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Nitrogen Management Affects Nitrous Oxide Emissions under Varying Cotton Irrigation Systems in the Desert Southwest, USA

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Abstract

Irrigation of food and fiber crops worldwide continues to increase. Nitrogen (N) from fertilizers is a major source of the potent greenhouse gas nitrous oxide (N_2O) in irrigated cropping systems. Nitrous oxide emissions data are scarce for crops in the arid western United States. The objective of these studies was to assess the effect of N fertilizer management on N_2O emissions from furrow-irrigated, overhead sprinkler-irrigated, and subsurface drip-irrigated cotton (*Gossypium hirsutum* L.) in Maricopa, AZ, on Trix and Casa Grande sandy clay loam soils. Soil test- and canopy-reflectance-based N fertilizer management were compared. In the furrow- and overhead sprinkler-irrigated fields, we also tested the enhanced efficiency N fertilizer additive Agrotain Plus as a N_2O mitigation tool. Nitrogen fertilizer rates as liquid urea ammonium nitrate ranged from 0 to 233 kg N ha^{-1}. Two applications of N fertilizer were made with furrow irrigation, three applications under overhead sprinkler irrigation, and 24 fertigations with subsurface drip irrigation. Emissions were measured weekly from May through August with 1-L vented chambers. N_2O emissions were not agronomically significant, but increased as much as 16-fold following N fertilizer addition compared to zero-N controls. Emission factors ranged from 0.10 to 0.54% of added N fertilizer emitted as N_2O-N with furrow irrigation, 0.15 to 1.1% with overhead sprinkler irrigation, and <0.1% with subsurface drip irrigation. The reduction of N_2O emissions due to addition of Agrotain Plus to urea ammonium nitrate was inconsistent. This study provides unique data on N_2O emissions in arid-land irrigated cotton and illustrates the advantage of subsurface drip irrigation as a low N_2O source system.

Core Ideas

- N_2O emissions under overhead sprinkler and furrow irrigation were 0.5 to 1 %.
- Subsurface drip irrigation combined with 24 fertigation events had an emission factor of 0–0.1 %.
- The use of enhanced efficiency fertilizers NBPT and DCD had inconsistent mitigation effects on N_2O emissions.
- Reduction in N_2O emissions with canopy reflectance-based N management was inconsistent.

Water and nitrogen (N) fertilizer are the first and second most critical constraints to cotton (*Gossypium hirsutum* L.) production in arid and semiarid areas, such as the western United States (Morrow and Krieg, 1990). Irrigation is required in desert environments because annual rainfall of <200 mm does not permit dryland farming. Irrigation worldwide will only increase in importance for increasing food and fiber production to meet a rising world population that is expected to reach 9 billion by 2050 (Gleick, 2003; FAO, 2009; Foley et al., 2011; Roberts, 2011). Countries with substantial area of arid lands, including India, Pakistan, China, and the United States, account for 72% of global irrigation water use (West et al., 2014). Cotton uses 11% of world irrigation water, behind wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) (West et al., 2014). Nitrogen fertilizer use for crop production has also been increasing steadily worldwide (FAO, 2015). China, for instance, used double the N fertilizer in the 2000s compared with the 1980s (Smith et al., 2016).

Canal infrastructure for irrigation water in Arizona means that like most of the world, surface irrigation methods, including level basin and furrow irrigation (FI), are still the most common irrigation methods. Fertigating liquid N fertilizer in FI is commonly practiced in the western United States (Bronson et al., 2017). Nitrogen fertilizer recovery, however, is usually <50% in cotton with FI (Navarro et al., 1997; Booker et al., 2007; Bronson et al., 2007; Bronson, 2008). Long-term drought in the western United States and competition for water from expanding urban areas has led to renewed interested in overhead sprinkler irrigation (OSI) and subsurface drip irrigation (SDI) systems. Recovery efficiency of N for irrigated cotton in SDI can be high relative to FI, >75%, implying that gaseous and leaching losses of N are relatively low (Yabaji et al., 2009; Bronson et al., 2011).

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Abbreviations: DCD, dicyandiamide; EEF, enhanced efficiency fertilizer; EF, emission factor; ET, evapotranspiration; FI, furrow irrigation; NBPT, N-(n-butyl) thiophosphoric triamide; NDVI, normalized difference vegetation index; OSI, overhead sprinkler irrigation; SDI, subsurface drip irrigation; UAN, urea ammonium nitrate; WFPS, water-filled pore space.

Nitrous oxide (N_2O) is a potent greenhouse gas with a heat-trapping potential 265 times that of carbon dioxide (IPCC, 2014). Agricultural practices, particularly N fertilizer application, make up approximately 74% of the N_2O emissions in the United States (USEPA, 2015). Nitrous oxide is produced in cropped soils during denitrification, the anaerobic reduction of nitrate (NO_3) to di-nitrogen (N_2), and during nitrification, the oxidation of ammonium (NH_4) to NO_3 (Firestone and Davidson, 1989; Thapa et al., 2016). Irrigation generally results in increased N_2O emissions, by stimulating soil C and N cycling and reducing soil O_2 (Trost et al., 2013; Scheer et al., 2013; Rolston et al., 1982), although not in all cases (Maharjan et al., 2014). Irrigated cotton production in arid regions is typically water-intensive and can also be energy-intensive if the water is conveyed across more than a 30-m elevation gradient. According to Maraseni et al. (2010), greenhouse gas emissions in Australia from irrigated cotton are primarily from electricity used in pumping for irrigation and second from N_2O emissions from N fertilizer.

During the last 30 yr, hundreds of field studies have measured N_2O emission from N-fertilized cropped fields, mostly on corn (*Zea mays* L.) (Halvorson et al., 2014; Hatfield and Venterea, 2014; Thapa et al., 2016). Many of those studies tested enhanced efficiency fertilizers (EEFs) such as Agrotain Plus (Koch Agronomic Services), which consists of the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT), and the nitrification inhibitor, dicyandiamide (DCD). The purpose of EEFs like NBPT and DCD are to keep N fertilizer in the NH_4 form as long as possible so that less NO_3 is available for leaching and/or promoting denitrification-derived losses of N_2O and N_2 (Venterea et al., 2012; Halvorson and Del Grosso., 2013). Mitigation of N_2O emissions associated with nitrification can also be achieved with EEFs (Bronson et al., 1992; Venterea et al., 2012; Qiao et al., 2015; Thapa et al., 2016). The ultimate goal of EEF use is to improve N use efficiency in crops and improve yields. Far fewer N management studies have been conducted on cotton than corn (Scheer et al., 2008; Liu et al., 2010, Wang et al., 2013). In fact, with the exception of studies in Australia (Rochester, 2003; Grace et al., 2010; Rochester et al., 2015; MacDonald et al., 2016; Scheer et al., 2016; Grace et al., 2016), N_2O emissions studies in cotton are much rarer than for other crops. Placement of N fertilizer is also an important tool to efficient N management (Halvorson and Del Grosso, 2013). We are aware of no measurements of N_2O emissions following fertigation into FI.

There is a great deal of interest in calculating "emission factors" (EFs) with N_2O flux field data from N fertilizer treatments. This is simply the percentage of applied N fertilizer emitted as N_2O, after accounting for the fluxes from zero-N treatments. The IPCC makes the assumption that on average, a single emission factor of 1.0% can be used for N-fertilized field crops (De Klein et al., 2006), but emission factors are often lower or higher than 1.0% (Lesschen et al., 2011). Emission factors are a useful way to compare the impact of different management practices on N_2O emissions, particularly for varying N fertilizer rates or EEF treatments (Dobbie and Smith, 2003; Liu et al., 2010; Lesschen et al., 2011; Scheer et al., 2013; Halvorson et al., 2014; MacDonald et al., 2015).

Recent research in Texas and Arizona has demonstrated that the use of proximal sensing of canopy reflectance can allow for reduced N fertilizer rates without affecting cotton lint yields (Bronson et al., 2011, 2017). Little research has been done on whether canopy reflectance-based N management translates to reduced N_2O emissions (Yabaji et al., 2009; Venterea et al., 2012).

Nitrous oxide emission studies with SDI are few (Kennedy et al., 2013; Dogan et al., 2008; Yabaji et al., 2009; Kallenbach et al., 2010). Studies comparing N_2O emissions from different irrigation systems, such as FI and OSI in corn, are likewise rare (Nelson and Terry, 1996). Cayuela et al. (2017) reported in a meta-analysis that EFs from SDI were less than with OSI in Mediterranean cropping systems, but no cotton studies were included. Guardia et al. (2017) reported that surface drip irrigation and an EEF resulted in reduced N_2O emissions compared with sprinkler irrigation in corn. Sánchez-Martin et al. (2008) found that N_2O emissions in melon (*Cucumis melo* L.) in Spain were lower with surface drip irrigation than with FI.

No previous studies have been done evaluating the effects of N management for different irrigation systems on N_2O emissions in irrigated cotton in the US desert Southwest. The objective of this study was to compare N_2O emissions and emission factors with various N management treatments in a surface-irrigated field, an overhead sprinkler-irrigated field, and a subsurface drip-irrigated field, all furrowed for cotton in Arizona. We hypothesize that N management approaches such as knifing-in of N, use of EEFs, and or reflectance-based N management can result in less N_2O emissions compared with fertigating urea ammonium nitrate (UAN) in FI, or soil test-based N approaches without EEFs.

Materials and Methods

Nitrogen fertilizer management studies were conducted at Maricopa, AZ, for six consecutive years (2012–2017). The Maricopa Agriculture Center research farm is located at 33.067 N, 111.97 W and 360 m above sea level and has average annual rainfall of 200 mm. Furrow irrigation, OSI, and SDI were used for 2012–2013, 2014–2015, and 2016–2017, respectively. Furrow irrigation and OSI fields had 30-cm-high beds constructed every year with 1-m spacing; the SDI field had 15-cm-high beds, also at 1-m spacing. The soil at the FI and OSI fields (500 m apart) is a Trix sandy clay loam/sandy clay (fine-loamy, mixed, superactive, calcareous, hyperthermic Typic Torrifluvent). Casa Grande sandy loam/sandy clay loam (fine-loamy, mixed, superactive, hyperthermic, Typic Natrargid) is the soil at the SDI site, which is 1.3 km from the other two sites. The specific N management treatments for each of the three studies are detailed in Tables 1 to 3. The experimental design for all studies was a randomized complete block, with three replicates for FI and SDI and four replicates in OSI.

In March of each year, pre-plant soil sampling to 1.8-m depth for NO_3 was done at two to four locations per plot. Nitrate-N in the 0- to 90-cm soil depth was used to determine the N fertilizer rate for a soil test-based treatment as detailed in Tables 1 to 3. Zero-N control plots were established in all six site-years. Canopy reflectance-based N management treatments were tested, where N rates were initially set at 50% of the soil test treatments. The goal of this treatment was to reduce N fertilizer use without affecting yields. Weekly canopy reflectance measurements with the active optical sensor CropCircle ACS-470 (Holland Scientific Inc.) were used to determine when reflectance plots showed N deficiency. Specifically, when the normalized difference vegetation index (NDVI) amber was significantly less than the NDVI amber in the soil test treatments, N fertilizer rates were raised to match the soil test N rate (Bronson et al., 2011, 2017). In 2014–2015, under OSI, a second reflectance-based N treatment was added, which used 1.3*soil test N rate as the reference (Table 2). Cotton 'Delta Pine 1044 B2RF' was planted in late April to 1 May from 2012 to 2015, and cotton 'Delta Pine 1549 B2XF' was planted in mid-April in 2016 and 2017. In 2012 and 2013, FI plots were eight rows 1 m wide by 170 m long. In 2014 and 2015 under OSI, plots were six rows 1 m wide by 37 m long. In 2016 and 2017, plots were eight rows 1 m wide by 100 m long in the SDI field.

The N fertilizer source used in all of the studies was UAN, 320 g N kg^{-1}. In the FI study, N fertilizer treatments (Table 1) were applied in two split applications of N applied at first square

Table 1. Nitrous oxide emissions as affected by N management in furrow-irrigated 'DP 1044 RR F' cotton, Maricopa, AZ, 2012 and 2013.

Nitrogen treatment	Fertilization mode	Fertilizer source	Fertilizer rate		Seasonal N_2O flux		N_2O emission factor	
			2012	2013	2012	2013	2012	2013
			kg N ha^{-1}		g N_2O-N ha^{-1} 96 d^{-1}	g N_2O-N ha^{-1} 83 d^{-1}	——— % ———	
Zero-N			0	0	160 b†	370 b	–	–
Soil test-based N‡	Knife	UAN§	148	119	348 b	520 ab	0.1 a	0.10 a
Soil test-based N‡	Fertigate	UAN	148	119	871 a	843 ab	0.5 a	0.4 a
Soil test-based N‡	Fertigate	$(NH_4)_2SO_4$ /UAN + Agrotain Plus	148	119	855 ab	994 a	0.5 a	0.5 a
SE					220	333	0.16	0.3

† Means followed by a similar letter are not statistically different at $P = 0.05$.

‡ Based on lint yield goal of 1960 kg ha^{-1} and a 196 kg N ha^{-1} N requirement, minus 0- to 90-cm soil NO_3–N and estimated irrigation input of 22 kg N ha^{-1} (estimated 100-cm irrigation of 2 mg L^{-1} NO_3–N water).

§ UAN, urea ammonium nitrate.

Table 2. Nitrous oxide emissions as affected by N management in overhead sprinkler–irrigated 'DP 1044 RR F' cotton, Maricopa, AZ, 2014 and 2015.

Nitrogen treatment	Fertilizer source	Fertilizer rate		Seasonal N_2O flux		N_2O emission factor	
		2014	2015	2014	2015	2014	2015
		kg N ha^{-1}		g N_2O-N ha^{-1} 91 d^{-1}	g N_2O-N ha^{-1} 113 d^{-1}	——— % ———	
1. Zero-N		0	0	75 b†	285 c	–	–
2. Soil test-based N‡	UAN§	179	131	1123 a	1620 b	0.58 a	1.01 a
3. 1.3*soil test-based N‡	UAN	233	170	1240 a	2830 a	0.53 a	1.05 a
4. Soil test-based N‡	UAN + Agrotain Plus	179	131	269 b	856 bc	0.15 a	0.44 a
5. Reflectance-based N-1¶	UAN	90	66	1013 ab	783 c	1.11 a	0.77 a
6. Reflectance-based N-2#	UAN	116	85	705 ab	1099 bc	0.60 a	0.95 a
7. Reflectance-based N-1¶	UAN + Agrotain Plus	90	66	646 ab	761 c	0.71 a	0.72 a
8. Reflectance-based N-2#	UAN + Agrotain Plus	116	85	532 b	935 bc	0.45 a	0.72 a
SE				269	332	0.3	0.4

† Means in a column followed by a similar letter are not statistically different at $P = 0.05$.

‡ Based on lint yield goal of 2240 kg ha^{-1} and a 224 kg N ha^{-1} N requirement minus 0- to 90-cm soil NO_3–N and estimated irrigation input of 22 kg N ha^{-1} (estimated 100-cm irrigation of 2 mg L^{-1} NO_3–N water).

§ UAN, urea ammonium nitrate.

¶ First split equals 50% treatment 2; second and third splits based on normalized difference vegetation index (NDVI) relative to treatment 2.

First split equals 50% treatment 2, second and third splits based on NDVI relative to treatment 3.

Table 3. Nitrous oxide emissions as affected by N management in subsurface drip-irrigated 'DP 1549 B2XF' cotton, Maricopa, AZ, 2016 and 2017.

Nitrogen treatment	Irrigation level		Fertilizer rate		Seasonal N_2O flux		N_2O emission factor	
	2016	2017	2016	2017	2016	2017	2016	2017
	——— mm ———		—— kg N ha^{-1} ——		g N_2O-N ha^{-1} 117 d^{-1}	g N_2O-N ha^{-1} 113 d^{-1}	——— % ———	
1. Zero-N	582	608	0	0	170 a†	6 b	–	–
2. Soil test-based N‡	838	851	175	172	290 a	196 a	0	0.08 a
3. Reflectance-based N§	838	851	158	125	173 a	135 a	0	0.006 a
4. Zero-N	838	851	0	172	298 a	59 b	0	–
5. Soil test-based N	582	608	175	172	230 a	218 a	0	0.12 a
SE					68	66	–	0.05

† Means followed by a similar letter are not statistically different at $P = 0.05$.

‡ Based on lint yield goal of 2240 kg ha^{-1} and a 224 kg N ha^{-1} N requirement (increased to 252 kg N ha^{-1} N requirement in 2017) minus 0- to 90-cm soil NO_3–N and estimated irrigation input of 22 kg N ha^{-1} (estimated 100-cm irrigation of 2 mg L^{-1} NO_3–N water).

§ Initial N fertigation rate equals 50% treatment 2; rate was increased when normalized difference vegetation index (NDVI) was significantly less than treatment 2 NDVI.

and first bloom either by fertigating in the water run (with a 110 L h^{-1} diaphragm pump) or knifing-in N in the side of the bed, 10 cm from the plant row, the day before FIs. Nitrogen fertilizer treatments (Table 2) in the OSI study were applied in three doses (first square, first bloom, and midbloom) with a high clearance tractor to spray N into the furrow with fertilizer nozzles just before OSI events. More details of the FI and OSI study are reported in Bronson et al. (2017). In the SDI study, N treatments (Table 3) was fertigated in 24 events in a 6-wk period from first square to midbloom. Fertigations were made for each N-fertilized, 8-row by 100-m plot with a 30 L d^{-1} diaphragm pump.

Irrigation was applied in 100- to 125-mm amounts every 10 d in the FI field, and in 8- to 15-mm amounts two to four times a week in the OSI field. In the SDI field, irrigations were initially twice a week at first square. Starting at early bloom in SDI, 7- or 10-mm irrigations were applied daily. Drip irrigation "tape" was buried 22 cm deep (28 cm deep in 2017) in the center of the 1-m-wide beds, to be near the plant roots. Sulfuric acid was injected into the main header line of the SDI system with a pH meter-cum-pump. The pH 7.8 irrigation water was maintained at <pH 6.5 to prevent precipitation of $CaCO_3$ and blockage of drip emitters. In all field studies, irrigations were managed using the soil water depletion approach based on crop evapotranspiration (ET) estimated by the FAO-56 dual crop coefficient procedures (Allen et al., 1998). Seasonal irrigation was applied to replace 100% estimated ET (with an additional irrigation treatment using 70% ET replacement for SDI in 2016 and 2017). Soil water depletion was maintained to <45% in FI and OSI and <30% in SDI. Irrigation amounts after plant stand establishment ranged from 72 to 85 cm across the six site-years (Tables 1–3).

Surface flux of N_2O was measured weekly for 12 to 16 wk (from shortly after emergence to up to first open boll growth stage) during the seasons using 1-L vented and insulated chambers between 9 and 10 AM (Hutchinson and Mosier, 1981; Yabaji et al., 2009). The minimum sampling frequency for N_2O emissions of once per week was suggested by Parkin (2008). However, after the first year, if a large N_2O flux was measured (i.e., >1 g N_2O-N ha^{-1} h^{-1}), then a second set of chamber measurements was made 2 to 3 d later to better characterize fluxes lasting longer than 1 d. Two chambers per plot were placed 3 cm deep in the middle of two different furrows for 24-min periods in the longer FI and SDI plots to capture spatial variation. In the shorter OSI plots, one chamber per plot was placed in the middle of the furrow for 24-min periods. In the buried drip system in 2016–2017, chambers were inserted in the side of the bed, halfway from the edge of the furrow bottom to the top of the bed. This was done to be closer to the irrigation tape, as the middle of the furrows in SDI usually stay dry. Fifty-milliliter samples of chamber headspace gas were taken at 0, 12, and 24 min with 60-mL plastic syringes fitted with a Luer-lock stop-cock. Nitrous oxide analysis was performed on a Shimadzu 2014 gas chromatograph (Shimadzu Scientific Instruments) fitted with a ^{63}Ni electron capture detector at 340°C with a 95% argon–5% methane carrier gas (Mosier and Mack, 1980). Nitrous oxide fluxes were calculated according to the logarithmic equation of Hutchinson and Mosier (1981). If the increase in N_2O concentration in the chamber headspace in the 12- to 24-min period was less than the 0- to 12-min increase in concentration, then linear regression was used, as suggested by Venterea and Baker (2008).

On each morning that N_2O flux sampling occurred, percentage volumetric soil water content for the 0- to 15-cm soil depth was determined with a portable time domain reflectrometer (MiniTrase, Soil Moisture, Inc.). Water-filled pore space (WFPS) was calculated as described by Linn and Doran (1984). Soil temperature at 15 cm was also measured with a digital thermometer.

Nitrous oxide emissions data were analyzed by date, and with date as a repeated measures effect on cumulative, seasonal N_2O emissions, with a mixed model using SAS (SAS Institute, 2013). Replicate was considered random, and N treatment, date, and date × N treatment were considered fixed. Since N_2O data often has a log-normal distribution, the statistical analysis was also conducted using PROC GLIMMIX with a log distribution. The significance levels of the F statistics for treatments in the mixed models analysis were not remarkably different between the normal and log-normal-transformed data. We therefore only present nontransformed data in all cases.

PROC CORR was used to correlate N_2O flux with soil moisture and soil temperature for each date (SAS Institute, 2013). Emission factors were calculated for each site-year by subtracting the zero-N seasonal mean N_2O emission, from the seasonal mean N_2O emission for each N treatment and dividing by the N fertilizer rate, as suggested by Venterea et al. (2013).

Results

Nitrous oxide fluxes were apparent in FI early in the season after N fertilizer applications (Fig. 1), with the exception of the second N dose in 2013, when relatively low (<0.2 g N ha^{-1} h^{-1}) fluxes were observed (Fig. 1b). Under OSI in 2014 (Fig. 2a), where three applications of N were made, elevated N_2O fluxes above 0.5 g N ha^{-1} h^{-1} were observed following the first N dose, none after the second dose, and a small flux was detected after the third N dose during 2014 (Fig. 2). In contrast, with OSI in 2015, the largest N_2O fluxes (1.4–5.5 g N_2O-N ha h^{-1}) appeared between the second and third N application. With both FI and OSI, on most dates with observable N_2O fluxes, the fluxes were significantly greater with N fertilizer than the zero-N treatments. The large N_2O fluxes observed with FI and OSI were in association with WFPS of >80% (Fig. 1 and 2). On the other hand, N_2O fluxes in SDI did not exceed 0.4 g N ha^{-1} h^{-1} (Fig. 3). In 2016, no effect of N fertilizer on N_2O fluxes were observed in SDI on any dates. In 2017, N fertilizer treatments had significantly higher N_2O fluxes than zero-N plots at both irrigation levels, but the fluxes were very small (<0.2 g N_2O-N ha^{-1} h^{-1}).

Figures 1 to 3 also show soil moisture percentage measured by time domain reflectrometer for the 0- to 15-cm depth as WFPS. The WFPS ranged from 40 to 100% with FI and from 50 to 90% with OSI (Fig. 1 and 2). The 15-cm depth of the time domain reflectrometer probe was not deep enough to reach the wet zone of soil near the emitters in SDI. In SDI, WFPS ranged from just 33 to 50% in 2016 and 23 to 39% in 2017. The late season spike to 67% WFPS in 2017 was due to a 30-cm rain (Fig. 3). Weak but significant positive correlations between weekly N_2O fluxes and soil moisture as well as soil temperature at 15 cm were infrequent (data not shown).

Tables 1 to 3 show the seasonal, cumulative N_2O emissions by treatment for the three irrigation system-studies. Nitrous oxide emissions were affected by N fertilizer in all four site-years of FI and OSI from 2012 to 2015 (Tables 1–2). The FI studies exhibited maximum emissions in 2013 of 994 g N_2O-N ha^{-1} with 119 kg 32–0–0 N ha^{-1} with Agrotain Plus (Table 1). Large seasonal N_2O fluxes were observed in the OSI studies of 2015 with a maximum emission of 1620 g N_2O-N ha^{-1} at a 131 kg fertilizer-N ha^{-1} rate in 2015 (Table 2). The buried drip study in 2016 had seasonal N_2O emission that did not exceed 300 g N_2O-N ha^{-1} (Table 3). In addition to low N_2O emissions in the SDI study, there was no increase with N fertilizer relative to zero-N, but there was in 2017.

Among N-fertilized treatments, differences in N_2O emissions for the six site-years of data were infrequent and inconsistent. With FI, knifing-in of N resulted in lower N_2O emissions than fertigating, but only in 2012 (Table 1). Ammonium sulfate and UAN with Agrotain Plus had similar N_2O emissions to UAN alone. Under OSI, the addition of Agrotain Plus to UAN reduced N_2O emissions compared with UAN only in 2014 with the soil test N rate of 179 kg N ha^{-1} (Table 2). There was no effect of Agrotain Plus on the two reflectance-based N treatments in 2014 or on the three treatments in 2015 with Agrotain Plus. The well-fertilized reference treatment of 1.3*soil test for the second reflectance strategy with OSI had greater N_2O emissions than the soil test treatment in 2015, but not in 2014. Reflectance-based N management in the OSI used reduced rates of N fertilizer compared with the soil test treatments (Table 2). However, this resulted in reduced N_2O emissions in 2015, but not in 2014. There was no effect of N management or irrigation level on N_2O emissions with SDI in 2016 (Table 3). In 2017, there was no effect of reflectance management with a reduced N rate or irrigation level.

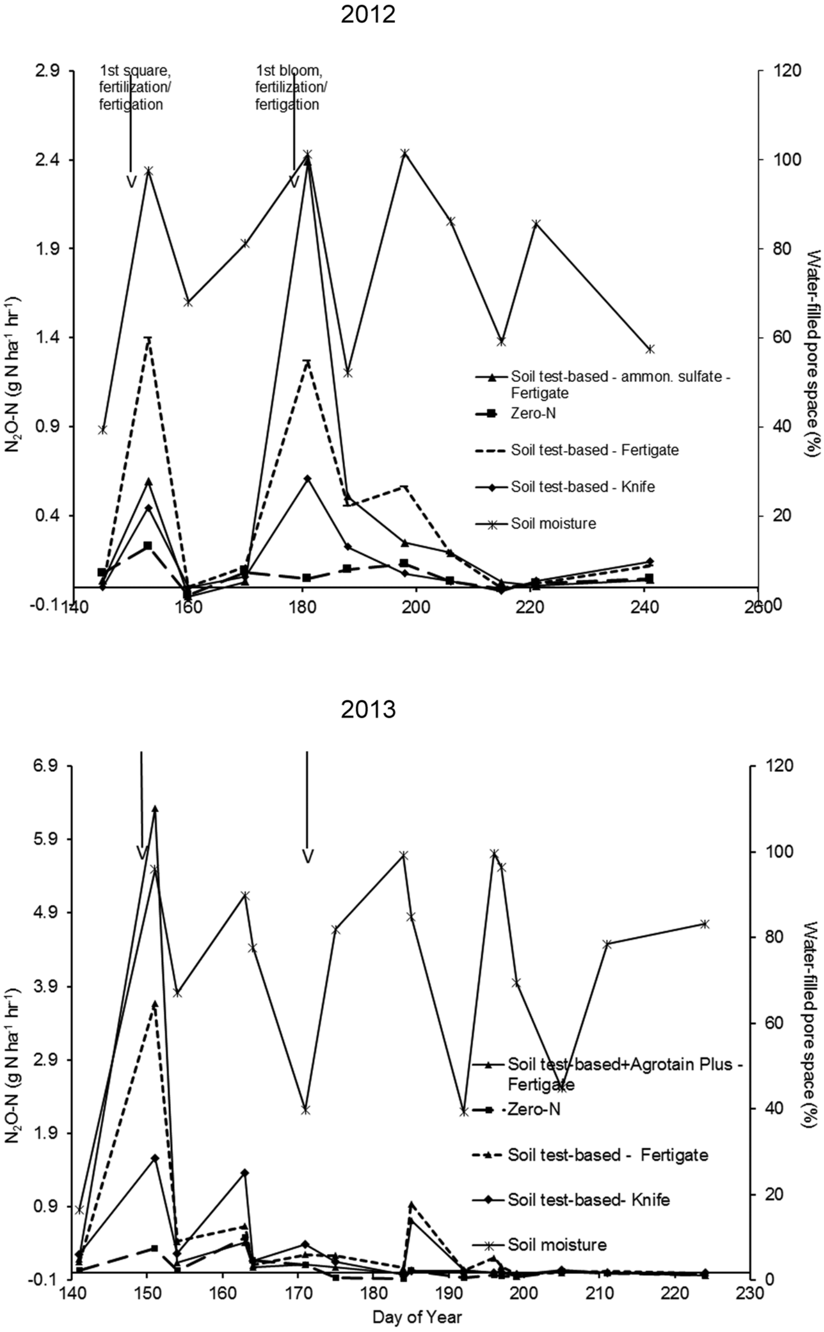

Fig. 1. Nitrous oxide emissions as affected by N fertilizer management in cotton under furrow irrigation, 2012–2013, Maricopa, AZ.

Discussion

The inconsistent effects of Agrotain Plus on N_2O emissions observed here were in contrast to some results with Agrotain Plus in corn, which have shown significant mitigation of N_2O emissions (Halvorson et al., 2014; Thapa et al., 2016). However, Watts et al. (2015) also reported no effect on N_2O emissions from DCD and NBPT addition to solid urea applied in rainfed cotton in Alabama in a 3-yr study. The DCD in Agrotain Plus probably breaks down quickly in high temperature environments, making its use as an N_2O emission inhibitor inconsistent (Bronson et al., 1989). The large N_2O fluxes in FI and OSI (Fig. 1 and 2) were likely from denitrification, rather than nitrification, as WFPS was >80% at these times (Linn and Doran, 1984; Bateman and Baggs, 2005). It is not possible to infer the source of N_2O emissions with SDI from the WFPS data, since as mentioned earlier, they were underestimated with the deep emitter line.

The in-season N management strategy of using canopy reflectance greatly reduced N rates in all six site-years. This approach has potential for reducing N_2O emissions, but in these studies, reduced N_2O emissions were only observed in 2015 under the OSI. Lint yields in those treatments had small (100–150 kg lint ha^{-1}) but statistically significant reductions compared with the soil test-based N treatments lint yields (Bronson et al., 2017). In the 2 yr of FI and in 2014 under OSI, reflectance-based N treatments did not affect lint yields compared with the soil test treatments (Bronson et al., 2017). We did not measure N_2O emissions in the reflectance-based N plots in the FI study.

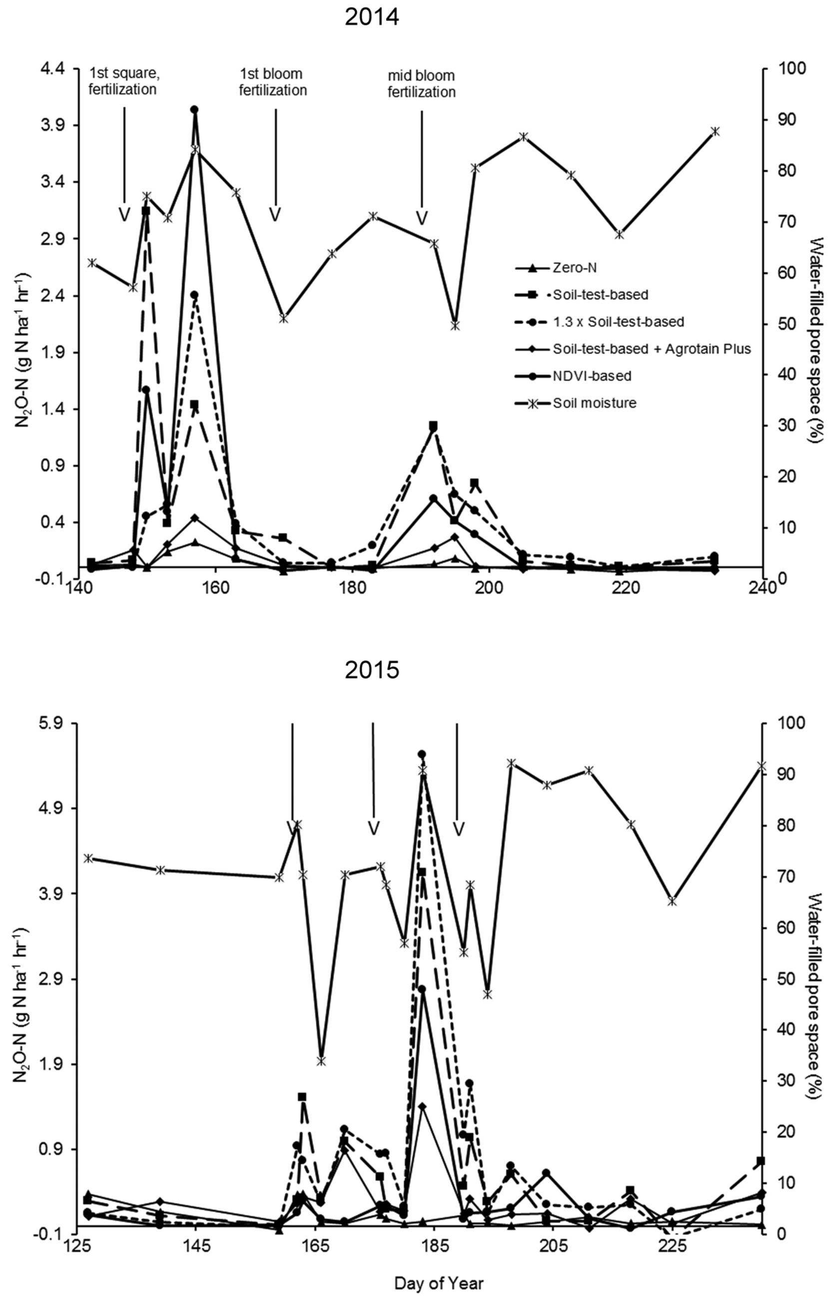

Fig. 2. Nitrous oxide emissions as affected by N fertilizer management in cotton under overhead sprinkler irrigation, 2014–2015, Maricopa, AZ. NDVI, normalized difference vegetation index.

As stated above, correlations between N_2O emission and soil water or temperature were inconsistent. Watts et al. (2015) reported positive correlations between N_2O emissions in rainfed cotton and soil temperature and soil moisture in 2 of 3 yr. The absence of N_2O emissions in the second half of the season in FI and OSI from 2012 to 2015 was likely due to the fact that N fertilization events were finished and that large plant biomass N uptake removed most of the available soil NO_3, and not due to a lack of soil moisture.

That N_2O emissions from cropping systems are rarely of economic importance at the farm level does not necessarily detract from its importance as a greenhouse gas. There was a two- to fivefold increase in seasonal N_2O emissions in the N-fertilized treatments relative to the zero-N control plots in the FI study of 2012–2103 (Table 1). In the OSI, a 16-fold increase in seasonal N_2O flux was observed, with the 1.3*soil test rate of 233 kg N ha^{-1} in 2014 (Table 2). The soil test treatment with OSI had a 16- and 5-fold increase in N_2O emissions for 2014 and 2015, respectively. The reduced reflectance-based N rates with OSI were in the range of a threefold increase above zero-N treatment. The SDI in 2017 saw a multifold increase in N_2O emissions of the soil test treatment to 218 g N ha^{-1} at low water compared with zero-N plot emission at 70% ET of 6 g N ha^{-1} (Table 3). However, the low N_2O fluxes with soil test-based N rates at both irrigation levels was in the range of the zero-N emissions in FI and OSI.

Note that there were no statistical tests to compare N_2O emissions among the three irrigation studies. This is because there were differences in the treatments, N rates, soil type, and the number of replicates, that is, there were three separate 2-yr, replicated studies. The zero-N treatments were consistent for 6 yr, except for the irrigations. The emission factor calculations can be used to standardize the variations in N fertilizer rate.

In FI cotton in Australia, EFs varied from 0.29, 0.58, and 1.83% for 100, 250 (current average producer rate), and 300 kg N ha^{-1} fertilizer rates, respectively (MacDonald et al., 2015; Grace et al., 2016). In our FI study, EFs of 0.5% were observed with N rates of 119 and 148 kg N ha^{-1} (Table 1), whereas the Australian FI studies did not measure EF of 0.5% until the N fertilizer rate was increased to 250 kg N ha^{-1} (Grace et al., 2016).

In our data from 2012 to 2017, the N_2O EFs measured were in line with the IPCC factor in just 4 of the 14 N-fertilizer treatment-year combinations under OSI (Tables 1–3). As a comparison, a N_2O emission factor of 0.5% of an 134 kg N ha^{-1} one-dose ground application of UAN in a center pivot-irrigated cotton field in West Texas was reported by Halvorson et al. (2012). Two recent studies on N_2O emissions with sprinkler-irrigated cotton in China reported EF of 1.0% (Liu et al., 2010; Wang et al., 2013), and a study in Uzbekistan measured an EF of 1.5% under FI (Scheer et al., 2008). In Queensland, Australia, in a clay soil, EFs ranged from 0.1 to 0.5% for N rates from 90 to 270 kg N ha^{-1} under an OSI (Scheer et al., 2016). The EF in our OSI study ranged from 0.4 to 1.1% (Table 2), the high value of which greatly exceeded the EF in the Australian OSI study.

The large N_2O emissions and EF with OSI were not expected. Apparently, the two to four times a week irrigation frequency of the OSI created optimal moisture conditions for N_2O emission via nitrification and denitrification. Leaching of losses of NO_3 were reported in the FI study, but not the OSI (Bronson et al., 2017). In this companion paper to the present study, Bronson et al. (2017) reported that deep percolation was as high as 11%

of irrigation and rain in the FI study but was negligible in the OSI. Nelson and Terry (1996) reported greater denitrification losses, measured by acetylene blockage, on a clay loam soil with FI than with OSI in Utah. They attributed this result to the disruption of soil aggregates and crusting under FI. This in turn led to reduced infiltration of irrigation water and a higher percentage of water-filled pore space. We did not observe crusting or reduced infiltration in our FI study. Surface (0–15 cm) soil moisture dipped to as low as 40% WFPS between irrigations with FI (Fig. 1). Soil drying and cracking was observed in the surface layer of the FI fields during the last 4 to 5 d of 10-d irrigation cycles. No surface soil cracking occurred in the OSI field. Cotton plants were therefore probably taking up water in the subsoil when surface soil cracking occurred, whereas root water uptake probably occurred in the consistently wet soil surface in OSI. Most N_2O production in soil occurs in the surface soil layers, with very little in the subsoil, since soluble carbon (C) is limited (Parkin and Meisinger, 1989). The combination of frequent, light irrigations in OSI apparently resulted in high moisture and high soluble C conditions that promoted nitrification and denitrification losses of N_2O.

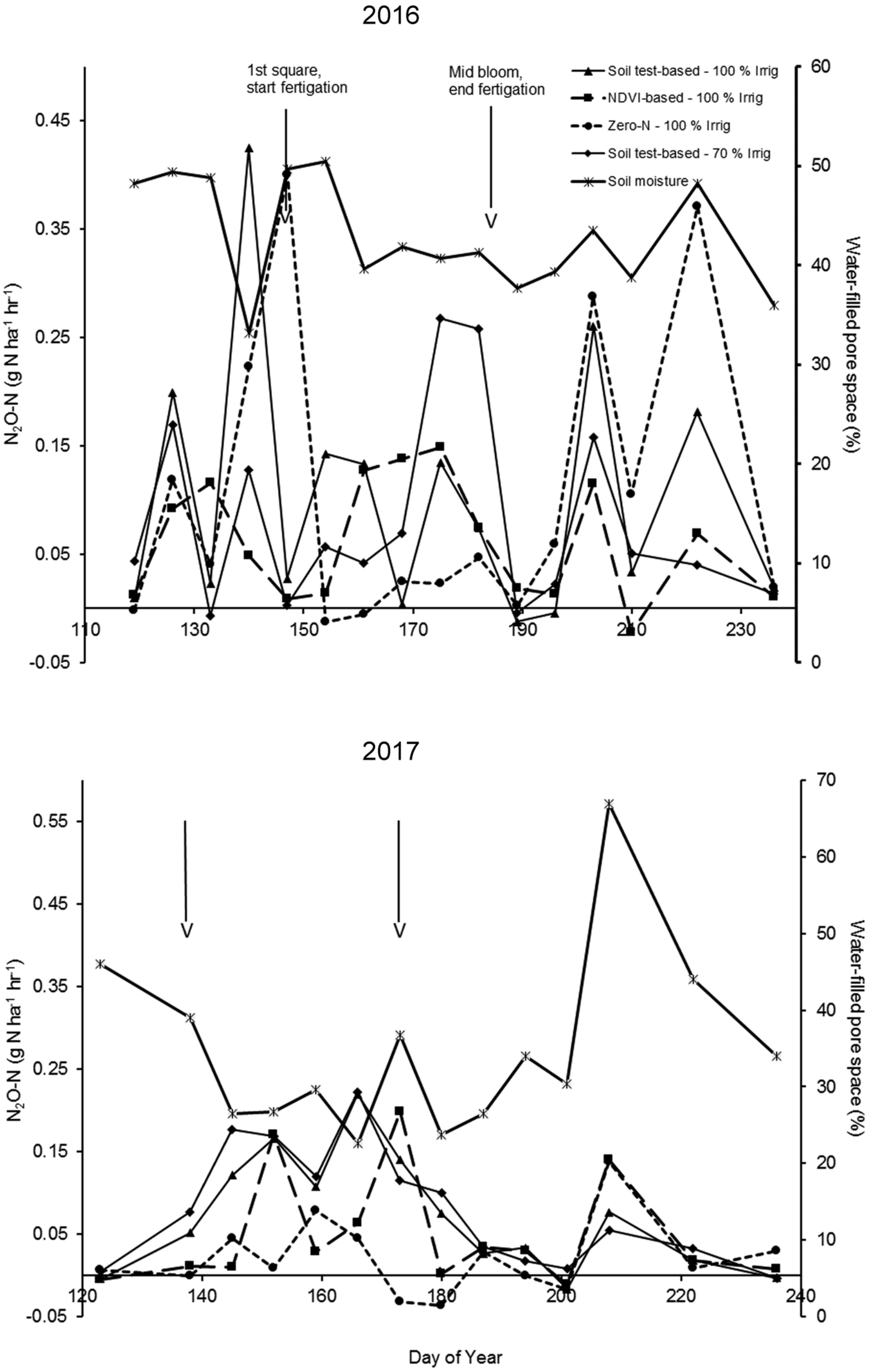

Fig. 3. Nitrous oxide emissions as affected by N fertilizer and water management in cotton under subsurface drip irrigation, 2016–2017, Maricopa, AZ. NDVI, normalized difference vegetation index.

The most notable finding in our study was with SDI, where the EF was 0% in 2016 and 0.1% in 2017 (Table 3). Yabaji et al. (2009) measured a zero EF of surface emissions of $N_2O + N_2$ in SDI cotton in West Texas with 20+ fertigation events. Subsurface drip irrigation is a highly efficient irrigation system, with little leaching or evaporative losses of irrigation water. Matrix forces wick the water away from the emitter so that saturation is not achieved. Additionally, fertigating in 24 doses in SDI amounts to "spoon feeding" N to the crop. Kallenbach et al. (2010) compared N_2O emission with SDI and FI with a cover crop–tomato (*Solanum lycopersicum* L.) system in California. In that study, N_2O emissions were similar between SDI and FI, and much greater than reported for these systems here. Nitrogen fertilizer was fertigated in SDI and side-dressed in two splits in FI. However, there were no zero-N treatments in the Kallenbach study, so an EF factor was not calculated.

Conclusions

Nitrous oxide emission factors reached a maximum of 1.1 and 0.5% for OSI and FI, respectively. Emissions of N_2O were very low in the SDI study, with an emission factor of 0 to 0.1%. The very high number (24) of small fertigations in the SDI study probably contributed to the low emissions. Fertigation of N fertilizer in SDI cotton, therefore, is a very "climate-friendly" management practice. Nitrogen management options such as N placement, use of Agrotain Plus, or reflectance-based N had inconsistent effects on N_2O emissions. With growing worldwide interest in the installation of SDI in arid land cropping systems (Gleick, 2003; Ibragimov et al., 2007; Du et al., 2008; Dogan et al., 2008), these new findings demonstrate that the low N_2O emission factor of SDI can help off-set greenhouse gas emissions associated with SDI.

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