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Combined Application of Organic and Inorganic Fertilizers Effects on the Global Warming Potential and Greenhouse Gas Emission in Apple Orchard in Loess Plateau Region of China

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Abstract: Inorganic fertilizers have been widely used to achieve high apple yields throughout China, especially in Northwest China. This approach has adverse effects on apple orchard soil environments and greenhouse gas (GHG) emissions. Therefore, we investigated the effects of combined organic and inorganic fertilizers on GHG emissions, soil properties, and apple yield to assess the greenhouse gas inventory and to determine which fertilization manner is good for the sustainable development of apple orchards. A split plot design was used, with main treatment of fertilizer ditch (FD) site and a bare soil (BS) site, each with four subtreatments: organic fertilizer–goat manure (M), chemical fertilizer (NPK), chemical fertilizer combined with organic fertilizer–goat manure (MNPK), and control (CK). The cumulative N_2O emissions at the FD site were higher than those at the BS site (by 105.72%). The N_2O emissions ranged from approximately 0.95–5.91 kg ha^{-1} and were higher in the MNPK treatment than in the other treatments. The cumulative CH_4 uptake from each treatment was generally negative (1.06–7.67 kg ha^{-1}). Compared to the other treatments, the MNPK treatment applied at the FD site led to an increased global warming potential. At both the FD and BS sites, the MNPK treatment led to a lower greenhouse gas intensity than the NPK treatment. Nitrates nitrogen (NO_3^--N), water-filled pore space, and temperature all influenced GHG emissions. These results showed that the MNPK treatment was more conducive than the other treatments to the sustainable development of apple orchards in the Loess Plateau region of China.

Keywords: organic fertilizer; chemical fertilizer; orchard plantation; global warming potential; greenhouse gas emission

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1. Introduction

Climate warming and its impacts are focal issues of common concern in the international community and have been extensively researched. Global temperatures have risen in recent years [1]. Global carbon dioxide (CO_2) emissions rebounded by an increase of 4.80% in 2021, reaching 34.90 Gt CO_2 [2]. If no further emission reduction efforts are made, the concentration of anthropogenic greenhouse gases (GHG) will continue to rise. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (HFC, PFC, SF_6, and NF_3) are the main sources of GHGs that have significant impacts on global climate change. Their contributions to the GHG effect reach 11%, 18%, 4%, and 2%, respectively [3]. Approximately 25%–30% of all world emissions are attributable to agriculture [4]. Greenhouse gas emissions in China are partly from agricultural activities, which account for about approximately 7.80% of total GHG emissions [5].

Northwest China has dryland areas that account for a large proportion of its agricultural areas. Therefore, this region is the main source of agricultural N_2O emissions. In

these areas, most irrigation systems are unsustainable and volatile. Rainfall is uneven all year round [6]. The content of soil organic matter (SOM) is relatively low due to improper cultivation and soil management [7]. N_2O emissions are enhanced, and the capacity of dryland soils to oxidize CH_4 is significantly impacted by the overuse of inorganic fertilizers in agricultural soils, creating a temporary decrease in soil CH_4 uptake to promote the growth of organic agriculture [8]. Cattle manure and farmyard manure can improve soil physically, chemically, and biologically, and can increase soil organic carbon (SOC) composition, soil carbon sequestration capacity, N_2O emissions, and increase crop yield [9,10].

Previous researchers have mainly focused on CH_4 uptake in rice fields, but the results of studies conducted in drylands have rarely been reported. The Weibei Dryland in Northwest China is not only an important apple-growing area but is widely known for GHG emissions [6].

Apple orchards cover an area of approximately 4.69% of the cultivated area in the Loess Plateau (approximately 7.83×10^5 ha^{-1}) and account for more than 62% of agricultural land in the study area [11]. According to previous data, in 2015, the total area used for apple cultivation in Shaanxi Province was 628,550 ha^{-1}, representing the largest area in China [12]. In general, apple trees thrive when macronutrients such as nitrogen (N), phosphorous (P), and potassium (K) are present. Nitrogen, the most important essential nutrient, helps encourage vegetative growth (leaves and branches). Phosphorus encourages root and blossom development [13,14]. Recently, many environmental problems associated with the production of apples, including the lack of reasonable management and the use of inappropriate fertilizers, have arisen. Fertilizer requirements differ by tree species and among fruit trees for different stages of maturity. These variations undoubtedly increase nitrogen fertilizer loss. In most apple orchard growing areas of the Loess Plateau region, chemical fertilizer (NPK) applications in the SOM only ranges from 1%–1.50% of organic inputs [15,16]. This result is lower than that for apple orchards grown in the United States of America (>2%) [17]. The excessive use of NPK fertilizers increases GHG emissions and N emissions (NH_3), nitrate-N (NO_3^--N) leaching, and P and K losses in soil water [18].

For sustainable agricultural development, applying chemical fertilizer combined with organic fertilizer (MNPK) benefits different environments, but affects soil GHG emissions. Some studies have shown that given the application of equal amounts of nitrogen between NPK and NPK combined pig manure, NPK combined pig manure significantly increased N_2O and CH_4 fluxes [19–21]. However, other studies have reported that there were no significant differences in N_2O emissions between applications of NPK combined cattle manure and NPK fertilizers [22,23]. Additionally, assuming equal levels of nitrogen fertilization, when the ratio of organic manure used to replace NPK fertilizers is higher than 50%, the concentration of N_2O emissions is effectively reduced [24]. This study demonstrated that using M fertilizers rather than NPK fertilizers successfully utilizes agricultural wastes and reduces fertilizer consumption and GHG emissions, thus promoting sustainable agricultural development. Therefore, it is currently unknown how the use of MNPK fertilizers affects GHG emissions. In this study, our main objectives were to (1) evaluate the effects of combined organic and inorganic fertilizers on GHG emissions (N_2O and CH_4) between fertilizer ditches (FD) and bare soil (BS) sites; (2) assess the greenhouse gas inventory in the Apple Orchard Agroforestry System; (3) determine how N_2O and CH_4 emissions affect dryland apple orchard production.

2. Materials and Methods

2.1. Study Site

This experiment was carried out over three years from March 2018 to December 2020 in the apple orchard in the Weibei Dryland Experimental Station of the Northwest Agriculture and Forestry University at (35°21′ N, 109°56′ E; 838 m above sea level), Baishui County, Shaanxi Province, China. This apple orchard has been a study site for 12 years (Figure 1). According to the USDA's soil classification method, the experimental soil type, silty loam, which contains 67% silt, 25% clay, and 8% sand, was categorized as haplustalfs

(Table 1). The experimental crop was established in 2005 with Fuji apple trees (*Malus domestica* Borkh). The trees had a density of 1200 plants ha^{-1} [6,16], the region had no irrigation system, and rainfall was the only water resource for agriculture.

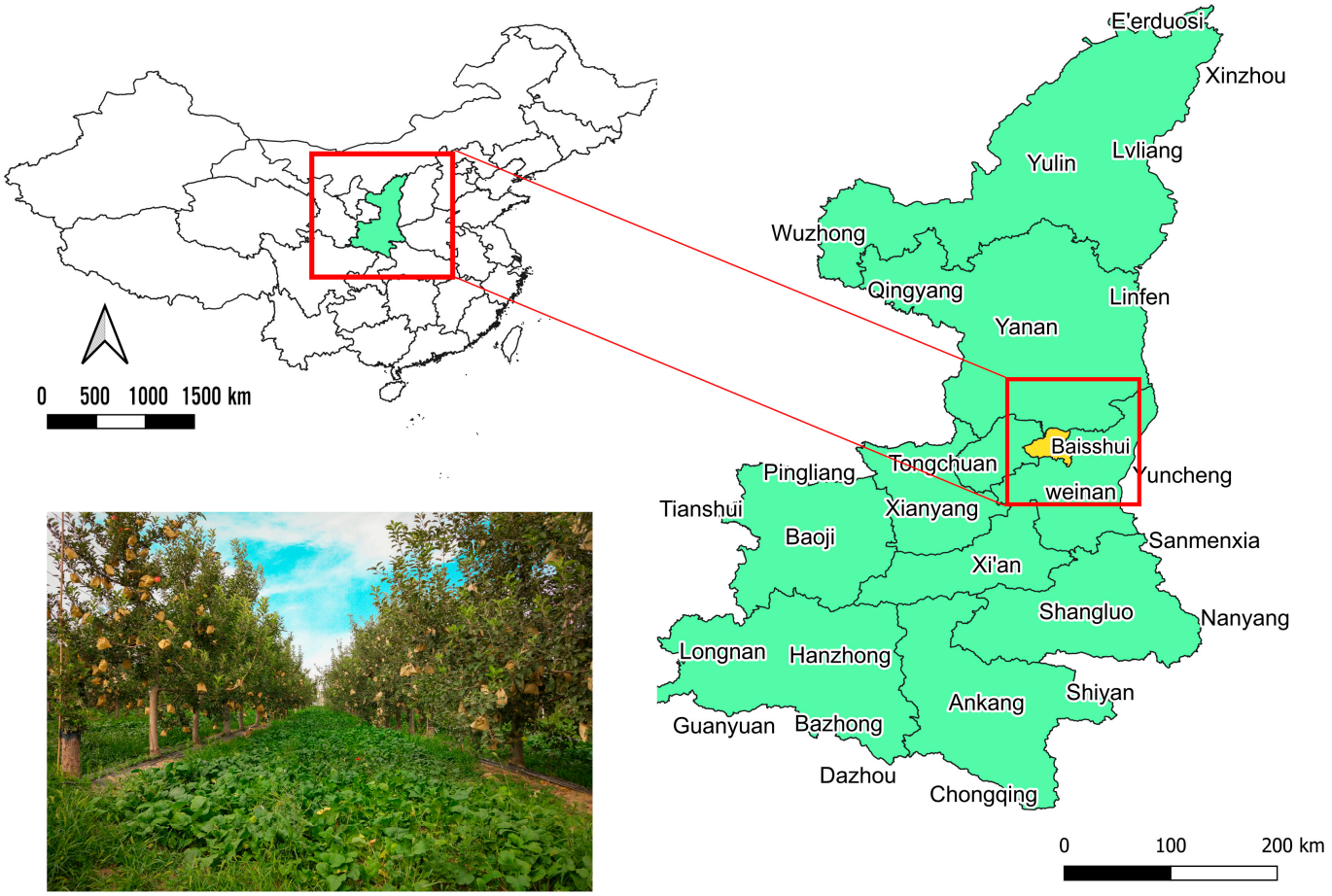


Figure 1. Geographical location map and experimental site.

Table 1. Physicochemical properties of the soils in the experimental plots (0–20 cm layer).

Parameters	Mean
pH (H_2O)	8.30
Soil organic carbon [g kg^{-1}]	13.00
Total nitrogen TN [g kg^{-1}]	1.05
Total phosphorus P [mg kg^{-1}]	15.95
Total potassium K [mg kg^{-1}]	151.22
Bulk density [g cm^{-3}]	1.40
Clay [<2 µm, %]	25.00
Silt [2–200 µm, %]	67.00
Sand [>200 µm, %]	8.00

For each of the three years of the period under study, air temperatures were 12 °C on average per year. The yearly average temperatures over the study period (2018, 2019, and 2020) were 19.44 °C, 19.23 °C, and 18.02 °C, respectively. The soil temperatures varied between 3.40 °C and 38.50 °C at a depth of 20 cm, with an average temperature of 21.20 °C. The annual rainfall in 2018, 2019, and 2020 was approximately 390 mm, 627 mm, and 719.10 mm, respectively. The annual rainfall in 2020 was higher than that in 2019 and 2018 by 9.00% and 26.20%, respectively. More than 80.00% of the rainfall in the apple orchard fell between July and September each year (Figure 2).

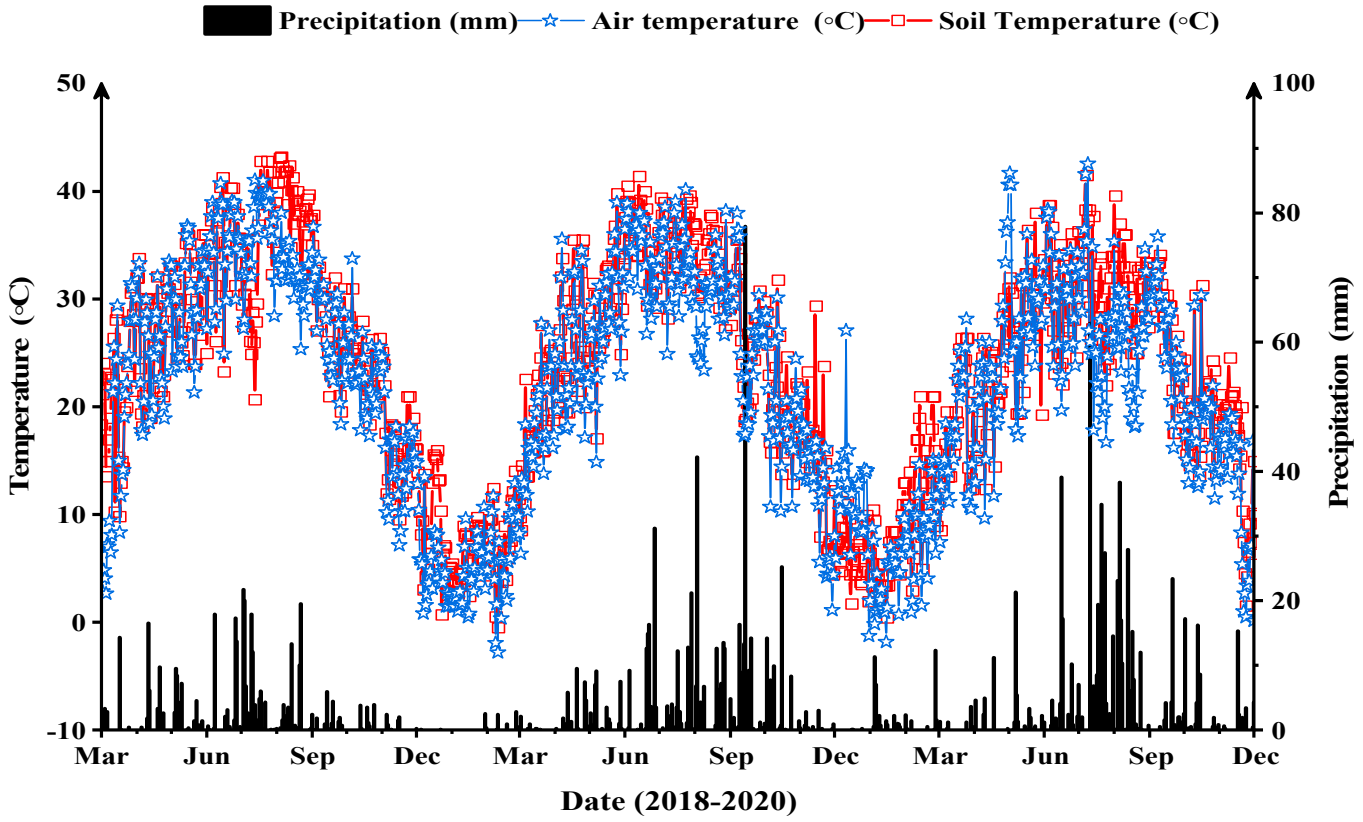


Figure 2. Seasonal dynamics of precipitation (mm) and soil temperature. ◎ Blue: air temperature, red: soil temperature (20 cm depth, °C) in the studied apple orchard from 2018 to 2020.

2.2. Experimental Treatments and Design

Between March 2018 and December 2020, a split plot design was used, with the main treatment of fertilizer ditch (FD) site and a bare soil (BS) site, each with four subtreatments: organic manure (M), chemical fertilizer (NPK), chemical fertilizer combined with organic manure (MNPK), and control (CK). Each treatment area was approximately 40 m^2. Urea N 46% (Zhongke Agricultural Biotechnology Co., Ltd., Jining, Shandong, China) was applied three times (60% in basal fertilizers in autumn, 20% in the flowering stage, and 20% in the fruit expansion period), and single super phosphate P_2O_5 16% (Heilongjiang Century Yuntianhua Agricultural Technology Co., Ltd., Suihua, Heilongjiang, China) was applied three times (60% in basal fertilizers in autumn, 20% in the flowering stage, and 20% in the fruit expansion period), Potassium sulfate K_2O 50% (SDIC Xinjiang Luobupo Potash Co., Ltd., Hami, Xinjiang, China) was applied three times (60% basal fertilizers in autumn, 20% in the flowering stage, and 20% in the fruit expansion period) and used as basal inorganic fertilizer. Organic fertilizer (Goat manure) was applied once in basal fertilizers in autumn (organic carbon 35.10%, nitrogen N 0.53%, phosphorus P_2O_5 0.31%, potassium K_2O 0.47%). The base fertilizers were deposited in the ditches, evenly spaced around each apple tree, similar to a cross (depth × breadth = 40 cm × 40 cm). A detailed amount of fertilizers in each treatment are shown in Table 2. The times and rates of fertilizers among the treatments in apple orchards were determined according to the method reported by Zhao et al. [6].

Table 2. Fertilization schemes under different treatments.

Treatments [1]	Fertilizers (kg ha^{-1}) [2]								
	Basal Fertilizers			Flowering STAGE			Fruit Expansion Stage		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
CK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M	191.88 *	111.24 *	168.12 *	0.00	0.00	0.00	0.00	0.00	0.00
NPK	115.2	64.8	100.8	38.4	21.6	33.6	38.4	21.6	33.6
MNPK	57.6	32.4	50.4	19.2	10.8	16.8	19.2	10.8	16.8
	95.94 *	55.62 *	84.06 *						

[1] CK: control, M: organic manure, NPK: chemical fertilizer, MNPK: chemical combined with organic manure. [2] Fertilizer rates applied: basal fertilizers, flowering stage, fruit expansion stage. '*' represents nutrients supplied by organic manure.

2.3. Gas Collection and Parameter Determination

To measure CH_4 and N_2O fluxes, air samples were collected from the ground and measured according to the procedures and methods of Fentabila [25]. A closed-chamber method was used to assess gas samples from FD and BS sites of apple orchards [26]. There were two components to the stainless-steel chamber: the base and the cover. The size (depth × length × width) of the base was 41 × 21 × 17 cm. The top of the stainless-steel base was fitted with a water trap to prevent air leakage during gas sampling. The chamber (depth × length × width = 40 × 20 × 15 cm) was buried in the soil during the treatments and was covered tightly with insulation paper to minimize heat and temperature fluctuations inside. A thermometer was installed to record the daily temperature, further installing a 12-volt battery-powered fan was installed to offer air mixing in the chamber. We collected four gas samples using a 50 mL plastic syringe from each statistical chamber approximately ten minutes after closing the chamber (n = 3).

The gas samples were typically collected every week but three to four times a week after fertilization in autumn, during the fruit setting and expansion periods. Sampling was performed in the morning from 08.00–11.00 am to minimize variations in emission patterns. The water troughs at the bottom of a chamber base were filled with water before the lid was put on the chamber to create an airtight seal. At intervals of 0, 10, 20, and 30 min, air samples were manually obtained from the closed chambers using 50 mL syringes. The air samples were transferred into vacuum-sealed bags, and the temperature inside the box (i.e., the thermometer reading) was recorded. A gas chromatograph analyzer (Model Agilent 7890B GC, Agilent Technologies Inc., Frankfurt, Burladingen, Germany) was used to determine the concentrations of CH_4 and N_2O in the samples collected within 12 h. An electron capture detector measured the N_2O emission, and the carrier gas was high-purity nitrogen. The chromatographic column was on an (80/100) Porapak Q-packed mesh column, and the make-up gas flow was 2 mL min^{-1} at a temperature of 300 °C.

The gas emission flow was calculated using the slope of the linear regression equation between the concentrations of CH_4 and N_2O, and the sampling period of four consecutive gas samples. The fluxes of N_2O and CH_4 emissions were calculated by the following equations [27]:

$$F = H \times (\mu \times P)/(T + 273) \times 1/R \times dc/dt \quad (1)$$

where F is the flux of CH_4 and N_2O, (mg m^{-2} h^{-1}), H is the height of the stainless chamber (cm), μ is the molar mass of CH_4 and N_2O (g mol^{-1}), T (°C) is the temperature inside the closed chamber during the sampling period, R is the general gas constant (8.31 J mol^{-1} kg^{-1}), P is the standard atmospheric pressure (1.01 × 105 Pa), and dc/dt is the rate of the slope of the concentrations of CH_4 and N_2O in the stainless chamber against the closure time (mL m^{-3} h^{-1}).

The cumulative gas emission (M, kg ha^{-1}) was followed in accordance with the procedure previously described by Liu et al. [7]:

$$M = \sum_{n=1}^{n} \left(\frac{F_{i+1} + F_i}{2} \right) \times (t_{i+1} - t_i) \times 24 \quad (2)$$

where M is the total cumulative flux of CH_4 and N_2O (kg ha^{-1}), F is the fluxes of CH_4 and N_2O (mg m^{-2} h^{-1}), i is the *th* gas sampling, $(t_{i+1} - t_i)$ represents the interval between two adjacent measurement dates (d), n is the total number of measurements during the cumulative emission observation time, and 24 is used for unit conversion.

According to annual cumulative GHG emissions (CH_4 and N_2O), the carbon dioxide equivalent (CO_2) based on the integrated global warming potential (GWP) of CH_4 and N_2O emissions was calculated [28]:

$$GWP = CH_4 \times 25 + N_2O \times 298 \quad (3)$$

GWP is the total CO_2 equivalent of CH_4, and N_2O (kg $CO_{2\text{–eq}}$ ha^{-1}), and 25 and 298 refer to the respective GWP multiples for CH_4, and N_2O flux emissions over a specified time horizon, generally 100 years.

The GHGI was determined according to the method of Liu [7]:

$$GHGI = GWP/Yield \quad (4)$$

where GWP is the combined warming potential of CH_4, N_2O and yield is the average fruit yield (t ha^{-1}).

The direct N_2O emission factor (EF_d) was determined via a standard method of IPCC [1]:

$$EF_d = (F_N - F_{CK})/N \times 100\% \quad (5)$$

where F_N and F_{CK} are the annual emissions of N_2O with and without fertilization (kg ha^{-1}), respectively, and N is the amount of N fertilizer (kg ha^{-1}).

The N_2O emission coefficient per unit out was determined using the method of Aliyu et al. [29]:

$$Yield - scaled\ N_2O\ emission = Cumulative\ N_2O/Yield \quad (6)$$

Cumulative N_2O is the cumulative emission of N_2O (kg ha^{-1}), and yield is the yield of apples (kg ha^{-1}). The emission factor calculation for CH_4 per production unit is the same as that for N_2O emissions.

2.4. Soil Sample Collection and Analysis

Soil samples were collected after GHG sampling event from both fertilizer ditch (FD) and a bare soil (BS) in the orchard dominated by apple trees. Dug by an open-faced bucket probe, DIK-1640 boring stick (Daiki Rika Kogyo, Co., Ltd., Saitama, Japan), the soil samples were selected near the closed-chamber to a depth of 20 cm and replicated three times in each treatment. The collected soil samples were mixed into one until thoroughly combined, packed in a well-labeled zip-lock bag, and kept in an ice cooler box which can keep the temperature at 4 °C in order to move to the laboratory within 12 h. The collected soil samples were divided into two sub-samples. One sub-sample was fresh soil, extracted to analyze soil bulk density, WFPS, NH_4^+-N, and NO_3^--N. The other sub-samples were air dried and stored in the room at 25 °C for seven days before they were ground by using a ball mill to pass through the (<2 mm) sieve to remove residue. After that, the samples were packed in zip lock bags to analyze pH, TN, TP, TK, and SOC.

The soil bulk density was determined by putting sampled soil in a core ring to a depth of 5 cm (Eijkelkamp Agrisearch Equipment, Co., Ltd., Giesbeek, The Netherlands), and the subsequent samples were placed in a conventional oven to dry for 24 h at 105 °C. Using

the formula below, water-filled pore space (WFPS) indicates the moisture condition of the soil being treated [30]:

$$w = \left(\frac{M_i - m_1}{m_i}\right)\gamma_i \times 100\% \quad (7)$$

$$w = \left(\frac{M_i - m_1}{m_i}\right)\gamma_i \times 100\% \quad (8)$$

$$\Delta S = W_{o,i} - W_o \quad (9)$$

where w_i is water-filled pore space (%), W_i is the soil water storage capacity (mm), ΔS_i is the soil moisture deficit (mm), M_i is the mass of wet soil (g), m_i is the soil mass after drying (g), γ_i is the soil bulk density (g cm^{-3}), h is the depth of the soil layer (cm), and $W_{o,i}$ and W_o represent the stable water storage capacity of the i-th layer soil and the actual soil water storage capacity (mm), respectively.

Soil ammonium (NH_4^+) and nitrate (NO_3^-) concentrations were determined using 2M KCI with a soil to solution ratio of 1:5. The extracts were shaken by an orbital shaker at 100 shakes per minute for one hour (Heidolph Unimax 1010, Heidolph Instruments GmbH & CO., KG, Schwabach, Germany). Following that, the extracts and soil samples were filtered on 0.45 m Whatman filter paper and analyzed by AA3, SEAL, Co., Ltd., Norderstedt, Germany. Soil pH was measured using a pH meter connected with a glass electrode with a soil to water ratio of 1:2.5 mixture using a pH meter connected with a glass electrode (Shanghai Insmark Instrument Technology Co., Ltd., Shanghai, China). The K_2CrO_7-H_2SO_4 oxidation method was used to measure soil organic carbon [31]. To measure total nitrogen (TN), phosphorus (P), and potassium (K) contents, soil was digested with H_2SO_4 and H_2O_2 in a Kjeldatherm digestion unit (C. Gerhardt GmbH & Co., KG Königswinter, Germany) [32]. Precipitation and temperature data are based on the metrological station directed by Weibei Dryland Experimental Station of Northwest Agriculture and Forestry University, which is about 50 m away from an experimental area. Soil temperature was measured at a depth of 20 cm by using Procheck (Decagon Devices Inc., Pullman, WA, USA). The measured area was selected near the closed-chamber during the process of random sampling.

2.5. Fruit Yield

We collected apple fruits from the trees in each treatment. Approximately nine trees were randomly selected as a measure of apple yield, apple weight, and replicate yield. The yield from each replica apple (t ha^{-1}) was calculated by apple, the number of apples $tree^{-1}$, and the number of trees ha^{-1} [16].

2.6. Statistical Analysis

In this study, SPSS version 22 (SPSS Inc., Chicago, IL, USA) was used to analyze data and the Kolmorov–Smirnov test was used to test the normality of the data. Levene test was tested and log x + 1 was transformed to analyze the homogeneity of variance. One-way analysis of variance (ANOVA) was used to evaluate the differences of seasonal and annual cumulative CH_4 uptake, N_2O emissions, GWP, GHGI, and yield between the treatments. Tukey's multiple range tests were used to determine whether significant differences occurred between the treatments at a significance level of 0.05. A two-way ANOVA was used to analyze the effects of treatments and their interactions on CH_4 uptake, N_2O emissions, GWP, GHGI and yield throughout the experimental period. Excel 2019 software (Microsoft Corporation, 2019) was used to visualize the data. The correlation between GHG Emissions and soil properties was determined using R version 4.2.0 software (R core Team 202, Vienna, Austria), and graphs were constructed using OriginPro 2021 (OriginPro, OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Environmental Factors

Water-filled pore space (WFPS) in 20 cm soil depth frequently increased from June to September, mostly due to the rainfall. The amount of WFPS in the apple orchard increased rapidly to 86% on 24 July 2020 after two days of rain at a temperature of 22 °C and decreased by 16% on May 26 2020 at a temperature of 40 °C. In 2018, 2019, and 2020, the average WFPSs at the FD site were 19.43%, 20.34%, and 22.56%, respectively, whereas the average WFPSs at the BS site were 18.14%, 18.82%, and 21.50%, respectively.

The WFPS contents from the MNPK treatments were significantly larger than NPK and CK treatments at both FD and BS sites ($p < 0.05$; Figure 3A,B).

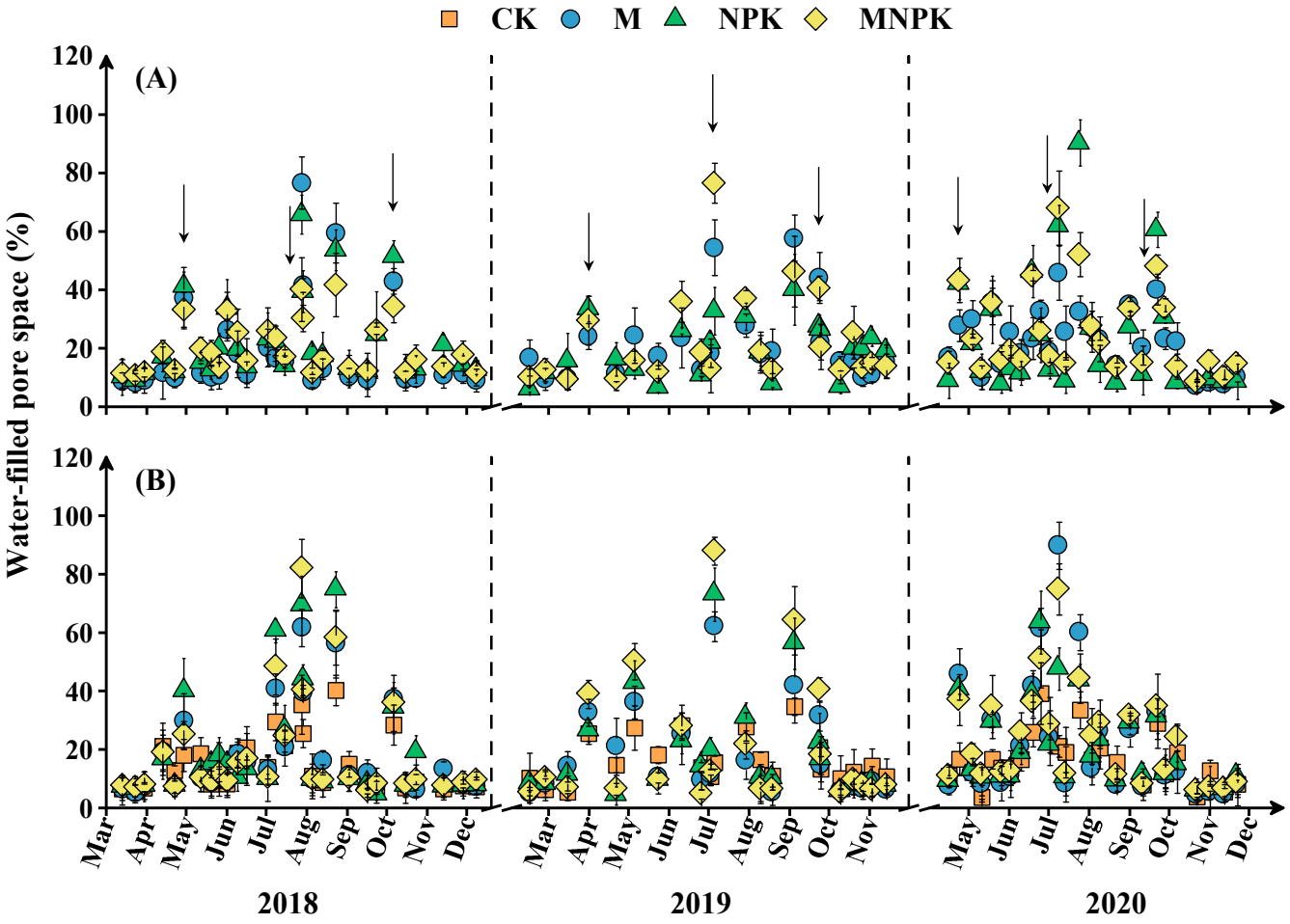


Figure 3. Seasonal dynamics of soil WFPS contents across the sampling sites and treatments from 2018 to 2020. (**A**) FD: fertilizer ditches WFPS, (**B**) BS: bare soil WFPS, CK: control, M: organic manure, NPK: chemical fertilizer, MNPK: chemical fertilizer combined with organic manure. The data points indicate the means of four replicates, and the error bars indicate the standard error (±SE). The black arrows represent the date of fertilizer application.

3.2. Soil NH_4^+-N and NO_3^--N Content

The seasonal dynamics of the soil, mostly at the FD site, were evaluated. The average soil NH_4^+-N contents for each treatment from 2018–2020 ranged from 13.14–18.97 mg kg^{-1}. The annual highest average amount of NH_4^+-N in MNPK treatment was 16.75 mg kg^{-1} and the lowest amount in M treatment was 14.65 mg kg^{-1}. Compared to M treatment, soil NH_4^+-N content in NMPK treatment was significantly higher (14.36%, $p < 0.01$). The average amount of NH_4^+-N in soil at the BS site was 7.33–14.07 mg kg^{-1} throughout the treatment. The annual highest average amount of NH_4^+-N in soil in MNPK treatment was

11.81 mg kg^{-1}, and the lowest amount in CK treatment was 7.64 mg kg^{-1}. Compared to CK treatment, soil NH_4^+-N content in NMPK treatment was significantly higher by 54.64% (Figure 4A,B).

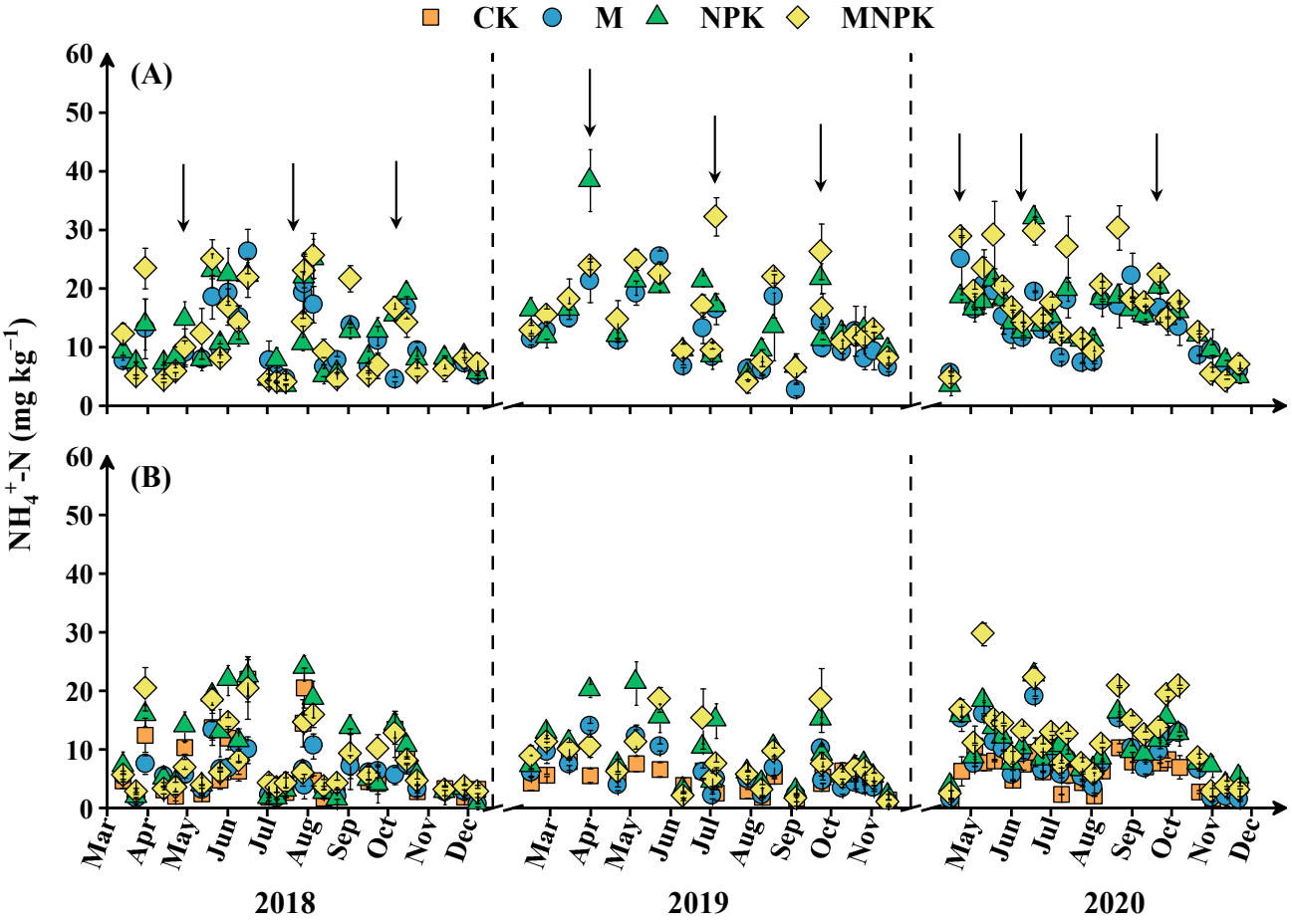


Figure 4. Seasonal dynamics of soil NH_4^+-N contents across all treatments from 2018 to 2020. (**A**) FD: fertilizer ditches, (**B**) BS: bare soil, CK: control, M: organic manure, NPK: chemical fertilizer, MNPK: chemical fertilizer combined with organic manure. The data points indicate the means of the four replicates, and the error bars indicate the standard error (±SE). The black arrows represent the date of fertilizer application.

The average amount of NO_3^--N in soil at the FD site was 15.48–25.64 mg kg^{-1} from 2018–2020. The annual highest average amount of NO_3^--N in soil in MNPK treatment was 21.64 mg kg^{-1} and the lowest amount in M treatment was 17.94 mg kg^{-1}. The conversion rate in MNPK treatment was 20.62% which was greater than in M treatment. The overall average amount of NO_3^--N in soil at the BS sites was 8.24–21.50 mg kg^{-1}. The annual highest average amount of NO_3^--N in soil in MNPK treatment was 18.48 mg kg^{-1} and the lowest amount in M treatment was 8.43 mg kg^{-1}. Moreover, the average amount of soil NO_3^--N in MNPK treatment was higher than CK treatment by 119.32%.

According to the results found in this study, the content of NO_3^--N at the FD site was higher than the BS site. Figure 5A,B show that the annual average amount of NO_3^--N in apple orchards in 2018 and 2019 were similar, while the amount of NO_3^--N in soil in 2020 was much greater.

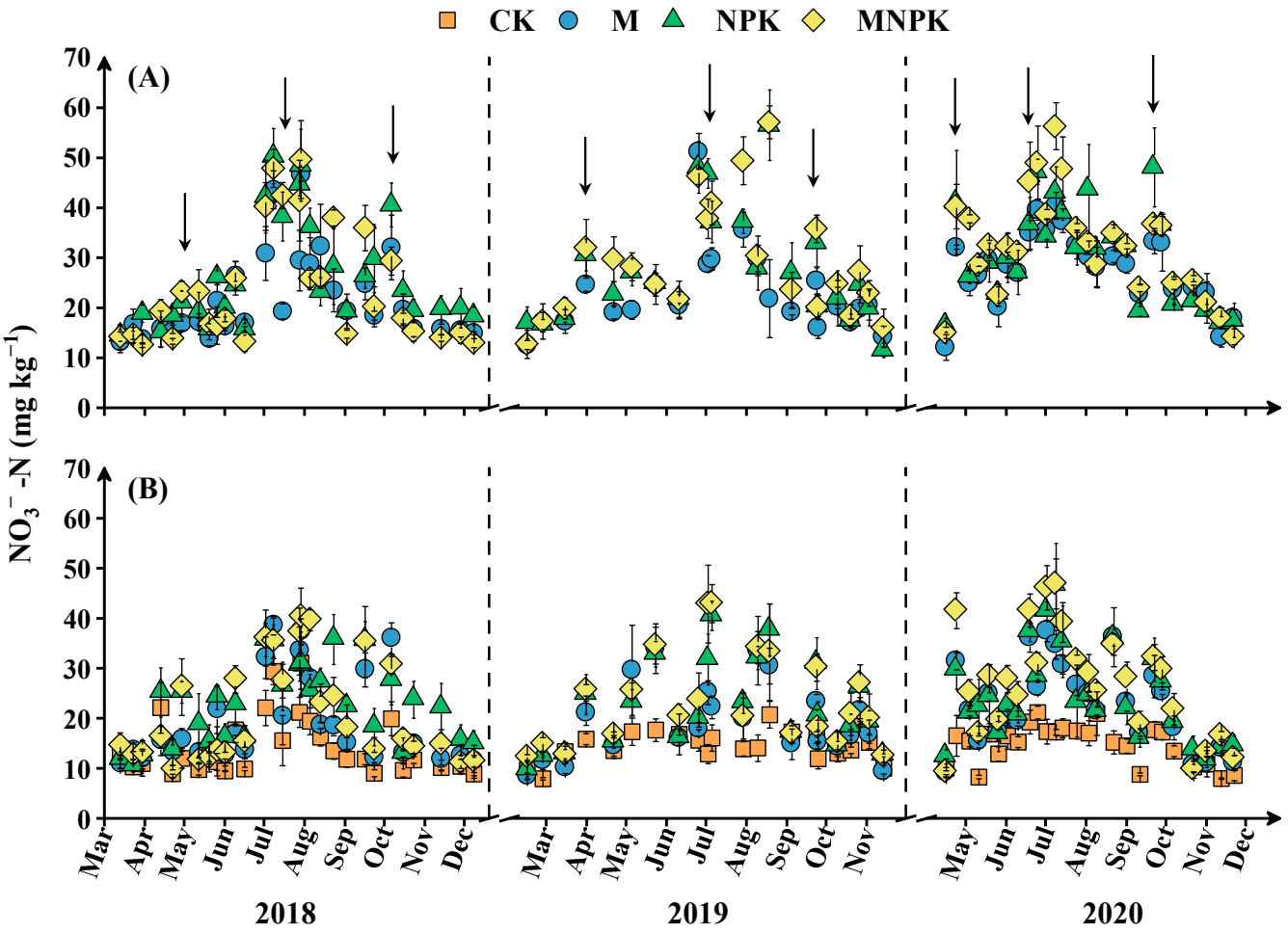


Figure 5. Seasonal dynamics of soil NO_3^--N contents across all treatments from 2018 to 2020. (**A**) FD: fertilizer ditches, (**B**) BS: bare soil, CK: control, M: organic manure, NPK: chemical fertilizer, MNPK: chemical fertilizer combined with organic manure. The data points indicate the means of the four replicates, and the error bars indicate the standard error (±SE). The black arrows represent the date of fertilizer application.

3.3. CH_4 Fluxes

The CH_4 fluxes followed similar patterns seasonally within each treatment and between years (Figure 6A–C). The CH_4 fluxes in the treatments from 2018–2020 ranged from 0.01–0.86 mg m^{-2} h^{-1}. At the FD site, the average CH_4 fluxes was 0.01–0.30 mg m^{-2} h^{-1}, in the NPK treatment between 0.01 and 0.50 mg m^{-2} h^{-1} in the MNPK treatment, and between 0.01 and 0.86 mg m^{-2} h^{-1} in the M treatment. The CH_4 fluxes at the BS site ranged from 0.02–0.76 mg m^{-2} h^{-1}. Within the BS site, the average CH_4 fluxes were 0.02–0.15 mg m^{-2} h^{-1} for the CK treatment, 0.01–0.26 mg m^{-2} h^{-1} for the NPK treatment, 0.02–0.38 mg m^{-2} h^{-1} for the MNPK treatment, and 0.02–0.76 mg m^{-2} h^{-1} for the M treatment.

Generally, the CH_4 fluxes within each treatment were highest in summer and spring and lowered in winter. At both the FD and BS sites, the M treatment had the highest CH_4 fluxes, whereas the CK and NPK treatments had the lowest fluxes. The values of the CH_4 fluxes in each treatment showed slight sinks in the apple orchard. Between treatment and trial years, we found significant changes ($p < 0.01$; Figure 6A–C).

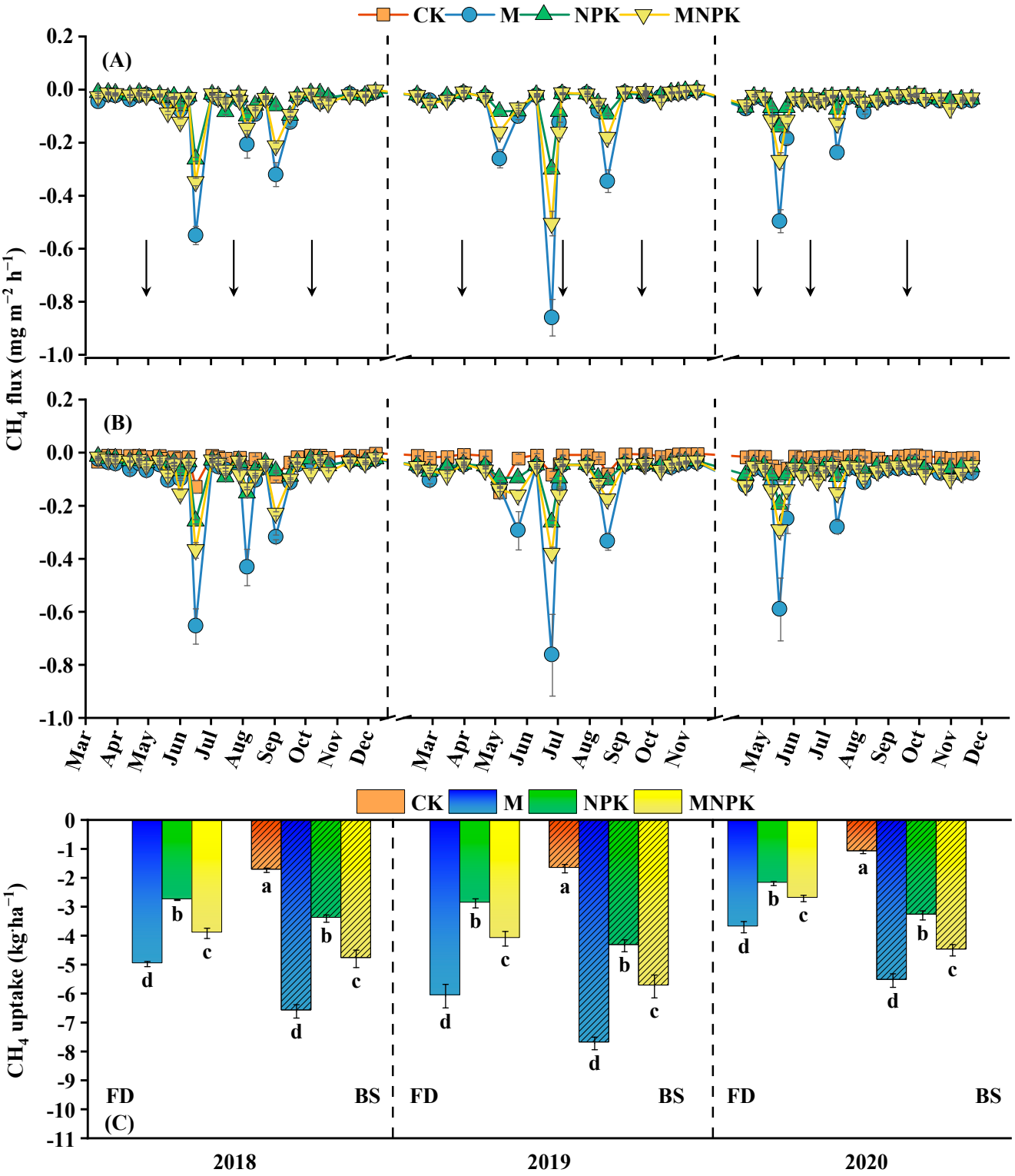


Figure 6. Variation in CH_4 fluxes under different treatments. (**A**) FD: Fertilizer ditches, (**B**) BS: Bare soil sites, (**C**) annual cumulative CH_4 uptake from different treatments. CK: control, M: organic manure, NPK: chemical fertilizer, MNPK: chemical fertilizer combined with organic manure. The data points indicate the means of the three replicates. The error bars indicate the standard error (±SE), and the black arrows indicate nitrogen fertilizer applications, the difference in lowercase letters indicate significant differences between the treatments ($p < 0.05$).

3.4. N_2O Fluxes

The N_2O fluxes at the FD site were in the range of 0.01 to 0.27 mg m^{-2} h^{-1}. The NPK fluxes were at 0.01 and 0.23 mg m^{-2} h^{-1}, and the M treatment was between 0.01 and 0.17 mg m^{-2} h^{-1}. The N_2O emissions, mostly in apple orchards, peaked in June and September and decreased between late October and April.

The N_2O fluxes increased with higher soil temperatures and an increase in WFPS. Large N_2O fluxes were found in soils in the MNPK treatment at the FD site. On 7 July 2020, N_2O fluxes as high as 0.27 mg m^{-2} h^{-1} were found during the second annual fertilization event, during the season when apple seeds grow well. On 1 August 2020, the WFPS was 45.02%. After the previous three consecutive days of rain, the N_2O flux of 0.19 mg m^{-2} h^{-1} in the MNPK was significantly increased compared to the other treatments ($p < 0.05$). The N_2O fluxes were higher after fertilization in each apple growing season and after rainfall. The seasonal N_2O fluxes in this study during the apple production period over the three years at the FD and BS sites were similar. The N_2O fluxes at the BS sites were between 0.01–0.18 mg m^{-2} h^{-1}. The overall N_2O fluxes in the MNPK, M, NPK, and CK treatments ranged from 0.01–0.22, 0.01–0.18, 0.01–0.14, and 0.01–0.07 mg m^{-2} h^{-1}, respectively, over the three years of the study's duration (Figure 7A–C).

3.5. Annual CH_4 and N_2O Emissions

The CH_4 uptake of the treatments ranged from 1.25 to 6.04 kg ha^{-1}. At the FD site, the average annual soil CH_4 uptake values for 2018, 2019, and 2020 in the M treatment were 4.93, 6.04, and 3.66 kg ha^{-1}, respectively; those in the NPK treatment were 2.73, 2.84, and 2.15 kg ha^{-1}, respectively; those in the MNPK treatment were 3.87, 4.06, and 2.67 kg ha^{-1}, respectively. The CH_4 uptake at the BS site was 1.06–7.67 kg ha^{-1}. At the BS sites, the annual average CH_4 uptake values for 2018, 2019, and 2020 in the CK treatment were 1.70, 1.64, and 1.06 kg ha^{-1}, respectively; those in the M treatment were 6.57, 7.67, and 5.50 kg ha^{-1}, respectively; those in the NPK treatment were 3.37, 4.31, and 3.25 kg ha^{-1}, and MNPK treatment was 4.75, 5.71, and 4.46 kg ha^{-1} ($p < 0.05$), respectively.

The N_2O emissions at the FD site ranged from 2.13–5.91 kg ha^{-1}. The annual average N_2O emissions for 2018, 2019, and 2020 at the FD site were 2.13, 4.45, and 4.69 kg ha^{-1} for the M treatment, respectively; 2.48, 4.82, and 5.38 kg ha^{-1} for the NPK treatment, respectively; and 2.98, 5.15, and 5.91 kg ha^{-1} for the MNPK treatment, respectively ($p < 0.05$). In the current study, the MNPK treatments produced more N_2O emissions than the NPK and M treatments (by 10.73% and 24.60%, respectively).

The N_2O emissions at the BS site ranged from 0.95–3.36 kg ha^{-1}. The N_2O emissions in the CK, M, NPK, and MNPK treatments for 2018, 2019, and, 2020 were 0.95, 1.25, and 1.76 kg ha^{-1} for the CK treatment, respectively; 1.35, 1.98, and 2.65 kg ha^{-1} for the M treatments, respectively; 1.56, 2.24, and 2.90 kg ha^{-1} for the NPK treatment, respectively; and 1.94, 2.69, 3.36 kg ha^{-1} for the CK treatment, respectively. Compared to NPK and CK, the MNPK treatment increased N_2O emissions by 19.11% and 101.77%, respectively. Significantly different N_2O emissions were observed during soil and water incubation temperatures ($p < 0.05$). Trends in N_2O emissions were observed, with similar emissions at both the FD and BS sites. According to Table 3, the FD site had higher N_2O emissions than the BS site by 105.72% ($p < 0.05$).

At both the FD and BS sites, the cumulative amount of N_2O emissions in 2020 was higher than that in 2019 and 2018. The MNPK and NPK treatments had more significant N_2O emissions than the M and CK treatments, and the treatments and years differed substantially ($p < 0.01$).

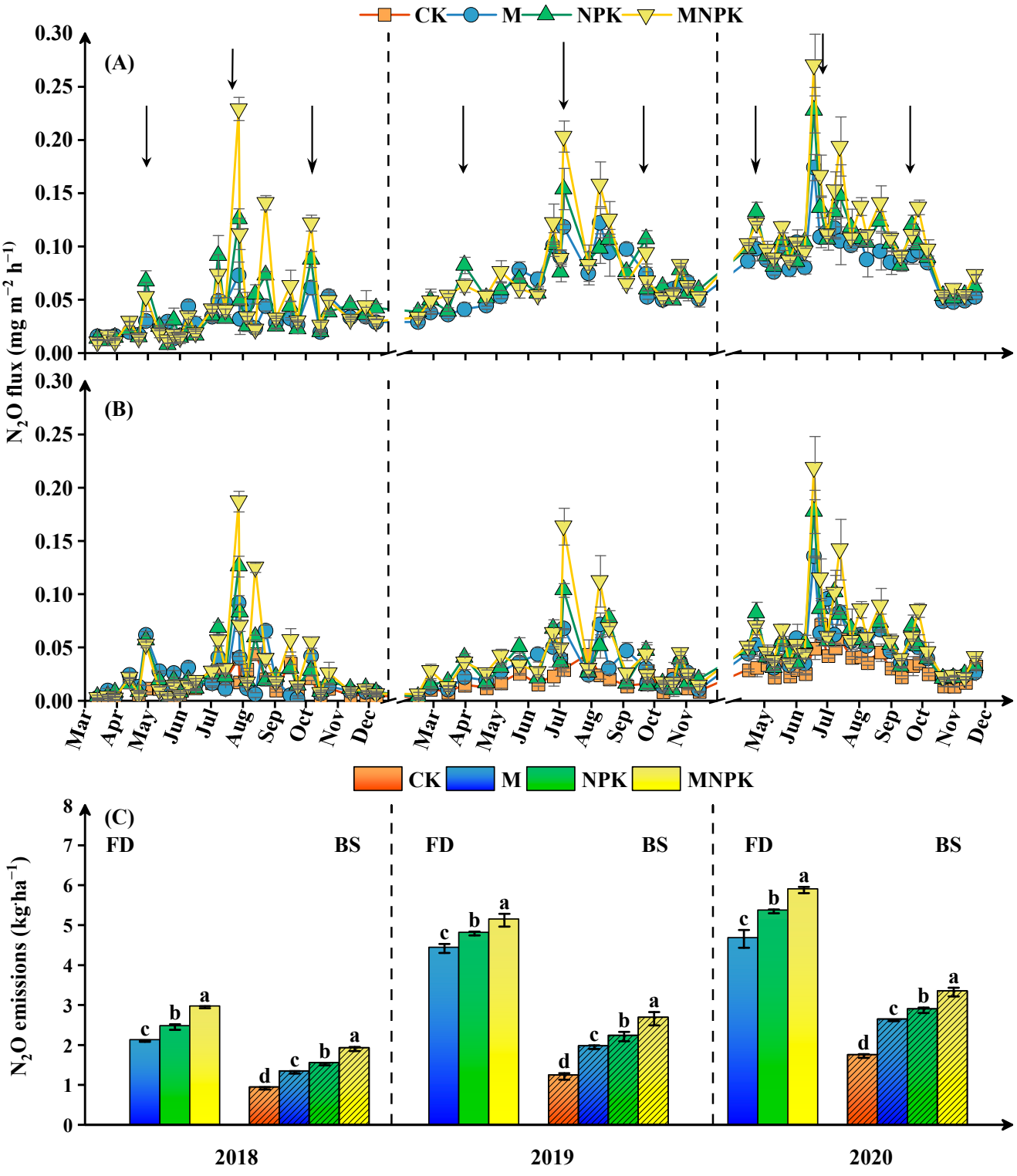


Figure 7. Seasonal variations in N_2O flux across the sampling sites and treatments. (**A**) FD: Fertilizer ditches, (**B**) BS: bare soil sites, (**C**) annual cumulative N_2O emissions from different treatments. CK: control, M: organic manure, NPK: chemical fertilizer, MNPK: chemical fertilizer combined with organic manure. The data points indicate the means of the three replicates, the error bars indicate the standard error (±SE), and the black arrows indicate nitrogen fertilizer applications. The difference in lowercase letters indicate significant differences between the treatments ($p < 0.05$).

Table 3. Total greenhouse gases emission (CH_4 and N_2O) and comprehensive greenhouse effect under different fertilization treatments.

Year	T [1]	CH_4 Emission (kg ha^{-1}) [2]		N_2O Emission (kg ha^{-1}) [3]		GWP (Emission CO_{2-eq} ha^{-1}) [4]		GHGI (g kg^{-1}) [5]	
		FD	BS	FD	BS	FD	BS	FD	BS
2018	CK	-	−1.70 ± 0.07 a	-	0.95 ± 0.05 d	-	240.70 ± 6.84 c	-	12.08 ± 1.64 a
	M	−4.93 ± 0.08 d	−6.57 ± 0.23 d	2.13 ± 0.02 c	1.35 ± 0.03 c	512.44 ± 7.62 c	238.09 ± 9.99 c	16.15 ± 2.03 bc	7.54 ± 1.33 b
	NPK	−2.73 ± 0.15 b	−3.37 ± 0.12 b	2.48 ± 0.07 b	1.56 ± 0.03 b	672.10 ± 20.81 b	379.67 ± 7.26 b	24.11 ± 4.45 a	13.56 ± 1.83 a
	MNPK	−3.87 ± 0.18 c	−4.75 ± 0.30 c	2.98 ± 0.02 a	1.93 ± 0.05 a	790.81 ± 5.43 a	457.78 ± 12.32 a	20.43 ± 0.66 ab	11.83 ± 0.52 a
2019	CK	-	−1.64 ± 0.15 a	-	1.25 ± 0.08 d	-	330.91 ± 24.66 d	-	14.25 ± 2.66 a
	M	−6.04 ± 0.40 d	−7.67 ± 0.22 d	4.45 ± 0.11 c	1.98 ± 0.05 c	1174.36 ± 29.13 c	398.21 ± 19.08 c	21.81 ± 1.58 b	7.39 ± 0.45 b
	NPK	−2.84 ± 0.16 b	−4.31 ± 0.21 b	4.82 ± 0.47 b	2.24 ± 0.12 b	1365.42 ± 18.14 b	560.80 ± 39.02 b	39.19 ± 1.29 a	16.07 ± 0.68 a
	MNPK	−4.06 ± 0.25 c	−5.71 ± 0.39 c	5.15 ± 0.15 a	2.69 ± 0.17 a	1434.34 ± 46.47 a	659.87 ± 26.52 a	20.63 ± 1.40 b	9.50 ± 0.94 b
2020	CK	-	−1.06 ± 0.05 a	-	1.76 ± 0.05 d	-	497.56 ± 14.46 d	-	18.40 ± 2.41 b
	M	−3.66 ± 0.19 d	−5.50 ± 0.23 d	4.69 ± 0.22 c	2.65 ± 0.02 c	1305.54 ± 31.81 c	652.13 ± 10.76 c	27.70 ± 1.15 c	13.85 ± 0.75 c
	NPK	−2.15 ± 0.07 b	−3.25 ± 0.16 b	5.38 ± 0.05 b	2.90 ± 0.07 b	1548.47 ± 15.62 b	783.85 ± 20.43 b	44.34 ± 4.98 a	22.47 ± 2.92 a
	MNPK	−2.67 ± 0.11 c	−4.46 ± 0.20 c	5.91 ± 0.08 a	3.36 ± 0.11 a	1693.97 ± 21.24 a	888.49 ± 27.86 a	33.40 ± 2.06 b	17.52 ± 1.36 bc
AV	CK	-	−1.47 ± 0.06 a	-	1.32 ± 0.02 d	-	356.39 ± 4.64 d	-	14.91 ± 1.27 b
	M	−4.88 ± 0.20 c	−6.58 ± 0.22 d	3.76 ± 0.10 c	1.99 ± 0.02 c	997.45 ± 25.63 c	429.48 ± 11.45 c	21.89 ± 0.89 b	9.59 ± 0.44 c
	NPK	−2.57 ± 0.07 a	−3.64 ± 0.15 b	4.23 ± 0.06 b	2.23 ± 0.05 b	1195.33 ± 18.18 b	574.77 ± 17.15 b	35.88 ± 2.73 a	17.37 ± 1.70 a
	MNPK	−3.54 ± 0.17 b	−4.97 ± 0.23 c	4.68 ± 0.06 a	2.66 ± 0.07 a	1306.38 ± 16.42 a	668.71 ± 15.64 a	24.82 ± 0.16 b	12.95 ± 0.18 b

[1] T: Treatment, FD: fertilizer ditches, BS: bare soils, CK: control, M: organic manure, NPK: chemical fertilizer, MNPK: chemical combined with organic manure, AV: average. [2] CH_4: methane. [3] N_2O: nitrous oxide. [4] GWP: global warming potential. [5] GHGI: greenhouse gas intensity, the values are shown as mean ± standard deviation (n = 3). Different letters (a, b, c, and d) at the same row meant significant difference between treatments ($p < 0.05$).

3.6. The GWP, GHGI, and N_2O EF_d

At the FD site, the GWPs in the NPK, M, and MNPK treatments for 2018, 2019, and 2020 were 672.10, 1365.42, and 1548.47 kg CO_{2-eq} ha^{-1} for the NPK treatment, respectively; 512.44, 1174.36, and 1305.54 kg CO_{2-eq} ha^{-1} for the M treatment, respectively; and 790.81, 1434.34, and 1693.97 kg CO_{2-eq} ha^{-1} for the MNPK treatment, respectively. Compared to the NPK and M treatments, the GWP for the MNPK treatments was higher, by 9.29% and 30.97%, respectively. In the present study, at the BS sites, the GWP equivalents of CO_2 in the CK, M, NPK, and MNPK treatments in 2018, 2019, and 2020 were as follows: 240.70, 330.91, and 497.56 kg CO_{2-eq} ha^{-1} for the CK treatment, respectively; 238.09, 398.21, and 652.13 kg CO_{2-eq} ha^{-1} for the M treatment, respectively; 379.67, 560.80, and 783.85 kg CO_{2-eq} ha^{-1} for the NPK treatment, respectively; and 457.78, 659.87, and 88.49 kg CO_{2-eq} ha^{-1} for the MNPK treatment, respectively. The GWP equivalent of CO_2 was higher for the MNPK treatment than for the M and CK treatments.

Within the apple orchard, at the FD and BS sites, cumulative GHGI changes were found among the years studied (Table 3). At the FD site, the GHGI in the NPK treatment was greater than that in the MNPK treatments ($p < 0.01$). Throughout the BS site, the values of the GHGI in 2018, 2019, and 2020 in the CK were 12.08, 14.25, and 18.40 g kg^{-1}, respectively; those in the M were 7.54, 7.39, and 13.85 g kg^{-1}, respectively; those in the NPK were 13.56, 16.07, and 22.47 g kg^{-1}, respectively; those in the MNPK were 11.83, 9.50, and 17.52 g kg^{-1}, respectively. At the BS site, the GHGI in the NPK treatment was 16.49% and 34.12% higher than that in the CK and MNPK treatments, respectively (Table 3). Both main treatments found that MNPK did not affect GHGI compared to NPK, although MNPK from GWP was higher than the other treatments. Nevertheless, the apple yield of MNPK is high, so the GHGI of MNPK is low compared to that of NPK.

The direct EF_d fell from 0.23%–0.65% at the FD site. Overall, the direct EF_d of the MNPK treatment (21.72%) increased significantly compared with that of the NPK treatment. On average, the direct EF_d in 2020 was higher than that in 2018 and 2019 by 117.63% and 3.93%, respectively. At the BS site, the average values of the direct EF_d in the NPK and MNPK treatments were 0.09%–0.25%. On average, compared to the NPK treatment, the MNPK treatment's direct EF_d value was significantly increased. Table 4 shows that the direct EF_d value of 2020 compared to 2018 and 2019 was higher than the values of 71.95% and 12.28%, respectively.

3.7. Apple Yield

Table 4 shows that the yield of apples varied significantly by year ($p < 0.05$). The average apple yields of all the treatments and years were 20.12 and 69.71 t ha^{-1}, respectively. The average apple yields in 2018, 2019, and 2020 in the CK, M, NPK, and MNPK treatments were 23.67, 44.44, 32.82, and 53.09 t ha^{-1}, respectively. The MNPK treatment's average apple yields were greater overall than those of the M, NPK, and CK treatments by 19.47%, 61.73%, and 124.27%, respectively.

Table 4. Apple Yield, N_2O EFd, and the yield-scaled greenhouse gas emissions.

Year	T [1]	Apple Yield (t ha^{-1}) [2]	Yield-Scaled CH_4 Absorption (kg t^{-1}) [3]		Yield-Scaled N_2O Emission (kg t^{-1}) [4]		N_2O Emission Factor EF_d (%) [5]	
			FD	BS	FD	BS	FD	BS
2018	CK	20.12 ± 2.22 c	-	−0.08 ± 0.19 a	-	0.05 ± 0.26 ab	-	-
	M	32.13 ± 4.86 b	−0.16 ± 0.24 b	−0.21 ± 0.03 c	0.07 ± 0.08 b	0.04 ± 0.31 b	-	-
	NPK	28.38 ± 4.20 b	−0.10 ± 0.14 a	−0.12 ± 0.02 b	0.09 ± 0.16 a	0.06 ± 0.11 a	0.23 ± 0.01 b	0.09 ± 0.07 b
	MNPK	38.73 ± 1.01 a	−0.10 ± 0.05 a	−0.12 ± 0.02 b	0.08 ± 0.25 ab	0.05 ± 0.18 ab	0.32 ± 0.07 a	0.15 ± 0.08 a
2019	CK	23.59 ± 3.22 d	-	−0.07 ± 0.04 a	-	0.05 ± 0.22 b	-	-
	M	53.98 ± 2.66 b	−0.11 ± 0.12 c	−0.14 ± 0.08 d	0.08 ± 0.06 b	0.04 ± 2.11 c	-	-
	NPK	34.87 ± 1.35 c	−0.08 ± 0.06 b	−0.12 ± 0.08 c	0.14 ± 0.04 a	0.06 ± 0.18 a	0.53 ± 0.01 b	0.15 ± 0.22 b
	MNPK	69.71 ± 4.30 a	−0.06 ± 0.01 a	−0.08 ± 0.02 b	0.07 ± 0.04 b	0.04 ± 0.25 c	0.62 ± 0.20 a	0.23 ± 0.02 a
2020	CK	27.30 ± 3.10 c	-	−0.04 ± 0.19 a	-	0.06 ± 0.19 b	-	-
	M	47.19 ± 2.93 a	−0.08 ± 0.05 c	−0.12 ± 0.16 c	0.10 ± 0.04 b	0.05 ± 0.17 b	-	-
	NPK	35.22 ± 3.90 b	−0.06 ± 0.06 b	−0.09 ± 0.42 b	0.15 ± 0.17 a	0.08 ± 0.11 a	0.54 ± 0.09 b	0.17 ± 0.02 b
	MNPK	50.82 ± 2.43 a	−0.05 ± 0.04 b	−0.09 ± 0.22 b	0.12 ± 0.07 b	0.06 ± 0.28 b	0.65 ± 0.15 a	0.25 ± 0.02 a
AV	CK	23.67 ± 2.30 d	-	−0.06 ± 0.01 a	-	0.06 ± 0.01 b	-	-
	M	44.44 ± 1.53 b	−0.12 ± 0.01 c	−0.16 ± 0.01 d	0.08 ± 0.03 b	0.04 ± 0.01 c	-	-
	NPK	32.82 ± 2.20 c	−0.08 ± 0.04 b	−0.11 ± 0.01 c	0.13 ± 0.09 a	0.07 ± 0.01 a	0.43 ± 0.01 b	0.14 ± 0.01 b
	MNPK	53.09 ± 0.89 a	−0.07 ± 0.02 a	−0.10 ± 0.04 b	0.09 ± 0.01 b	0.05 ± 0.01 bc	0.52 ± 0.01 a	0.21 ± 0.01 a

[1] T: Treatment, FD: fertilizer ditches, BS: bare soils, CK: control, M: organic manure, NPK: chemical fertilizer, MNPK: chemical combined with organic manure, AV: average. [2] Apple production measured as fresh weight. [3] Yield-scaled CH_4 absorption. [4] Yield-scaled N_2O emission. [5] EFd: N_2O emission factor. The values are shown as mean ± standard deviation (n = 3), respectively. Different letters (a, b, c, and d) at the same row meant significant difference between treatments ($p < 0.05$).

3.8. Relationship between GHG Emissions and Influencing Factors

The correlation analysis (shown in Figure 8) revealed a negative association between CH_4 uptake with NO_3^--N, NH_4^+-N, air temperature, and WFPS ($p < 0.05$). The N_2O emissions were significantly positively linked with the NO_3^--N concentration, air, soil temperature, pH, and WFPS at different levels. However, NH_4^+-N was concentrated in the soil and showed no significant relationship with N_2O emissions. In addition, our study found that the correlations between average annual rainfall and WFPS were 20.75%, 21.57%, and 24.20% for 2018, 2019, and 2020, respectively. We found that the WFPS in 2018 was lower than that in 2019 and 2020 by approximately 3.80% and 14.26%, respectively. This decrease would have caused a corresponding decrease in nitrification and denitrification, causing N_2O emissions to be reduced in 2018 compared with 2019 and 2020. In addition to fertilizer application in the agricultural process, the amount of rainfall each year, the WFPS, air temperature, soil climate, concentration of NO_3^--N, and pH also influence GHG emissions (Figure 8).

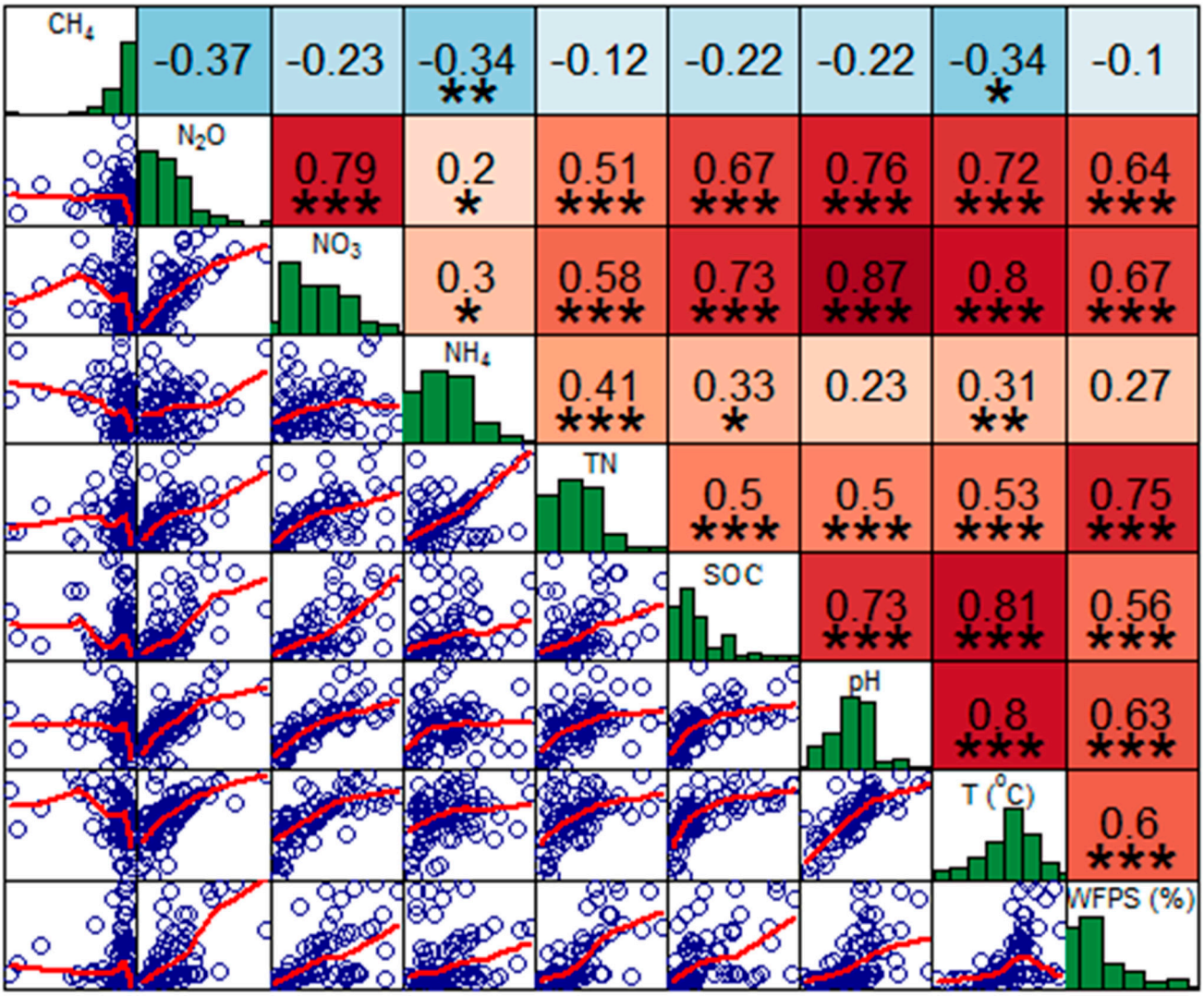


Figure 8. Correlations between GHG emissions and soil properties. N_2O: nitrous oxide, CH_4: methane, NO_3^--N: nitrate nitrogen, NH_4^+-N: ammonium nitrate, TN: total nitrogen, SOC: soil organic carbon, T: soil temperature, WFPS: water-filled pore space. Significance levels: * 0.05, ** 0.01, *** 0.001. Negative correlations are highlighted in blue, and positive correlations are highlighted in red. A richer color indicates a stronger correlation. Dark blue indicates linear correlation.

4. Discussion

4.1. The Effect of CH_4 Emissions from Soils in the FD and BS Sites under Different Fertilizer Applications

All cumulative CH_4 emissions were negative, and the negative values indicate the ability of the soil to sink the CH_4 gases. Our study findings are similar to those of a previous agricultural study [20,33,34]. The cumulative CH_4 uptake at both the FD and BS sites was higher in the M treatment than in the NPK and CK treatments (Table 3). However, when comparing the CH_4 and M treatments with the MNPK treatment, the MNPK treatment had a 50% lower cumulative yield-scaled CH_4 absorption than the M treatment.

Nevertheless, a few studies have shown that a consistent application of nitrogen and manure decreased the amount of CH_4 that soils absorbed [20]. The results of our study are consistent with those of earlier research. Fan et al. [35] observed that the uptake of CH_4 following fermented cattle manure was higher than that following NPK fertilizer alone. It is possible that using an organic fertilizer can lead to the availability of more carbon (C) for methanotrophs than other treatments [20]. Animal manures and farmyard manure applied over a long period may increase soil porosity and improve soil permeability, structure, and increased CH_4 uptake [36–39].

Previous studies have suggested that NH_4^+-N might be used as a methanotroph substrate to prevent CH_4 fluxes, since its molecular composition is comparable to CH_4 uptake [40]. The amount of NH_4^+-N in the soil is negatively related to CH_4 uptake (Figure 8). In our study, NH_4^+-N levels in the soil and CH_4 oxidation levels were not correlated. When the soil NH_4^+-N content decreases, the amount of CH_4 absorption increases. This situation occurs because of competition between the bacteria that oxidize CH_4 and the high concentration of NH_4^+-N that remains after fertilization. This competition of the development and activities of CH_4-oxidizing bacteria reduces CH_4 oxidative absorption, which then raises CH_4 and lowers its oxidative capability [38].

At both the FD and BS sites, the NPK and MNPK treatments increased the soil contents of NO_3^--N in the soil and decreased the fluxes of CH_4 in the M treatment (Figure 5A,B). However, several studies have shown that the amount of NO_3^--N in the soil can inhibit CH_4 fluxes [41]. CH_4 production decreases when NO_3^--N decreases, creating a more competitive environment for common substrates than methanogens, which are more abundant [42]. CH_4 uptake is negatively correlated with WFPS and soil temperatures [33,35,43], as shown in (Figure 8). Increases in the WFPS of soils result in the oxygen content and gas diffusion coefficient in the soil decreasing with increases in water content [44]. M fertilizer utilization and WFPS had important effects on soil CH_4. This study showed that applying M fertilizers can reduce cumulative CH_4 emission. At both the FD and BS sites, all treatments effectively reduced CH_4 emission. However, apple orchards had no high CH_4 emission on the Loess Plateau.

4.2. The Effect of N_2O Emissions from Soils at FD and BS Sites under Different Fertilizer Applications

N_2O emissions mainly produce nitrification and denitrification by microorganisms in agricultural soil [45–47]. The concentration of C and N substrates significantly impacts the amount of N_2O emissions produced in the soil. When the carbon substrate is sufficient, nitrous oxide emissions are mainly restricted by the level of nitrogen supply [48]. The results of this study demonstrated that MNPK fertilizer had the highest performance. This approach reduced the use of NPK fertilizers and stimulated and promoted the use of organic waste from integrated agriculture. Apple orchard residues emerged as a promising source for diverse value-added products derived from cellulose-rich materials (branches and leaves, apple pomace, fruit waste) that can be converted into biofertilizers, biochar, biomethane, bioethanol, biofuels, and biochemicals, such as organic, acids, and enzymes [49]. According to this study, the N_2O emissions from the FD site increased by 105.72% compared to those from the BS site. The accumulated N_2O in the MNPK treatment was significantly more significant than that in the NPK, M, and CK treatments ($p < 0.01$).

Feng et al. [50] reported that under similar conditions, i.e., when N was applied in equal amounts, the treatments using solely M or NPK fertilizers had lower N_2O than the MNPK treatment. This result may have occurred because the application of only NPK fertilizers provides enough substrate nitrogen for soil microorganisms, and N_2O fluxes are constrained by the level of carbon supply [51]. Applying MNPK fertilizer provides sufficient carbon sources for microorganisms involved in the nitrogen cycle, which increases the activity of soil microorganisms, thereby promoting soil N_2O [52,53]. Compost application to soil produces a high amount of organic carbon, which leads to N_2O emissions [54]. Compared to using only NPK fertilizers, cattle manure increased N_2O emissions by 32.70% [55].

The findings of our study align with other research, showing that MNPK fertilizer applications enhanced N_2O emissions in sandy loam soil [56]. Upland N_2O fluxes may be increased by the incorporation of organic materials into the soil [57,58]. However, several studies have shown that when sustainably using chemical fertilizer with cattle manure, biofertilizer was applied with chemical fertilizer, and chemical fertilizers were replaced. Sheep manure may significantly reduce N_2O emissions, because the animal manure more slowly releases N compared to NPK fertilizer, plants use N slowly, which reduces N_2O emissions. Additionally, animal manure can increase soil microbial activity, soil fertility, and yield and reduce N_2O emissions [59–61]. In contrast, Hou et al. [62] discovered that N_2O emissions in tea gardens in Japan following chicken manure were lower than those following NPK fertilizer treatments. Ding et al. [63] reported that this result may have been due to lower N contents in the fertilizer. Animal manure was compared to NPK fertilizers, and the differences between fertilizer types may have accounted for variances in N_2O fluxes [64]. It is still uncertain as to whether applying MNPK fertilizer promotes or inhibits soil N_2O emissions. Our studies indicated a strong correlation between temperature and soil moisture levels. Additionally, pH and WFPS are important controls that stimulate soil N_2O emissions [65]. The results show a strong correlation between dryland N_2O emission and WFPS. Soil denitrification is promoted and N_2O emissions are increased when the quantity of WFPS exceeds the capacity of the soil in the apple orchard. According to this research, N_2O emissions were more significant in 2020 and 2019 than in 2018, which may be related to the relatively heavy rains that enhance the denitrification of the soil.

4.3. Combined Application of Organic and Inorganic Fertilizers on Apple Yield, GWP, and GHGI

The MNPK treatment produced the maximum yield, whereas the NPK and M treatments did not significantly differ in apple yield, as shown in Table 4. This is because plants receive nutrients from both types of fertilizers, which include various minerals; NPK fertilizers are rich in minerals, while the nutrients from M fertilizers can be absorbed and used directly [66]. Therefore, the apple yield was similar regardless of whether only M fertilizer was applied or NPK fertilizer was applied over long periods. We found no significant difference between the treatment types. However, long-term application of M and NPK fertilizers (i.e., the MNPK treatment) can boost soil N retention, nitrogen use efficiency, and crop yields [67]. According to previous studies in related fields, the experiment using MNPK had a higher effectiveness in the increase of apple yield compared to the one that only uses NPK, as MNPK increased the amount of WFPS, SOC, and TN in soil [16,17].

Additionally, using M fertilizers can reduce agricultural waste. The average direct EF_d from the FD site was higher than that from the BS site, and compared to NPK, the MNPK treatment was higher (Table 4). In the apple orchard ecosystem, numerous factors affect N_2O emissions, including stimulation by fertilization, nitrogen evaporation, and runoff leaching (Figure 8).

A further crucial method of lowering agricultural production costs was the deployment of MNPK. The findings of numerous past studies have indicated that using organic fertilizers may boost production and improve soil quality, lowering chemical fertilizer usage [16,21,68,69]. The GWP of the crop production area is based on the standards calculated according to the GWP of CH_4 and N_2O [70]. N_2O emissions, which are released cumulatively, comprise a significant portion of the average GWP rise of approximately

70% compared to the contribution of CH_4 30% [71]. The study results parallel those of previous studies, which have indicated that CH_4 fluxes are not significant to the increase in GWP; rather, the main factor is the amount of C in the soil and N_2O fluxes. In addition, Zhang et al. and Xu et al. [72,73] explained how yearly increases in N fertilizers result in a buildup of N_2O emissions and a rise in GWP (Table 3). The GWP of the FD experiment increased more than that of the BS site, and GWP of MNPK increased more than that of M and CK by 53.25% and 84.06%, respectively.

The GHGI is a comprehensive indicator for measuring the greenhouse effect and economic benefits of agricultural soil [74]. In this study, the comparison between the FD and BS sites showed that the GHGI in FD was higher than that in BS sites; we also found that NPK treatments were higher than MNPK by 44.57% and 34.12%, respectively. This result occurred because the increased apple yield had a positive effect on GHGI [75,76]. In comparison to NPK, we discovered that MNPK treatment considerably enhanced apple production by 61.73% (Table 4). However, the MNPK treatment also increased N_2O emissions and the GWP. Nevertheless, MNPK can increase the apple yield and reduce the GHGI in apple orchards. Therefore, the MNPK application offers the best method to reduce agricultural greenhouse gas emissions, increase productivity, and achieve balanced economic and ecological benefits while reducing chemical fertilizers.

5. Conclusions

This study provides evidence that MNPK fertilizer affects on the increase of GHG emissions and yield in the apple orchard in the Loess Plateau region. The CH_4 uptake was significantly negatively correlated with the WFPS. Compared to the BS site, the FD site had more significant N_2O emissions (58.70%). Our study found that at the FD and BS sites, compared to the other treatments, the MNPK treatment resulted in greater N_2O emissions. In addition, N_2O fluxes strongly correlated with soil NO_3^--N, WFPS, pH, and temperature. The average GWP of the FD was higher than that of the BS site (47.36%), and the comparisons between the treatments showed that the MNPK had a greater GWP than the NPK and M treatments (9.29% and 30.97%, respectively). As a result, the GHGI in the MNPK treatment was lower than that in the NPK treatment, with values of 30.83% and 24.40% in the FD and BS sites, respectively. Therefore, our study recommends the MNPK treatment, which combines organic and inorganic fertilizers to increase apple yields and reduce the GHGI. This approach demonstrates how agroforestry can help sustainably intensify apple orchards in the Loess Plateau regions of China.

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