Greenhouse gas emissions and mitigation potential of hybrid maize seed production in northwestern China

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Abstract

Although hybrid maize seed production is one of the most important agriculture systems worldwide, its greenhouse gas (GHG) emissions and potential mitigation measures have not been studied. In this study, we used life cycle assessment (LCA) to quantify the GHG emissions of 150 farmers run by 6 companies in an area of northwest China known for hybrid maize seed production. The results indicated that the average reactive nitrogen (Nr) losses and GHG emissions from hybrid maize seed production were 53 kg N ha^{-1} and 8077 kg CO_2 eq ha^{-1}, respectively, which are higher than those of the conventional maize production system. Furthermore, the average nitrogen and carbon footprints of the process were 12.2 kg N Mg^{-1} and 1495 kg CO_2 eq Mg^{-1}, respectively. Nitrogen fertilizer and electricity consumption for irrigation were the main contributors to high GHG emissions, accounting for 60% and 30% of the total, respectively. The GHG emissions from seed production for different companies varied greatly with their resource input. There was also a large variation in environmental burdens among the 150 farmers. Based on an analysis of the yield group, we found that the carbon footprint of the first group (the one with the highest yield) was 27% lower than the overall average. Scenario analysis suggests that a combined reduction of N input rate, optimizing irrigation, and increasing yield can eventually mitigate the carbon footprint of hybrid maize seed production by 37%. An integrated systematic approach (e.g., ISSM: integrated soil-crop system management) can reduce the GHG emissions involved in producing hybrid maize seeds. This study provides quantitative evidence and a potential strategy for GHG emissions reduction of hybrid maize seed production.

1. Introduction

Agriculture is an important source of greenhouse gases (GHGs), accounting for 30% of the total anthropogenic GHG emissions (FAO, 2016). It is of great significance to quantify the emissions of different agricultural systems and define the measures to reduce GHG emissions (Gan et al., 2011). Several studies focused on cereal and cash crops (Khan et al., 2017; Hussain et al., 2015); some researches have clarified rational application of N fertilizer and improving crop yield can reduce carbon footprint effectively (Guardia et al., 2019; Hou et al.,2020). Maize is a bulk agricultural product and its planting area is increasing rapidly (Yao et al., 2021). In the past 50 years (1968–2018), the size of the maize production area worldwide has grown rapidly from 112 million hectares to 194 million hectares, an increase of 73% (FAO, 2020). Maize seed production is an important basis for maize productivity and thus global food security. Hybrid maize seed production is currently one of the most important cropping systems worldwide, with an estimated area of approximately 1.94 million hectares, based on a 1:100 area ratio of the production of seed to common maize. However, GHG emissions and the mitigation potential of hybrid maize seed production systems have received little attention to date, although their planting area has increased rapidly.

N fertilizer has been consistently identified as a major contributor to GHG emissions from agriculture (Mueller et al., 2012; Zhang et al., 2015). GHG emissions from the production, transportation, and application of N fertilizers account for more than 60% of the total N emissions (Wang et al., 2018). By reducing the N application rate, GHG emissions in the wheat–maize rotation system on the North China Plain could be decreased significantly (Tan et al., 2017). GHG emissions from maize production systems in China can reduce from 8269 to 4436 kg CO_2 eq ha^{-1} if the N rate is optimized from 402 to 220 kg ha^{-1} (Chen et al., 2014). Hybrid maize seed production requires a more complex management process compared with conventional maize; for example, for the former, male parent material must be planted and the tassels must be cut off after pollination. This more complex management relies on more machinery, thereby increase energy consumption and related GHG emissions. However, seed farmers are not sensitive about the application of fertilizer as "insurance" due to the high economic value of the seed. It was found that N fertilizer consumption was as high as 525 kg ha^{-1} in a hybrid seed production system (Qin et al., 2014); this is twice the optimum N demand for common maize (Chen et al., 2011). There has been a lack of quantitative research on the effects of N fertilizer application on GHG emissions from hybrid maize seed production.

In addition to the amount of N fertilizer used, the energy required for irrigation could also be an important contributor to GHG emissions from maize seed production systems. Maize seed production bases are typically located in agricultural areas in arid oases, e.g., areas in northwestern China with an annual precipitation below 200 mm; that climate is suitable for hybrid maize seed production, such that the quality of the seed improves owing to the dry climate and favorable irrigation conditions (Li et al., 2015). Electricity generated from coal-based sources makes irrigation a key source of GHG emissions from agriculture (Rothausen & Conway, 2011; Zou et al., 2015). When compared with rain-fed agriculture, a greater part of GHG emissions from irrigation-oriented production systems comes from the energy used for irrigation (Grassini & Cassman, 2012; Hennecke et al., 2016). Irrigation-related energy consumption accounted for 13.3% of the total GHG emissions in maize production systems on the Loess Plateau in China (Zhang et al., 2018). In the United States, the energy used for irrigation accounts for 42% of the energy input in high-yield maize systems (Grassini & Cassman, 2012). Furthermore, maize production systems in Mexico emit 62.0–2019.9 kg CO_2 eq ha^{-1} due to the electricity used for irrigation (Juárez-Hernández and Sheinbaum Pardo, 2019). However, the GHG emissions from electricity consumed in maize seed production in northwestern China, with its dry climate, remain unknown.

Reducing emissions in agricultural systems involves both mitigating GHG emissions per unit area and increasing yields (Gan et al., 2011). Many studies have shown that diverse field-based practices affect resource and energy inputs and GHG emissions (Forte et al., 2017; Sainju et al., 2012). Irrigation and fertilization are considered to be potential field practices where steps to mitigate GHG emissions could be applied (Liu et al., 2011; Scheer et al., 2012). Furthermore, previous evidence proved that the intensity of GHG emissions from agricultural systems could be reduced markedly when optimization measures focused on increases in yield (Adviento-borbe et al., 2007; Bhatia et al., 2010; Burney et al., 2010). An analysis of large samples of farming practices can clarify approaches to reducing emissions (Wang et al., 2018). Additionally, science-based scenario analysis can effectively determine the potential for mitigation (Zhang et al., 2018). Farmers' inputs to hybrid maize seed production systems vary greatly;

therefore, our hypothesis is that such methods can also reveal the measures by which emissions can be reduced and the mitigation potential thereof.

China produces more than 20% of the global maize crop; hybrid seeds are produced mainly in its northwestern region where oasis-based agriculture is typical. We selected Changji Prefecture from Xinjiang province as a case study area to quantify the GHG emissions and mitigation potential in the hybrid maize seed production system. The specific objectives of our study were to (a) evaluate the resource inputs and environmental impacts, for example, GHG emissions and reactive N losses, of hybrid maize seed production and (b) determine potential measures to increase maize seed yield and reduce the GHG emissions from this process.

2. Materials And Methods

2.1 Study area and data sources

A survey was conducted among farmers in Changji Prefecture (44°3' N – 44°11' N, 87°0' E – 87°46' E) of Xinjiang Province in northwestern China. Changji Prefecture is a typical oasis with an agricultural production system, located in the middle temperate zone with a continental arid climate. The annual frost-free period is 159 – 180 d, with an effective accumulated temperature of 3400 – 3900 °C for temperatures greater than or equal to 10 °C. The annual average precipitation is approximately 190 mm. There is a large difference in daytime and nighttime temperatures. The growth period of seed maize is usually April–September every year. Abundant light and heat, convenient irrigation conditions, and the continuous availability of high-quality land are natural conditions favorable for maize seed production. Changji Prefecture is one of the most important maize seed production bases in China (MARA, 2013).

The hybrid maize production mode in the study area is based on a company and farmers. Seed production companies sign seed purchase contracts with farmers every year. Company technicians provide guidance on standardized management of field operations such as sowing, emasculation, and the removal of some strains to maintain the quality of hybrid seeds. All fertilizer, pesticide, and machinery rental costs, including the purchase of parent seeds (provided by the seed company), are borne by the farmers. The company purchases maize seeds according to the terms of the contract after the harvest.

We chose six companies with the capability for large-scale seed production in the study area and randomly selected 150 farmers from a face-to-face survey in late 2018. This was done to inquire and record details of the farmers' inputs and outputs, e.g., fertilizers, frequency of irrigation and electricity use, use of machinery in the production process, and grain yield (Table 1).

2.2 System boundary and functional units

The system boundary was defined as cradle-to-grave and included material production goods, as well as the transportation and farming stages of hybrid maize seed production (Fig. 1). The material goods used energy and the main inputs of capital goods included (commercial synthetic) fertilizers, pesticides, diesel, and plastic products such as drip irrigation belts and film. In the farming stage, we considered the application of fertilizer, the use of tilling machinery, and electric power used to pump irrigation water wells and canals. The functional unit for this research was the metric gram of maize seeds produced per hectare of land. The output from hybrid maize seed production was then converted into grain yield with a standard moisture content of 14%, regardless of whether the companies acquired seeds or cobs from the farmers.

2.3 Indicators used in life cycle evaluations

2.3.1 N uptake and N surplus

The N surplus recorded in the survey data was calculated and expressed as the difference between the rates of N fertilizer applied minus the N uptake of the aboveground dry matter as given below:

$$N\ surplus = N_F - N_G \tag{1}$$

$$N_G = N\ uptake/_{100kg\ grain} \times Yield \tag{2}$$

where N_F is the rate of N fertilizer application, and N_G represents N uptake by the obtained hybrid maize seed grains. N uptake was calculated as the amount of N absorbed by the grain at different yield levels, as in Hou et al. (2012).

2.3.2 Nr losses and N footprint

The reactive nitrogen (Nr) losses and N footprint of hybrid maize seed production were analyzed quantitatively using LCA. The calculation of Nr losses was expressed as the sum of the Nr losses in stages involving material goods and the direct and indirect N_2O at the farming stage (Cui et al., 2013; IPCC, 2014). Therefore, the Nr losses contained two components: 1) those that occurred in the process of manufacturing and materials and those from the energy (e.g., diesel and electricity) consumed in farming operations; and 2) direct and indirect N_2O emissions generated after the application of N fertilizers.

$$Nr = Nr\text{-}MS + Direct\ N_2O + Indirect\ N_2O \tag{3}$$

Nr-MS refers to Nr losses from the raw material production stage. This value was obtained by multiplying the amount of material in each input stage by the corresponding emission factors. In this study, indirect N_2O refers to NH_3 volatilization and NO_3^- leaching that occurred throughout the maize growth stage. These parameters were calculated according to the following formula (Cui et al., 2018):

$$Direct\ N_2O\ emissions:\ Y = 0.68e^{0.0035x} \tag{4}$$

Indirect N_2O emissions:

$$NH_3\ volatilization:\ Y = 2.53 + 0.058X \tag{5}$$

NO_3^- leaching: $Y = 2.38e^{0.0041x}$ (6)

Indirect N_2O emissions were estimated by levels of NH_3 volatilization and NO_3^- leaching, whereof 1% and 2.5%, respectively, were converted to nitrous oxide.

The Nr losses per unit area were expressed in kg N ha^{-1} and the Nr losses per unit yield were considered the as the N footprint (kg N Mg^{-1}).

2.3.3 GHG emissions and the carbon footprint

We calculated GHG emissions per unit area and per unit yield, denoted as kg CO_2 eq ha^{-1} and kg CO_2 eq Mg^{-1}, respectively, based on the LCA method of Rebitzer et al. (2004). The GHG emissions from the production of 1 Mg of seeds is defined as the carbon footprint; it is obtained by dividing the total GHG emissions by the yield.

The total GHG emissions consist of CO_2, CH_4, and N_2O emitted throughout the life cycle of hybrid maize seed production and includes the production of input material and related transportation (e.g., fertilizer, plastic film, drip irrigation belts, diesel, farm chemicals), direct N_2O and indirect N_2O emissions (from NH_3 volatilization and N leaching) during N fertilizer application, the electricity used to power irrigation, and diesel used in machines at the farming stage. The coefficients of CO_2, CH_4, and N_2O in terms of equivalents for global warming potential (CO_2 eq $Unit^{-1}$) were 1, 28, and 265, respectively (IPCC, 2014).

The total GHG emissions were the sum of the GHG emissions from the material production stage (MS) and the farming stage (FS). GHG emissions were calculated using the following equations:

GHG emissions = Inputs-GHG + total $N_2O \times 44 / 28 \times 265$ (7)

Total N_2O = direct N_2O + indirect N_2O (8)

The Inputs-GHG value was calculated by multiplying the material and energy input of each item by its corresponding emission factor as listed in Table S1. Calculations of direct N_2O emissions, NO_3^- leaching, and NH_3 volatilization were done using Eqs. (4–6).

2.4 Grouping analysis

All 150 farmers were divided into four groups, according to their yields, from high to low, based on the quartering method (Zhang et al., 2015). The groups were divided in to the 1st quartile (upper 25%), 2nd quartile (25 – 50%), 3rd quartile (50 – 75%), and 4th quartile (lower 25%). The average amount of N fertilizer applied, irrigation water used, crop yield, GHGs emitted, and Nr losses per metric gram and per hectare for the four groups are shown in Table 4.

2.5 Scenario analysis

We simulated three scenarios based on the results of the previous analysis to identify the potential to mitigate the environmental impacts of maize seed production. We determined the appropriate N fertilizer input and water resource usage for maize through a literature review (Table 5). The choices of optimal N rate and ideal yield depend on the most representative study and optimal irrigation is from the that of research closest to our study site. The optimal achievable yield and N application rate in northern China were 13.0 Mg ha^{-1} and 250 kg ha^{-1} respectively, according to Chen et al. (2011). In Scenario 1 (S1) the N fertilizer rate was optimized. In Scenario 2 (S2), the irrigation level was adjusted to the local optimal rate (387 mm) (Zheng et al., 2013). Integrated soil-crop management was adopted in Scenario 3 (S3), and which projected a 25% increase in yield under optimal fertilizer application and irrigation conditions (Chen et al., 2011). The GHG emissions and carbon footprints from each scenario were calculated and then compared with the present results.

2.6 Statistical analysis

All data analyses were performed using the software IBM Statistics SPSS 19.0. Analysis of variance was used to differentiate and analyze the values of different indices. We then employed the least significant difference test to compare the paired indicators at the $p < 0.05$ level. The contribution rate of each link in the life cycle was obtained via path analysis, and links with a direct path coefficient less than 0.1 were eliminated. The two factors with the largest contribution rates were then analyzed against GHG emissions using regression.

3. Results

3.1 Hybrid maize seed yield and agricultural inputs

The grain yield ranged from 6.6 to 7.4 Mg ha^{-1} (95% confidence intervals, CI) with an average of 7.0 Mg ha^{-1}. There was a significant difference in hybrid maize seed yields among the six companies. The seed yield showed obvious differences; the highest yield, 8.9 Mg ha^{-1}, was recorded for company DH. The yields of companies GY and HX were significantly lower than the average yield, by 34% and 31%, respectively, while the other four companies had yields that were higher than the mean (Table 2).

The 150 farmers applied N, P, and K fertilizers at rates of 395, 235, and 72 kg ha^{-1}, respectively, on average (Table 1). The irrigation water rate was 510 mm, and 3268 kWh ha^{-1} electricity was used mainly to pump water from a well or canal to the branch drip belt. There were significant differences in fertilizer input among the companies (Table 2). DH had the highest N input, followed by XT and HX; their N inputs were higher than the average, 395 kg ha^{-1}, by 13%, 4%, and 2%, respectively. The N inputs of companies CN, JY, and GY were lower than the average. Company JM had the highest rate of phosphorus fertilizer application, 41% higher than the average, followed by companies CN and HX. The amount of potash fertilizer input did not differ significantly among the companies.

3.2 N uptake and surplus

The average N uptake of hybrid seed maize for all companies was 130 kg N ha^{-1} (Fig. 2). Overall, only 23% of the applied N fertilizer was absorbed by the female parent plant. However, the N uptake of the hybrid maize combination from company XT was 158 kg N ha^{-1}, which was significantly higher than that of the other companies. The N uptake rate of seeds from companies GY and HX was less than 100 kg N ha^{-1}, which was significantly lower than those of the other companies.

The mean N surplus in maize seed production was 265 kg N ha^{-1}. Nearly 67% of the N input was surplus. The N surplus of companies HX and DH were the highest, at 312 and 301 kg N ha^{-1}, respectively. There were no significant differences for this input among the other companies.

3.3 Nr losses and N footprint

The mean Nr losses and N footprint of hybrid maize seed production were 53 ± 9.1 kg N ha^{-1} and 12.2 ± 3.2 kg N Mg^{-1}, respectively. The MS stage of N fertilizer accounted for 23% of the total Nr losses (Fig. 3). Ammonia volatilization and N leaching accounted for 47% and 25% of the total Nr losses, respectively. Among the companies, company DH had the highest Nr loss, of up to 59 ± 7.0 kg N ha^{-1} (Fig. 3A). The lowest Nr losses were observed for company GY, at 44 ± 3.7 kg N ha^{-1}; this value was 8 – 25% lower than those of other companies. HX had the highest N footprint, of 16.2 ± 4.6 kg N ha^{-1}, which was 5 – 28% higher than those of other companies.

3.4 GHG emissions, carbon footprints, and sources

The GHG emissions and carbon footprint of the companies averaged 8077 ± 1055 kg CO_2 eq ha^{-1} and 1459 ± 530 kg CO_2 eq Mg^{-1}, respectively (Fig. 4). The company with the highest GHG emissions was DH; its emissions were 2 – 30% higher than those of the other companies. Company HX had the highest carbon footprint for hybrid maize seed production; it was 45% higher than the average. Our analysis of the contributions of each life-cycle sector found that fertilizer production and transportation (MS-Fertilizer), fertilizer application (FS-Fertilizer), and electric power consumption (FS-Electricity) accounted for 43%, 17%, and 30% of GHG emissions, respectively. As GHG emissions at the production stage accounted for a small proportion of the total for polyethylene (PE) plastic film and drip irrigation belt, its average GHG emission rate and carbon footprint were only 18 kg CO_2 eq ha^{-1} and 3 kg CO_2 eq Mg^{-1}, respectively (Fig. 4A and 4B).

Our analyses of the direct and indirect path coefficients for the N rate, electricity consumption, and irrigation water use showed that the contribution of the N rate to GHG emissions was the greatest (Table 3). Irrigation was the second contributor to GHG emissions from hybrid maize seed production. There were linear relationships for N fertilizer use and irrigation water with GHG emissions (Fig. 5A and 5B).

3.5 Groups by yield and resources input

There were significant differences in the resource inputs, seed outputs, and environmental effects among the different groups (Table 4). The yield for the 1st quartile was significantly higher than that of the 2nd, 3rd, and 4th quartiles (being 27%, 65%, and 148% higher, respectively). The 1st quartile had the largest N and water inputs, which corresponded to the highest GHG emissions and Nr losses. The N footprint of the high-yield group (the 1st quartile) was lower than those of the other three groups by 7%, 20%, and 39%. In the 1st quartile group, farmers mainly worked with company XT and DH. In the 2nd, 3rd, and 4th quartiles, the distribution of farmers working with each company was similar, indicating that when the different genetic characteristics of inbred lines are a factor of production, a higher yield can be achieved using an appropriate nutrient input and good field management.

3.6 Scenario analyses

The GHG emissions and carbon footprints in the scenarios decreased by 22% and 23%, respectively, compared with farmer practices, when N fertilizer application was adjusted to an optimal rate of 250 kg ha^{-1} (S1, Table 6). Similarly, when irrigation was adjusted to the local optimum volume, GHG emissions and carbon footprints decreased by 30% and 29%, respectively (S2, Table 6). Under integrated optimized conditions in which N fertilizer usage and irrigation were reduced by 37% and 24%, respectively, the hybrid maize seed yield increased by 25% while GHG emissions and carbon footprints reduced by 30% and 37%, respectively (S3, Table 6).

4. Discussion

4.1 GHG emissions and carbon footprints

To our knowledge, this is an advanced and comprehensive assessment of hybrid maize seed production in China. The GHG emissions from hybrid maize seed production measured in this study (8077 kg CO_2 eq ha^{-1}) are 60% higher than that of irrigated maize on the Loess Plateau in northwestern China (Zhang et al., 2018) and 1.8-fold higher than those from common maize produced via farmer practices common in northern China (Chen et al., 2014). Our results are even 3.5 times greater than the GHG emissions from the common maize production system in the United States (Hoffman et al., 2018). There is a great potential to mitigate GHG emissions in hybrid maize seed production systems.

The high resource input and energy consumption needed for hybrid maize seed production were the main contributors to its tremendously high GHG emissions. N fertilizer was the largest contributor, accounting for 60% of the total GHG emissions in this study (Fig. 4). Furthermore, the production and application phases of N fertilizer accounted for 43% and 17%, respectively, of the total GHG emissions. Excessive N fertilizer application has become a relatively common agricultural production practice, particularly for crops with a high economic value (Wang et al., 2018). The N fertilizer rate used to produce hybrid maize seed, a crop with high economic value, is 395 kg N ha^{-1} (Table 1); this is almost 1.5 times greater than that for common maize production in northwestern China, which used 15 Mg ha^{-1} (Yan et al., 2014). In contrast, the average N application rate for maize production in the United States was only 208 kg N ha^{-1}

in 2010 (Kanter et al., 2018). The application of massive amounts of fertilizer directly leads to high GHG emissions. There is an urgent need to optimize the application of fertilizer and a particular need to reduce the amount of N fertilizer used. Irrigation-related electricity consumption was the second largest contributor to GHG emissions, accounting for 30% of the total. The mean GHG emissions from power consumed by irrigation in this study were 2457 kg CO_2 eq ha^{-1}, which is slightly higher than the maximum value of that for maize production with a high irrigation input in Mexico (2019.9 kg CO_2 eq ha^{-1}; Juárez-Hernández and Sheinbaum Pardo, 2019). However, it is much higher than that of high-yield irrigated maize in the United States (870 kg CO_2 eq ha^{-1} from irrigation; Rothausen and Conway, 2011). Zwart and Bastiaanssen (2004) identified the relationship between water use and grain yield and developed a method to analyze global maize crop water productivity. Li et al. (2019) found that irrigation is a restrictive factor for agricultural production in northwestern China; this provided a good a reference for optimizing the contribution of irrigation to GHG emissions in this study.

The carbon footprint is influenced by GHG emissions and productivity simultaneously (Hillier et al., 2009; Pandey et al., 2013). The carbon footprint of the hybrid maize seed production system (1459 kg CO_2 eq Mg^{-1}) in this study was remarkably higher than that of common maize production in China (Cui et al., 2018). Likewise, carbon footprint in this study was 2.5–6.3 times greater than that of common maize production in Canada (583 kg CO_2 eq Mg^{-1}), Italy (450 kg CO_2 eq Mg^{-1}) (Ma et al., 2012; Fantin et al., 2017), and high-yield irrigated maize in the United States (231 kg CO_2 eq Mg^{-1}) (Grassini & Cassman, 2012). Yield is a critical factor that, in addition to GHG emissions, leads to substantial differences in carbon footprints. Hybrid seed maize cultivation is different from that of common maize as the grain yield comes only from female parents. However, the male parents–which are used for pollination and then removed at the end of the pollination process–also make up a proportion of the seed production field. The planting ratio of the parents depends mainly on the ability to combining the parents' inbred lines, and this affects grain yield markedly. A hybrid combination with an outstanding ability to combine generally achieves a high yield. This is partly responsible for the lower yield of hybrid seed maize compared to that of common maize (Guo et al., 2017). Screening parents with high compatibility is an important area of research for increasing yield and reducing the carbon footprint of the hybrid seed maize production system.

4.2 Potential to mitigate the carbon footprint of hybrid maize seed production

4.2.1 Potential to achieve an ideal N balance

An analysis based on yield groupings confirmed a positive relationship between N input and yield (Table 4) (Chen et al., 2010). It has always been a goal of general cropping systems to achieve zero N surplus, which is considered to be balanced (Ju et al., 2009). However, the hybrid maize seed production system did not reach the N balance; it had a high N input and surplus (Fig. 2). It was difficult to achieve a zero surplus because of the cultivation of a certain number of male parents required for pollination. The optimum amount of N fertilizer was obtained by analyzing the density and yield of the hybrid maize, as it is generally planted closely and paternal yield is not counted. Therefore, we combined the amount of fertilizer applied at similar density levels with the optimal N rate of high-yield maize (Chen et al., 2011; Hou et al., 2020). This revealed that the carbon footprint could be reduced by 23% via the optimization of N fertilization (S1, Table 6). The rate and timing of the N fertilizer application should also be sufficient for the full growth period of the female parent and the end of pollination by the male parent. It is clear that the fertilizer requirements of maize seed production need to be studied further through field experiments.

4.2.2 Optimizing irrigation to achieve increased productivity and reduced GHG emissions

The analysis of scenarios used in this study shows that optimizing irrigation can reduce the GHG emissions from hybrid maize seed production in northwestern China. Optimizing irrigation can both reduce water usage by 24% and reduce GHG emissions from energy consumption associated with N management by 30% (S2, Table 6). Many scientists have studied the impact of irrigation on GHG emissions against its contribution to yield (Rodrigues et al., 2010). On the one hand, irrigation contributes markedly to improving productivity although it causes a proportion of the related GHG emissions (Grassini & Cassman, 2012). On the other hand, higher soil moisture increases CO_2 and N_2O emissions from the shallow soil layer (Gao et al., 2020) in addition to generating GHG emissions. Two of our scenario analyses (those for S2 and S3) provided a potentially effective strategy to achieve relatively high yield and low GHG emissions; this is a win–win scenario. Optimizing irrigation by reducing or adjusting its times, and rate would promote hybrid seed maize production systems to produce more seeds at lower GHG emission rates.

4.2.3 Balancing ecological and economic benefits to mitigate carbon footprint

An increase in the total production of hybrid maize seeds presents clear economic benefits; farmers are willing to use large quantities of water and fertilizer to avoid yield losses. Therefore, knowing how to balance ecological and economic benefits of hybrid maize seed production is of great significance. From the perspective of genetics, seed companies need to breed varieties that combine better such that the parent plants have excellent biological characteristics and allow reasonable planting ratios. Improving genetic combinations also plays an important role in increasing the efficiency of water and nutrient use (Mueller et al., 2019). In terms of agricultural management, the female parents' density, formation of population morphology, timely emasculation, and removal of false hybrids are factors key to the productivity of hybrid maize seed systems (Agustin et al., 2004; Kaul et al., 2010). Integrated soil-crop management enables an optimal balance between resource inputs and grain outputs (Chen et al., 2011). Environmental mitigation measures based on profit realization are likely to be accepted widely by farmers.

5. Conclusion

It is critical to study the environmental impact and mitigation potential of hybrid maize seed production as it is an important crop. A study of different companies and a large sample of farmers shows that resource inputs and outputs related to hybrid maize seed production can be optimized under oasis irrigation agriculture such as that practiced in northwestern China. Grouping farms by productivity clearly showed that high resource and energy inputs lead to increased GHG emissions while increasing their yield reduces the carbon and N footprints. Scenario analysis showed that GHG emissions and carbon footprints could be decreased by 30% and 37%, respectively, if optimized N fertilizer input and rational irrigation were combined with a yield improvement scenario. Systematic strategy-based N fertilizer management (e.g., ISSM) and the optimization of irrigation are key points for the sustainable production of maize seed globally.

Declarations

Supplementary data

Supplementary material related to this article can be found in appendix.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files.

Authors' contributions

D.L.: investigation, methodology, data analysis, writing original draft and editing.

W.Z., X.W. and Y. G.: review and editing.

X.C.: conceptualization, writing—review and editing, supervision, funding acquisition.

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Declarations

Ethical approval Not applicable

Consent to participate Not applicable

Consent to publish Not applicable

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Tables

Table 1

Inputs and output of hybrid maize seed production in northwest of China based on farmer survey. The mean value, standard deviation and 95% CI of each item are shown.

Items	Mean	95% CI	SD
Inputs			
Fertilizer rate			
N (kg ha^{-1})	395	385-405	65.9
P (P_2O_5 kg ha^{-1})	235	221-248	90.2
K (K_2O kg ha^{-1})	72	63-82	57.0
Parents seeds (kg ha^{-1})	54	52-55	11.4
Pesticide (kg ha^{-1})	5.5	5.4-5.6	0.7
Irrigation water (mm ha^{-1})	510	497-524	84.8
Electricity (kWh ha^{-1})	3268	3178-3357	552
Diesel (L ha^{-1})	104	103-104	4.0
Plastic film and irrigation belt (kg ha^{-1})	183	180-186	17
Output			
Grain yield（Mg ha^{-1}）	7.0	6.6-7.4	2.2

Table 2

Comparison of fertilizer input and yield among different companies.

Company	Number of farmers	Fertilizer input (kg ha^{-1})			Yield
		N	P_2O_5	K_2O	(Mg ha^{-1})
XT	36	411 ± 70.6* ab	222 ± 74.2 bc	63 ± 73.5 b	8.9 ± 2.1 a
DH	22	446 ± 50.0 a	183 ± 66.3 c	46 ± 26.5 b	7.9 ± 1.7 b
CN	30	372 ± 46.1 bc	256 ± 92.8 b	67 ± 47 b	7.6 ± 1.2 b
JM	16	367 ± 63.9 bc	331 ± 93.3 a	60 ± 48 b	7.2 ± 0.9 b
GY	15	344 ± 23.7 c	173 ± 10.3 c	89 ± 7.3 ab	4.8 ± 0.6 c
HX	31	403 ± 72.1 b	250 ± 92.7 b	106 ± 64.3 a	4.6 ± 1.5 c
Average	150	395 ± 65.9	235 ± 90.2	72 ± 57.0	7.0 ± 2.2

* Means ± SD. Least significant difference testing was performed in six companies. Those acronyms XT, DH, CN, JM, GY and HX stand for different seed companies. Different lowercase letters in the same column indicate significant differences between companies at $p<0.05$.

Table 3

Path analysis between material, energy, resources inputs and GHG emissions in hybrid maize seed production in 150 farmers. The path coefficients and indirect effects of nitrogen rate, electricity and irrigation water are shown. Variables whose absolute value of direct path coefficient was less than 0.1 had been ignored.

Dependent variable	Path coefficients	Indirect path coefficients			Total
GHG emissions		N rate	Electricity	Irrigation water	
N rate	0.8140		0.1500	0.1428	0.2928
Electricity	0.2780	0.0512		0.2672	0.3184
Irrigation water	0.1590	0.0279	0.1528		0.1807

Table 4

Grain yield, nitrogen rate, irrigation water, GHG emission, carbon footprint, Nr loss and nitrogen footprint for four groups. Grouping by the quartering method (Zhang et al.,2015). 1st quartile,2nd quartile, 3rd quartile and 4th quartile represent the farmer groups with yields in the top 25%, 25%-50%, 50%-75% and the last 25%, respectively.

Group	Yield (Mg ha^{-1})	N rate (kg ha^{-1})	Water (mm)	GHG emissions (kg CO_2 eq ha^{-1})	Carbon footprint (kg CO_2 eq Mg^{-1})	Nr loss (kg N ha^{-1})	Nitrogen footprint (kg N Mg^{-1})
1st quartile *n*=37	9.9 ± 0.6 a	416 ± 73.9 a	568 ± 62.6 a	8569 ± 991 a	1095 ± 80 c	57 ± 10.0 a	9.9 ± 0.6 c
2nd quartile *n*=44	7.8 ± 0.6 b	382 ± 65.1 b	520 ± 70.8 b	7940 ± 985 b	1244 ± 126 c	51± 8.6 b	10.7 ± 0.8 c
3rd quartile *n*=32	6.0 ± 0.5 c	399 ± 49.4 ab	495 ± 69.8 b	8052 ± 841 b	1528 ± 155 b	53 ± 6.8 ab	12.4 ± 0.9 b
4th quartile *n*=37	4.0 ± 0.7 d	387 ± 67.9 ab	456 ± 94.3 c	7768 ± 1219 b	2165 ± 644 a	51 ± 9.9 b	16.2 ± 4.1 a

Table 5

Comparison in location, yield, nitrogen fertilizer rate and irrigation water dosage of maize seed production in the literature.

Location	Yield (Mg ha^{-1})	N rate (kg ha^{-1})	Irrigation (mm ha^{-1})	Reference
Northwest of China	13.0	250	—	(Chen et al., 2011)
Gansu	9.2	270	345	(Zhang et al., 2018)
Gansu	7.6	—	613	(Zhao et al., 2013)
Gansu	7.1	—	408	(Wang, 2016)
Xinjiang	6.9	350	387	(Zheng et al., 2013)

Table 6

Grain yield, N rate, irrigation water, GHG emissions and carbon footprint potential under three scenarios for hybrid maize seed production.

Scenarios	FP	S1*	S2#	S3§
Yield (Mg ha^{-1})	7.0 ± 2.2	7.0	7.0	9.9
N rate (kg ha^{-1})	395 ± 66	250	250	250
Irrigation water (mm ha^{-1})	510 ± 84	510	387	387
GHG (kg CO_2 eq ha^{-1})	8077 ± 1055	6294	5656	5656
Carbon footprint (kg CO_2 eq Mg^{-1})	1495 ± 530	1151	1060	842

* Scenario 1 (S1) was to optimize nitrogen application rate;

Scenario 2 (S2) was to optimize nitrogen fertilizer and irrigation simultaneously;

§ Scenario 3 (S3) was to increase the yield by 25% keeping the optimal nitrogen rate and irrigation water in S2.

Figures

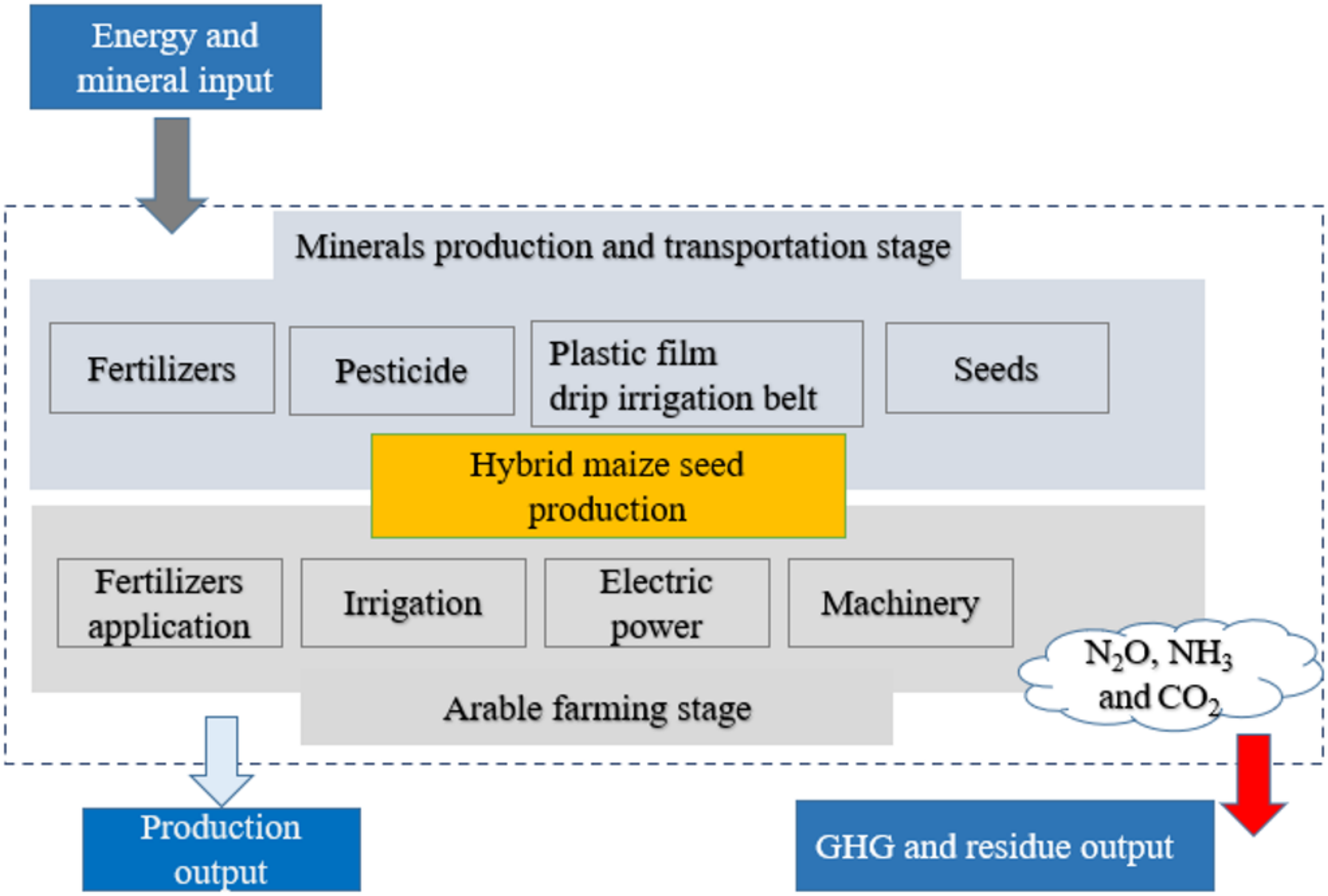

Figure 1

System boundary of hybrid maize seed production in oasis agriculture with drip irrigation and film mulching.

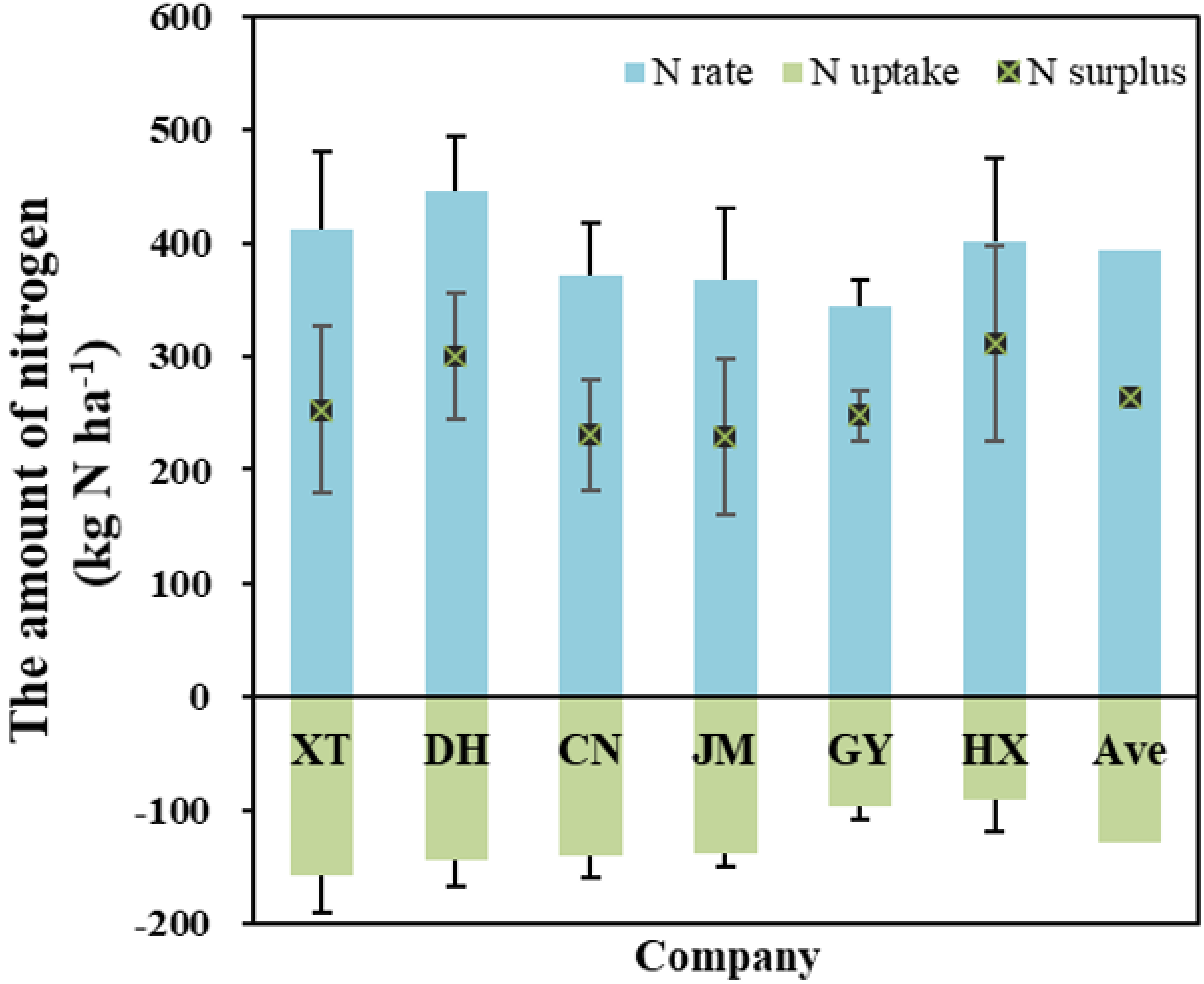

Figure 2

Nitrogen rate, nitrogen uptake and nitrogen surplus of six companies. Standard deviation of nitrogen rate, nitrogen surplus and nitrogen uptake are indicated by the error bars. Those acronyms XT, DH, CN, JM, GY and HX stand for different seed companies.

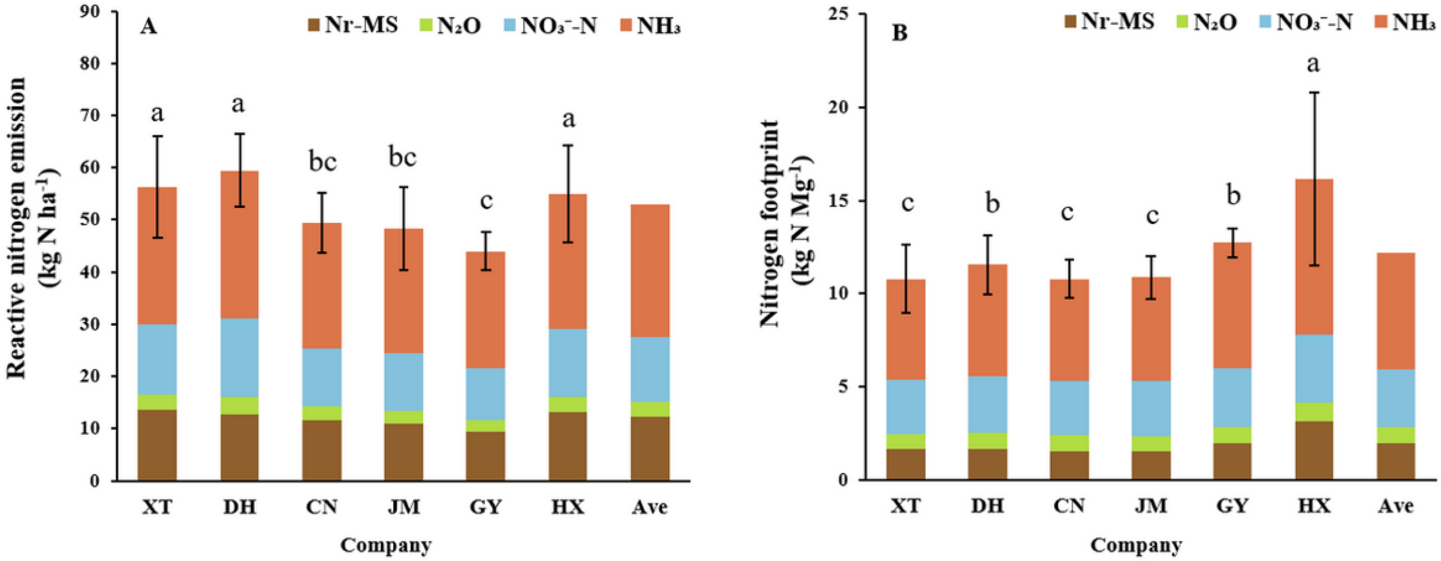

Figure 3

Reactive nitrogen loss (A) and nitrogen footprint (B) of six seeds companies. Standard deviation is indicated by the error bars. Lowercase letters mean a high significant difference at the 0.05 level between companies. Nr-MS represents the reactive nitrogen loss in the material production stage, direct nitrous oxide (N2O), nitrogen leaching (NO3–N) and ammonia volatilization (NH3) represent the three reactive nitrogen loss pathways during the agricultural stage. Anacronyms XT, DH, CN, JM, GY and HX stand for different seed companies. Ave refers to mean value.

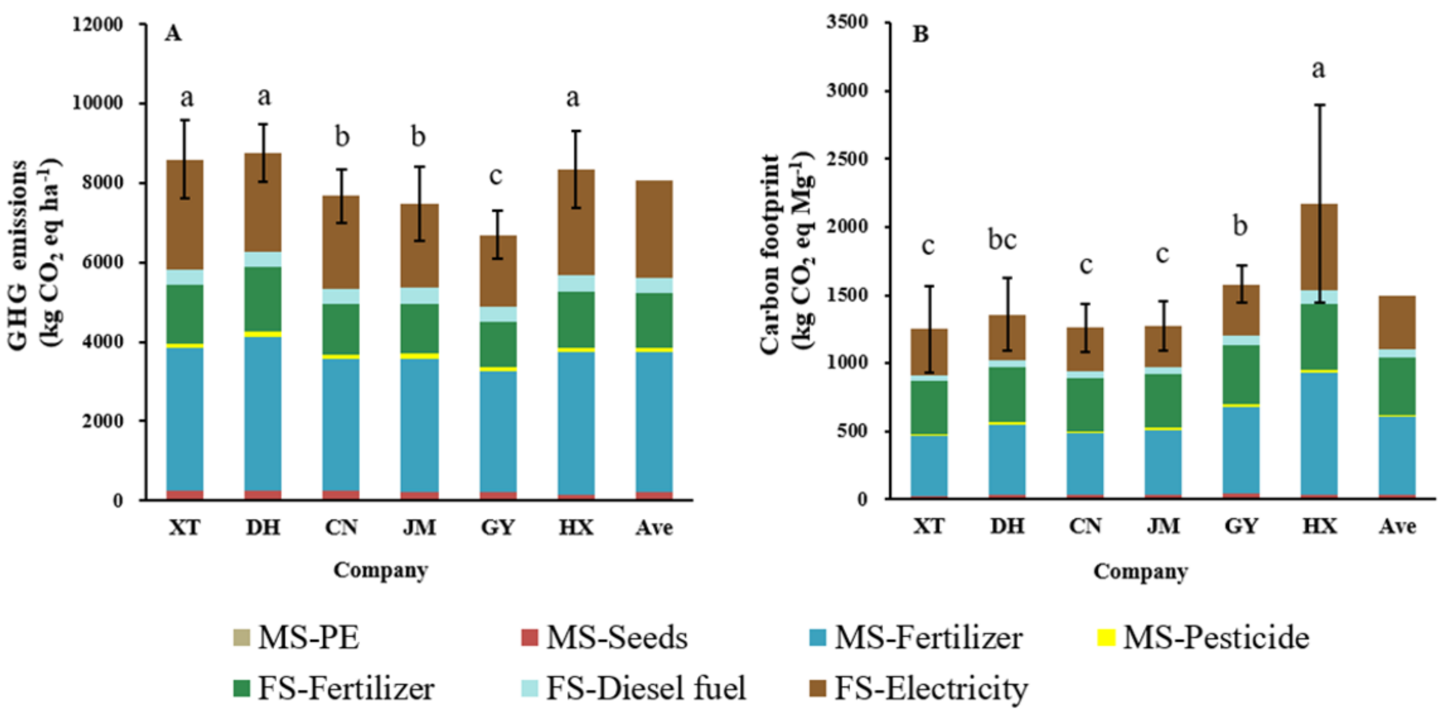

Figure 4

Greenhouse gas emission (A) and carbon footprint (B) of six seeds companies. Standard deviation is indicated by the error bars. Lowercase letters mean a significant difference at the $p<0.05$ level between companies. MS-PE, MS-Seeds, MS-Fertilizer and MS-Pesticide represent the GHG emissions of PE, seeds, pesticides and fertilizers in the material production stage, respectively. FS-Fertilizer, FS-Pesticide and FS-Electricity represents GHG emissions from fertilizers, pesticide and electricity in arable stage, respectively. Anacronyms XT, DH, CN, JM, GY and HX stand for different seed companies. Ave refers to the averaged value.

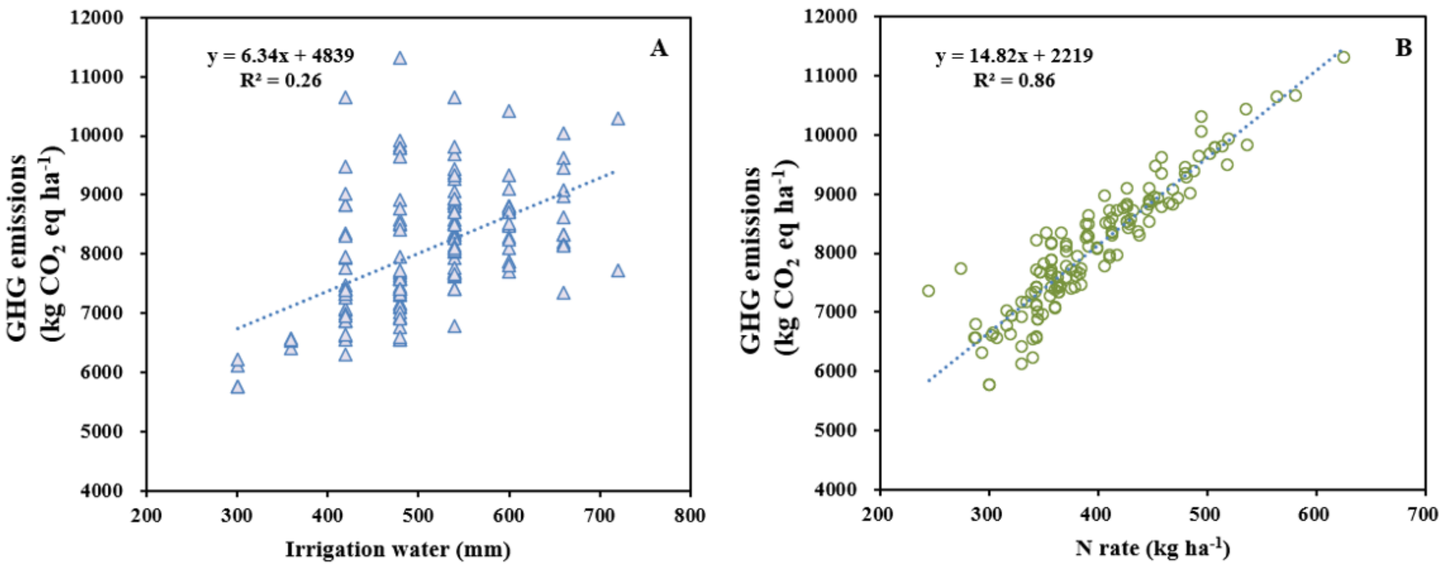

Figure 5

Relationships between irrigation water and GHG emissions (A); between N rate and GHG emissions in 150 farmers (B); GHG emissions increased linearly with irrigation and N rate. The dot line represents the best fitted response curve of irrigation water (A) and N rate to GHG emissions (B)

Supplementary Files

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