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*Article*

# Pollution-Reducing Nitrogen Management Practices in a Maize Farmland in North China Plain Adapting to Climate Change

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**Abstract:** Quantification of the trade-offs among greenhouse gas (GHG) emissions, yield and farmers' incomes is essential for proposing economic and environment nitrogen (N) management strategies for optimizing agricultural production. A four-year (2017–2020) field experiment (including four treatments: control experiment (CK), suitable utilization of fertilization (SU), emission reduction treatment (ER), and high fertilization (HF)) was conducted on maize (*Zea mays* L.) in the North China Plain. The Life Cycle Assessment (LCA) method was used in this study to quantify the GHG emissions and farmers' incomes during the whole maize production process. The total GHG emissions of CK, SU, ER and HF treatments in the process of maize production are 10,755.2, 12,908.7, 11,950.1, and 14,274.5 kg $CO_2$-eq $ha^{-1}$ respectively, of which the direct emissions account for 84.8%, 76.8%, 74.9%, and 71.0%, respectively. Adding inhibitor significantly reduced direct GHG emissions, and the $N_2O$ and $CO_2$ emissions from the maize fields in the ER treatment decreased by 30.0% and 7.9% compared to those in the SU treatment. Insignificant differences in yield were found between the SU and ER treatments, indicating that adding fertilizer inhibitors did not affect farmers' incomes while reducing GHG emissions. The yield for SU, ER and HF treatments all significantly increased by 12.9%–24.0%, 10.0%–20.7% and 2.1%–17.4% compared to CK, respectively. In comparison with CK, both SU and ER significantly promoted agricultural net profit (ANP) by 16.6% and 12.2% with the mean ANP values of 3,101.0 USD $ha^{-1}$ and 2,980.0 USD $ha^{-1}$, respectively. Due to the high agricultural inputs, the ANP values in the HF treatment was 11.2%, 16.6% and 12.4% lower than those in the SU treatment in 2018–2020. In conclusion, the combination of N fertilizer and inhibitors was proved to be an environmentally friendly, high-profit and low-emissions production technology while sustaining or even increasing maize yields in the North China Plain, which was conducive to achieving agricultural sustainability.

**Keywords:** maize yield; nitrogen management; life cycle assessment; greenhouse gas; agricultural net profit

## 1. Introduction

Modern agricultural production is an energy- and carbon-intensive process [1] releasing tremendous greenhouse gases (GHGs) into the atmosphere [2].Agriculture is one major contributor to the anthropogenic carbon dioxide emission and had caused a 35% increase of the global GHG emission during 1970–2010 [3,4]. China's agricultural development is crucial to national food security and social stability, however, it also impacts global carbon emissions that cannot be ignored. In China, GHG emissions forced by agricultural activities contributed approximately 17%–32% of national GHGs emission [5,6]. The farming-associated GHGs released into the atmosphere are derived from direct and indirect emissions. In the process of crop production, $N_2O$ is directly emitted dominantly by the application of nitrogen fertilizer in the field. In addition, the energy consumption in the production and transportation of the inputs (seeds, fertilizers, and herbicides) for farming leads to GHG emissions, as well as the energy consumption in the field management (tillage, irrigation, sowing, and harvesting) [7,8]. Therefore, how to balance agricultural carbon emissions and crop yields has become a critical issue for reducing energy consumption and improving the agricultural sustainability.

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The North China Plain is a crucial maize producing region in China and holds 22.89% of the national total cultivated land [9]. To obtain high crop yield, nitrogen fertilizer has long been used far exceeding the demand of crops in the North China Plain. For example, more than 600 kg N ha$^{-1}$ yr$^{-1}$ was used for the annual wheat-maize system in some areas [10]. However, such practice did not significantly improve crop yield but doubled N released into the environment [11]. Excessive fertilization reduces the nitrogen use efficiency (NUE) of crops and causes higher $CO_2$ and $N_2O$ emissions from soils [12–14]. Promoting cleaner agricultural practices with less fertilizer and less environmental pollution is imperative to achieve sustainable agricultural development for China. Site-specific management of nitrogen fertilizer has the potential to reduce nitrate pollution while reducing economic variability and maintaining profitability [15]. It has become increasingly evident that optimizing the fertilizer type has positive effects on the improvement of environmental quality and the ideal balance for economic profitability. Using controlled-release nitrogen fertilizer, biochar, organic fertilizer, and microbial inoculum could effectively enhance crop yields and improve N use efficiency, environment effectiveness efficiency of fertilizer in agroecosystems [16–19]. Chemical nitrification inhibitors (NI) and urease inhibitors (UI) have been proven effective to reduce the losses of N from soils. Wheat straw mulching with NI application achieved better balance among agronomic, economic and environmental benefits for dryland maize in northwest China [20]. Although application of inhibitors to reduce $N_2O$ emissions has been well reported in many areas [21,22], inconsistent results have been obtained [23–26], especially the comprehensive impact of the combined use of NI and UI on the agronomic, economic and environmental benefits of summer maize farmland in the North China Plain has not been fully investigated.

Reducing carbon emissions while ensuring crop yield in the North China Plain is a challenge to achieve national carbon neutrality. Developing and utilizing sustainable agricultural technologies with high carbon sequestration, high yield, and low emission is one of the important objectives of agricultural development in the future. According to the above considerations, we introduce an energy evaluation of maize production systems based on the Life Cycle Assessment (LCA) in this study. Some researchers have quantified the ecological and environmental impacts of a multitude of agricultural products [27].Therefore, the present study was undertaken to (i) explore the effects of NI, UI, and different fertilizer rates on direct and indirect GHG emissions (including $N_2O$, $CO_2$, and $CH_4$) in maize growth process; (ii) evaluate the economic and environmental benefits of different treatments in maize life cycle; and (iii) provide a scientific basis for emission reduction and profit increase technology to maize production in the study region.

## 2. Results

### *2.1. GHG emissions analysis*

#### 2.1.1. Direct emissions

In comparison with the $N_2O$ emission under CK, the total $N_2O$ emissions of the SU, ER and HF treatments increased by 107.8%, 62.1% and 143.1%, respectively (Figure 1a). The HF treatment produced the highest $N_2O$ emission, reaching 2.73 kg ha$^{-1}$, 3.98 kg ha$^{-1}$ and 3.56 kg ha$^{-1}$ in 2018, 2019 and 2020, respectively (Figure 1d). Nitrification inhibitor and urease inhibitor significantly decreased the $N_2O$ emission with the annual $N_2O$ emission of ER treatment 30.0% less than that of SU treatment.

Annual $CO_2$ emissions were significant lower under ER treatment than SU, with the emissions decreased by 7.9% compared with SU. The highest $CO_2$ emissions were observed at 9,700.2 kg ha$^{-1}$ in 2018 and 8,742.5 kg ha$^{-1}$ in 2019 under HF, respectively (Figure 1b). Under HF treatment, $CO_2$ emissions were highest in 2018, 2019 and 2020, at 9,700.2 kg ha$^{-1}$, 8,742.5 kg ha$^{-1}$ and 9,371.3 kg ha$^{-1}$, respectively, 5.3% higher on average than CK treatment.

Within 3 years, the absorption of $CH_4$ by HF treatment was 0.33 kg ha$^{-1}$, 0.31 kg ha$^{-1}$, and 0.34 kg ha$^{-1}$, respectively, which were 1.8, 2.3, and 2.5 times that of CK treatment. Average $CH_4$ uptake under ER treatment was 32.6% lower than SU treatment in maize growing seasons.

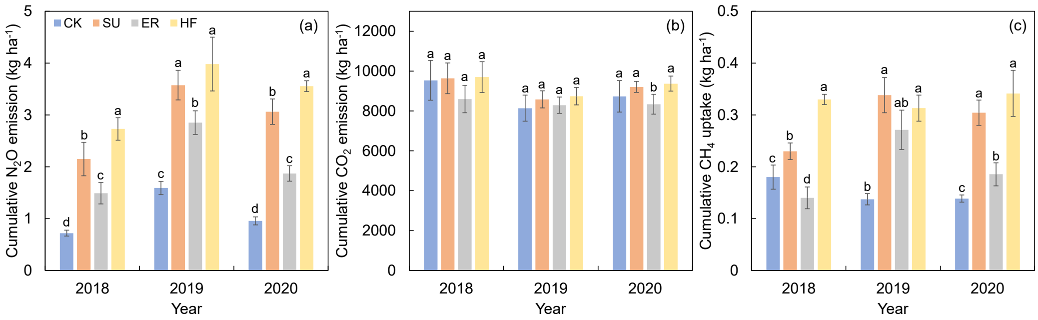


**Figure 1.** Cumulative emission/uptake quantities of $N_2O$ (a), $CO_2$ (b) and $CH_4$ (c) under different fertilizer treatments during the maize growing seasons in 2018, 2019 and 2020. CK: control experiment; SU: suitable utilization of fertilization; ER: emission reduction treatment, same fertilization as SU with a nitrification inhibitor and urease inhibitor; HF: higher fertilization than SU. The vertical bars represent the LSD value ($P = 0.05$). Different letters in the inset denote significant difference ($P < 0.05$) of cumulative $N_2O$, $CO_2$ or $CH_4$ fluxes among treatments.

2.1.2. Total GHG emissions

According to the different GHG emission sources, the average direct and indirect emissions for the maize production were computed and it was found that the direct GHG emissions were the main contributors (Figure 2). The direct GHG emissions of crop growth accounted for 84.8%, 76.8%, 74.9%, and 71.0% of total GHG emissions for CK, SU, ER and HF, respectively, with mean values of 9,121.5 kg $CO_2$-eq ha$^{-1}$, 9,910.2 kg $CO_2$-eq ha$^{-1}$, 8,951.5 kg $CO_2$-eq ha$^{-1}$, and 10,135.7 kg $CO_2$-eq ha$^{-1}$ (Figure 2). Among the direct GHG emissions, the total $CO_2$ emissions were the highest, and $CH_4$ served as a carbon sink in the agricultural ecosystem. The farm management practices and production of various agricultural materials produced smaller GHG emissions, ranging from 1,663.7 kg $CO_2$-eq ha$^{-1}$ (CK) to 4,138.8 kg $CO_2$-eq ha$^{-1}$ (HF) in 2018–2020.

The HF treatment produced significantly higher emissions than CK in 2018–2020, with the direct and indirect GHG emissions increased by 11.1% and 153.3%, respectively (Figure 2). Adding inhibitor significantly reduced direct emissions, i.e., in comparison to SU, the total emission for ER treatment decreased by 3.8–9.2% in 2018–2020, mainly resulting from the decreases in $N_2O$.

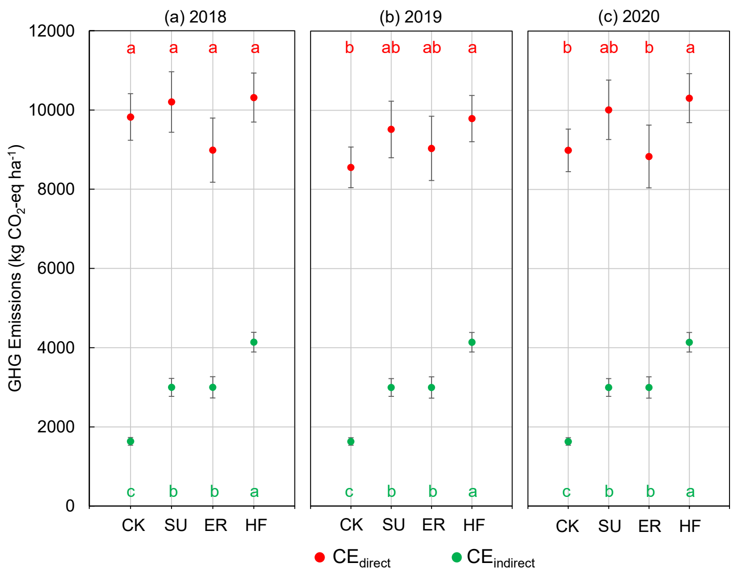


**Figure 2.** The direct and indirect GHG emissions of maize production in 2018–2020. CK: control experiment; SU: suitable utilization of fertilization; ER: emission reduction treatment, same fertilization as SU with a nitrification inhibitor and urease inhibitor; HF: higher fertilization than SU. The vertical bars represent the LSD value ($P = 0.05$).

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*2.2. Yield and its components*

Table 1 shows the yield and yield components of summer maize under different treatments from 2017 to 2020. During the 4-year trial, the maize yield in the study area ranged from 9,212 kg ha$^{-1}$ kg ha$^{-1}$ to 13,005.6 kg ha$^{-1}$; SU, ER and HF treatments all significantly increased the minimum and maximum maize yields by 12.9%–24.0%, 10.0%–20.7% and 2.1%–17.4% compared to CK, respectively (Table 1). CK exhibited the lowest number of kernels per ear, while insignificant differences for the number of ears and 1000-kernals weight were found among the four treatments. The yield for SU, ER and HF treatments had no significant differences in all four years, as well as the ear number, number of kernels per ear and 1000-kernals weight (Table 1). Compared to SU, the maize yield in the ER treatment was slightly reduced in most years, but those differences were not significant, indicating that adding nitrification inhibitor and urease inhibitor had no effect on the maize yield under the same nitrogen application level.

**Table 1.** Yield and yield components under different treatments.

| Year | Treatment | Number of ears (667 m$^{-1}$) | Number of kernels per ear (ear$^{-1}$) | 1000-kernals weight (g) | Yield (kg ha$^{-1}$) | Yield increase rate compared with CK (%) |
|---|---|---|---|---|---|---|
| 2017 | CK[a] | 4724.6a[b] | 456.2b | 348.7a | 10961.9b | - |
| | SU | 4594.9a | 500.4ab | 366.6a | 12376.8a | 12.9 |
| | ER | 4706.0a | 520.7a | 370.4a | 13005.6a | 18.7 |
| | HF | 4446.7a | 491.1ab | 374.1a | 12042.5ab | 9.9 |
| 2018 | CK[a] | 4705.0a | 465.3b | 353.1a | 9797.9b | - |
| | SU | 4817.2a | 521.7a | 375.6a | 12131.9a | 23.8 |
| | ER | 4779.8a | 525.0a | 367.3a | 11761.3a | 20.0 |
| | HF | 4668.6a | 511.2ab | 375.1a | 11504.8a | 17.4 |
| 2019 | CK[a] | 4451.5a | 536.7a | 348.7a | 10646.0b | - |
| | SU | 4444.7a | 571.4a | 375.7a | 12166.1a | 14.3 |
| | ER | 4348.6a | 564.2a | 374.7a | 11714.8ab | 10.0 |
| | HF | 4506.4a | 554.0a | 341.1a | 10869.8b | 2.1 |
| 2020 | CK | 4417.2a | 479.7b | 328.5b | 9212.8b | - |
| | SU | 4430.9a | 538.4a | 363.9a | 10813.6a | 24.0 |
| | ER | 4492.7a | 521.4ab | 359.7ab | 10635.7a | 20.7 |
| | HF | 4444.7a | 523.6ab | 345.1ab | 10246.6a | 15.0 |
| Average | CK | 4517.1a | 484.5a | 343.8a | 10153.7b | - |
| | SU | 4508.6a | 532.8a | 367.7a | 11867.2a | 18.7 |
| | ER | 4493.3a | 532.8a | 364.1a | 11777.7a | 17.4 |
| | HF | 4476.5a | 520.7a | 364.5a | 11155.6ab | 11.1 |
| Treatment | | 0.946 | ** | ** | ** | |
| Year | | ** | ** | ** | ** | |
| Year×Treatment | | 0.901 | 0.505 | 0.740 | 0.587 | |

[a] Definitions of the codes for the treatments are shown in the footnotes for Table 4. [b] Different letters following values denote significant difference at $P < 0.05$ based on Duncan's new multiple-range test d two treatments with the same letter (a, b, c, etc.) indicates insignificant difference.

*2.3. Economic profits analysis based on GHG emission and yield*

The $CE_Y$ ranges of different treatments were 1.02 kg kg$^{-1}$–1.26 kg kg$^{-1}$, 0.95 kg kg$^{-1}$–1.28 kg kg$^{-1}$ and 1.11–1.41 kg kg$^{-1}$ in 2018 2019, and 2020, respectively (Figure 3). The ER treatment could decrease $CE_Y$ by 4.7% compared to SU during 2018–2020, which indicated that the ER planting system emitted less GHGs per unit maize production. Results also showed that there were no significant $CE_Y$ differences between ER and CK; and the $CE_Y$ of HF treatment was significantly improved by 21.2% compared to CK.

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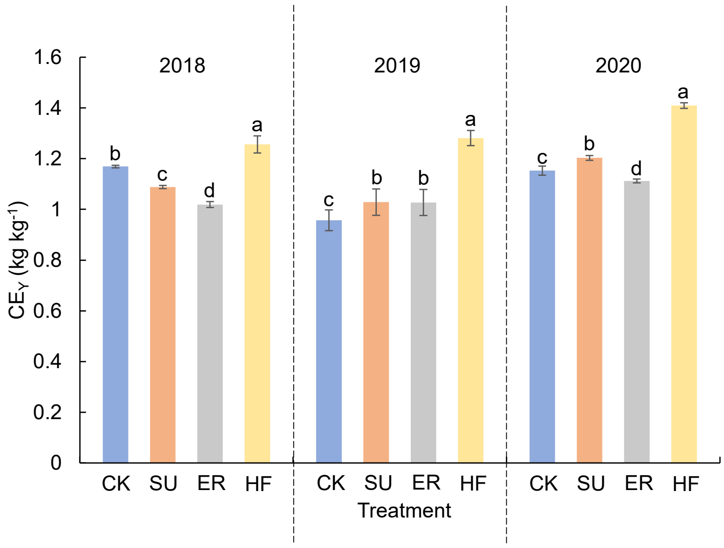


**Figure 3.** The direct and indirect GHG emissions of maize production in 2018–2020. CK: control experiment; SU: suitable utilization of fertilization; ER: emission reduction treatment, same fertilization as SU with a nitrification inhibitor and urease inhibitor; HF: higher fertilization than SU. The vertical bars represent the LSD value (P = 0.05).

The differences in the ANP and GHG emissions for the all treatments were further explored, and four emission–profit modes were defined (Figure 4), i.e., high emission–high yield (HE–HY), low emission–high yield (LE–HY), high emission–low yield (HE–LY), and low emission–low yield (LE–LY). Compared to CK (LE–LY), the HF treatments showed HE–LY mode, i.e., higher GHG emissions and lower maize yield, indicating that the high nitrogen application rate in HF should be avoided in the maize production in the study area. Although the SU treatment could lead to a high yield, it produced a higher GHG emissions compared with CK, and thus this treatment is not a proper measure for the green and low-carbon development. As exhibiting a LE–HY mode, the ER treatment's fertilization management can be used for demonstration and promotion of efficiency and emission reduction technology for summer maize planting and production in the North China Plain.

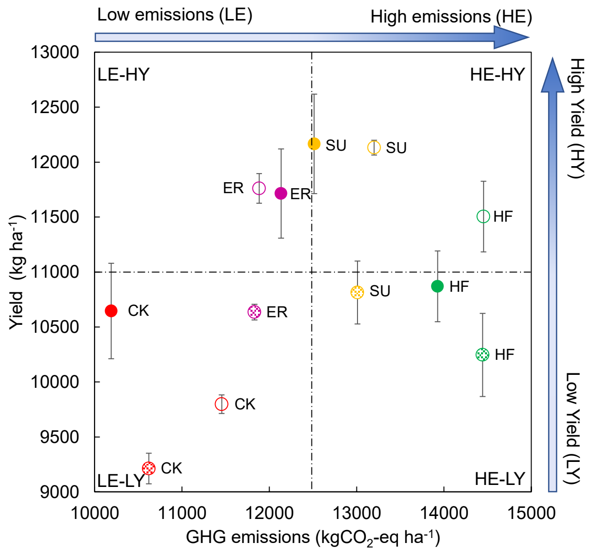


**Figure 4.** Classification of different nitrogen management based on GHG emissions-maize yield. Low emissions (LE): 10000<GHG emissions<12500; high emissions (HE): 12500<GHG emissions<15000; how yield (LY): 9000<yield<11000; high yield (HY): 11000<yield<13000. The hollow circle, solid circle and slant filled circle represent the GHG emissions and maize for 2018, 2019 and 2020, respectively. The vertical bars represent the LSD value (P = 0.05).

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The agricultural outputs in all treatments in 2018–2020 were higher than the costs of agricultural inputs, with the ANP ranging from 2,415.0 US$ to 3542.7 US$ (Figure 5). In comparison of CK, both SU and ER significantly promoted ANP by 16.6 % and 12.2%, and the mean benefits were 3,101.0 US$ and 2,980.0 US$, respectively. On the contrast, due to the high agricultural inputs, the ANP values in the HF treatment was significantly lower than those in SU: 11.2% lower in 2018, 16.6% lower in 2019 and 12.4% lower in 2020.

The average values of the cost-benefit ratio ranged from 4.6 to 6.9 for the four treatments in the study area (Figure 5). The cost-benefit ratios of SU and ER were lower than those achieved under the CK, and the decreases compared to CK were 8.4% and 13.3% in 3 years, respectively. Compared to CK, the cost-benefit ratio in the HF treatment was reduced by 28.2% in 2018, 38.9% in 2019 and 29.8% in 2020. Results also showed that there were no significant differences in ANP and cost-benefit ratio between the SU and ER treatments, indicating that adding fertilizer inhibitors did not affect farmers' income while reducing emissions.

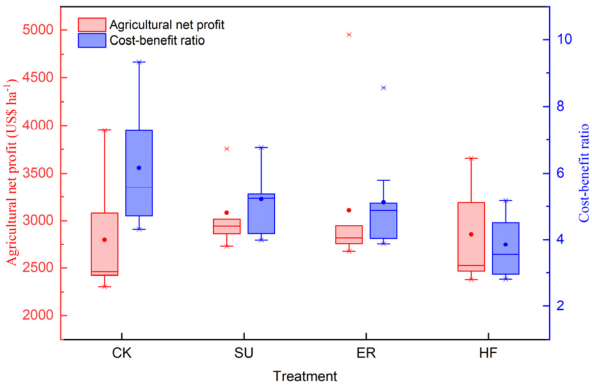


**Figure 5.** Maize agricultural net profit and cost-benefit ratio under different treatments in the North China Plain. ANP: Agricultural net profit. CK: control experiment; SU: suitable utilization of fertilization; ER: emission reduction treatment, same fertilization as SU with a nitrification inhibitor and urease inhibitor; HF: higher fertilization than SU. The solid line in the box represents the median value, the box boundary indicates the 25th and 75th percentiles, and black dots indicate the average value.

## 3. Discussion

### *3.1. Soil gases emissions*

#### 3.1.1. $N_2O$ emission

In order to achieve high grain yield in the North China Plain, excessive nitrogen fertilizer had been applied in the fields and resulted in the loss of a large number of N elements through $N_2O$ emissions, nitrogen leaching, and ammonia volatilization, which increased GHG emissions. The results showed that the application of nitrogen fertilizer was the main factor affecting $N_2O$ emission from farmland soils [28]. Fertilization provides not only nutrients for crop growth but also sufficient substrates for microorganisms, which promotes the generation and emission of $N_2O$ in the process of nitrification and denitrification; irrigation or rainfall creates an anaerobic environment for denitrifying microorganisms and improves the generation and emission of $N_2O$ during denitrification. Therefore, $N_2O$ emission peak usually occurs after fertilization and irrigation.

Adding DCD and NBPT to nitrogen fertilizer is an important measure to reduce $N_2O$ emission and increase crop yield [29,30]. Urease inhibitor can block the reaction process of urea hydrolysis to ammonium carbonate and $NH_3$ formation by urease, and prolong the time of urea entering the soil; Nitrification inhibitors mainly delay the conversion of ammonium ions ($NH_4^+$) into $NO_3^-$, decrease

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nitrification rate, reduce nitrogen volatilization (such as nitrogen oxides) or nitrogen leaching (such as $NO_3^-$ or $NO_2^-$), thus limiting $N_2O$ emissions from soil denitrification.

Previous studies have found that environment conditions (precipitation and temperature) could significantly affect the GHG emissions from the farmland [31–33]. We further compared the $N_2O$ emissions in 2018 (dry year with 300.89 mm in maize growing season) and 2019 (wet year with 555.79 mm in maize growing season), and found that the total $N_2O$ emissions was 69.3% higher in wet year than that in dry year, which was consistent with the results in Ju et al. [34].

3.1.2. $CO_2$ and $CH_4$ emissions

At present, the effect of nitrogen addition on soil respiration was inconsistent. Several studies have shown that the carbon allocation to roots was decreased by N additions, resulting in the lower microbial respiration in the soil and rhizosphere [35,36]. In contrast, other studies have reported that N additions stimulate soil respiration by accelerating soil organic matter decomposition [37,38] (Cleveland and Townsend, 2006; Jassal et al., 2010). In this study, our results indicated that the $CO_2$ emission was higher in the treatment of nitrogen application, and the increase of nitrogen had an obvious promoting effect on $CO_2$ emission. Except for ER, there was no significant difference in the $CO_2$ emissions of the other treatments. Seasonal dynamics of soil $CO_2$ flux followed air and soil temperatures variations, crop growth speed, and respiration rate in both years [39].

Methane-oxidizing bacteria in dryland soils could consume and absorb $CH_4$ from the air near the ground and use $CH_4$ as the sole carbon source [40]. Nitrogen application inhibited $CH_4$ uptake, but the addition of inhibitors increased nitrogen content in soil, which was not conducive to the survival of methane-oxidizing bacteria and significantly reduced $CH_4$ absorption. Compared with the SU treatment, the uptake of $CH_4$ in the ER treatment decreased by 32.6%. During the summer maize growing season, there was no clear change mechanism of $CH_4$ uptake by soil. The effect mechanism of fertilization on $CH_4$ emission flux is complex. Increasing nitrogen fertilizer promoted the proliferation of methanogens, but inhibited the growth of methane oxidizing bacteria. Therefore, except for ER, there was no significant difference in the $CH_4$ emission flux of the other treatments.

*3.2. Direct and indirect carbon emissions*

In recent years, there are still controversies about the types of GHGs and system boundaries of the carbon budget [41,42]. Therefore, in many studies of the estimation of carbon emissions from food crop productions, the settled results of maize are quite different with a great uncertainty. The contribution of material and energy inputs to GHGs cannot be ignored. It is an incomplete evaluation of the carbon budget in the agricultural system without considering the emission flux of $CO_2$ to the atmosphere caused by energy consumption. In particular, the impact of nitrogen fertilizer as the largest energy consumption input in agricultural production on $CO_2$ emission should not be ignored [43]. Chemical fertilizer and irrigation were the largest contributor to GHG emission in agricultural fields [6]. Compared with the energy production of some other developed countries, coal combustion is the major energy source for agriculture in China. However, the energy conversion efficiency of coal is usually low, which indicates that $CO_2$ emissions from agricultural production in China would be more than those in other developed countries. Chen et al. [44] calculated the GHG emission coefficients (from raw materials to factory gates) in the manufacturing process of various nitrogen fertilizers, phosphate fertilizers and potash fertilizers in line with China’s current situation by collecting and integrating relevant domestic data. The GHG emissions coefficient of nitrogen, phosphorus and potassium fertilizers is generally about twice that of the European and American average. Therefore, the use of foreign coefficients to estimate China's agricultural GHG emissions will seriously underestimate the impact of chemical fertilizer application. In this study, the carbon emissions from chemical fertilizer accounted for more than 70% of the carbon emissions from agricultural production. Using the life cycle assessment method, Zhang et al. [45] estimated that the GHG emissions of nitrogen fertilizer production, processing and transportation in China is as high as 8.3 kg $CO_2$-eq, which is 60% higher than the greenhouse effect caused by GHG emissions caused by field application. Some studies suggested that $CH_4$ accounted for a small proportion of GHG

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emissions in dryland, so it should not be included in the calculation. Soil $N_2O$ emissions have not been calculated either. In this study, $CO_2$, $NO_2$, and $CH_4$ released indirectly by agricultural input were included in the analysis, and the carbon balance of different fertilization treatments was comprehensively and systematically analyzed.

### *3.3. Effects of N management on yield and economic profits*

To pursuit high grain yield, the farmers in the North China Plain prefer to excessive application of nitrogen fertilizer. However, this study found that no higher yield was obtained with the high fertilizer rate in the HF treatment, and ironically the farmers' income was decreased due to the higher input. As Nitrogen fertilizer rate was the main factor affecting $N_2O$ emissions from farmland soils [28], significant increases (143.1% higher than CK) of the GHG emissions in the HF treatment were found in this study. Tan et al. [46] also concluded through field experiments that a 30% reduction in nitrogen input in a winter wheat–summer maize rotation system can significantly reduce total GHG emissions while maintaining grain yield. Wu et al. [47] found that if maize production areas in China take optimized nitrogen fertilizer measures, 1.4 million tons of nitrogen fertilizer and 18.6 million tons of GHG emissions can be reduced each year. Adding nitrification inhibitor and urease inhibitor was reported to an effective method to reduced GHG emissions [48,49], and this study exhibited that the $N_2O$ and $CO_2$ emissions in the ER treatment were both decreased by 30.0% and 7.9% under the same nitrogen application rate. Meanwhile, insignificant yield differences were found between the ER and SU treatments, which was consistent with previous research results [50,51]. ER has two characteristics, i.e., low GHG emission and high ANP. While reducing GHG emissions, ER significantly improved the net income of maize, which is in line with the connotation core of low-carbon modern agriculture. Therefore, controlling the application rate of N fertilizer is necessary to reduce both direct and indirect GHG emissions.

In this study, since only one nitrification inhibitor and urease inhibitor were used, it is necessary to further explore the effects of the mixed application of nitrogen fertilizer, NIs, and UIs, on reducing emissions and increasing economic profits. In summary, as for the maize production in the North China Plain, using fertilizer inhibitor was a green agriculture method because of low GHG emission and high crop income, while application of high fertilization was an opposite measure leading to high GHG emission and low crop income way. To achieve carbon neutrality and effectively adaptation to climate change, we highly recommend the agricultural practices with low GHG emissions and high crop income to be used and promoted in China.

## 4. Materials and Methods

### *4.1. Experimental sites*

North China Plain is the largest alluvial plain in China including two province-level municipalities (i.e., Beijing and Tianjin) and three provinces (i.e., Hebei, Shandong, and Henan), with a total area of 536,628 $km^2$ [52]. A four-year (from 2017 to 2020) field experiment was conducted at the Wuqiao Experimental Station (37.5° N, 116.4° E) in the North China Plain (Figure 6). Wuqiao County has a typical temperate monsoon climate, i.e., hot and rainy summers with the average temperature over 20 °C, and cold and dry winters. The average annual total precipitation is about 500 mm and 70 % of rainfall occurs between June and September. Daily mean temperature and precipitation during the maize growing season in 2017–2020 are plotted in Figure 7. An automated-weather station was installed in the experimental field for collecting daily meteorological data. Soil type in the experimental area is fluvo aquic soil (Cambisols, FAO), with a pH value of 8.25. The content of soil organic matter, total nitrogen, ammonium nitrogen, alkali-hydrolyzable nitrogen, available phosphate and available potassium in 0–20 cm soil layer was 1.61%, 1.21 g $kg^{-1}$, 7.80 mg $kg^{-1}$, 80.18 mg $kg^{-1}$, 29.57 mg $kg^{-1}$, and 212.10 mg $kg^{-1}$, respectively.

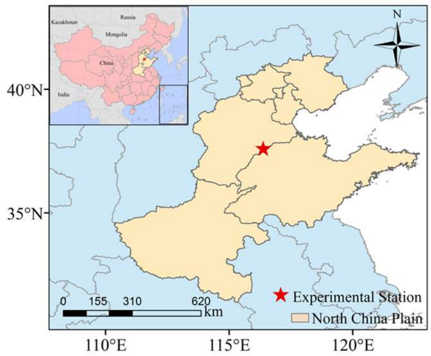


**Figure 6.** Map showing the location of the experimental station and study area.

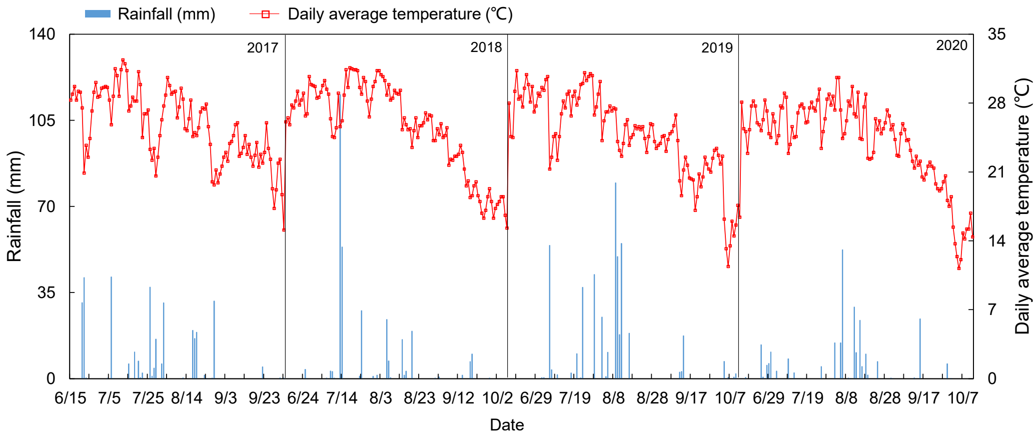


**Figure 7.** Precipitation and average temperature during the maize growth period of 2017–2020 at the Wu Qiao Experimental Station.

*4.2. Experimental design and field management*

The field experiment was conducted from 2017 to 2020 in maize (*Zea mays L.* Cv. Zhengdan 958) fields. The experiment had four treatments in a randomized block design with three replicates; each plot was 9.0 m long and 5.4 m wide. There four treatments were: (1) CK, control experiment; (2) SU, suitable utilization of fertilization; (3) ER, emission reduction treatment with the same fertilization as SU, but with a nitrification inhibitor and urease inhibitor; (4) HF, higher fertilization than SU. The N type was urea (U, 46 % N) for all treatments. The detailed NPK fertilizer usages for these treatments are shown in Table 2. Dicyandiamide (DCD, a nitrification inhibitor, content ≥ 98%) was manufactured by Wuxi Yatai United Chemical Co., Ltd., and hydroquinone (NBPT, a urease inhibitor, content ≥98.5%) was manufactured by Shandong Baiqian Chemical Co., Ltd. The fertilizer was applied just once on June 20 (ditch application between two rows of maize), and no extra fertilizer was applied during maize growth period. There was no artificial irrigation during the experiment period, and manual weeding was performed throughout the experiment. All treatments had the same plant spacing (0.25 m) and row spacing (0.6 m), producing a planting density of 67,500 plants $ha^{-1}$, which was consistent with the common practice of local farmers (Figure 8). Seeds were sown on 15 June of all years and harvested on early October in 2017–2020, and the average growth period of maize was 114 days.

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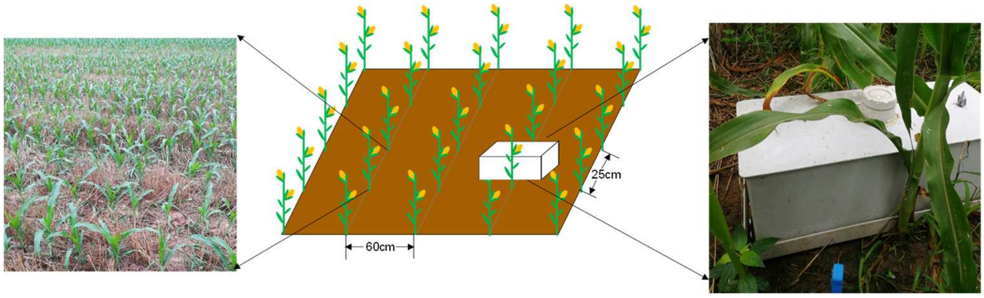


**Figure 8.** A schematic diagram for the layout of maize and static chamber locations. The white box represents the static chamber (0.6 meters in length, 0.25 meters in width and 0.23 meters in height), which was permanently installed between plants perpendicular to the planting row in the middle of the plot in the whole maize season. Each chamber could be matched to a frame base, which was inserted 10 cm into the soil at the beginning of the experiment, where it remained. The chamber was fitted into the frame base with a groove (5 cm width) during sampling, and the groove was sealed by infusing water between the chamber and the frame base.

**Table 2.** Application rates of fertilizers in different treatments during maize season in the long-term experiments (kg $ha^{-1}$).

| Treatment | N | $P_2O_5$ | $K_2O$ | Others |
|---|---|---|---|---|
| CK[a] | 23.4 | 60 | 90 | - |
| SU | 180 | 120 | 105 | - |
| ER | 180 | 120 | 105 | DCD[b]:21.75, NBPT:0.9 |
| HF | 300 | 180 | 210 | - |

[a] CK: control experiment; SU: suitable utilization of fertilization; ER: emission reduction treatment, same fertilization as SU with a nitrification inhibitor and urease inhibitor; HF: higher fertilization than SU. [b] DCD, dicyandiamide, a nitrification inhibitor; NBPT, hydroquinone, a urease inhibitor.

### *4.3. Measurements and calculation*

#### 4.3.1. Crop yield

Three rows in each plot were selected randomly, dried initially at 105 °C for 30 min and then oven-dried to a constant weight at 80 °C. At harvest, 20 $m^2$ in the middle of each plot was manually harvested to determine the grain yield and yield components. The yield was expressed at 14% moisture content, according to the standard moisture for maize grain. The number of grains per spike and the 1000-grain weight were recorded.

#### 4.3.2. GHG sampling and measurements

Static chamber/gas chromatography method was used to measure soil $CO_2$, $CH_4$ and $N_2O$ emissions from 2018 to 2020. A PVC static chamber held by frame was permanently installed between plants perpendicular to the planting row in the middle of each plot during the whole maize growing season (Figure 8). No plants and weeds existed on the soil surface covered by the collar to ensure that all the GHG collected were produced by soil. The top edge of the collar had a groove, and the static chamber (0.6 meters in length, 0.25 meters in width and 0.23 meters in height) was placed with the rim of the chamber fitted into the groove while gas was sampled. The groove was filled with water to seal the rim of the chamber.

Four GHG samples were collected for each treatment between 09:00 and 11:00 am since the soil temperature during the sampling period was close to the daily average soil temperature [53]. The first sample was taken immediately after the static chamber was placed, and the other samples were collected after 10, 20, and 30 minutes. Each GHG sample (80–120 mL) was taken from the static chamber using plastic syringes. The growth status of maize, soil moisture content, and temperature in the box were recorded simultaneously. Daily GHG samples were measured for seven consecutive

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days after fertilization, and then the samples were collected every ten days. An additional measurement was taken after each precipitation event.

The emission flux of $N_2O$, $CO_2$, and $CH_4$ was calculated as follows [54]:

$$F = \rho \times H \times \frac{\Delta C}{\Delta t} \times \frac{273}{273+T} \times k \quad (1)$$

where $F$ is the GHG emission flux (mg m$^{-2}$ h$^{-1}$/μg m$^{-2}$ h$^{-1}$), $\rho$ is the gas density (g m$^{-3}$) at 273 K and 0.101 MPa pressure, $H$ is the height of the chamber (m), $\frac{\Delta C}{\Delta t}$ is the rate change in gas concentration inside the chamber (g m$^{-3}$ min$^{-1}$), $T$ is the air temperature (K) inside the chamber, and $k$ is the time conversion factor (min h$^{-1}$). A positive or negative $F$ value indicates that soil is the source or sink of the GHG, respectively.

The amount of $N_2O$, $CO_2$, and $CH_4$ emissions on the sampling day is calculated as follows:

$$R = F \times a \times b \times c \quad (2)$$

where $R$ is the total amount of $CO_2$, $N_2O$, and $CH_4$ emissions (kg ha$^{-1}$), $F$ is the GHG emission flux (mg m$^{-2}$ h$^{-1}$/μg m$^{-2}$ h$^{-1}$), $a$ is the time conversion factor (h day$^{-1}$), $b$ is the area convention coefficient (10,000 m$^2$ ha$^{-1}$), and $c$ is the weight conversion factor ($10^6$ mg kg$^{-1}$/$10^9$ μg kg$^{-1}$). Liner interpolation method was used to calculate the daily GHG emission between two sampling dates.

#### 4.3.3. Carbon Dioxide Equivalent ($CO_2$-eq) in maize life cycle

The life cycle assessment (LCA) methodology was used in this study to quantify the GHG emissions during the whole maize production process. GHG emissions at the system boundary of maize planting in the LCA were divided into direct and indirect emissions. The direct GHG emissions are from maize farmland under different N fertilizer treatments, including $CO_2$, $N_2O$, and $CH_4$. The indirect GHG emissions comprises farm management practices (sowing, tillage, irrigation, and harvesting), as well as the production and transportation of agricultural materials (seeds, fertilizer and pesticide).

The Carbon Dioxide Equivalent ($CO_2$-eq) in maize life cycle was net emissions of GHG, and was calculated as follows:

$$CE = CE_{direct} + CE_{indirect} \quad (3)$$

$$CE_{indirect} = \sum_{i=1}^{n} CE_i = \sum_{i=1}^{n} m_i \beta_i \quad (4)$$

$$CE_{direct} = R_{CO_2} + R_{N_2O} \times 265 + R_{CH_4} \times 28 \quad (5)$$

where $m_i$ and $\beta_i$ are the agricultural inputs and relevant emission coefficients of the indirect GHG emissions [55], as shown in Table 3. $R_{N_2O}$ is the total amount of $N_2O$ emissions (kg ha$^{-1}$), and $R_{CH_4}$ is the total amount of $CH_4$ emissions (kg ha$^{-1}$). The factors of 265 and 28 are the default molecular GWPs of $N_2O$ and $CH_4$, respectively, for a 100-year time horizon [56]. A positive $CE$ value indicates a net C source and a negative value reflects a net C sink.

As widely used to evaluate the efficiency of the crop system that produces yield and GHG emissions, carbon emission efficiency ($CE_Y$) is the carbon equivalent per unit crop yield [57]. The $CE_Y$ was calculated as:

$$CE_Y = \frac{CE}{Y} \quad (6)$$

where $CE_Y$ is the GHG emissions per unit yield; $Y$ is the crop yield (kg ha$^{-1}$).

**Table 3.** Carbon equivalent emissions for agricultural inputs used in the field experiment.

| Emission sources | GHG emissions (kg C per unit input) | References |
|---|---|---|
| N | 2.116 | Chen et al., 2015 [44] |
| $P_2O_5$ | 0.636 | Chen et al., 2015 [44] |
| $K_2O$ | 0.18 | Chen et al., 2015 [44] |
| Herbicide | 6.3 | Lal, 2004 [58] |
| Insecticide | 5.1 | Lal, 2004 [58] |
| Diesel fuel | 0.94 | Lal, 2004 [58] |
| Electricity for irrigation | 0.31 | Yuan et al., 2006 [59] |
| Seed | 1.05 | West and Marland, 2002 [60] |

4.3.4. Agricultural economy in maize life cycle

LCA method was also used for agricultural economic analysis by considering all agricultural inputs and outputs in the maize growth process. The agricultural inputs were the same as in the calculation of $CO_2$ Equivalent, i.e., the costs of farm management practices and materials production and transportation in maize planting, and the output was the economic benefits generated by the maize yield. The unit prices of agricultural inputs are plotted in Table 4. The maize prices at domestic market from 2018 to 2020 were 291.0, 336.8 and 321.5 US\$ $t^{-1}$.

**Table 4.** The amounts and unit prices for agricultural inputs used in the field experiment.

| Agricultural inputs | Amount | Unit price |
|---|---|---|
| N | As shown in Table 2 | 367.4 US\$ $t^{-1}$ |
| $P_2O_5$ | As shown in Table 2 | 765.5 US\$ $t^{-1}$ |
| $K_2O$ | As shown in Table 2 | 459.3 US\$ $t^{-1}$ |
| Herbicide | 2.0 kg·ha$^{-1}$ | 1148.3 US\$ $t^{-1}$ |
| Insecticide | 0.6 kg·ha$^{-1}$ | 888.0 US\$ $t^{-1}$ |
| Diesel fuel | 68 kg·ha$^{-1}$ | 1.2 US\$ kg$^{-1}$ |
| Electricity for irrigation | 750 kWh·ha$^{-1}$ | 0.1 US\$ kWh$^{-1}$ |
| Seed | 28.2 kg·ha$^{-1}$ | 3.1 US\$ kg$^{-1}$ |
| Nitrification inhibitor | As shown in Table 2 | 1.2 US\$ kg$^{-1}$ |
| Urease inhibitor | As shown in Table 2 | 1.7 US\$ kg$^{-1}$ |

In addition, as world carbon emissions trading market being established, we assumed that the agricultural economic analysis should comprise the cost of carbon trading, which was calculated as follows:

$$\text{Cost of carbon trading } (US\$) = CE(tCO_2 - eq^{-1}) \times 9.4(US\$\ t^{-1}) \tag{7}$$

the average carbon trading price was 9.4 US\$ $t^{-1}$, which was obtained from China Beijing Green Exchange Institute (https://www.cbeex.com.cn/).

The agricultural net profit (ANP) of summer maize was the difference between agricultural outputs and inputs (including the cost of carbon trading), and the cost benefit ratio was the ratio of total agricultural outputs to inputs.

*4.4. Statistical analysis*

Experimental data were compiled using Excel 2021. The effects on various parameters were analyzed by analysis of variance (ANOVA) for treatments using SPSS 20.0 (SPSS software China, Beijing, China). The mean values of various treatments were tested for statistical significance at a 5% ($P < 0.05$) level of probability using Duncan's multiple range test.

## 5. Conclusions

Across 4-year maize growing seasons in North China Plain, different N management had effects on annual GHG emissions and economic profit, but the effects sizes were varied. The yield for SU and ER treatments had no significant differences in all four years. Under the same nitrogen application rate, adding inhibitors significantly mitigated direct emissions resulting from the decreases in $N_2O$ and $CO_2$. Nitrogen fertilizer contributed to direct and indirect GHG emissions, thus the HF treatment produced significantly higher emissions from the whole life cycle perspective. Non-significant difference in ANP was found for the SU and ER treatments, indicating that adding fertilizer inhibitors did not affect farmers' income while reducing emissions. These results suggest a feasible pathway for maintaining yield while minimizing GHG emissions and maximizing ANP.

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