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Effect of Weed Management Strategy and Row Width on Nitrous Oxide Emissions in Soybean

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Nitrous oxide (N_2O) is a potent greenhouse gas with implication for climate change. Agriculture accounts for 10% of all greenhouse gas emissions in the United States, but 75% of the country's N_2O emissions. In the absence of PRE herbicides, weeds compete with soybean for available soil moisture and inorganic N, and may reduce N_2O emissions relative to a weed-free environment. However, after weeds are killed with a POST herbicide, the dead weed residues may stimulate N_2O emissions by increasing soil moisture and supplying carbon and nitrogen to microbial denitrifiers. Wider soybean rows often have more weed biomass, and as a result, row width may further impact how weeds influence N_2O emissions. To determine this relationship, field studies were conducted in 2013 and 2014 in Arlington, WI. A two-by-two factorial treatment structure of weed management (PRE + POST vs. POST-only) and row width (38 or 76 cm) was arranged in a randomized complete block design with four replications. N_2O fluxes were measured from static gas sampling chambers at least weekly starting 2 wk after planting until mid-September, and were compared for the periods before and after weed termination using a repeated measures analysis. N_2O fluxes were not influenced by the *weed* by *width* interaction or *width* before termination, after termination, or for the full duration of the study at $P \leq 0.05$. Interestingly, we observed that POST-only treatments had lower fluxes on the sampling day immediately prior to POST application ($P = 0.0002$), but this was the only incidence where *weed* influenced N_2O fluxes, and overall, average fluxes from PRE + POST and POST-only treatments were not different for any period of the study. Soybean yield was not influenced by *width* ($P = 0.6018$) or *weed* by *width* ($P = 0.5825$), but yield was 650 kg ha^{-1} higher in the PRE + POST than POST-only treatments ($P = 0.0007$). These results indicate that herbicide management strategy does not influence N_2O emissions from soybean, and the use of a PRE herbicide prevents soybean yield loss.

Nomenclature: Soybean; *Glycine max* (L.) Merr.

Key words: Climate change; N_2O emissions; preemergence herbicide; postemergence herbicide; weed growth and decomposition.

Nitrous oxide (N_2O) is a greenhouse gas 310 times more potent than carbon dioxide (CO_2) in its ability to trap and radiate heat in Earth's atmosphere (USEPA 2014). Agriculture accounts for 10% of all greenhouse gas emissions in the United States but 75% of the country's N_2O emissions (USEPA 2014). In the agricultural sector N_2O is typically associated with corn (*Zea mays* L.) production, where increased nitrogen (N) fertilization is related to higher N_2O emissions (Hoben et al. 2011; McSwiney and Robertson 2005; Millar et al. 2010; Mosier et al. 2006; Parkin and Kaspar 2006). Because soybean production does not rely on N fertilizers like corn production does, N_2O emissions from soils planted with soybean are generally two to five times lower than N_2O emissions from soils planted with corn (Drury et al. 2008; Nangia et al. 2013; Parkin and Kaspar 2006; Wagner-Riddle et al. 2007). For example, N_2O emissions were 3.1 times lower for monoculture soybean (0.84 kg N ha^{-1}) than monoculture corn (2.62 kg N ha^{-1}) when data were averaged over three growing seasons in Ontario, Canada (Drury et al. 2008). Even though emissions from soybean are lower than those from corn, they are important to understand given the environmental impact of N_2O.

N_2O emissions are influenced by soil nitrate (NH_3^-), ammonium (NH_4^-), carbon (C), water availability, pH, and temperature (Bateman and Baggs 2005; Bouwman 1990; Bremner and Shaw 1958; Weier et al. 1993; Zumft 1997). Management

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practices that alter these properties in the soil, therefore, can influence N_2O emissions. In soybean, row width and weed management strategy are interrelated factors that may have an impact on N_2O emissions, particularly in respect to weed growth and how weeds affect soil NH_3^- and water availability. Weeds compete with crops for soil N and water (Dalley et al. 2006; Kropff and Van Laar 1993; Patterson 1995; Zimdahl 1980), and as a result weeds may reduce N_2O emissions while growing. This effect may be greater in wider row widths where soybean canopy closure occurs later (Hock et al. 2006; Murdock et al. 1986) and weeds can accumulate more total biomass than if they were grown in narrower rows (Légère and Schreiber 1989; Rich and Renner 2007; Wax and Pendleton 1968). For example, soybean planted in 76-cm rows experienced full canopy closure 20 d later than soybean planted in 19-cm rows, and the biomass of common sunflower (*Helianthus annuus* L.) from the 76-cm rows was 375 g plant^{-1}, but only 275 g plant^{-1} in the 19-cm rows (Hock et al. 2006). The increased weed biomass in wider rows presumes more uptake of nutrients and competition for water, but in the absence of weeds several studies in both corn and soybean have shown discrepancies in whether reduced soil moisture or higher evaporative losses are favored in narrow vs. wide rows (Dalley et al. 2006; Sharratt and McWilliams 2005; Zhou et al. 2010).

Although selecting a narrow row width is a useful cultural practice for reducing weed biomass and growth, herbicide management strategy often proves to be more important than row width in controlling weeds (Koger et al. 2002; Nelson and Renner 1998), and ultimately, how weeds may impact N_2O emissions. Compared to a PRE + POST herbicide management system where weed growth is minimized, weeds in a POST-only management system could potentially reduce N_2O emissions while growing by reducing soil NO_3^- and water. However, after POST herbicide termination, the additional weed biomass in the POST-only system could stimulate N_2O emissions by increasing soil moisture, supplying C, and encouraging N cycling (Baggs et al. 2003; Harre et al. 2014; Huang et al. 2004; Lindsey et al. 2013; Wang et al. 2012; Weier et al. 1993). There is limited research on how weeds impact N_2O emissions, but Garcia-Ruiz and Baggs (2007) and Garcia-Ruiz et al. (2012) reported that organic olive (*Olea europaea* L.)crop weed residues increased N_2O emissions in 28-d laboratory studies. In one of the studies, soil without residue incorporation had cumulative emissions of 12.8 ng N_2O–N g^{-1} soil, but when soil was amended with common oat (*Avena sativa* L.), sticky restharrow (*Ononis viscosa* L.), and false fennel [*Ridolfia segetum* (L.) Moris], emissions increased to 13.6, 18.7, and 22.5 ng N_2O–N g^{-1} soil, respectively (Garcia-Ruiz et al. 2012). As reported in these and other studies, residue quality, C : N ratio, and placement (e.g., surface-applied or incorporated) can affect the rates of decomposition, N mineralization, and gaseous N losses (Baggs et al. 2003; Garcia-Ruiz and Baggs 2007; Garcia-Ruiz et al. 2012; Harre et al. 2014; Huang et al. 2014; Lindsey et al. 2013; Wang et al. 2012).

Many studies have evaluated N_2O emissions in corn, but there are only a few related to N_2O emissions in soybean. None of those studies, however, has considered how weed management or row width influences N_2O emissions in soybean. The objectives of this study were to evaluate the effects of weed management strategy (PRE + POST vs. POST-only) and row width (38 or 76 cm) on N_2O emissions in Midwest soybean production, and also to compare emissions between treatments before and after weed termination.

Materials and Methods

Site Description. Field studies were established in 2013 and 2014 in adjacent fields previously planted with corn at Arlington Agricultural Research Station near Arlington, WI (43.30°N, 89.32°W). Soil in these fields was a well-drained Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudoll). In 2013, soil from a depth of 0 to 15 cm had a pH of 6.6, 3.5% organic matter (OM), and Bray-1 extractable P and K concentrations of 31 and 130 mg kg^{-1}, respectively, whereas in 2014 the soil had a pH of 6.4, 3.7% OM, and Bray-1 extractable P and K concentrations of 45 and 119 mg kg^{-1}, respectively. For the study duration, precipitation totaled 422 mm in 2013 and 389 mm in 2014, and mean air temperature was 18.1 C in 2013 and 18.2 C in 2014.

Study Design. This study evaluated N_2O emissions influenced by weed management strategy (PRE + POST vs. POST-only) and row width (38 or 76 cm) as a two-by-two factorial in a glufosinate-resistant soybean system. Treatments were arranged in a randomized complete block design with four replications, and plots measured 3 m wide by 15.4 m long.

On May 14, 2013, and May 22, 2014, plots were planted with the target soybean population of

Table 1. Calendar dates and corresponding days after planting (DAP) for key management events

Year	Treatment	Planting date and PRE application		POST applied		Last gas sample collected		Harvest	
		Date	DAP	Date	DAP	Date	DAP	Date	DAP
2013	PRE + POST	May 14	0[a]	July 3	50	September 16	125	October 10	149
	POST-only	May 14	0[b]	June 14	31	September 16	125	October 10	149
2014	PRE + POST and POST-only	May 22	0	July 3	42	September 18	119	October 10	159

[a] PRE applied 1 DAP.
[b] No PRE application.

322,000 seeds ha^{-1} using a Kinze 2000 interplanter. 'Tracy 2213 LL' glufosinate-resistant soybean seed with relative maturity 2.2 was used in both years, and no N or other fertilizers were applied. PRE treatments of 1.22 kg ai ha^{-1} *S*-metolachlor (Prefix™, Syngenta Crop Protection, Inc., Greensboro, NC) plus 0.27 kg ai ha^{-1} fomesafen (Prefix, Syngenta Crop Protection, Inc.) plus 0.42 kg ai ha^{-1} metribuzin (Sencor® 75 DF, Bayer CropScience LP, Research Triangle Park, NC) were applied at a carrier volume of 140 L ha^{-1} within a day of planting. Weed counts were collected from two 0.5-m^2 quadrats in each POST-only treatment plot prior to POST application in 2013 and 2014. In 2014, weeds were also harvested for biomass, dried for 1 wk at 54 C, and analyzed for total C and N content by dry combustion with a CNS-2000 carbon, nitrogen, and sulfur Analyzer (LECO®, St. Joseph, MI).

POST application timing of herbicides was made based on weed community composition and height according to product label recommendations. As a result, POST applications varied according to year and treatment (Table 1), but generally coincided with a weed height of 5 to 15 cm and the V3 to V5 soybean growth stage. In 2013 POST applications were made 50 d after planting (DAP) if following a PRE treatment and 31 DAP for POST-only treatments; in 2014, all POST applications were made 42 DAP. POST applications following a PRE treatment received 0.59 kg ai ha^{-1} glufosinate (Liberty® 280 SL, Bayer CropScience LP) plus 2.8 kg ha^{-1} spray-grade ammonium sulfate, while POST-only applications were a tank mixture of *S*-metolachlor, fomesafen, and glufosinate at rates of 1.22, 0.27, and 0.59 kg ai ha^{-1}, respectively, along with 2.8 kg ha^{-1} spray-grade ammonium sulfate. Soybean was harvested at maturity from the center 1.5 m of each plot using a small plot combine and yield was adjusted to 13% moisture.

Gas Sampling. Gas samples were collected from static chambers placed within each plot. Weather permitting, gas samples were collected weekly from 2 wk after planting until the POST timing, twice a week for the 2 wk after POST treatment, and every 2 to 3 wk until mid-September. Chambers were made from white plastic painters' buckets (23.5 cm high, 25.4 cm in diam) from which the bottom was removed. Chamber lids were fitted with a rubber butyl septum, which was used as a sampling port, and a vent. The vent was constructed with a brass bulkhead union (Swagelock®, Solon, OH) and 3.2-mm-diam copper tube (inner diam, 1.65 mm) cut to 43 cm and coiled to 13 cm in length, and its purpose was to alleviate air pressure differences within and outside the chamber that could alter N_2O fluxes (Davidson et al. 2002; Hutchinson and Livingston 2001). The chambers had a footprint of 0.0507 m^2 and a headspace volume of 7.7 L (0.0077 m^3).

After planting and PRE application, a chamber was installed in each plot 5 cm deep in the soil, the recommended depth to prevent lateral gas exchange under the bottom rim of the chamber wall (Parkin and Venterea 2010). Chambers in the 38-cm row width were placed equidistant between two rows, while in the 76-cm rows chambers were placed adjacent to one of the rows. This was to make sure that the soybean population proximal to the chambers was equally represented at the different row widths. The chambers remained in the field throughout the duration of the study and were only covered with their lids when gas sampling occurred. Therefore, weeds were able grow within and outside the chambers and POST herbicides were applied directly over the chambers to all weeds in the plot.

To collect samples, the lid was secured on the chamber, and samples were collected immediately (i.e., time-point 0), and then at intervals of 20, 40, and 60 min thereafter. Samples were collected from the chambers by extracting gas with a 30-ml syringe attached to a stopcock and 23.5-gauge needle that was inserted through the lid's rubber butyl septum. Thirty milliliters of air was drawn out of the sample chamber, and 20 ml of that sample was then injected into a 5.6-ml vial (Labco Exetainer®, UK) with a vent needle placed in the vial's septum. This procedure evacuated existing air in the sample vial. Once the vial was flushed, the vent needle was removed, and the remaining 10 ml of gas were injected into the vial. Ten milliliters of gas in a 5.6-ml vial created a positive pressure, which helped preserve sample integrity and aid in removing the gas for analysis (Duran and Kucharik 2013; Parkin and Venterea 2010).

Gas samples were always collected between 8:30 A.M. and noon to help reduce diurnal variability in measurements (Parkin and Venterea 2010). At the start of sample collections, soil temperature (± 0.3 C) to a depth of 8 cm was measured with a thermometer (HI98509 Checktemp® 1, HANNA® instruments, Woonsocket, RI) and volumetric water content (± 3%) was measured using a time-domain reflectometer (FieldScout® TDR 100, Spectrum Technologies, Aurora, IL) with 12-cm rods. Additionally, the ambient air temperature was recorded for use in gas flux calculations.

A gas chromatograph (7890A GC system with a 555-MBq ^{63}Ni electron capture detector, Agilent Technologies, Santa Clara, CA) was used to analyze the concentrations of N_2O collected from each sample. The detector temperature was 350 C, the oven temperature was 75 C, and the method detection limit for N_2O was calculated on soils from Arlington, WI, to be 0.006 ppmv. Gas samples were injected into the Micro-ECD inlet using a MPS 2XL MultiPurpose sampler (Gerstel Inc., Baltimore, MD). Before each analysis the instrument was calibrated using 15 to 25 laboratory standards of 1 ppmv N_2O; the average coefficient of variation for these calibration standards was 0.014 across all gas sampling dates.

Gas fluxes for each treatment were determined by linear regression of the four samples within collection timings. Though various linear and nonlinear schemes are used to calculate gas fluxes (e.g., linear regression, quadratic, Hutchinson/Mosier, etc.), a linear model is appropriate for comparing relative differences in fluxes from experimental factors such as row width (Venterea et al. 2009). As a result, we generated a linear fit to the concentration data using the "HMR" add-on package for flux estimation (Pedersen et al. 2010) in

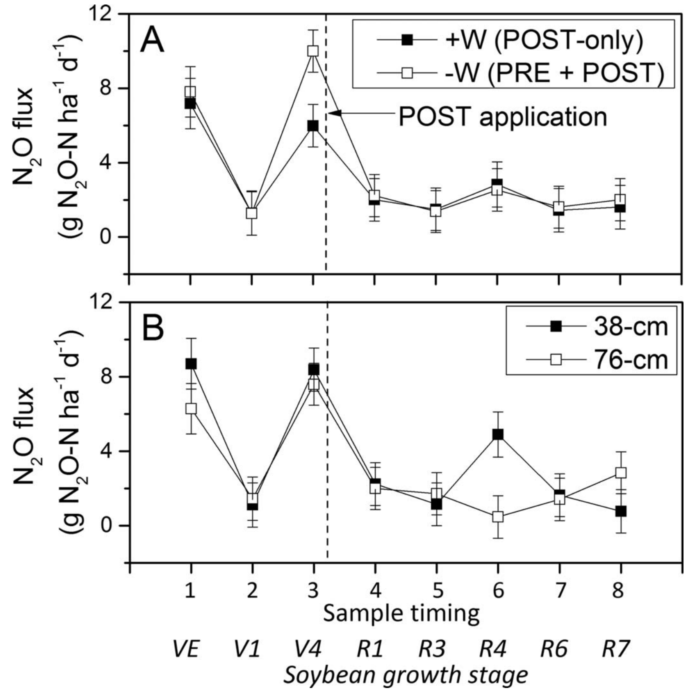

Figure 1. Nitrous oxide fluxes by the main effects of (A) weed management strategy and (B) row width across both years for sample timings corresponding to soybean growth stages. The vertical dashed line represents the POST application timing. Error bars represent the standard error of the mean.

R version 2.15.2 (R Development Core Team, Vienna, Austria).

Data Analysis. In 2013, localized standing water in the field resulted in poor soybean emergence for a plot in the 38-cm-width, POST-only treatment. This plot was excluded from all analyses. Yield data from a second plot in the same treatment and year were omitted due to a harvesting error, but all other metrics associated with this plot were included for analysis. Furthermore, because there were two POST applications in 2013—one at 31 DAP for the POST-only treatment and one at 50 DAP for the PRE + POST treatment (Table 1, Supplemental Figure S1; http://dx.doi.org/10.1614/WS-D-15-00010.S1)—the time period between these POST applications had both living and dying weeds, which invalidated a comparison of soil volumetric water content (VWC), soil temperature, and N_2O fluxes between treatments. These confounding data points were omitted and only relevant data from the period before any POST was applied (0 to 31 DAP) and after all POST applications were made (50 DAP to end of experiment) were used from the 2013 data.

Total counts of all weeds as well as individual weed species were compared by year and row width in a mixed model procedure with *rep*(*year*) treated as

Table 2. Gas sample timings for both years with their corresponding days after planting, dates of collection, and soybean growth stages.

Sample timing[a]	DAP[b] 2013[c]	DAP[b] 2014	Date 2013	Date 2014	Soybean growth stage 2013	Soybean growth stage 2014
1	—	15	—	June 6	—	VE
2	27	22	June 10	June 13	V1–2	V1
3	30	36	June 13	June 27	V3–4	V4–5
4	55	53	July 8	July 14	R1	R1–2
5	62	62	July 15	July 23	R3	R3
6	84	76	August 6	August 6	R4	R4
7	104	99	August 26	August 29	R6	R6
8	125	119	September 16	September 18	R7	R7

[a] As indicated by the dashed horizontal line, sample timings 1 to 3 occurred before weed termination, whereas sample timings 4 to 8 occurred after weed termination.
[b] Days after planting. Planting occurred on May 14, 2013, and May 22, 2014.
[c] Sampling days (31 to 50 DAP) that had confounding treatment effects were omitted.

a random effect using SAS 9.3 (SAS Institute, Cary, NC). Total C and N content, C : N ratio, and weed dry weight data from 2014 were compared by row width using a Student's *t* test. Multiple linear regression was used to determine the combined effects of soil VWC and soil temperature on daily variation of observed N_2O fluxes for each year.

Since gas sample timings for both years coincided with soybean growth stages (Fehr et al. 1971) (Table 2), soil VWC, soil temperature, and N_2O flux data were each subjected to a mixed model procedure with repeated measures analysis. Fixed effects were *weed*, *width*, *sample*, and their interactions; random effects were *year* and *rep(year)*; the subject was *plot*(*year*); and the repeated measure was *sample*. Data from the 2 yr were successfully combined since covariance tests for *year* indicated the Pr $>$ Z was 0.2557, 0.3059, and 0.2652 for the before, after, and total time periods, respectively. Soil VWC, soil temperature, and daily average N_2O fluxes were compared for different time periods in the study: before termination (i.e., the period between planting and POST application), after termination (i.e., from POST application to the end of the study), and for the total duration of the study, as well as for individual sample timings. Yield data were subjected to ANOVA in a mixed model procedure with *weed*, *width*, and *weed* by *width* treated as fixed effects and *year* and *rep*(*year*) as random effects. All means were separated with Fischer's protected $LSD_{0.05}$ test.

Results and Discussion

Weed Characterization. Weed species present in both years included common lambsquarters (*Chenopodium album* L.), giant foxtail (*Setaria faberi* Herrm.), Powell amaranth (*Amaranthus powellii* S. Wats.), velvetleaf (*Abutilon theophrasti* Medik.), and eastern black nightshade (*Solanum ptychanthum* Dunal). Additionally, ladysthumb smartweed (*Polygonum persicaria* L.) was present in 2013 and yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes] was present in 2014. From the mixed model analysis, the combined densities of all weeds did not differ by *width* by *year* (P = 0.3654), *year* (P = 0.5834), or *width* (P = 0.2298). Densities of individual broadleaf weed species did not significantly differ by row width, but the more abundant species (i.e., common lambsquarters, Powell amaranth, and velvetleaf) followed a trend of having higher densities in the 78-cm rows. Giant foxtail was the only species that had a significantly higher density in the 38-cm rows (Table 3). Weeds harvested for analysis in 2014 had similar composition of C and N and C : N ratios at both row widths. Consistent with previous research (Légère and Schreiber 1989; Rich and Renner 2007; Wax and Pendleton 1968), weed biomass was nearly two times greater in the 76-cm vs. the 38-cm rows (60 vs. 31 g plant m^{-2}, respectively, P = 0.0384) (Table 4). The increased weed biomass in the wider rows also corresponded to higher N uptake of the weeds in the wider vs. the narrower row width (1.5 vs. 0.7 g N m^{-2}, respectively, P = 0.0179) (Table 4).

Treatment Effects on Soil Measurements. Despite the differences in weed biomass by row width and those inferred by weed management strategy, repeated measures analyses indicated there were no effects of *weed* by *width* by *sample*, *weed* by *sample*, *width* by *sample*, *weed* by *width*, or *weed* on either soil VWC or soil temperature before termination,

Table 3. Comparison of weed density by row width at the POST application timing for the combined years.

Weed species[a]	Years present	Density by row width[b]		P value[c]
		38 cm	76 cm	
		plants m^{-2}		
CHEAL	Both	76 (17)	148 (38)	0.0793
SETFA	Both	54 (16)	29 (8)	0.0139
AMAPO	Both	17 (2)	27 (5)	0.0629
ABUTH	Both	5 (2)	12 (6)	0.2160
SOLPT	Both	3 (1)	2 (1)	0.5946
POLPE	2013	3 (2)	3 (2)	0.8216
SETPU	2014	4 (2)	2 (1)	0.2090
All weeds		162 (41)	220 (40)	0.2298

[a] Abbreviations: CHEAL, common lambquarters; SETFA, giant foxtail; AMAPO, Powell amaranth; ABUTH, velvetleaf; SOLPT, eastern black nightshade; POLPE, ladysthumb smartweed; SETPU, yellow foxtail.
[b] Mean (standard error) of back-transformed data.
[c] From mixed model analysis.

after termination, or for the full study at $P \leq 0.05$. As expected, due to daily variability in measurements, *sample* was significant for all periods. The effect of *width* did not influence soil VWC during any measurement period or soil temperature before termination, but soil temperature was higher in 76-cm vs. 38-cm row widths for the period after termination (19.5 vs. 19.0 C, respectively, $P = 0.0094$) and overall (18.9 vs. 18.6 C, respectively, $P = 0.044$). This was largely the result of wider rows having 1.2 C higher soil temperature than narrow rows at the fifth sample timing (data not shown). However, other than the instance just described, there was no treatment effect of *weed* or *width* on soil VWC or soil temperature at a specific sample timing.

Although we expected weeds to influence soil moisture and temperature, we may not have seen an effect for several reasons. First, differences in soil moisture between weedy and weed-free environments are most readily observed when moisture is limited (Green et al. 1988; Young et al. 1983), but in our study, there was adequate rainfall in the period before weed termination (Supplemental Figure S1 (http://dx.doi.org/10.1614/WS-D-15-00010.S1). Second, there may not have been enough weed biomass to remove substantial amounts of water via uptake or transpiration, to create a shaded microcosm before termination, or to provide a substantial mulching effect after termination. For example, Wortman et al. (2012) found that cover crop mulches with 307 g plant m^{-2} increased soil VWC by 1.3% following termination with an undercutter. The most biomass we had was 60 g plant m^{-2} from the wider rows—an amount six times less than in that study—and arguably not enough to significantly alter soil VWC or soil temperature.

Treatment Effects on N_2O Fluxes. The fixed effects of *weed* by *width* by *sample*, *weed* by *sample*, *weed* by *width*, *weed*, or *width* did not influence N_2O fluxes before termination, after termination, or for the full duration of the study at $P \leq 0.05$ (Table 5). However, we observed that POST-only treatments had lower N_2O fluxes than PRE + POST treatments at the sample timing immediately prior to POST application ($P = 0.0002$; Figure1A), which made *weed* a significant effect at $P \leq 0.1$ before termination. Likewise, *width* influenced total fluxes at $P \leq 0.1$, mainly due to the higher fluxes in the 38-cm vs. 76-cm rows at the sixth sample timing

Table 4. Data from analysis of weeds collected at the POST application timing in 2014 compared by row width.

Parameter	Row width[a]		P value[b]
	38 cm	76 cm	
Total C (%)	33 (3)	35 (1)	0.6359
Total N (%)	2.4 (0.3)	2.6 (0.1)	0.5320
C : N	14 (1)	14 (1)	0.4906
Biomass (g plant m^{-2})	31 (8)	60 (7)	0.0384
N uptake (g N m^{-2})	0.7 (0.2)	1.5 (0.1)	0.0179

[a] Mean (standard error).
[b] From Student's *t* test.

Table 5. Flux averages for *weed* and *width* and P values for test of fixed effects on nitrous oxide (N_2O) fluxes for different durations of the study.

Factor	Treatment	Before termination		After termination		Total	
		Flux[a]	P value	Flux	P value	Flux	P value
Weed	PRE + POST	6.8 (1.0)[b]	0.0611	1.8 (0.3)	0.8139	3.6 (0.4)	0.1020
	POST-only	5.3 (0.7)		1.9 (0.3)		3.0 (0.3)	
Width	38 cm	6.5 (1.0)	0.2483	2.0 (0.3)	0.2457	3.6 (0.4)	0.0967
	76 cm	5.6 (0.7)		1.7 (0.3)		3.0 (0.3)	
Weed by *width*			0.6460		0.9977		0.6855
Sample			< 0.0001		0.2076		< 0.0001
Weed by *sample*			0.1375		0.9341		0.1004
Width by *sample*			0.5169		< 0.0001		0.0057
Weed by *width* by *sample*			0.7200		0.2459		0.7451

[a] g N_2O-N ha^{-1} d^{-1}.
[b] Mean (standard error).

(P = 0.0001; Figure 1B). This also contributed to an effect of *width* by *sample* on N_2O fluxes after termination (P < 0.0001) and for the total flux (P = 0.0057). Differences in *sample* were more noted in the period before termination than after termination, but sample timing significantly influenced total N_2O fluxes (P < 0.0001) (Table 5), which is consistent with the propensity for N_2O fluxes to exhibit temporal variability (Goodroad et al. 1984; Jacinthe and Dick 1997; Parkin 2008).

Any observed differences in N_2O fluxes were likely not a result of differences in soil moisture or temperature. As mentioned, there were no differences in these parameters by *weed* or *width* for any sample timing except one, where *width* influenced soil temperature at the fifth sample timing. Furthermore, there was poor correlation between soil VWC and soil temperature on N_2O fluxes. Multiple linear regression indicated that N_2O fluxes were only influenced by soil VWC before termination in 2013. For this measurement period, a Sutdent's *t* test indicated that Pr > |t| was 0.0001 for soil VWC and 0.1698 for soil temperature (Pr > F of model was 0.0001, $R^2 = 0.4893$). However, after termination in 2013 and both before and after termination in 2014, there was no correlation of soil VWC and temperature with N_2O fluxes at P ≤ 0.05. For reference, soil VWC, soil temperature, and N_2O fluxes, as well as air temperature and daily precipitation totals, are shown for individual years in Supplemental Figure S1 (http://dx.doi.org/10.1614/WS-D-15-00010.S1)

These results suggest that other factors, such as soil N or mineralizable C availability, were more important regulators of N_2O fluxes (Ciampitti et al. 2008). For example, before the point where weeds reduced N_2O fluxes just prior to POST application, weeds had not yet emerged or were still very small, and it may not have been until they began more rapid N uptake closer to termination that a noticeable effect on N_2O fluxes occurred. It would have been beneficial to take repeated soil samples to determine inorganic N levels in the soil and assess this hypothesis, or to have included a season-long weedy check plot to see if the trend in decreased fluxes would have continued as weeds grew. As for the lack of observed *weed* effect after termination, there may not have been enough weed biomass to stimulate N_2O fluxes by supplying N and C as the weeds decayed. Weed residues in this study had a C : N ratio of 14 (Table 4). Despite the fact that residues with C : N ratios < 20 are optimal for mineralization (Lindsey et al. 2013), less-frequent rainfall in the latter part of the study (Figure S1; http://dx.doi.org/10.1614/WS-D-15-00010.S1) may have also contributed to lower rates of weed decomposition, N mineralization, and denitrification. Residues from the previous years' corn crop as well as litter from soybean leaf drop were also confounding factors in isolating an influence of weed residues on N_2O fluxes. Furthermore, C addition from plant residues usually has more of an impact on N_2O fluxes in fertilized, NO_3^--rich systems such as corn (Huang et al. 2004; Mitchell et al. 2013). Therefore, an effect of weeds after termination may have been too small to detect, overshadowed by other factors and plant residues, or simply nonexistent.

Regarding row width, the higher fluxes from 38-cm rows may be an artifact of the gas sampling chamber placement and soybean root architecture. Although soybean populations surrounding the chambers were the same, two soybean rows were directly near the chambers in the 38-cm width, whereas only one row was near the chambers in the 76-cm rows. This probably meant that 38-cm rows had a more uniform soybean root structure underneath the chambers, and that any influence on N_2O fluxes from soybean root exudates (Rochette and Janzen 2005) was more pronounced in the narrower rows. This reasoning, along with the finding that senescent nodule degradation stimulates N_2O fluxes as soybean plants mature (Ciampitti et al. 2008; Yang and Cai 2005), may partially explain the large increase in N_2O fluxes from the 38-cm width at the sixth sample timing (R4 growth stage). Overall, however, the effect of row width on N_2O fluxes was only identified at $P \leq 0.1$ in the season-long comparison, suggesting that width did not markedly affect fluxes.

Yield and Conclusions. Soybean yield was not influenced by the *weed* by *width* interaction ($P = 0.5825$) and was not different between 38- and 76-cm row widths (3,990 and 3,900 kg ha^{-1}, respectively; $P = 0.6018$). Over the years, soybean row width has been investigated extensively for yield-determining effects with results remaining widely variable (Devlin et al. 1995). Many previous studies in the Midwest have shown narrow rows to yield more than wider rows (Cox and Cheney 2011; De Bruin and Pedersen 2008; Lambert and Lowenberg-DeBoer 2003). However, several other studies contradict those findings (Alessi and Power 1982; Taylor 1980), and recent research has shown that newer soybean genetics have better capability to produce yield on plant branches (Suhre et al. 2014). Yield was significantly higher in PRE + POST treatments (4,270 kg ha^{-1}) than in POST-only treatments (3,620 kg ha^{-1}; $P = 0.0007$). This was not surprising as it is well documented that yield can be improved by reducing weed interference with PRE herbicides (DeWerff et al. 2014; Koger et al. 2002; Reddy et al. 2003).

In summary, this research was the first to explore how weed management strategy and row width influence N_2O emissions in soybean. We found that the interaction of *weed* by *width* did not influence emissions and that N_2O fluxes from 38- and 76-cm rows were similar at $P \leq 0.05$. Although weeds reduced emissions at the sample timing just prior to POST application, average N_2O fluxes were not different for PRE + POST and POST-only herbicide management strategies before termination, after termination, and for the full study. Therefore, we conclude that one weed management strategy is not preferred over the other in terms of N_2O mitigation from soybean, but use of a PRE herbicide is still important to prevent soybean yield loss. From our research, one might surmise there is little reason to alter weed management methods or consider weed management strategies as an important factor in greenhouse gas emission mitigation or modeling. One limitation is that this investigation looked at weed management in a conventional setting where herbicides were used to control weeds early in the growing season. Weed management strategies may play a much more important role in organic systems where repeated tillage vs. a less-tilled environment with more weeds could have larger differences, and those systems should be considered for future research.

Literature Cited

Alessi J, Power JF (1982) Effects of plant row spacing on dryland soybean yield and water-use efficiency. Agron J 74:851–854

Baggs EM, Stevenson M, Pihlatie M, Regar A, Cook H, Cadisch G (2003) Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. Plant Soil 254:361–370

Bateman EJ, Baggs EM (2005) Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. Biol Fert Soils 41:379–388

Bouwman AF (1990) Soils and the Greenhouse Effect. Chichester, UK: Wiley, 575 p

Bremner JM, Shaw K (1958) Denitrification in soil. II. Factors affecting denitrification. J Agric Sci 51:40–52

Ciampitti IA, Ciarlo EA, Conti ME (2008) Nitrous oxide emissions from soil during soybean [*Glycine max* (L.) Merrill] crop phenological stages and stubbles decomposition period. Biol Fertil Soils 44:581–588

Cox WJ, Cherney JH (2011) Growth and yield responses of soybean to row spacing and seeding rate. Agron J 103:123–128

Dalley CD, Bernards ML, Kells JJ (2006) Effect of weed removal timing and row spacing on soil moisture in corn (*Zea mays*). Weed Technol 20:399–409

Davidson EA, Savage K, Verchot LV, Navarro R (2002) Minimizing artifacts and biases in chamber-based measurements of soil respiration. Agric Forest Meteorol 113:21–37

De Bruin JL, Pedersen P (2008) Effect of row spacing and seeding rate on soybean yield. Agron J 100:704–710

Devlin DL, Fjell DL, Shroyer JP, Gordon WB, Marsh BH, Maddux LD, Martin VL, Duncan SR (1995) Row spacing and seeding rates for soybean in low and high yielding environments. J Prod Agric 8:215–222

DeWerff RP, Conley SP, Colquhoun JB, Davis VM (2014) Can soybean seeding rate be used as an integrated component of herbicide resistance management? Weed Sci 62:625–636

Drury CF, Yang XM, Reynolds WD, McLaughlin NB (2008) Nitrous oxide and carbon dioxide emissions from monoculture and rotational cropping of corn, soybean and winter wheat. Can J Soil Sci 88:163–174

Duran BEL, Kucharik CJ (2013) Comparison of two chamber methods for measuring soil trace-gas fluxes in bioenergy cropping systems. Soil Sci Soc Am J 77:1601–1612

Fehr WR, Caviness CE, Burmood DT, Pennington JS (1971) Stage of development descriptions for soybeans, *Glycine max* (L.) Merrill. Crop Sci 11:929–931

https://doi.org/10.1614/WS-D-15-00010.1 Published online by Cambridge University Press

Garcia-Ruiz R, Baggs EM (2007) N_2O emission from soil following combined application of fertiliser-N and ground weed residues. Plant Soil 299:263–274

Garcia-Ruiz R, Gomez-Munoz B, Hatch DJ, Bol R, Baggs EM (2012) Soil mineral N retention and N_2O emissions following combined application of ^{15}N-labelled fertiliser and weed residues. Rapid Commun Mass Spectrom 26:2379–2385

Goodroad LL, Keeney DR, Peterson LA (1984) Nitrous oxide emissions from agricultural soils in Wisconsin. J Environ Qual 13:557–561

Green JD, Murray DS, Stone JF (1988) Soil water relations of silverleaf nightshade (*Solanum elaeagnifolium*) with cotton (*Gossypium birsutum*). Weed Sci 36:740–746

Harre NT, Schoonover JE, Young BG (2014) Decay and nutrient release patterns of weeds following post-emergent glyphosate control. Weed Sci 62:588–596

Hoben JP, Gehl RJ, Millar N, Grace PR, Robertson GP (2011) Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. Glob Change Biol 17:1140–1152

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. Weed Sci 54:38–46

Huang Y, Zou JW, Zheng XH, Wang YS, Xu XK (2004) Nitrous oxide emissions as influenced by amendment of plant residues with different C:N ratios. Soil Biol Biochem 36: 973–981

Hutchinson GL, Livingston GP (2001) Vents and seals in non-steady-state chambers used for measuring gas exchange between soil and the atmosphere. Eur J Soil Sci 52:675–682

Jacinthe PA, Dick WA (1997) Soil management and nitrous oxide emissions from cultivated fields in southern Ohio. Soil Till Res 41:221–235

Koger CH, Reddy KN, Shaw DR (2002) Effects of rye cover crop residue and herbicides on weed control in narrow and wide row soybean planting systems. Weed Biol Manag 2:216–224

Kropff MJ and Van Laar HH, eds (1993) Modelling Crop–Weed Interactions. Wallingford, UK: CAB International, 274 p

Lambert DM, Lowenberg-DeBoer J (2003) Economic analysis of row spacing for corn and soybean. Agron J 95:564–573

Légère A, Schreiber MM (1989) Competition and canopy architecture as affected by soybean (*Glycine max*) row width and density of redroot pigweed (*Amaranthus retroflexus*). Weed Sci 37:84–92

Lindsey LE, Steinke K, Warncke DD, Everman WJ (2013) Nitrogen release from weed residue. Weed Sci 61:334–340

McSwiney CP, Robertson GP (2005) Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. Glob Change Biol 11:1712–1719

Millar N, Robertson GP, Grace PR, Gehl RJ, Hoben JP (2010) Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture. Mitig Adapt Strateg Glob Change 15:185–204

Mitchell DC, Castellano MJ, Sawyer JE, Pantoja J (2013) Cover crop effects on nitrous oxide emissions: role of mineralizable carbon. Soil Sci Soc Am J 77:1765–1773

Mosier AR, Halvorson AD, Reule CA, Liu XJ (2006) Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. J Environ Qual 35:1584–1598

Murdock EC, Banks PA, Toler JE (1986) Shade development effects on pitted morningglory (*Ipomoea lacunosa*) interference with soybean (*Glycine max*). Weed Sci 34:711–717

Nangia V, Sunohara MD, Topp E, Gregorich EG, Drury CF, Gottschall N, Lapen DR (2013) Measuring and modeling the effects of drainage water management on soil greenhouse gas fluxes from corn and soybean fields. J Environ Manag 129:652–664

Nelson KA, Renner KA (1998) Weed control in wide- and narrow-row soybean (*Glycine max*) with imazamox, imazethapyr, and CGA-277476 plus quizalofop. Weed Technol 12:137–144

Parkin TB (2008) Effect of sampling frequency on estimates of cumulative nitrous oxide emissions. J Environ Qual 37: 1390–1395

Parkin TB, Kaspar TC (2006) Nitrous oxide emissions from corn–soybean systems in the Midwest. J Environ Qual 35: 1496–1506

Parkin TB, Venterea RT (2010) Chapter 3. Chamber-based trace gas flux measurements. Pages 3–1 to 3–39 *in* Follett RF, ed. Sampling Protocols. Available at: http://www.ars.usda.gov/research/GRACEnet. Accessed December 18, 2014

Patterson DT (1995) Effects of environmental stress on weed/crop interactions. Weed Sci 43:483–490

Pedersen AR, Petersen SO, Schelde K (2010) A comprehensive approach to soil-atmosphere trace-gas flux estimation with static chambers. Eur J Soil Sci 61:888–902

Reddy KN, Zablotowicz RM, Locke MA, Koger CH (2003) Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Sci 51:987–994

Rich AM, Renner KA (2007) Row spacing and seeding rate effects on eastern black nightshade (*Solanum ptycanthum*) and soybean. Weed Technol 21:124–130

Rochette P, Janzen HH (2005) Towards a revised coefficient for estimating N_2O emissions from legumes. Nutr Cycl Agroecosyst 73:171–179

Sharratt BS, McWilliams DA (2005) Microclimatic and rooting characteristics of narrow-row versus conventional-row corn. Agron J 97:1129–1135

Suhre JJ, Weidenbenner NH, Rowntree SC, Wilson EW, Naeve SL, Conley SP, Casteel S, Diers BW, Esker PD, Specht JE, Davis VM (2014) Soybean partitioning changes revealed by genetic gain and seeding rate interactions. Agron J 106: 1631–1642

Taylor HM (1980) Soybean growth and yield as affected by row spacing and by seasonal water supply. Agron J 72:543–547

[USEPA] U.S. Environmental Protection Agency (2014) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012. Washington, DC: US Environmental Protection Agency. 529 p

Venterea RT, Spokas KA, Baker JM (2009) Accuracy and precision analysis of chamber-based nitrous oxide gas flux estimates. Soil Sci Soc Am J 73:1087–1093

Wagner-Riddle C, Furon A, McLaughlin NL, Lee I, Barbeau J, Jayasundara S, Parkin G, von Bertoldi P, Warland J (2007) Intensive measurement of nitrous oxide emissions from a corn–soybean–wheat rotation under two contrasting management systems over 5 years. Glob Change Biol 13: 1722–1736

Wang J, Sainju UM, Barsotti JL (2012) Residue placement and rate, crop species, and nitrogen fertilization effects on soil greenhouse gas emissions. J Environ Prot 3:1238–1250

Wax LM, Pendleton JW (1968) Effect of row spacing on weed control in soybeans. Weed Sci 16:462–465

Weier KL, Doran JW, Power JF, Walters DT (1993) Denitirfication and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. Soil Sci Soc Am J 57:66–72

Wortman SE, Francis CA, Bernards ML, Drijber RA, Lindquist JL (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. Agron J 104:1425–1435

Yang LF, Cai ZC (2005) The effect of growing soybean (*Glycine max*. L.) on N2O emission from soil. Soil Biol Biochem 37:1205–1209

Young FL, Wyse DL, Jones RJ (1983) Effect of irrigation on quackgrass (*Agropyron repends*) interference in soybeans (*Glycine max*). Weed Sci 31:720–727

Zhou XB, Yang GM, Sun SJ, Chen YH (2010) Plant and row spacing effects on soil water and yield of rainfed summer soybean in the northern China. Plant Soil Environ 56:1–7

Zimdahl RL (1980) Weed-Crop Competition: A Review. Corvallis, OR: International Plant Protection Center, Oregon State University, 195 p

Zumft WG (1997) Cell biology and molecular basis of denitrification. Microbiol Mol Biol Rev 61:533–616

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