Global warming potential from maize and maize-soybean as affected by nitrogen fertilizer and cropping practices in the North China Plain

Yawan Shen a, b, Peng Sui a, Jianxiong Huang c, Dong Wang a, Joann K. Whalen b,⁎, Yuanquan Chen a,⁎

a Research Center of Circular Agriculture, College of Agronomy and Biotechnology, China Agricultural University, No.2 Yuanmingsyu West Road, Haidian District, Beijing, 100193, China
b Department of Natural Resource Sciences, McGill University, Ste-Anne-de-Bellevue, QC, H9X 3V9, Canada
c Research Center for Utilization of Under-forest Resources, Rubber Research Institute of China Tropical Agriculture Science Institute, Danzhou Hainan, 571737, China

A R T I C L E  I N F O

Keywords:
• Nitrogen fertilizer
• Maize-soybean intercropping
• Soil greenhouse gases emission
• Carbon budget
• Net primary productivity
• Global warming potential

A B S T R A C T

Nitrogen fertilizer is required to meet grain targets, but the fossil fuel consumption and greenhouse gas emissions resulting from its use are a barrier to achieve low C agriculture. The objective of this study is to evaluate the net global warming potential (GWP) of maize and soybean monoculture and maize-soybean intercrop systems with an ecosystem-level C budget and determine the optimal N fertilizer requirement of maize-soybean intercrop based on the GWP in CO2 -eq during cropping season. The field experiment had five treatments: maize and soybean monoculture receiving 240 kg N ha⁻¹ and maize-soybean intercropping receiving 120, 180 and 240 kg N ha⁻¹ for three years (2012, 2013, and 2014). Considering greenhouse gas (GHG: CO₂, CH₄ and N₂O) emissions from the field plots, indirect GHG emissions from agricultural inputs (e.g., fertilizer, diesel and pesticides) and CO₂ fixation by crops, soybean monoculture was the net C source due to its lower net primary production, while all maize monoculture and intercrop treatments were net C sinks except for the maize-soybean intercrop receiving 240 kg N ha⁻¹ in 2013. Maize monoculture was the largest C sink due to its higher net primary production, even though it had significantly (p < 0.05) greater direct and indirect GHG emission than of the maize-soybean intercrop treatments with lower N rates. Nitrogen fertilizer contributed to direct and indirect GHG emissions, with peak N₂O fluxes from field plots up to two weeks after N fertilization and 26%–74% of indirect emission attributable to N fertilizer use. Higher N fertilizer rates did not improve yield in the maize-soybean intercrop, and the nitrogen-scaled GWP showed that maize-soybean intercrops fertilized with 150–182 kg N ha⁻¹ had a comparable C fixation potential to maize monoculture receiving 240 kg N ha⁻¹. In conclusion, we demonstrate the ability of maize-soybean intercrop to function as a C sink, similar to maize monoculture, in the North China Plain.

1. Introduction

Low carbon (C) agriculture aims to reduce greenhouse gas (GHG) emissions, lower energy consumption and generate less pollution by improving resource use efficiency (Xiong et al., 2016). Several assessment methods hold promise to determine if a particular agroecosystem meets the standards for low C agriculture. An ecosystem-level C budget can account for the balance between C fixation and C losses in an agroecosystem by calculating the C emissions (e.g., from soil cultivation, during crop production, from transportation and fertilizer use) as well as the C retained in crop residues and soil organic matter, and the C exported in agricultural products (Cowie et al., 2012). The ecosystem-level C budget approach is consistent with life cycle assessment methods that evaluate the environmental impact of agriculture, but less broad in scope because it does not account for energy consumption or direct and indirect impacts from land-use change and pollutants (Kramer et al., 1999; Wood and Cowie, 2004). Still, an ecosystem-level C budget reflects the annual gains in C due to net primary production (NPP) as well as the GHG emissions associated with agricultural inputs like fertilizer and fuel, as well as the direct carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) emissions from the soil-plant system. From ecosystem-level C budgets, Lehuger et al. (2011) determined that cropping systems in western Europe could be sinks and sources of GHG, as the global warming potential (GWP) ranged from -650 kg CO₂-eq ha⁻¹ y⁻¹ for a rapeseed-wheat-barley rotation to 670 kg CO₂-eq ha⁻¹ y⁻¹ for a maize-wheat-barley-mustard rotation on

⁎ Corresponding authors.
E-mail addresses: joann.whalen@mcgill.ca (J.K. Whalen), rardc@163.com (Y. Chen).

https://doi.org/10.1016/j.fcr.2018.06.007
Received 23 January 2018; Received in revised form 13 June 2018; Accepted 13 June 2018
Available online 26 June 2018
0378-4290/ © 2018 Elsevier B.V. All rights reserved.
a loamy soil. Agroecosystems with the lowest GWP were characterized by less reliance on synthetic nitrogen (N) fertilizers, more vegetative cover, and less intensive tillage (Ceschia et al., 2010; Grace et al., 2011).

Maize production systems often have higher GWP values due to the amount of N fertilizer, water, fuel and agrochemicals needed to reach production targets. Grace et al. (2011) estimated that maize production systems in the Midwest USA had a GWP of 1.7 Gt CO₂-eq from 1964 to 2005, and 35–59% of these emissions were due to N₂O loss from N fertilizer. One possibility to lower the GWP of maize production is to integrate legumes in the cropping system, which can be done by including legumes in the crop rotation or by growing maize and legumes together (Dyer et al., 2012; Ma et al., 2012). Huang et al. (2013) reported 22–108% lower CO₂-eq emissions from maize-soybean intercrop than maize monoculture, which supports further investigations on maize-soybean intercrop as a method to achieve low C agriculture in northern China.

There are several ways a legume crop and maize-legume intercrop system could contribute to low C agriculture. First, a legume crop and maize-legume intercrop system require less N fertilizer because the legume crop can rely on biological N₂ fixation and the soil N supply to meet its requirements for maximum yield. Consequently, 50–60% of soybean N demand was met by biological N₂ fixation. Moreover, biological N₂ fixation is inhibited by soil nitrate concentrations and declines from a maximum N₂ fixation of 129 kg N ha⁻¹ to 17 kg N ha⁻¹ when the fertilizer N input increases from 100 to 300 kg N ha⁻¹ (Salvagiotti et al., 2008). Second, Intercropping of maize with faba bean has been reported to increase acquisition of N by maize, possibly by uptake of N fixed by the legume and transferred to maize (Zhang and Li, 2003). Together, lower N fertilizer inputs coupled with higher N fertilizer use efficiency by cereal could result in 31% lower N₂O emissions from the soil-plant system of a cereal-legume intercrop (Senbayram et al., 2016). Still, the direct N₂O emissions are only part of the GWP potential of maize-legume intercrops, and must be considered in the context of other direct and indirect GHG emissions from the agroecosystem, as well as the GHG mitigation due to C fixation by the intercrop (Ashworth et al., 2015; Hauggaard-Nielsen et al., 2016). The yield-scaled GWP and the N fertilizer-scaled GWP should reveal the relative efficiency of monoculture and intercrop systems to offset GHG emissions on a comparable basis, i.e., per unit of grain produced or per unit of N fertilizer applied (Smith, 2012). In addition, maize production has increased by 39.4% while soybean area declined by 24.9% in China since 2005 (National Bureau of Statistics of China, 2017). To meet domestic demand for soybean, the Chinese government policy aims to reform the supply structure by increasing the area under soybean production. As soybean and maize can grow together, the need to increase soybean production area was the reason that we studied the maize-soybean intercrop. The working hypothesis for this study is that maize-soybean intercrop has lower N fertilizer requirements than maize monoculture, and consequently maize-soybean intercrop has potential as a system for low C agriculture.

The objectives of this research were (1) to calculate the GWP of maize monoculture and maize-soybean intercrop systems using an ecosystem-level C budget approach, and (2) to compare the N fertilizer requirements and GWP of maize monoculture and maize-soybean intercrop systems. Experimental data to evaluate these objectives came from a 3-year field experiment (2012 to 2014) where urea fertilizer was applied to maize monoculture (240 kg N ha⁻¹) and maize-soybean intercrop systems (receiving 120,180 and 240 kg N ha⁻¹) in the North China Plain.

2. Materials and methods

2.1. Site description

The field experiment was located at the Wu Qiao Experimental Station (37°41′N, 116°37′E) of China Agricultural University in Cang Zhou, China. Mean annual temperature is 12.9 °C and total precipitation is 562 mm y⁻¹, mostly as rainfall from June to August. Soil at the experimental site is a loamy Aquic Cambisol (166 g sand kg⁻¹ and 145 g clay kg⁻¹, with pH 8.0) developed on an alluvial plain. At the time the experiment was established, soil test analysis showed 16.1 g organic matter kg⁻¹ (potassium dichromate oxidation method), 1.02 g total N kg⁻¹ (Kjeldahl method), with 20.3 mg kg⁻¹ of Olsen-extractable P and 87.5 mg kg⁻¹ of ammonium acetate-exchangeable potassium. The site was under winter wheat production in 2011. Prior to this experiment, wheat roots and stubble were finely chopped (< 10 cm fragments) with a rototiller, spread uniformly across the field and incorporated to a depth of 15 cm.

2.2. Experimental design

In June 2012, four treatments were established at the site in a randomized complete block design with five treatments and three blocks, for a total of 15 experimental plots. Plot size was 9 m x 10 m and planted rows were oriented in a south-north direction to optimize sunlight exposure. Treatments were maize monoculture (Zea mays cv. Zhongdan 958) that received 240 kg N ha⁻¹, soybean monoculture (Glycine max cv. Zhonghuang 13) that received 240 kg N ha⁻¹ and maize-soybean intercrop that was fertilized with 120 kg N ha⁻¹, 180 kg N ha⁻¹, or 240 kg N ha⁻¹ (MS-120, MS-180 and MS-240). Maize monoculture was planted with a 60 cm row spacing at a seeding rate equivalent to 54 000 plants ha⁻¹, and soybean monoculture was planted with a 40 cm row spacing at a seeding rate of 250 000 plants ha⁻¹, while maize-soybean intercrop consisted of two rows of maize (60 cm row spacing) alternating with two rows of soybean (40 cm row spacing) with a 40 cm gap between adjacent maize and soybean rows, giving 36 000 maize plants ha⁻¹ and 111 111 soybean plants ha⁻¹. Before planting, plots were fertilized with calcium superphosphate (75 kg P₂O₅ ha⁻¹) and potassium sulphate (90 kg K₂O ha⁻¹), which

| Table 1 | Equations and constants used to calculate the global warming potential (GWP) of net primary production components, including the harvestable yield (GWPyield), straw (GWPstraw), roots (GWProot) and root turnover/exudates (GWPexudates) produced during the growing season in maize and soybean agroecosystems. The GWPapp is the sum of GWPyield, GWPstraw and GWProot. Since net primary production fixes carbon dioxide from the atmosphere, all net primary production components have negative GWP values. |
| --- | --- | --- | --- |
| Component (kg CO₂-eq ha⁻¹) | Equation | Constants | Reference |
| GWPyield | Yield x 0.4 x 44/12 | 0.4 kg CO₂-eq is the C concentration of harvestable yield for both maize and soybean | Dubey and Lal (2009) |
| GWPstraw | GWPyield/1.1 | 1.1 is the grain: straw ratio for both maize and soybean | Dubey and Lal (2009) |
| GWProot | GWProot = (GWPyield + GWPstraw)/a | a is the shoot: root ratio, a = 6.25 for maize, a = 5.2 for soybean | Bolinder et al. (2007); Amos and Walters (2006) |
| GWPexudates | GWPexudates = GWPapp x 0.11 | 0.11 kg CO₂-eq is the proportion of fine root turnover and exudates for both maize and soybean | Gregory et al. (2006) and Huang et al. (2013) |
was broadcast and incorporated (15 cm depth). Crops were sown by hand on 15 June 2012, 18 June 2013 and 18 June 2014.

Urea fertilizer was the N fertilizer source, added in a split application by broadcasting on the soil surface after rainfall (> 10 mm) or onto dry soil that was then irrigated. The first urea application occurred at the 5-leaf stage of maize (9 July 2012, 10 July 2013 and 10 July 2014) and delivered 120, 120, 60 and 0 kg N ha\(^{-1}\) to the maize monoculture and maize-soybean intercrops receiving 240, 180 and 120 kg N ha\(^{-1}\), respectively. The second application provided 120 kg N ha\(^{-1}\) to all treatments at the 10-leaf stage of maize (30 July 2012, 7 August 2013 and 3 August 2014). Urea was applied following rainfall events in 2012 and 2013, but during the prolonged drought in 2014, 75 mm irrigation water was applied to all plots at 5-leaf following rainfall events in 2012 and 2013, but during the prolonged drought in 2014, 75 mm irrigation water was applied to all plots at 5-leaf and 10-leaf stages after broadcasting urea on the soil surface. Insecticide and herbicide applications, weeding, and other agricultural management were done according to local farming practices. Plots were harvested on 1 Oct. 2012, 2 Oct. 2013 and 2 Oct. 2014.

2.3. Measurements and calculations

2.3.1. GHG fluxes

Greenhouse gas fluxes were assessed using steady state static chambers following the procedures of (Ju et al., 2011; Huang et al., 2014). Chamber bases (24 cm inner diameter and 26 cm outer diameter) were inserted to 5 cm depth between maize rows, soybean rows and between maize and soybean rows in the intercropped plots. One base per plot was installed in 2012, and two bases per plot were deployed in 2013 and 2014. On sampling days (16, 18 and 18 dates in 2012, 2013 and 2014, respectively), the soil temperature was measured by inserting a glass thermometer to a depth of 5 cm adjacent to the base. Then, a vented chamber cover (25 cm diameter and 20 cm height) was placed on the base and gases in the headspace 35 mL were collected with a gas-tight syringe at 10 min intervals for 30 min. Headspace gas were transferred into pre-evacuated 12 mL glass exetainers and CO\(_2\), CH\(_4\) and N\(_2\)O concentrations were quantified with a gas chromatograph (Shimadzu GC-2014C). Fluxes of CO\(_2\)-C (mg m\(^{-2}\) min\(^{-1}\)), CH\(_4\)-C (ug m\(^{-2}\) min\(^{-1}\)) and N\(_2\)O-N (ug m\(^{-2}\) min\(^{-1}\)) were calculated according to the ideal gas law, considering the molar ratios of CO\(_2\)-C (44:12), CH\(_4\)-C (16:12) and N\(_2\)O-N (28:2). The cumulative emissions were calculated over the growing season, according to (Iqbal et al., 2008).

Cumulative emissions (kg ha\(^{-1}\)) of CO\(_2\), CH\(_4\) and N\(_2\)O were estimated by linear interpolation between successive sampling days for each growing season (2012, 2013 and 2014), following the procedure of Zhai et al. (2011). Cumulative heterotrophic respiration (Rh) was calculated by multiplying the accumulated CO\(_2\) emission during the growing season by 0.46 (Cai et al., 2006; Huang et al., 2013), which represents soil respiration only. The CO\(_2\) from root respiration is a component of the gross primary production, but not part of net primary production, described in the next section.

2.3.2. Crop yield and CO\(_2\) fixation

Grain was harvested along a 5 m transect in two adjacent rows in the middle of the plot by hand. Grain was air dried for 2 weeks under the sun and then dried in an oven for 48 h at 80 °C to a constant mass. The yield (kg ha\(^{-1}\)) data was reported on a 13.5% moisture basis. Since plant populations were unequal in monoculture and intercropping systems, the yield was evaluated on a land equivalent ratio (LER, unitless) basis (Eq. (1)): 

\[
LER = \frac{Y_{m,i}}{Y_{m,s}} + \frac{Y_{s,i}}{Y_{s,s}} 
\]

where \(Y_{m,i}\), \(Y_{m,s}\), \(Y_{s,i}\) and \(Y_{s,s}\) are grain yields (in kg m\(^{-2}\)) of intercropped maize, sole maize, intercropped soybean and sole soybean, respectively.

The global warming potential of net primary production (GWPNPP in kg CO\(_2\)-eq ha\(^{-1}\)) and its components was estimated from the measured yield data (expressed on a dry matter basis) in each growing season. Since net primary production fixes CO\(_2\) from the atmosphere, the GWPNPP and its components have negative values. The GWPNPP calculations were based on the ecosystem-level C balance approach described by Bolinder et al. (2007) and Winans et al. (2015), where:

\[
GWPNPP = GWP_{Yield} + GWP_{Straw} + GWP_{Root} + GWP_{Exudate} 
\]

and GWP\(_{Yield}\), GWP\(_{Straw}\), GWP\(_{Root}\) and GWP\(_{Exudate}\) represent the kg CO\(_2\)-eq ha\(^{-1}\).

Table 3

Global warming potential of soil (GWP\(_{soil}\), in kg CO\(_2\)-eq ha\(^{-1}\)) under maize and soybean monoculture that received 240 kg N ha\(^{-1}\) y\(^{-1}\) or maize-soybean intercrops (MS) that received 120, 180 or 240 kg N ha\(^{-1}\) y\(^{-1}\). The GWP\(_{soil}\) was the sum of the CO\(_2\) from heterotrophic respiration (Rh) plus (N\(_2\)O × 298 + CH\(_4\) × 25) emitted from June to October of each study year (2012 to 2014) at the Wu Qiao Experimental Station, Cang Zhou, China. Within a study year, values in each column with the same letter are not significantly different (p < 0.05, LSD test).

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>CO(_2) (Rh)</th>
<th>N(_2)O</th>
<th>CH(_4)</th>
<th>GWP(_{soil})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>kg CO(_2)-eq ha(^{-1})</td>
<td>g</td>
<td>mg</td>
<td>kg CO(_2)-eq ha(^{-1})</td>
</tr>
<tr>
<td>2012</td>
<td>Maize</td>
<td>6042 a</td>
<td>5031 a</td>
<td>-13.2 a</td>
<td>11060 a</td>
</tr>
<tr>
<td></td>
<td>Soybean</td>
<td>5218 a</td>
<td>4110 ab</td>
<td>-9.2 a</td>
<td>9318 ab</td>
</tr>
<tr>
<td></td>
<td>MS-240</td>
<td>5799 a</td>
<td>3188 bc</td>
<td>-10.7 a</td>
<td>8977 ab</td>
</tr>
<tr>
<td></td>
<td>MS-180</td>
<td>5701 a</td>
<td>2086 c</td>
<td>-11.0 a</td>
<td>7776 b</td>
</tr>
<tr>
<td></td>
<td>MS-120</td>
<td>5135 a</td>
<td>3007 bc</td>
<td>-10.0 a</td>
<td>8132 b</td>
</tr>
<tr>
<td></td>
<td>Maize</td>
<td>6784 a</td>
<td>2929 a</td>
<td>-7.11 a</td>
<td>9707 a</td>
</tr>
<tr>
<td></td>
<td>Soybean</td>
<td>6504 a</td>
<td>2666 ab</td>
<td>-9.7 a</td>
<td>9160 ab</td>
</tr>
<tr>
<td></td>
<td>MS-240</td>
<td>6661 a</td>
<td>2461 ab</td>
<td>-6.09 a</td>
<td>9117 ab</td>
</tr>
<tr>
<td></td>
<td>MS-180</td>
<td>6874 a</td>
<td>1680 bc</td>
<td>-5.29 a</td>
<td>8549 ab</td>
</tr>
<tr>
<td></td>
<td>MS-120</td>
<td>6723 a</td>
<td>1162 c</td>
<td>-8.72 a</td>
<td>7876 b</td>
</tr>
<tr>
<td>2013</td>
<td>Maize</td>
<td>6760 a</td>
<td>3121 a</td>
<td>-8.72 a</td>
<td>9872 a</td>
</tr>
<tr>
<td></td>
<td>Soybean</td>
<td>6467 a</td>
<td>1885 ab</td>
<td>-5.2 a</td>
<td>8346 abc</td>
</tr>
<tr>
<td></td>
<td>MS-240</td>
<td>6704 a</td>
<td>2551 a</td>
<td>-4.82 a</td>
<td>9251 ab</td>
</tr>
<tr>
<td></td>
<td>MS-180</td>
<td>5860 a</td>
<td>908 b</td>
<td>-17.9 a</td>
<td>6749 c</td>
</tr>
<tr>
<td></td>
<td>MS-120</td>
<td>6383 a</td>
<td>903 b</td>
<td>-5.32 a</td>
<td>7280 bc</td>
</tr>
</tbody>
</table>
-eq ha\(^{-1}\) fixed in grain, straw, roots and fine roots/exudates, as described in Table 1. We calculated the GWP\(_{\text{NPP}}\) of maize and soybean separately, and then summed them to determine the GWP\(_{\text{NPP}}\) of the maize-soybean intercrop.

### 2.3.3. Net GWP in maize monoculture, soybean monoculture and maize-soybean intercrop systems

The net GWP (in kg CO\(_2\) -eq ha\(^{-1}\)) of maize monoculture, soybean monoculture and maize-soybean intercrop systems was calculated separately for three growing seasons (2012, 2013 and 2014) following the procedures of Smith et al. (2010) and Huang et al. (2013), as:

\[
\text{Net GWP} = \text{GWP}_{\text{NPP}} + \text{GWP}_{\text{import}} + \text{GWP}_{\text{export}} + \text{GWP}_{\text{Soil}} + \text{GWP}_{\text{Indirect}}
\]

The GWP\(_{\text{import}}\) accounts for C inputs from manure, compost, and other C-rich materials, which was 0 kg CO\(_2\) -eq ha\(^{-1}\) in this study. The GWP\(_{\text{Export}}\) was the harvested grain that was removed from the agroecosystem and 95% of the soybean residue, which was removed and used to make fodder. The GWP\(_{\text{Soil}}\) was estimated as:

\[
\text{GWP}_{\text{Soil}} = \text{heterotrophic respiration (Rh)} \times 1 + \text{CH}_4 \text{ emission} \times 25 + \text{N}_2\text{O emissions} \times 298
\]

based on the cumulative emissions (kg ha\(^{-1}\)) of heterotrophic respiration, CH\(_4\) and N\(_2\text{O}\) in each growing season, multiplied by the GWP coefficient for each gas (Tian et al., 2012).

The GWP\(_{\text{Indirect}}\) (kg CO\(_2\) -eq ha\(^{-1}\)) in maize monoculture, soybean monoculture and maize-soybean intercrop systems accounts for GHG emissions associated with inorganic fertilizer nutrients, energy and pesticides applied to agroecosystems (Table 2), and was calculated as:

\[
\text{GWP}_{\text{Indirect}} = \Sigma \text{In} \times \text{Cn}
\]

where In is the amount of each agricultural input applied and Cn is the GHG coefficient for annual cropping systems in China.

### 2.4. Statistical analysis

One-way analysis of variance (ANOVA) was used to determine how treatments (maize monoculture, soybean monoculture and maize-soybean intercrop systems) affected the global warming potential of soil (GWP\(_{\text{Soil}}\), GWP\(_{\text{Rh}}\), GWP\(_{\text{N2O}}\) and GWP\(_{\text{CH4}}\) in kg CO\(_2\) -eq ha\(^{-1}\)), net primary production (GWP\(_{\text{NPP}}\), GWP\(_{\text{Yield}}\), GWP\(_{\text{Straw}}\), GWP\(_{\text{Root}}\), GWP\(_{\text{Exudate}}\) In kg CO\(_2\) -eq ha\(^{-1}\) and export (GWP\(_{\text{Export}}\) in kg CO\(_2\) -eq ha\(^{-1}\)), annual grain yield (kg ha\(^{-1}\)), net global warming potential (GWP, kg CO\(_2\) -eq ha\(^{-1}\)) and yield-scaled GWP (kg CO\(_2\) -eq kg \(-1\) yield). Significant (p < 0.05) treatment effects were evaluated with a post-hoc least significant difference (LSD) test to compare the means of maize monoculture, soybean monoculture and maize-soybean intercrop systems in each cropping season.

### 3. Results

#### 3.1. Global warming potential of soil and net primary production in maize monoculture, soybean monoculture and maize-soybean intercrop systems

Agricultural soils at the study site were a net source of CO\(_2\) (Fig. A1)
and a weak sink for CH₄ (Fig. A2), with periodic N₂O fluxes occurring in the 1–2 weeks following N fertilizer applications and then returning to baseline levels (Fig. A3). Consequently, the GWP_soil was dominated by the CO₂ emissions, with smaller contributions from the N₂O and CH₄ emissions (Table 3). Maize monoculture had the greatest GWP_soil, which was significantly (p < 0.05) greater than the GWP_soil of the maize-soybean intercrop receiving 180 kg N ha⁻¹ in two of three growing seasons and significantly (p < 0.05) greater than the GWP_soil

Table 6

<table>
<thead>
<tr>
<th>Year</th>
<th>coefficient</th>
<th>intercept</th>
<th>Y (kg CO₂ -eq fixed kg⁻¹ N added to maize monoculture)</th>
<th>X (kg N ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>–36.26</td>
<td>213</td>
<td>30.7</td>
<td>152</td>
</tr>
<tr>
<td>2013</td>
<td>–17.50</td>
<td>94</td>
<td>6.7</td>
<td>150</td>
</tr>
<tr>
<td>2014</td>
<td>–42.84</td>
<td>248</td>
<td>25.8</td>
<td>181</td>
</tr>
</tbody>
</table>

Fig. 1. Indirect global warming potential (GWP_indirect) of maize and soybean monoculture that received 240 kg N ha⁻¹ y⁻¹ or maize-soybean intercrops that received 120, 180 or 240 kg N ha⁻¹ y⁻¹. Estimates are based on the greenhouse gas emission coefficients for agricultural inputs (Table 2) applied to these cropping systems during the 2012–2014 growing seasons at the Wu Qiao Experimental Station, Cang Zhou, China.

Fig. 2. N fertilizer-scaled global warming potential (kg CO₂ -eq fixed kg⁻¹ N fertilizer) of maize-soybean intercrops during the 2012–2014 growing seasons at the Wu Qiao Experimental Station, Cang Zhou, China.

Fig. 3. N fertilizer rate (X, kg N ha⁻¹) for maize-soybean intercrop to achieve the same CO₂ -eq fixation as a maize monoculture fertilized with 240 kg N ha⁻¹ y⁻¹. Optimal N fertilizer rates were estimated from Y, the maximum CO₂ -eq fixation of the maize monoculture, per unit of N fertilizer added, during the 2012–2014 growing seasons at the Wu Qiao Experimental Station, Cang Zhou, China.
of the maize-soybean intercrop receiving 120 kg N ha\(^{-1}\) in all growing seasons (Table 3).

Maize monoculture had more net primary production than soybean monoculture and the maize-soybean intercrops in all growing seasons, resulting in significantly (p < 0.05) greater CO\(_2\) fixation in net primary production components, greater grain yield and the smallest GWP\(_{\text{PP}}\) in maize monoculture than soybean monoculture and maize-soybean intercrop systems during the study. Soybean monoculture had the lowest (p < 0.05) CO\(_2\) fixation among all the treatments (Tables 4 and 5).

3.2. Global warming potential from agricultural inputs in maize monoculture, soybean monoculture and soybean-maize intercrop systems

Most of the GWP\(_{\text{Indirect}}\) was associated with N fertilizer and electricity use, with other agricultural inputs (P and K fertilizers, diesel and pesticides) only accounting for 12 to 21% of the GWP\(_{\text{Indirect}}\) (Fig. 1). Compared to the maize and soybean monoculture and maize-soybean intercrop receiving 240 kg N ha\(^{-1}\), there was 13% less GWP\(_{\text{Indirect}}\) from the maize-soybean intercrop receiving 180 kg N ha\(^{-1}\) and a 27% lower GWP\(_{\text{Indirect}}\) value when maize-soybean intercrop was fertilized with 120 kg N ha\(^{-1}\) (Fig. 1). Most of the year-to-year variation in the GWP\(_{\text{Indirect}}\) was due to electricity and diesel consumption. Electricity requirements for pumping irrigation water were low in 2012 because a shallow well was the water source, but more electricity was used in the 2013 and 2014 growing seasons when irrigation water was pumped from a deep well. Also, more irrigation was applied in the dry growing season in 2014 than the previous years. Diesel-related GWP increased from 2012 to 2014 because we changed the tractor from a 85 horse-power (HP) model in 2012 to a 120 HP model in the last two years.

3.3. Net GWP in maize monoculture, soybean monoculture and soybean-maize intercrop systems

The net GWP was -1618 to −7369 kg CO\(_2\)-eq ha\(^{-1}\) in maize monoculture and 10,507 to 10,224 kg CO\(_2\)-eq ha\(^{-1}\) in soybean monoculture during the study period, indicating that the maize monoculture was a net sink for CO\(_2\) (i.e., more CO\(_2\) retained in the agroecosystem than emitted to the atmosphere) while soybean monoculture was a net CO\(_2\) source. The net GWP of maize monoculture was more than 2-fold times lower than the net GWP in maize-soybean intercrop receiving 240 kg N ha\(^{-1}\) (Table 5; Fig. A4), although there was no significant difference (p > 0.05) in the net GWP of maize monoculture and maize-soybean intercrop systems (Table 5). The yield-scaled GWP was almost always negative, indicating that these agroecosystems were a net sink for GHGs, with the lowest negative values in the maize monoculture, the maize-soybean intercrop receiving 120 kg N ha\(^{-1}\) (all years) and the maize-soybean intercrop receiving 180 kg N ha\(^{-1}\) (Table 5).

Higher N fertilizer inputs did not improve the yield of maize-soybean intercrops, but they increased the net GWP values (Table 5) and caused an exponential reduction in the N fertilizer-scaled GWP (Fig. 2). Consequently, there is a trade-off between N fertilizer inputs and GWP in these agroecosystems. Maize-soybean intercrops receiving an estimated 150–182 kg N ha\(^{-1}\) have similar N fertilizer-scaled GWP as maize monoculture in the 2012–2014 growing seasons (Table 6).

4. Discussion

4.1. Impact of N fertilization on the global warming potential of maize monoculture, soybean monoculture and maize-soybean intercrop systems

Nitrogen fertilizer inputs were responsible for 26% to 74% of the indirect GWP, while N\(_2\)O-N represented 12–45% of the direct GWP from soil, indicating the importance of N fertilization to the GWP of maize monoculture, soybean monoculture and maize-soybean intercrop systems (Zhong et al., 2016; Rivera et al., 2017).

It was hypothesized that the lower N fertilizer requirements of maize-soybean intercrop would result in a lower GWP relative to the maize monoculture. Higher N fertilizer rates did not increase grain yield in the maize-soybean intercrop, confirming that the intercrop has lower N fertilizer requirements. In addition, the maize-soybean intercrop had an equivalent land production capability as monoculture maize.

But the net primary production potential of the maize-soybean intercrop was 16–39% lower than that achieved in the maize monoculture. Consequently, the maize monoculture had the lowest net GWP and the maize-soybean intercrops that were fertilized in excess of 180 kg N ha\(^{-1}\) had numerically more net GWP, LER-scaled GWP and N fertilizer-scaled GWP than the maize monoculture. For maize-soybean intercrop to be considered as a system for low C agriculture, it would be important to limit the N fertilizer inputs to a level that will still guarantee adequate yield of both maize and soybean.

Farmers in the North China Plain apply relatively high rates of N fertilizer to maize, and frequently apply N fertilizer to soybean. The inorganic N fertilizer rate for maize, representing a typical farmer’s practice in most North China Plain areas, was from 240 kg N ha\(^{-1}\) to 300 kg N ha\(^{-1}\) (Zhao et al., 2006; Cui et al., 2008). According to Gan et al. (2002), farmers in this area apply 75 kg N ha\(^{-1}\) to soybean. The global meta-data analysis of Salvagiotti et al. (2008) demonstrated that the biological N\(_2\) fixation of soybean declines from 337 kg N ha\(^{-1}\) when no N fertilizer is applied to about 129 kg N ha\(^{-1}\) with a N fertilizer rate of 100 kg N ha\(^{-1}\) and becomes negligible (17 kg N ha\(^{-1}\) from N\(_2\)) when soybean receives 300 kg N ha\(^{-1}\) of N fertilizer. Thus, a moderate input of N fertilizer can be beneficial for soybean production without fully inhibiting biological N\(_2\) fixation. We found that 150–180 kg N ha\(^{-1}\) in maize-soybean intercrop achieved as similar yield as with 240 kg N ha\(^{-1}\) application to maize monoculture, indicating that farmers would spend less money on fertilizer and potentially have lower labor costs without decreasing yield production, if the fertilizer could be applied in fewer split applications. Our recommendation is substantiated by Yong et al. (2014), who noted that the grain yield, N agronomy efficiency and N uptake efficiency of maize and soybean increased significantly when fertilizer was applied at 180 kg N ha\(^{-1}\) in a maize-soybean intercrop system.

4.2. Net primary production lowers the global warming potential of maize monoculture, soybean monoculture and maize-soybean intercrop systems

Among the components involved in net GWP balance, crop net primary production was the most important for sequestering CO\(_2\) from atmosphere. However, the GWP of exported grain and straw accounted for 40%–45% of fixed CO\(_2\) from maize-based agroecosystems and more than 86% of fixed CO\(_2\) in soybean monoculture (Table 4). The C fixation potential of soybean monoculture and maize-soybean intercrop was much less than the maize monoculture, regardless of the greater direct and indirect GWP from N fertilizer and other agricultural inputs needed for the maize monoculture production. The main reason was the larger net primary production of maize, a C\(_4\) crop. Another reason is that 95% of the soybean straw residue (accounting for 34% of the net primary production) was removed from the field for animal forage. Notably, we may underestimate the GWP for maize based crops, because we only determined the GHG flux during the cropping season and did not include the period between crops when maize residues left in the field likely decomposed and released carbon dioxide. Our findings are consistent with Adviento-Borbe et al. (2007), who calculated lower net GWP for continuous maize than maize-soybean rotations, primarily due to the greater crop residue retained in the continuous maize system. The higher GHG mitigation potential of maize-soybean intercrop than maize monoculture reported by Huang et al. (2013) was also related to net primary production, which was greater in the maize-soybean intercrop because it had greater plant density than maize monoculture. Cropping practices that increase net primary production and optimize use of inputs, especially N fertilizer are expected to increase CO\(_2\) fixation and contribute to the goals of low C agriculture.
5. Conclusion

Growing conditions in the North China Plain support high levels of net primary production in maize monoculture and maize-soybean intercrop systems with low GWP. The C sink associated with CO₂ fixation by these crops exceeded the CO₂ -eq losses from direct and indirect emissions during cropping season. The N fertilizer inputs to maize-soybean intercrop should not exceed 150–182 kg N ha⁻¹ because higher N fertilizer rates are associated with greater GWP, relative to maize monoculture that received 240 kg N ha⁻¹. As our estimates were based on plot-scale measurements, the findings must be validated with realistic field- and farm-level data that accounts for the inherent heterogeneity of agroecosystems in the North China Plain, as well as the different level of mechanization, efficiencies and economies that operate at larger scales. However, our ecosystem-level C balance approach remains valid at field to regional scales, and could be used to integrate the spatio-temporal data from multiple site-years, and expanding the scope of measurements to include the CO₂ -eq losses during the period between crops, into a C accounting model. Our recommendation for future work on this topic would be to partition the C balance according to the actual N fertilizer inputs and cropping systems employed in a spatio-temporal unit, which would confirm the net GWP, yield-scaled GWP and N fertilizer-scaled GWP for various cropping systems. We recommended that future research on this topic should compare multiple N fertilizer rates across the maize-soybean intercrop, maize monoculture and soybean monoculture systems. Such research will strengthen our conclusions about the suitability of maize-soybean intercrop as a system for low C agriculture in the North China Plain.

Acknowledgements

This study was supported by the National Key Research and Development Program of China (2016YFD0300210 and 2016YFD0300203). YS acknowledges financial support from the China Scholarship Council (CSC). We appreciate the insightful comments of two anonymous reviewers on an earlier version of this work.

Appendix A

Fig. A1. Seasonal variation of soil CO₂ emissions in maize and soybean monoculture that received 240 kg N ha⁻¹ y⁻¹ or maize-soybean intercrops that received 120, 180 or 240 kg N ha⁻¹ y⁻¹. The growing season was from July to October of each study year (2012–2014) at the Wu Qiao Experimental Station, Cang Zhou, China. Arrows indicate the urea application date.
Fig. A2. Seasonal variation of soil CH$_4$ emissions in maize and soybean monoculture that received 240 kg N ha$^{-1}$ y$^{-1}$ or maize-soybean intercrops that received 120, 180 or 240 kg N ha$^{-1}$ y$^{-1}$. The growing season was from July to October of each study year (2012–2014) at the Wu Qiao Experimental Station, Cang Zhou, China. Arrows indicate the time of urea applications.
Fig. A3. Seasonal variation of soil N$_2$O emissions in maize and soybean monoculture that received 240 kg N ha$^{-1}$ y$^{-1}$ or maize-soybean intercrops that received 120, 180 or 240 kg N ha$^{-1}$ y$^{-1}$. The growing season was from July to October of each study year (2012–2014) at the Wu Qiao Experimental Station, Cang Zhou, China. Arrows indicate the time of urea applications.
Fig. A4. Net GWP (kg CO$_2$-eq ha$^{-1}$) in maize and soybean monoculture that received 240 kg N ha$^{-1}$ y$^{-1}$ or maize-soybean intercrops that received 120, 180 or 240 kg N ha$^{-1}$ y$^{-1}$. The Net GWP was the sum of the estimated carbon fixation (GWP$_{NPP}$), exported grain and residue (GWP$_{Export}$), greenhouse gas emissions from soil (GWP$_{Soil}$) and indirect greenhouse gas emissions from agricultural inputs (GWP$_{Indirect}$). Data were measured in cropping systems during the 2012–2014 growing seasons at the Wu Qiao Experimental Station, Cang Zhou, China.

References


Smith, P., 2012. Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learnt in the last 20 years? Global Change Biol. 18, 35–43.


