Updated N_2O Emissions for Soybean Fields

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In recent written comments on CA-GREET by Stefan Unnasch (Unnasch, 2015), it was brought out that previous versions of GREET did not take into account N_2O emissions from nitrogen fixation by legumes of soybean plants. The comments were based primarily on Venkat (2010) who stated that the N_2O emissions of soybean fields from nitrogen fixed in the nodules of soybean plants in their late growing season could be significant. This means that the original approach in the GREET™ model that considers N_2O emissions from nitrogen fertilizer and those from the nitrogen in soybean plant residues in the field after soybean harvest may not be sufficient to account for the N_2O emissions from all N_2O emission sources including those from the soybean root nodules during the late growing season of soybean plants.

Unnasch (2015) proposed an N_2O emission rate of 1.5 kg N_2O/ha for N_2O emissions from biological nitrogen fixation in soybean nodules during the late growing season. The 1.5 kg N_2O/ha emission rate was suggested by Venkat (2010) and was estimated on the basis of the N_2O emission flux curve in Yang and Cai (2006). In particular, Venkat assumed that an average of about 310 micrograms of N_2O emissions per hour per square meters would be emitted over last 20 days, resulting in 1.5 kg N_2O/ha during the late growing season.

Yang and Cai (2006) conducted a soybean pot experiment by growing soybeans in 15 experimental pots. They reported that the N_2O emissions increased strikingly in the late growth period (i.e., the grain-filling stage), accounting for about 94% of the total N_2O emissions of biologically fixed nitrogen from the entire soybean crop growth cycle. They suggested that the emissions were mostly from senescence and the decomposition of roots and nodules containing the nitrogen fixed by soybean plant legumes.

Soybean is a leguminous crop that hosts symbiotic nitrogen-fixing soil bacteria (rhizobia) that can produce N_2O. In agricultural soil, N_2O is emitted from fertilizer and soil nitrogen. In soybean ecosystems, N_2O is also emitted from the degradation of the root nodules. Organic nitrogen inside the nodules is mineralized to NH_4^+, followed by nitrification and denitrification that produce N_2O, as shown in Figure 1 (Itakura et al., 2013). The number of nodules decreased significantly from full pod to full maturity, which indicates the senescence of nodules (Shah, 2014). A recent study by Inaba et al. (2012) that citied the Yang and Cai (2006) study found that N_2O emissions from degraded soybean nodules in late growth phase depends on denitrification by Bradyrhizobium japonicum in the rhizosphere. The ^{15}N tracer experiment in Inaba et al. (2012) indicated that the N_2O emissions come from nitrogen fixed in the nodules. Besides, they found that both soil microbes and nodule degradation are required for the emissions of N_2O from the soybean rhizosphere.

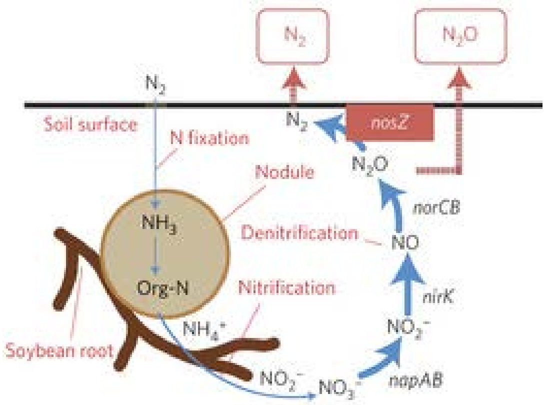

Figure 1. N_2O emissions from decomposition of soybean nodules associated with nitrogen fixation in soybean field, adapted from Itakura et al. (2013).

Indeed, field measurement studies on the N_2O emissions from soybean fields show that the N_2O emission fluxes can vary significantly from site to site, indicating that there is considerable uncertainty and variability relative to the emissions of N_2O from soybean nitrogen fixation. Soil N_2O emissions from three corn–soybean systems in central Iowa were measured from the spring of 2003 through February 2005 (Parkin and Kaspar, 2006). It showed that in 2003 mean N_2O fluxes were 2.7, 2.2, and 2.3 kg N_2O/ha from the soybean plots under chisel plow, no-till, and no-till cover crop, respectively, showing no significant tillage or cover crop effects on N_2O flux (Parkin and Kaspar, 2006). However, there was no significant spike of N_2O emissions during the late phase of soybean growth. It is noted that these emissions include background emissions that could have been generated, if planting soybeans has not occurred. Venterea et al. (2010) measured the N_2O emission fluxes from soybean field after corn cropping in Minnesota and found that the N_2O emissions ranged from about 0.7 to 1.2 kg N_2O/ha , including fertilizer and background emissions. Seasonal and annual emissions of N_2O measured from experimental plots at Elora, Canada shows the N_2O emissions were about 2.21 kg N_2O/ha , including background emissions (Wagner-Riddle et al., 1997); Later on, about 0.49 and 1.07 kg N_2O/ha emissions were measured from soybean fields with conventional tillage in eastern Canada, including background emissions (Wagner-Riddle et al., 2007); About 0.72–4.84 kg N_2O/ha emissions were measured from multiple soybean fields in Eastern Canada (Rochette et al., 2004); Lower emissions of 0.42–1.52 kg N_2O/ha were measured from soybean fields in Quebec, Montreal, and Ottawa, Canada, including background emissions (Rochette et al., 2008).

In comparison, the total N_2O emissions from nitrogen fertilizer and soybean residues estimated in GREET, which are about 0.51 kg N_2O/ha , are close to the lower end of the wide range reported in literature. Here, we updated the nitrogen content in soybean residues according to a review of 159 measurements, which represented an average nitrogen content of 1.21% in the residues, resulting in about 557 grams nitrogen in residues per bushel of soybean grain (Salvagiotti et al., 2008), in comparison to about 200 grams nitrogen in residues per bushel of soybean grain that was previously estimated in GREET. In addition, we adopted the Intergovernmental Panel on Climate Change (IPCC) Tier 2 emission factor of 1.225% for N_2O emissions from crop residues (IPCC, 2006) for soybean residues. With this update, the total N_2O emissions from nitrogen fertilizer and soybean residues estimated in GREET are about 1.14 kg N_2O/ha.

The cited studies, as shown in Table 1, provided useful information on the total N_2O emissions in the soybean fields, but did not address the specific question about the N_2O emissions that are solely attributable to soybean nitrogen fixation. The IPCC has removed biological nitrogen fixation as a direct source of N_2O, given the uncertainty regarding the direct role of Rhizobia in N_2O emission under field conditions (Intergovernmental Panel on Climate Change, 2006). The U.S. Environmental Protection Agency (EPA) has been adopting the DAYCENT model to simulate N_2O emissions from direct sources that include nitrogen fertilizers, organic amendments, nitrogen fixation, crop residues, and mineralization of soil organic matter, as well as indirect emissions from nitrogen leaching/runoff and ammonia volatilization in soybean fields for the Renewable Fuel Standard, without separating the emissions from nitrogen fixation from other sources (U.S. Environmental Protection Agency, 2010). Mostly recently, a greenhouse study was performed by growing inoculated and noninoculated soybean seeds in polyvinyl chloride columns (0.15 m diameter × 0.36 m length) (Shah, 2014). The objective was to measure the contribution of Bradyrhizobium Japonicum and mineral-nitrogen fertilizer to N_2O emissions. A closed chamber technique was used for gas sampling from soils with inoculated and noninoculated soybean seeds, in comparison to the control (bare soil). N_2O measurements were carried out shortly after nodulation. It was found that Bradyrhizobium Jopanicum induced a cumulative N_2O emission of 121.8 μg/kg of soil (20% water content by weight) for inoculated seeds, which was significantly ($p = 0.05$) higher than those of mineral nitrogen fertilized treatment of non-inoculated seeds and the control. An emission spike during the late growth period was found for inoculated soybean, showing the N_2O emissions induced by degradation of nodules formed with nitrogen fixation by legume symbiosis of Bradyrhizobium Japonicum (Shah, 2014). Using the net N_2O emission flux of 121.8 μg/wet kg of soil for inoculated seeds, a soil bulk density of 1.3 tonne/m^3 (Parkin and Kaspar, 2006), and assuming that soybean root systems with the nodules reach an average soil depth of 0.36 meters, which was the length of the polyvinyl chloride columns used for soybean cultivation and N_2O emission flux measurement in Shah (2014), we calculated the Bradyrhizobium Jopanicum-induced N_2O emissions in soybean fields by Shah (2014) to about 0.71 kg N_2O/ha . Adding this source of N_2O emissions (nitrogen fixation) to those from nitrogen fertilizer and soybean residues results in a total N_2O emission of about 1.85 kg N_2O/ha from soybean fields. Considering that this estimate does not include background N_2O emissions, it is within the wide range of measured N_2O emission fluxes shown in Table 1, all of which include background emissions. In comparison, The U.S. Environmental Protection Agency estimated a total N_2O emission flux of about 4.74 kg N_2O/ha according to the DAYCENT modeling of the direct and indirect emissions from synthetic fertilizer (2.82 kg N_2O/ha) and crop residues (1.92 kg N_2O/ha) (U.S. Environmental Protection Agency, 2010). This estimation, however, was not reported in the EPA FASOM final report in which the DAYCENT modeling results were presented (Beach and McCarl, 2010). Besides, the direct N_2O emissions from nitrogen fertilizers modeled by the EPA were close to those for corn on a per acre basis, which was inconsistent with the nitrogen fertilizer use for soybean, which was about 1/15 of that for corn on a per acre basis as shown in the same 2010 Regulatory Impact Assessment for the Renewable Fuel Standard program (RFS2) (U.S. Environmental Protection Agency, 2010). In Europe, the N_2O emission rate of 2.23 kg N_2O/ha, including background N_2O emissions, by the BioGrace greenhouse gas (GHG) calculation tool (The European Union, 2015) is close to the higher end of the wide range of measured total N_2O emission fluxes as shown in Table 1. Given these variable observations and limited studies that addresses the issue of N_2O emissions from soybean biological nitrogen fixation, our estimation of the total N_2O emissions from nitrogen fixation, soybean residues, and nitrogen fertilizers, which is 1.85 kg N_2O/ha, is within the wide range of the total N_2O emissions measured from the soybean field or simulated in the literature, as shown in Table 1. This estimation of the total N_2O emissions from soybean field, including 0.71 kg N_2O/ha from nitrogen fixation, will be incorporated into GREET 2015.

With a soybean yield of 39.4 bushels per acre in 2012 (Han et al., 2014), the soybean nitrogen fixation induced N_2O emissions (0.71 kg N_2O/ha) translates to 7.3 g N_2O emissions per bushel of soybean, representing an increase in GHG emissions by 2.2 g CO_2e/MJ for soybean-based biodiesel. Oil crops, such as canola, jatropha, and camelina, do not contain symbiotic bacteria within root nodules of their root systems for nitrogen fixation. Thus, the nitrogen fixation induced N_2O emissions for soybeans are not applicable to those oil crops.

Table 1. A comparison of N_2O emission flux measurements from soybean fields in literature and the estimation in this analysis

Studies	**Background emissions in measurement?**	**Location**	**N_2O flux, kg/ha**	**Notes**
Parkin and Kaspar, (2006)	Yes	Central Iowa	2.7, 2.2, and 2.3	Under chisel plow, no-till, and no-till cover crop, respectively
Venterea et al. (2010)	Yes	Minnesota	0.7 − 1.2	
Wagner-Riddle et al. (1997)	Yes	Ontario, Canada	2.21	No fertilizer application; with manure application in previous fallow

Studies	Background emissions in measurement?	Location	N_2O flux, kg/ha	Notes
Wagner-Riddle et al. (2007)	Yes	Ontario, Canada	0.49 and 1.07	For fields with conventional tillage practices in separate years
Rochette et al. (2004)	Yes	Quebec, Canada	0.72–4.84	No fertilizer application
Rochette et al. (2008)	Yes	Eastern Canada	0.42–1.52	No fertilizer application; measurement was from soils under moldboard plow
BioGrace (The European Union, 2015)	Yes	European Union	2.23	This includes emissions from nitrogen fertilizers and soybean residues modeled by GNOC.
This analysis	No		1.85	This includes emissions from nitrogen fertilizers, soybean residues, and nitrogen fixation.

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