and utilization of nutrients by plants and the feedback of soil are important driving mechanisms for plant growth. Root exudates produced by intercropping crops are involved in soil nutrient cycling, organic matter decomposition, and energy flow, etc., which is beneficial to the accumulation of organic matter and the bioavailability of mineral nutrients [47]. This is similar to the findings of Luo et al. [48] and Wu et al. [49]. In addition, soil water is an effective medium for the nutrient cycle and also is the key parameter to support the growth dynamics of microorganisms and crops. The present results showed that the soil water content was significantly higher under intercropping than in monoculture, especially for jujube-rattan grass intercropping (Table 4). This might be due to the physical barriers formed by plant residues on the soil surface, which reduced rainwater runoff and soil evaporation [3]. Furthermore, an increasing number of studies has suggested that increasing soil salinity improved various aspects of fruit quality. Zhang et al. [50] found that the firmness, pectin content, and nutrient substances of jujube improve with increasing calcium since Ca^{2+} is cross-linked with the carboxyl group in pectin, which can inhibit the decomposition of the cell wall.

Soil organic carbon is an important source of soil fertility, providing a variety of nutrients for plant growth, thereby promoting the growth and development of fruit trees and achieving high yields. We observed that the contents of SOC, DOC, EOC, and MBC increased under the intercropping system compared with the monoculture system in 0–40 cm soil depth (Figure 3). Many research results have shown that grass intercropping inputs SOC through litter, root exudates, or root and plant residues into the soil; afterwards, it inputs the soluble compounds to promote the formation as well as stabilization of soil aggregates and then improves soil structure and contributes to carbon sequestration [51]. Different grass species have various effects on organic carbon. A study has shown that the effect of Gramineae plants (*Lolium perenne* L.) on organic carbon is greater than that of leguminous plants (*Vicia villosa*, *Vicia sativa*). However, Liu et al. [52] indicated that planting perennial legumes could significantly increase soil organic carbon fractions more than perennial grass of apple orchards in Weibei dryland. The result is inconsistent with the findings of the present study, which may be related to the regional environment, grass age, and soil clay content [51].

Soil enzymes are directly involved in the process of soil nutrient availability and can also reflect the dynamic process of soil nutrient transformation to some extent. The BG and CBH participate in the hydrolysis of polysaccharides in plants (cellulose and hemicellulose), which is related to the decomposition of intercropping crop residues. These two enzyme activities were significantly increased by intercropping with ryegrass and exhibited a very good correlation with the TN, DOC, and EOC contents (Figures 6, S2–S5), which was similar to results from other studies where intercropping with perennial ryegrass in an apple orchard for 13 years significantly increased the activities of BG and CBH. This indicated that continuous organic matter input under ryegrass intercropping mulch stimulated the expression of microbial functions, which was conducive to the accumulation of SOM [53]. The LAP, NAG, and UR directly participate in N cycle in the soil ecosystem and can enhance N availability for plants [54]. We observed higher NAG activity and lower UR activity intercropping with nature grass. The increase in NAG activity under intercropping with nature grass is closely related to the increase in fungi caused by plant residues covering the soil surface. This is probably because NAG is a N cycling enzyme that degrades chitin, which is mainly found in the cell wall of fungi [32]. AKP is produced by soil microorganisms and plays a pivotal role in the release of organic P compounds. Intercropping with rattan grass significantly increased the activity of AKP and positively correlated with SWC, PH, and DOC (Figures 6, S2–S5). This may be because when the soil-available phosphorus content is low, the activity of AKP will increase to supplement the soil phosphorus content [55]. In general, the possible reason for the increase in soil enzyme activity is that litter and root exudates provide abundant nutrients for soil microorganisms in orchards and have an impact on soil fertility, the species, quantity, and distribution of soil microorganisms and further affect plant growth and fruit quality.

5. Conclusions

Intercropping Gramineae herbage in a semiarid jujube (*Ziziphus jujuba* Mill. *cv*. 'LingwuChangzao') orchard significantly improved LER, the appearance traits, and quality of jujube fruit (such as size, taste, and nutrient value). The intercropping system improved some nutritional quality indicators of forage. Consequently, 'LingwuChangzao' jujube intercropped with a Gramineae herbage cropping system can be popularized in the Ningxia area of Northwest China and jujube fruit should also be more popular with consumers. We propose that intercropping increases the biodiversity of cropping systems and, thus, it was not surprising that introducing Gramineae herbage into a 'LingwuChangzao' jujube conventional clean tillage cropping system significantly increased soil nutrients, soil organic carbon fractions, and C-N cycling enzyme activities. Our hypothesis that the dynamics of C-N cycling enzyme activities correlate with soil nutrients and soil organic carbon fractions was verified at 0–40 cm depth. The contents of EOC and DOC were significantly related to C-N cycling enzyme activities in 0–20 cm depth and the contents of SOC, EOC, DOC, and MBC were significantly related to C-N cycling enzyme activities in 20–40 cm depth, indicating our second hypothesis was partially confirmed. Our present results underline the importance of inter-plant interactions and plant–soil feedback mechanisms and thereby, contribute to a better understanding of diverse systems with maximum compensation often able to deliver a wide range of ecosystem functions and services.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae8090834/s1. Figure S1: Monthly precipitation at the study site in 2020 (bars) and average monthly temperature in 2020 (black line and points); Figure S2: Pearson correlation between soil enzyme activities and soil physicochemical properties at the level of 0–20 cm depth of soil under intercropping or monocropping treatments; Figure S3: Pearson correlation between soil enzyme activities and soil physicochemical properties at the level of 20–40 cm depth of soil under intercropping or monocropping treatments; Figure S4: Pearson correlation between soil enzyme activities and soil organic carbon fractions at the level of 0–20 cm depth of soil under intercropping or monocropping treatments; Figure S5: Pearson correlation between soil enzyme activities and soil organic carbon fractions at the level of 20–40 cm depth of soil under intercropping or monocropping treatments.

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