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Effects of Fertilizer Placement on Trace Gas Emissions from Nursery Container Production

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***Abstract*. Increased trace gas emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are widely believed to be a primary cause of global warming. Agriculture is a large contributor to these emissions; however, its role in climate change is unique in that it can act as a source of trace gas emissions or it can act as a major sink. Furthermore, agriculture can significantly reduce emissions through changes in production management practices. Much of the research on agriculture's role in mitigation of greenhouse gas (GHG) emissions has been conducted in row crops and pastures as well as forestry and animal production systems with little focus on contributions from specialty crop industries such as horticulture. Our objective was to determine efflux patterns of CO_2, CH_4, and N_2O associated with three different fertilization methods (dibble, incorporated, and topdressed) commonly used in nursery container production. Weekly measurements indicated that CO_2 fluxes were slightly lower when fertilizer was dibbled compared with the other two methods. Nitrous oxide fluxes were consistently highest when fertilizer was incorporated. Methane flux was generally low with few differences among treatments. Results from this study begin to provide data that can be used to implement mitigation strategies in container plant production, which will help growers adapt to possible emission regulations and benefit from future GHG mitigation or offset programs.**

Over the past several decades global warming has received increased attention from the scientific community including possible impacts of increased temperature on the global environment. Anthropogenically enhanced climate change is still highly debatable; however, emissions of the three most important long-lived GHGs (CO_2, CH_4, and N_2O) are known to have substantially increased in the past 25 years (Dlugokencky et al., 2005; Keeling and Whorf, 2005; Prinn et al., 2000). Experts in almost every industry are searching for ways to reduce GHG emissions and lessen their respective carbon (C) footprint.

One area of particular interest in GHG mitigation research is agricultural production. Agriculture occupies 37% of the earth's land surface producing ≈20% of total GHG emissions (Cole et al., 1997; Smith et al., 2008). High levels of CO_2 are emitted from agricultural production primarily through land use changes (deforestation), fossil fuel use, biomass burning, and soil disturbance accounting for 33% of total C emissions between 1850 and 1998, exceeding all other anthropogenic activities besides energy production (Houghton, 2003; IPCC, 2007; Johnson et al., 2007; Watson et al., 2000). Agricultural production is the largest contributor of anthropogenic CH_4 and N_2O emissions accounting for 52% and 84%, respectively, of annual anthropogenic global emissions (Smith et al., 2008). The major sources of CH_4 production from agriculture include enteric fermentation in ruminant animals, flooded rice fields, biomass burning, and manure management and storage (Cole et al., 1997; Johnson et al., 1993; USDA, 2008). Nitrous oxide emissions are a direct result of increased use of synthetic fertilizers and production of legumes, resulting in 80% of the total N_2O emissions in the United States (Mosier et al., 2003).

Agriculture production is unique compared with other industries in that it can act as a GHG source but can also act as a sink for GHG through changes in production management. Increased C storage through conservation or "no-till" has been shown to maintain or increase soil C levels and reduce fossil fuel use (Paustian et al., 1997; Reicosky et al., 1999; Smith et al., 1998). Methane emissions have been shown to be greatly reduced by adding feed supplementation to the diets of ruminant animals and by proper manure handling (Cole et al., 1997; Leng, 1991; Lin et al., 1994; Safley et al., 1992). Nitrous oxide emissions can be reduced by improving nitrogen (N) use efficiency (Kroeze et al., 1999; Kroeze and Mosier, 2000). Proper N fertilization timing (Weier et al., 1993) and placement (Oenema et al., 2001; Youngdahl et al., 1986) have also been shown to successfully reduce total N loss.

Several best management practices have been developed for reducing emissions of CO_2 (Paustian et al., 2000), CH_4 (Mosier et al., 1998), and N_2O (Snyder et al., 2007) from agricultural production. Other programs such as Greenhouse Gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) have also been initiated by the USDA-ARS to focus on reducing GHG emissions by altering current agricultural production practices. Past research has focused predominantly on agronomic, forestry, and animal production systems with little attention given to specialty industries such as horticulture. The green industry (nursery, greenhouse, and sod production) is one of the fastest growing sectors in agriculture (Hall et al., 2005); however, almost no research has focused on the impacts of this industry on GHG emissions.

Providing best management options for reducing GHG would not only reduce the environmental impact of the industry, but could benefit growers financially. There are now government and industry programs that provide tax incentives and payments to encourage farmers to reduce emissions and provide C offsets by altering current production practices (Chicago Climate Exchange, 2009; Environmental Protection Agency, 2009; National Farmers Union, 2009; Schmidt, 2009). There is also speculation that agricultural GHG emissions could be "capped" or taxed in the future (Adams, 2009; Blanford and Josling, 2009; Moore and Bruggen, 2011).

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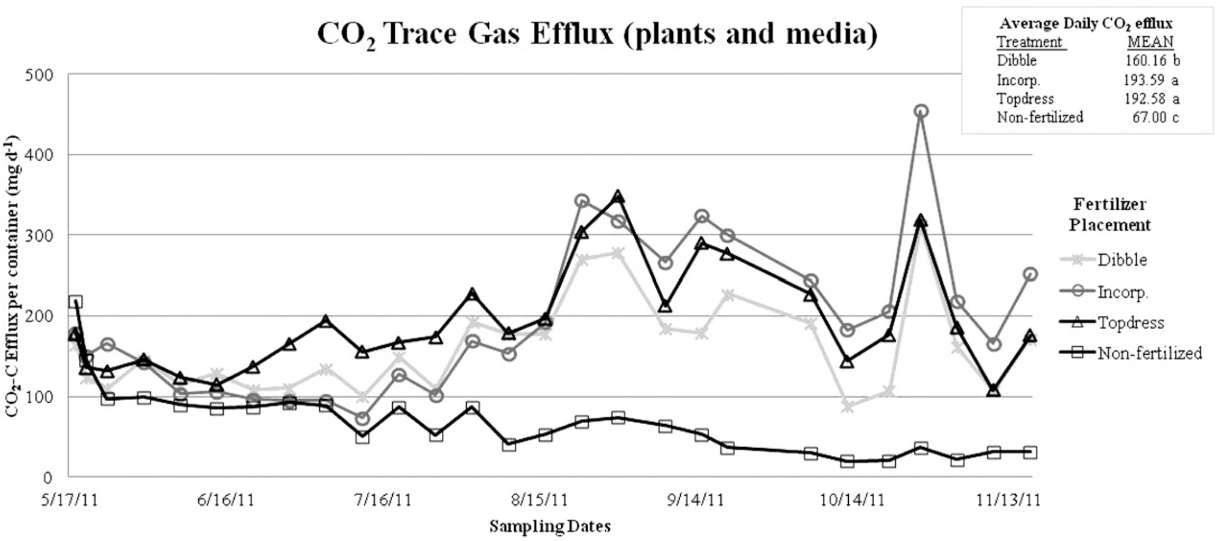

Fig. 1. CO_2-C efflux (mg·d^{-1}) for gumpo azaleas grown with three different fertilizer placements for 6 months (17 May to 17 Nov. 2011). The inset shows average daily efflux (means followed by the same letter are not significantly different from each other, $P \leq 0.05$).

Table 1. Cumulative trace gas (CO_2, CH_4, and N_2O) efflux from container-grown woody nursery crops[z] using three different fertilization placements.

	Cumulative efflux		
Fertilizer placement[y]	CO_2-C (mg)	N_2O-N (µg)	CH_4 (µg)
Dibble	651.80 b[x]	602.62 b	–3.82 c
Incorporated	785.93 a	1883.84 a	21.70 bc
Topdressed	781.45 a	572.27 b	56.16 ab
Non-fertilized	325.19 c	21.09 c	76.42 a

[z] Containers measured contained white gumpo azaleas (*Azalea ×hybrida* 'Gumpo White') potted into a pine bark:sand (6:1 v:v) media. Cumulative efflux was calculated using the trapezoid rule (n = 7).

[y] The same fertilizer rate [25 g of product (Polyon® 17-5-11) per 3-L container] was used for all placement treatments with the exception of non-fertilized pots, which received no Polyon® fertilizer. Media in all treatments was amended with dolomitic limestone (3.0 kg·m^{-3}), and Micromax® (0.9 kg·m^{-3}).

[x] Means were separated using Fisher's least significant difference test in the Proc Mixed procedure (P = 0.05).

CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide.

There is a need to develop mitigation strategies for nursery production practices to help growers adapt to possible future legislation and benefit from C trading or offset programs.

One method of GHG mitigation that has been previously investigated is fertilizer placement in agricultural soils [Breitenbeck and Bremner, 1986; Council for Agricultural Science and Technology (CAST), 2004; Engel et al., 2009; Hosen et al., 2000; Liu et al., 2006; Millar et al., 2010; Mosier et al., 1996; Prasertsak et al., 2002; Stefanson, 1976]. The placement of fertilizers into the soil and near the zone of active root uptake may reduce N loss from leaching and increase plant N use efficiency, which would reduce the amount of N that could be lost through N_2O emissions (CAST, 2004). Concentrated N placement of urea fertilizer in agricultural soils using a band or nest placement has been shown to increase N_2O production when compared with a broadcasted application, attributable in part to higher soil N accumulations (Engel et al., 2009). Breitenbeck and Bremner (1986) reported that after injection of anhydrous ammonia fertilizer, N_2O production increased with injection depth, whereas in contrast, Hosen et al. (2000) and Stefanson (1976) reported that emission rate of N_2O did not change with depth of fertilizer application.

Although less studied, fertilizer placement could also affect CO_2 and CH_4 emissions by impacting plant growth. In agricultural soils, CO_2 is primarily produced from oxidation of soil organic materials by heterotrophic microorganisms and the respiration of plant roots, whereas CH_4 is produced under anaerobic conditions by microbial decomposition of organic materials (Yamulki and Jarvis, 2002). Fertilizer placement has been shown to affect shoot and root growth of container-grown nursery crops (Altland et al., 2004), which could indirectly impact net GHG emissions because increased crop growth will sequester more C in growing biomass. In a study by Liu et al. (2006), deep N placement (10 to 15 cm) resulted in lower N_2O emissions compared with shallow N placement (0 to 5 cm), although CO_2 and CH_4 emissions were unaffected by N placement depth.

Due to a lack of a general conclusion regarding the affect of N placement on GHG emissions, Mosier et al. (1996) concluded that the diverse combinations of physical and biological factors, which control gas fluxes, are likely the cause of the conflicting results seen in previously published literature. Smith et al. (1997) also concluded that emission rates from different placements will likely vary from one system to another because of complex interactions of soil, crop, and environmental factors that must be taken into account. The same could be said for fertilizer type or formulation, which has also yielded conflicting results depending on the production system being evaluated (Snyder et al., 2009). Although fertilization placement has been shown to affect emission rates, individual production systems will likely have varying results and different mitigation strategies may need to be developed for different production systems. Previous work has focused on agronomic crops; however, it is important to also understand how fertilizer placement will affect emissions in specialty crop industries such as horticulture. Therefore, the objective of this study was to determine the effects of fertilizer placement on CO_2, CH_4, and N_2O emissions from container production of a woody nursery crop.

Materials and Methods

This experiment was initiated at the Paterson Greenhouse Complex, Auburn University, AL. On 17 May 2011, *Azalea ×hybrid* 'Gumpo White' (white gumpo azaleas) that were ≈15 cm in height with a 10-cm canopy width were transplanted from 72 cell-pack liners (2.5 cm) into 3.8-L containers; enough transplants were obtained to ensure there were no differences in plant size among treatments at study initiation. Containers were filled with a pine bark:sand (6:1 v:v) media, which had been previously amended with 3.0 kg.m^{-3} of ground dolomitic limestone and 0.9 kg.m^{-3} of Micromax® micronutrient (The Scotts Company, LLC, Marysville, OH). Polyon® (Harrell's LLC, Lakeland, FL) 17N–2.2P–4.2K (17-5-11) controlled-release fertilizer (10 to 12 month) was applied at a potting at a rate of 25 g per container using the three different methods described by Altland et al.

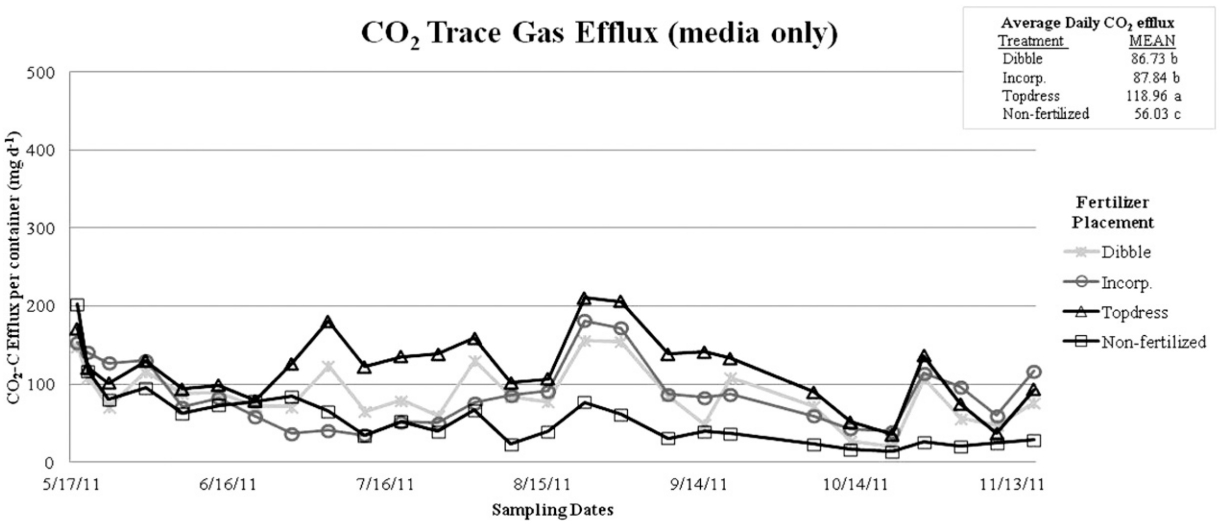

Fig. 2. CO_2-C efflux (mg·d^{-1}) from container media with three different fertilizer placements for 6 months (17 May to 17 Nov. 2011). The inset shows average daily efflux (means followed by the same letter are not significantly different from each other, $P \leq 0.05$).

Table 2. Cumulative trace gas (CO_2 CH_4, and N_2O) efflux from container media during container-grown plant production using three different fertilization placements.[z]

	Cumulative efflux		
Fertilizer placement[y]	CO_2-C (mg)	CH_4 (μg)	N_2O-N (μg)
Dibble	370.85 b[x]	25.62 a	629.25 b
Incorporated	384.67 b	15.94 a	2434.83 a
Topdressed	501.19 a	84.28 a	789.74 b
Non-fertilized	266.49 c	36.52 a	14.45 c

[z] Container media used was a pine bark:sand (6:1 v:v) media that had been previously amended with dolomitic limestone [3.0 kg m^{-3} (5.0 lbs/yd^3)] and Micromax® [0.9 kg·m^{-3} (1.5 lbs/yd^3)]. Cumulative efflux was calculated using the trapezoid rule (n = 3).

[y] The same fertilizer rate [25 g of product (Polyon® 17-5-11) per 3-L container] was used for all placement treatments with the exception of non-fertilized pots, which received no Polyon® fertilizer.

[x] Means were separated using Fisher's least significant difference test in the Proc Mixed procedure (P = 0.05).

CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide.

(2004): dibble, incorporation, and topdressing. Dibbled fertilizer was placed immediately beneath the rootball of azalea transplants (8 cm below the container media surface). Incorporated fertilizer was premixed into the pine bark media just before potting. Topdressed fertilizer was placed on the container surface immediately after potting. An additional treatment received only incorporated lime and Micromax® amendments with no other fertilization. The study used seven replicates for each fertilizer placement treatment with plants and three additional replications per treatment with media only. After potting, all containers with plants were placed in a retractable roof shade structure in a randomized complete block design and received daily overhead irrigation (1.3 cm). Media-only containers were placed adjacent to containers with plants in the retractable roof shade structure in a similar manner. At the time of study initiation, an additional 10 gumpo azaleas, similar in size to those used in the study, were used to determine initial plant biomass. Plant growth index [(plant height + width1 + width2)/3] was measured, shoots were cut at the media surface, media was removed from roots, and shoots and roots were dried for ≈72 h at 55 °C in a forced-air oven before weighing. Roots and shoots were then ground separately to pass through a 0.2-mm mesh sieve. Concentrations of C and N were determined using a LECO 600-CHN analyzer (LECO Corp., St. Joseph, MI).

Trace gases emitted from the containers were sampled in situ weekly for 6 months (17 May to 17 Nov.) using the static closed chamber method (Hutchinson and Livingston, 1993; Hutchinson and Mosier, 1981). Custom-made gas flux chambers were designed and constructed based on criteria described in the GRACEnet protocol (Baker et al., 2003; Parkin and Kaspar, 2006) to accommodate nursery containers rather than field plot studies. A structural base consisting of polyvinyl chloride (PVC) cylinders (25.4 cm i.d. × 38.4 cm tall) was sealed at the bottom. During gas measurements, the entire plant–pot system was placed inside the base cylinder and a vented flux chamber (25.4 cm diameter × 11.4 cm height) was placed on top of the base cylinder. Top flux chambers were constructed with PVC, covered with reflective tape, and contained a center sampling port. Gas samples were taken at 0-, 15-, 30-, and 45-min intervals after chamber closure. At each time interval, gas samples (10 mL) were collected with polypropylene syringes and injected into evacuated glass vials (6 mL) fitted with butyl rubber stoppers as described by Parkin and Kaspar (2006). Corresponding air temperature data were collected for each sampling period using Hobo Portable Temperature Data Loggers (Model H08-032-08 with Solar Shield; Onset Computer Corp., Bourne, MA). Although container media moisture levels were not measured during this study, gas samples were collected in the morning before any irrigation event (with the exception of uncontrollable weather events) allowing container moisture levels to equilibrate before sampling.

Gas samples were analyzed using a gas chromatograph (Shimadzu GC-2014, Columbia, MD) equipped with three detectors: thermal conductivity detector for CO_2, electrical conductivity detector for N_2O, and flame ionization detector for CH_4. Gas concentrations were determined by comparison with standard curves developed using gas standards obtained from Air Liquide America Specialty Gases LLC (Plumsteadville, PA). Gas fluxes were calculated from the rate of change in concentration of trace gas (CO_2, N_2O, or CH_4) in the chamber headspace during the time intervals, whereas chambers were closed (0, 15, 30, and 45 min) as described by Parkin and Venterea (2010). Calculations in this study were used to express data as milligrams CO_2-C, micrograms CH_4-C, and micrograms N_2O-N trace gas per day. Estimates of cumulative efflux were calculated from gas efflux at each sampling date integrated over time using a basic numerical integration technique (i.e., trapezoidal rule; Yeh, 1991).

On study completion, all plants were measured and destructively harvested as described previously for determination of C accumulation in plant biomass. Trace gas data were analyzed on each individual sampling date (data not shown), across all dates, and cumulatively. All trace gas and growth data were analyzed using the Proc Mixed procedure in SAS (SAS® Institute Version 9.1, Cary, NC).

Means were separated using Fisher's least significance difference test in the Proc Mixed procedure. In all cases, differences were considered significant at $P \leq 0.05$.

Results

Average daily trace gas emissions from containers with plants indicated that CO_2-C efflux was lower in the dibble treatment (160.16 mg CO_2-C) when compared with incorporated or topdressed treatments (193.59 and 192.58 mg CO_2-C, respectively); all fertilized treatments had higher values than the non-fertilized containers (Fig. 1). The incorporated treatment had higher CO_2-C efflux than any other treatment on 10 of the 29 sampling dates, whereas the topdressed treatment was highest on six dates (data not shown). Efflux from the dibble treatment was lower than incorporated or topdressed on nine dates and had similar values to the non-fertilized treatment on four dates (data not shown); this pattern was also observed for cumulative CO_2-C losses (Table 1). Average daily efflux from media-only containers showed dibble and incorporated treatments had lower CO_2-C efflux (86.73 and 87.84 mg CO_2-C, respectively) than the topdressed treatment (118.96 mg CO_2-C) (Fig. 2); this pattern was also seen for cumulative efflux (Table 2).

Average N_2O efflux (with plants) was highest in the incorporated treatment (489.02 μg N_2O-N) with no differences observed between dibble and topdressed treatments (156.82 and 148.96 μg N_2O-N, respectively; Fig. 3); all placement treatments had significantly higher N_2O-N efflux than the non-fertilized containers. Cumulative N_2O efflux also illustrated that more N_2O-N was lost from the incorporated treatment (Table 1). On 15 of the 29 dates, the incorporated treatment had a higher N_2O-N efflux than any other treatment (data not shown). Efflux from the media-only containers followed similar trends (Fig. 4; Table 2) except that a much higher efflux was observed when no plants were present.

Methane efflux patterns were inconsistent (both with and without plants) but remained relatively low in all treatments for most of the study with no differences observed in daily averages among treatments (Figs. 5 and 6). Cumulative CH_4 efflux (with plants) showed the lowest value in the dibble treatment and the highest value in the non-fertilized treatment with other treatments showing no significant difference (Table 1). No differences were observed in cumulative CH_4 efflux among media-only containers (Table 2). On many sampling dates, it is likely CH_4 efflux values were close to or below the detection limits of the gas chromatograph.

Gumpo azalea root and shoot dry weights did not differ among fertilizer placements at

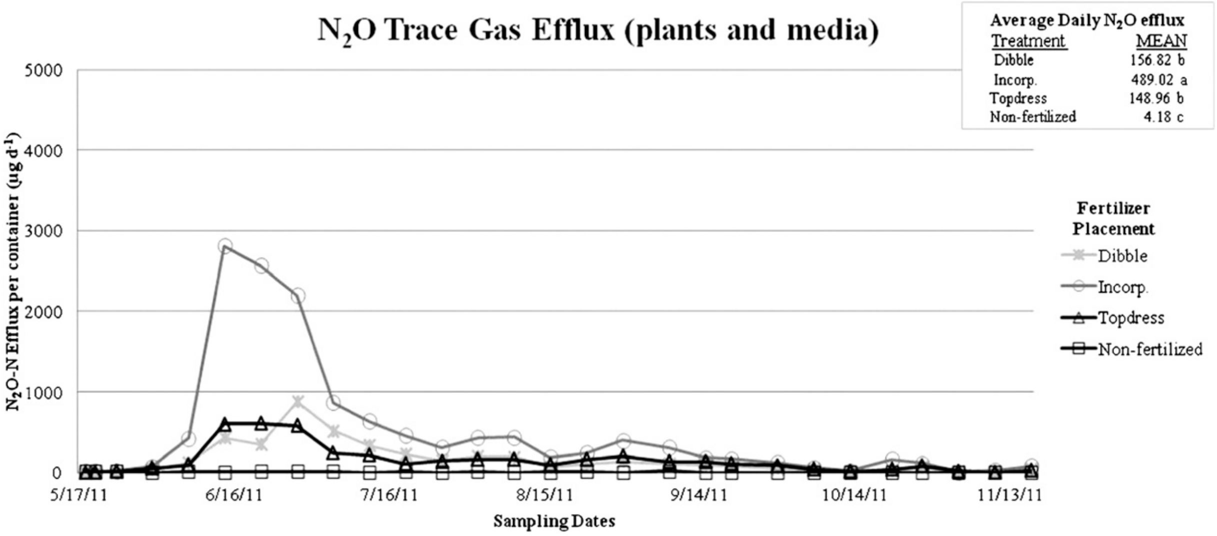

Fig. 3. N_2O-N efflux (μg·d^{-1}) for gumpo azaleas grown with three different fertilizer placements for 6 months (17 May to 17 Nov. 2011). The inset shows average daily efflux (means followed by the same letter are not significantly different from each other, $P \leq 0.05$).

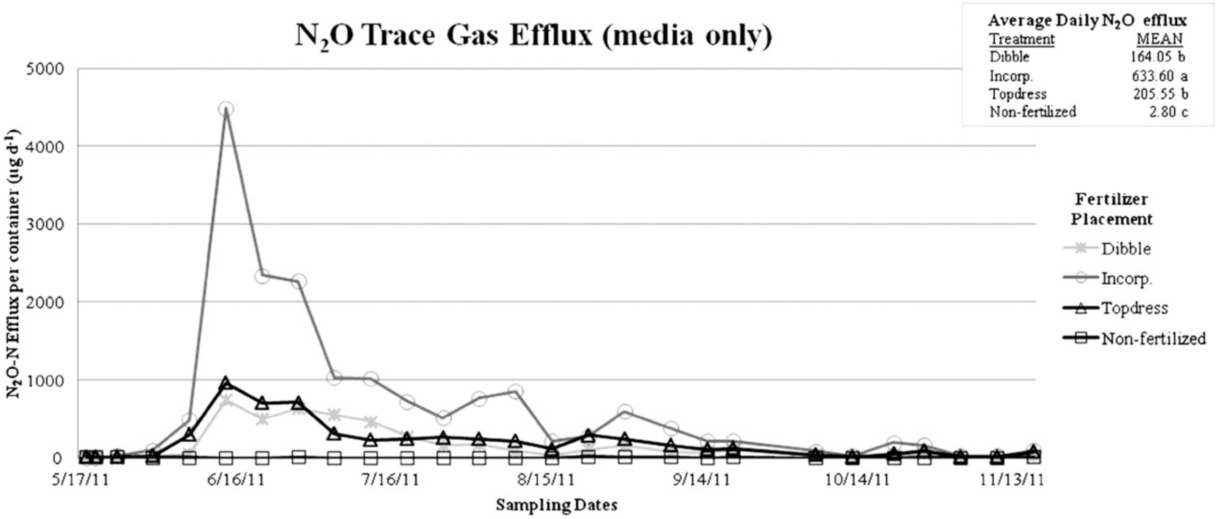

Fig. 4. N_2O-N efflux (μg·d^{-1}) from container media with three different fertilizer placements for 6 months (17 May to 17 Nov. 2011). The inset shows average daily efflux (means followed by the same letter are not significantly different from each other, $P \leq 0.05$).

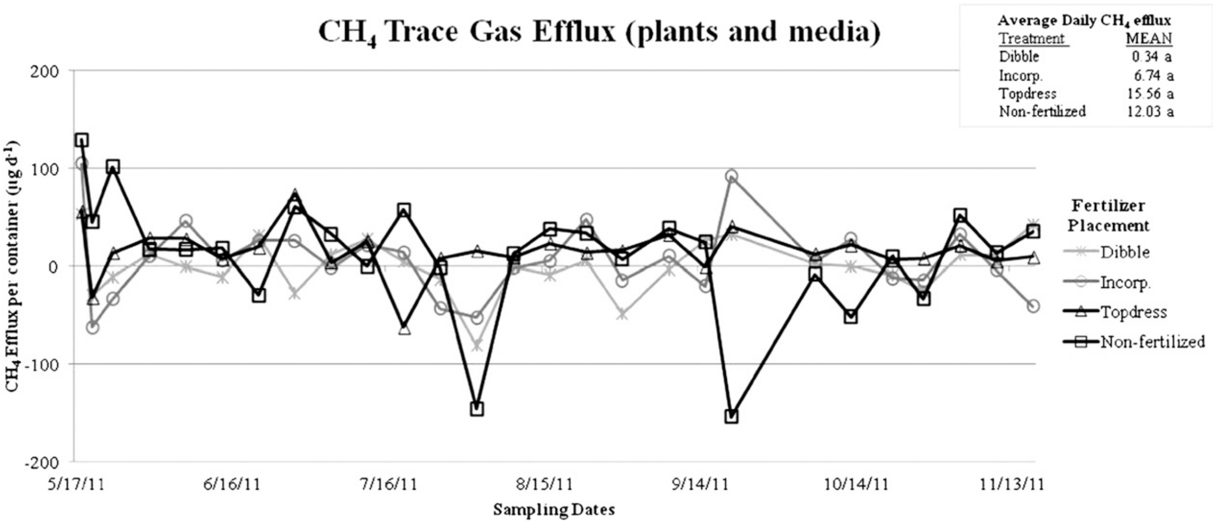

Fig. 5. CH_4 efflux ($\mu g \cdot d^{-1}$) from container media with three different fertilizer placements for 6 months (17 May to 17 Nov. 2011). The inset shows average daily efflux (means followed by the same letter are not significantly different from each other, $P \leq 0.05$).

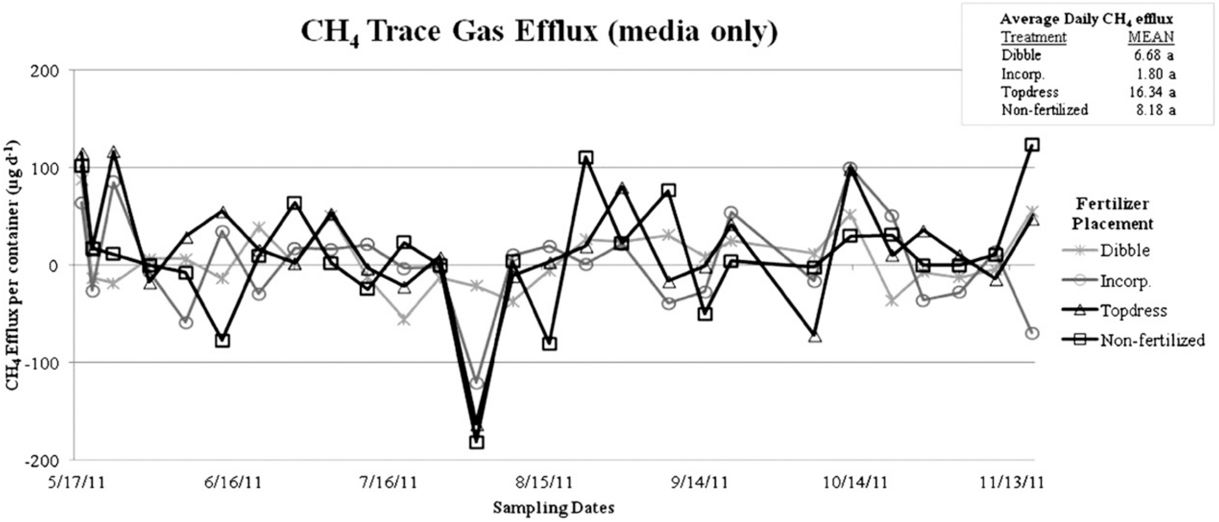

Fig. 6. CH_4 efflux ($\mu g \cdot d^{-1}$) for gumpo azaleas grown with three different fertilizer placements for 6 months (17 May to 17 Nov. 2011). The inset shows average daily efflux (means followed by the same letter are not significantly different from each other, $P \leq 0.05$).

termination of the study; all were higher than the non-fertilized treatment (Table 3). Shoot C followed this same pattern. However, root C was lowest in the topdressed treatment and highest in the non-fertilized treatment. Shoot N was higher in all treatments compared with the non-fertilized treatment and was higher in the incorporated treatment than the other placements; root N followed this same pattern.

Table 3. Biomass, carbon, and nitrogen content of white gumpo azalea shoots and roots[z] after container production using three different fertilization placements.

Fertilizer	Shoots			Roots		
placement[y]	Dry wt (g)	Carbon (%)	Nitrogen (%)	Dry wt (g)	Carbon (%)	Nitrogen (%)
Dibble	21.5 a[x]	45.4 b	1.6 b	10.1 a	46.4 ab	0.9 b
Incorporated	27.1 a	45.3 b	1.7 a	11.6 a	47.2 ab	1.2 a
Topdressed	24.6 a	45.4 b	1.6 b	11.0 a	46.0 b	1.1 b
Non-fertilized	0.9 b	46.7 a	0.3 c	1.2 b	47.5 a	0.3 c

[z] Azalea shoots show the carbon and nitrogen content of all aboveground plant material (leaves, stems, branches). Azalea roots show the carbon and nitrogen content of belowground plant material (roots only).

[y] The same fertilizer rate [25 g of product (Polyon® 17-5-11) per 3 L container] was used for all placement treatments with the exception of non-fertilized pots, which received no Polyon® fertilizer. Media in all treatments was amended with dolomitic limestone [3.0 $kg \cdot m^{-3}$ (5.0 lbs/yd^3)] and Micromax® [0.9 $kg \cdot m^{-3}$ (1.5 lbs/yd^3)].

[y] Means were separated using Fisher's least significant difference test in the Proc Mixed procedure ($P \leq 0.05$).

Discussion

Lower CO_2-C efflux in the media-only non-fertilized treatment must be the result of lower heterotrophic respiration, likely attributable to N limitation in the microbial populations. Lower efflux in the non-fertilized treatment (with plants) was likely the result of a combination of lower heterotrophic respiration and lower autotrophic respiration resulting from smaller plant size. Higher CO_2-C efflux for the topdressed treatment (media only) compared with the other treatments may be the result of stimulation of the microbial populations near the media surface where the topdressed fertilizer was placed. Lower efflux for the dibble treatment (with plants) compared with the other placements may be the result of patterns of root growth impacting autotrophic respiration. Altland et al. (2004) has shown that dibble placement of fertilizer can slightly reduce root growth of container-grown crops.

Furthermore, growth index taken approximately halfway through the study (data not shown) indicated plants receiving dibble treatment were slightly smaller. Other studies using nursery crops have reported variable growth responses to fertilizer placement. Meadows and Fuller (1983) showed that dibble application of a controlled-release fertilizer resulted in better growth of four azalea cultivars and two holly cultivars than when fertilizers were incorporated. Meadows and Fuller (1984) showed different results in a later study in which surface application or topdressing resulted in better growth of three azalea cultivars than dibble application. Cobb and Holt (1984) also showed that topdressing with a sulfur-coated urea fertilizer increased growth of woody nursery crops when compared with dibbling or incorporating fertilizers. Our results demonstrate that plant growth was similar among all fertilization treatments at the conclusion of the study, but dibble fertilizer placement reduced CO_2-C losses in azalea container production.

Nitrous oxide emissions were generally higher in media-only containers. When no plants were present to use N before it is emitted as N_2O, a much higher N_2O flux can be expected (Wagner-Riddle et al., 1994). Nitrous oxide emissions were consistently higher when fertilizer was incorporated. There are two possible explanations as to why efflux from the incorporation treatment was much higher than that observed from dibble or topdressed treatments. Because fertilizer was placed closer to roots in the dibble treatment, the plant was likely able to use the fertilizer more efficiently, especially at earlier dates when plant roots were small and localized, which has been shown to reduce N_2O emissions (CAST, 2004); however, dibble placement did not appear to increase plant growth or N concentration when compared with other fertilization placements. Second, the controlled-release fertilizer used has a release rate that is highly dependent on temperature and moisture. The incorporation treatment had much greater contact with media (and subsequently moisture) than the topdressed treatment and likely had a faster release rate. A faster release rate from the incorporated treatment also likely caused the higher N in azalea shoots and roots; however, this higher N did not result in plant growth differences (Table 3). In fact, all fertilized plants had N concentrations within the recommended sufficiency range (Mills and Jones, 1996). Previous investigations examining the effects of fertilizer placement on GHG emissions from agriculture have shown inconsistent results (Millar et al., 2010). For example, Liu et al. (2006) showed deep (10 to 15 cm) N placement resulted in a reduction of up to 70% in N_2O loss when compared with a shallow placement (5 cm), whereas Drury et al. (2008) showed N_2O flux increased 26% with deep injection (10 cm) compared with a shallow (2 cm) injection. Based on our results (using a controlled-release product), it appears that incorporating fertilizer significantly increased N_2O efflux compared with the other two methods.

Although CH_4 was produced at times in this study, efflux was generally low and differences among treatments were only observed when plants were included. Previous work has shown that CH_4 fluxes from dry or well-drained soils are generally small compared with saturated soils (Bharati et al., 2001; Robertson et al., 2000). Because the media used in this study was well drained, the anaerobic conditions needed for methane production were likely infrequent. Methane is generally thought to contribute significantly to the atmospheric pool from agriculture through enteric fermentation in ruminant animals, rice production, and manure handling (Cole et al., 1997). Based on results from this study, CH_4 efflux does not appear to have a significant effect on total trace gas emissions from container-grown nursery crops.

Results from this study indicate that dibbling fertilizer may reduce total trace gas emissions (CO_2, CH_4, and N_2O collectively) from container production systems. When plants were included (like in a nursery production setting), dibbling reduced CO_2 emissions compared with incorporation and topdressed treatments, whereas plant growth was statistically similar at the conclusion of the study. Dibbling and topdressing also significantly reduced N_2O emissions (68% and 70%, respectively) compared with the incorporated treatment. Although dibbling also resulted in lower CH_4 emissions than topdressed treatments, the fact that CH_4 efflux was low in all treatments indicates that CH_4 is not a trace gas of concern from container production systems regardless of the fertilization method used. Further work is needed to determine the impact of different production variables on trace gas emissions from container plant production. However, results from this study begin to provide evidence of mitigation strategies, which can be implemented in container plant production to help growers benefit from C offset programs, adapt to future legislation, and improve the environmental impact from container plant production without negatively affecting crop growth.

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