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

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ABSTRACT

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 CO_2 -eq during cropping season. The field experiment had five treatments: maize and soybean monoculture receiving 240 kg N ha^{-1} and maize-soybean intercrop receiving 120, 180 and 240 kg N ha^{-1} for three years (2012, 2013, and 2014). Considering greenhouse gas (GHG: CO_2, CH_4 and N_2O) emissions from the field plots, indirect GHG emissions from agricultural inputs (e.g., fertilizer, diesel and pesticides) and CO_2 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 N_2O 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 (CO_2), methane (CH_4) and nitrous oxide (N_2O) 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 CO_2 -eq ha^{-1} y^{-1} for a rapeseed-wheat-barley rotation to 670 kg CO_2 -eq ha^{-1} y^{-1} for a maize-wheat-barley-mustard rotation on

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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 CO_2 -eq from 1964 to 2005, and 35–59% of these emissions were due to N_2O 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 CO_2 -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 N_2 fixation and the soil N supply to meet its requirements for maximum yield. Consequently, 50–60% of soybean N demand was met by biological N_2 fixation. Moreover, biological N_2 fixation is inhibited by soil nitrate concentrations and declines from a maximum N_2 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 N_2O emissions from the soil-plant system of a cereal-legume intercrop (Senbayram et al., 2016). Still, the direct N_2O 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 × 10 m and planted rows were oriented in a south-north direction to optimize sunlight exposure. Treatments were maize monoculture (*Zea mays* cv. Zhengdan 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 P_2O_5 ha^{-1}) and potassium sulphate (90 kg K_2O 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 (GWP_{Yield}), straw (GWP_{Straw}), roots (GWP_{Root}) and root turnover/exudates ($GWP_{Exudate}$) produced during the growing season in maize and soybean agroecosystems. The GWP_{NPP} is the sum of GWP_{Yield}, GWP_{Straw} and GWP_{Root}. Since net primary production fixes carbon dioxide from the atmosphere, all net primary production components have negative GWP values.

Component (kg CO_2 -eq ha^{-1})	Equation	Constants	Reference
GWP_{Yield}	Yield $\times 0.4 \times 44/12$	0.4 kg kg^{-1} is the C concentration of harvestable yield for both maize and soybean 44/12 is the molar ratio of CO_2:C	Dubey and Lal (2009)
GWP_{Straw}	$GWP_{Yield}/1.1$	1.1 is the grain: straw ratio for both maize and soybean	Dubey and Lal (2009)
GWP_{Root}	$GWP_{Root} = (GWP_{Yield} + GWP_{Straw})/a$	a is the shoot: root ratio, a = 6.25 for maize, a = 5.2 for soybean	Bolinder et al. (2007); Amos and Walters (2006)
$GWP_{Exudate}$	$GWP_{Exudate} = GWP_{NPP} \times 0.11$	0.11 kg kg^{-1} is the proportion of fine root turnover and exudates for both maize and soybean	Gregory et al. (2006) and Huang et al. (2013)