Greenhouse Gas Emissions from an Ornamental Crop as Impacted by Two Best Management Practices: Irrigation Delivery and Fertilizer Placement[1]

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Abstract

Agriculture is one of the largest contributors of greenhouse gas (GHG) emissions. To date, much work on reducing GHG emissions has centered on row crops, pastures, forestry, and animal production systems, while little emphasis has been placed on specialty crop industries such as horticulture. In this horticulture container study, Japanese boxwood (*Buxus microphylla* Siebold & Zucc.) was used to evaluate the interaction of irrigation (overhead vs drip) and fertilizer placement (dibble vs incorporated) on GHG emissions (CO_2, N_2O, and CH_4). Plants were grown in 11.4 L (#3) containers with a 6:1 pine bark:sand substrate with standard amendments. All containers received 6.35 mm (0.25 in) water three times daily. Gas samples were collected in situ using the static closed chamber method according to standard protocols and analyzed using gas chromatography. Total cumulative CO_2 loss was not affected by differences in irrigation or fertilizer placement. Total cumulative N_2O efflux was least for drip-irrigated plants, regardless of fertilizer placement. For overhead-irrigated plants, N_2O efflux was greatest for those with incorporated fertilizer. Efflux of CH_4 was generally low throughout the study. Findings suggest that utilizing drip irrigation could decrease N_2O emissions, regardless of fertilizer placement. However, when limited to overhead irrigation, dibbled fertilizer placement could decrease N_2O emissions.

Index words: carbon dioxide, methane, nitrous oxide, trace gas

Species used in this study: Japanese boxwood (*Buxus microphylla* Siebold & Zucc.)

Significance to the Horticulture Industry

Agriculture is considered to be second only to energy production in greenhouse gas (GHG) emissions [carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4)]. While research to date has focused primarily on the evaluation of mainstream agricultural practices such as row crops, forestry, pastures and animal production systems, relatively little has explored mitigation strategies for specialty crop industries, such as container production. Protocols for establishing baseline estimates have been determined in previous work, though uncertainty still remains in determining specific best management practices for lowering GHG emissions in container production. In this work, the effects of two irrigation regimes (overhead vs drip) as well as two fertilizer placements (incorporated vs dibble) on GHG emissions were measured from Japanese boxwood (*Buxus microphylla*). Results showed that cumulative CO_2 emission over the duration of the nine month-long study was not affected by differences in irrigation or fertilizer placement. For plants receiving overhead irrigation, N_2O emissions were greatest for those with incorporated fertilizer. However, total cumulative N_2O efflux was least for drip-irrigated plants, regardless of fertilizer placement. Methane emissions were low throughout the study. Overall, results indicated that when attempting to mitigate GHG emissions from container-grown boxwood, utilizing drip irrigation could decrease N_2O emissions regardless of fertilizer placement. When a grower is limited to overhead irrigation however, dibbling rather than incorporating fertilizer into the standard mix, may decrease overall N_2O emissions.

Introduction

While there is evidence of global climate change and a documented increase in Earth's surface temperature (IPCC 2007), the degree to which these changes are anthropogenically enhanced is debated among scientists worldwide. Emissions of the three main GHGs (CO_2, CH_4, and N_2O) from agricultural practices and related industries comprise an estimated one-fifth of the annual increase in GHG emissions (Cole et al. 1997). When emissions from land use changes (e.g., clearing/burning of land, biomass burning, and general soil degradation) are included, the contribution to annual increases rises to almost one-third. While limited research has been conducted modeling the contribution to global warming potential of a whole nursery production system with respect to certain horticultural crops (Ingram and Hall 2016, Ingram et al. 2016, Kendall and McPherson 2011), limited research has focused on the estimation of GHG emissions in container plant production as affected by changes in best management practices.

The horticulture industry greatly impacts the landscape of rural, suburban, and urban environments. It is one of the fastest growing sectors in agriculture with an economic impact of $148 billion annually in the United States (Hall et al. 2005) and $2.8 billion in Alabama alone (AAES 2009). In 2006, there were 7,300 producers in the top 17 states, occupying approximately a half million acres

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(USDA 2007). Furthermore, it is estimated that an additional 150 million U.S. acres of urban/suburban land (Lubowski et al. 2006) is or could be planted with ornamental trees and shrubs as a means of potential C sequestration.

While the economic impact of this specialty crop industry is known, the overall impact of its contribution to GHG emissions and ultimately, climate change, remains unclear since limited work on GHG emissions has been conducted in the ornamental horticulture sector. The authors' earlier work examined emissions of dwarf yaupon holly (*Ilex vomitoria* 'Nana') in differing container sizes [3.0 L (trade gal), 3.8 L (#1), 7.6 L (#2), and 11.4 L (#3)] to establish a baseline between potting media volume and GHG emissions. Over the duration of the one year study, both CO_2 and N_2O emissions were highest in the largest containers with a positive relationship between container size and flux, but CH_4 emissions were consistently low and unaffected by container size (Marble et al. 2012a). It is important to note that, while CO_2 and N_2O emissions were highest in larger containers, smaller containers would most likely have higher overall total emissions on a per area basis due to the fact that more small containers will fit into a given production area.

As a follow up to the container size work, common fertilizer placement methods (dibble, incorporated, and topdressed) were evaluated with the growth of azalea (*Azalea* × hybrid 'Gumpo White') (Marble et al. 2012b). In general, CO_2 emissions were lowest with dibbled fertilizer placement compared to both incorporated and topdressed treatments. Nitrous oxide (N_2O) emissions were highest with incorporated fertilizer, while CH_4 was low and unaffected by placement method. Results from these studies began to address uncertainties regarding the environmental impact of the horticulture industry on climate change. Much more work will be required to accurately develop baseline GHG emissions from container production systems needed to develop future mitigation strategies.

As with row crop management (Johnson et al. 2007), opportunities exist to reduce GHG emissions from the plant-pot ornamental production system by altering current best management practices such as irrigation delivery method, fertilizer dosage and delivery method, and container substrate selection. Pine bark (PB) is the most commonly used substrate for container ornamentals in the southeastern United States, though some uncertainty exists about the future availability of this resource (Lu et al. 2006). While alternative substrates for ornamental plant production have been the focus of much research over the past decade (Boyer et al. 2008, 2009, Fain et al. 2008, Murphy et al. 2011), and lab analysis has shown that these media have C concentrations similar to that of PB (Marble et al. 2011), little is known about the way these substrates structurally compare to PB in their ability to naturally sequester C.

Additionally, fertilizer (including manure) management can also greatly influence GHG emissions. As N inputs (from both organic and inorganic sources) increase, N_2O emissions also generally increase. However, the N source used, as well as its relative soil placement, can greatly impact N_2O loss (Mosier et al. 2003, Eichner 1990). Previous work has shown that soil N_2O emissions were higher in organically fertilized plots versus minerally fertilized plots (Kaiser and Ruser 2000).

One other interacting factor that has the potential to significantly impact N loss in container plant production is the frequency and volume of irrigation applied. This issue is important not only in relation to climate change (as excessive irrigation could increase both N leaching and N_2O emissions), but also to general water conservation, a critical national issue. Additional investigation is necessary to determine irrigation and fertilizer best management strategies (dosage and delivery) for reducing N_2O emissions and maximizing overall water use efficiency in container-plant production.

Therefore, the objective of this research was to further evaluate GHG emissions (CO_2, CH_4, and N_2O) as influenced by fertilizer placement (dibble vs incorporated) in combination with different irrigation methods (overhead vs drip). Common Japanese boxwood (*Buxus microphylla*) was selected due to its widespread use in urban and suburban landscapes.

Materials and Methods

This experiment was conducted on an outdoor nursery pad at the Paterson Greenhouse Complex on Auburn University campus (Auburn, AL). On July 25, 2013, 11.4 L (#3) containers were filled with a standard 6:1 PB:sand (v:v) substrate amended with 3.0 $kg \cdot m^{-3}$ dolomitic limestone. Fertilizer [Polyon 17-5-11, 5-6 month release, with micronutrients (Harrell's LLC, Lakeland, FL)] was either incorporated or dibbled (placed directly beneath the boxwood liner) into each pot at a rate of 76 g (2.7 oz) per container (equivalent to 6.5 $kg \cdot m^{-3}$). Containers were watered daily with either overhead irrigation (impact sprinklers approximately 1.8 m (6 ft) high) or individual drip irrigation (Netafilm PC Spray Stakes; Double Spray; 6.6 GPH). Both irrigation delivery methods were calibrated to deliver 6.35 mm (0.25 in) water three times daily. GHG (CO_2, CH_4, N_2O) emitted from plants and substrate were sampled in situ for nine months (July 25, 2013 to April 28, 2014) using the static closed chamber method (Hutchinson and Mosier 1981, Hutchinson and Livingston 1993). Custom-made gas efflux chambers were designed and constructed based on descriptions in the GRACEnet protocol (Baker et al. 2003, Parkin and Kaspar 2006) to accommodate 11.4 L (#3) nursery containers. A structural base consisting of polyvinyl chloride (PVC) cylinders (25.4 cm inside diameter by 38.4 cm tall) was sealed at the bottom and coated with reflective tape. The top efflux chambers [25.4 cm inside diameter by 11.4 cm tall (10 in by 4.5 in)] were constructed of PVC, covered with reflective tape, and fitted with a center sampling port. During gas measurements, the entire plant-pot system was placed inside the base cylinder. The efflux chamber was placed on top of the base cylinder and a wide [10.4 cm (4 in)] rubber band was placed around the cylinder to seal it. GHG were sampled once or twice weekly at 10:00 AM (after irrigation event). Gas samples were collected at 0, 20, and 40 min intervals following chamber closure. Samples were collected with polypropylene syringes and subsequently injected into evacuated glass vials (6 ml) topped with butyl rubber stoppers. Gas samples were analyzed using a gas chromatograph (Shimadzu GC-2014, Columbia, MD). Gas concentrations were determined by comparison with standard curves developed using gas standards obtained from Air Liquide America Specialty Gases LLC (Plumsteadville, PA). Gas effluxes were calculated from the rate of change in concentrations of GHGs in the chamber headspace during the time intervals while chambers were closed (0, 20, and 40 min) (Parkin and Venterea 2010). Calculations in this study were used to express data as mg CO_2-C, CH_4-C, and N_2O-N emitted per container per day. Additionally, global warming potential (GWP), a measure of the impact of each greenhouse gas in CO_2 equivalents, was calculated on a per container basis from cumulative GHG emissions across the entire study period. Each GHG has an established GWP based on the ratio of radiative forcing from 1 kg of a gas to 1 kg of CO_2 over a specific interval of time. The GWP of CO_2 is 1, whereas the GWP of CH_4 is 25, and that of N_2O is 298 (Forster et al. 2007). The experiment was conducted as a split-plot with three replications. Irrigation was the whole plot treatment and fertilizer placement was the split plot treatment. Data analyses were conducted using the Mixed Models Procedure (Proc Mixed) of the Statistical Analysis System (Littell et al. 1996). Error terms appropriate to the split-plot design were used to test the significance of main effects and their interactions. A significance level of ($P \leq 0.05$) was established *a priori*.

Results and Discussion

Cumulative CO_2-C loss, across the entire nine-month sampling period, was not significantly affected by irrigation method, fertilizer placement, or their interaction (Table 1). Though not statistically significant, presumably due to variability among blocks, CO_2-C emissions for drip irrigated plants were 11% more than those receiving overhead irrigation. Trends in daily CO_2 efflux were similar among treatments and highly seasonal, with the least amount of CO_2 emitted during the coldest months (Fig. 1). Data for cumulative CO_2 were comparable to those established by Marble et al. (2012b), where three fertilizer placements were evaluated using *Azalea* × *hybrid* 'Gumpo White' (white gumpo azalea). All plants in the referenced study received overhead irrigation similar to that used in the overhead treatment of the current study. Cumulative CO_2 for plants grown with incorporated fertilizer in the former study was 36.04 g CO_2/pot (over six months) (Marble et al. 2012b), while plants grown with incorporated fertilizer in the current study had an observed efflux of 65.80 g CO_2/pot (over nine months) (Table 1). The authors believe that differences in timing of the studies (duration and seasonality) may explain the differences in cumulative efflux values between the two studies, while differences in plant species may also have affected cumulative CO_2 efflux. Plants fertilized with the dibble method followed a similar pattern. Cumulative CO_2 for plants grown with dibbled fertilizer in the former study was 29.78 g CO_2/pot (over six months), while plants grown with dibbled fertilizer in the current study had an observed efflux of 68.44 g CO_2/pot (over nine months).

Table 1. Cumulative CO_2, N_2O, and CH_4 efflux over nine months from container-grown boxwood[z] using two different irrigation regimes[y] and two different fertilizer placements[x].

Main Effects			Cumulative Efflux CO_2-C (g/pot)	N_2O-N (mg/pot)	CH_4 (mg/pot)
Irrigation Effect					
Drip			74.61[w,ns]	84.98 b	16.92 a
Overhead			67.12	13.56 a	0.62 b
p:			*0.287*	*<0.001*	*0.001*
Fertilizer Placement Effect					
Dibble			71.45[ns]	98.87 b	16.75 a
Incorporated			70.28	125.70 a	0.78 b
p:			*0.709*	*0.016*	*0.001*
Interaction Effects					
Irrigation Regime		**Fertilizer Placement**			
Drip	-	Dibble	74.46[ns]	75.31 c	30.79 a
Drip	-	Incorporated	74.77	94.66 c	3.05 b
Overhead	-	Dibble	68.44	122.43 b	2.72 b
Overhead	-	Incorporated	65.80	156.74 a	-1.48 b
p:			*0.638*	*0.418*	*0.006*

[z]Boxwood (*Buxus microphylla*) was potted into one-gallon nursery containers containing a 6:1 (v:v) pinebark:sand substrate, amended with 3.0 kg m^{-3} dolomitic limestone. Cumulative efflux for nine months (July 25, 2013 - April 17, 2014) was calculated using the trapezoid rule (n=6).

[y]The same volume of irrigation [6.35 cm (0.25 in), three times daily] was delivered to all plants via either overhead impact sprinklers (1.8 m high) or individual drip stakes (Netafilm PC Spray Stakes; Double Spray; 6.6 GPH).

[x]The same fertilizer rate [76 g of Polyon 17-5-11 with blended minors (Harrell's LLC, Lakeland, FL)] was used for both dibble and incorporated fertilizer treatments.

[w]Within a column, means followed by the same letter are not significantly different ($p \leq 0.05$) according to the LSMeans statement under the Proc Mixed procedure of SAS.

[ns]Not significantly different.

Cumulative N_2O efflux was greatest for treatments receiving overhead irrigation and fertilized with the incorporated method (156.74 mg/pot over nine month period) (Table 1). This increase in N_2O can be seen in the daily efflux graph as early spikes in N_2O emissions (Fig. 2). Switching from incorporated to dibbled fertilizer while still under overhead irrigation reduced N_2O efflux from 156.74 mg/pot to 122.43 mg/pot. However, utilizing drip irrigation significantly reduced N_2O efflux over the duration of the study, regardless of fertilizer placement (75.31 mg/pot for dibble; 94.66 mg/pot for incorporated). Cumulative N_2O for boxwood evaluated in this study were higher than those observed by Marble et al. (2012b). Cumulative N_2O for plants grown with incorporated fertilizer in the former study was 92.93 g N_2O/pot (Marble et al. 2012b), while plants grown with incorporated fertilizer in the current study had an observed efflux of 156.74 g N_2O/pot (Table 1). Similarly, cumulative N_2O for plants grown with dibbled fertilizer in the former study was 29.99 g N_2O/pot (Marble et al. 2012b), while plants grown with dibbled fertilizer in the current study had an observed efflux of

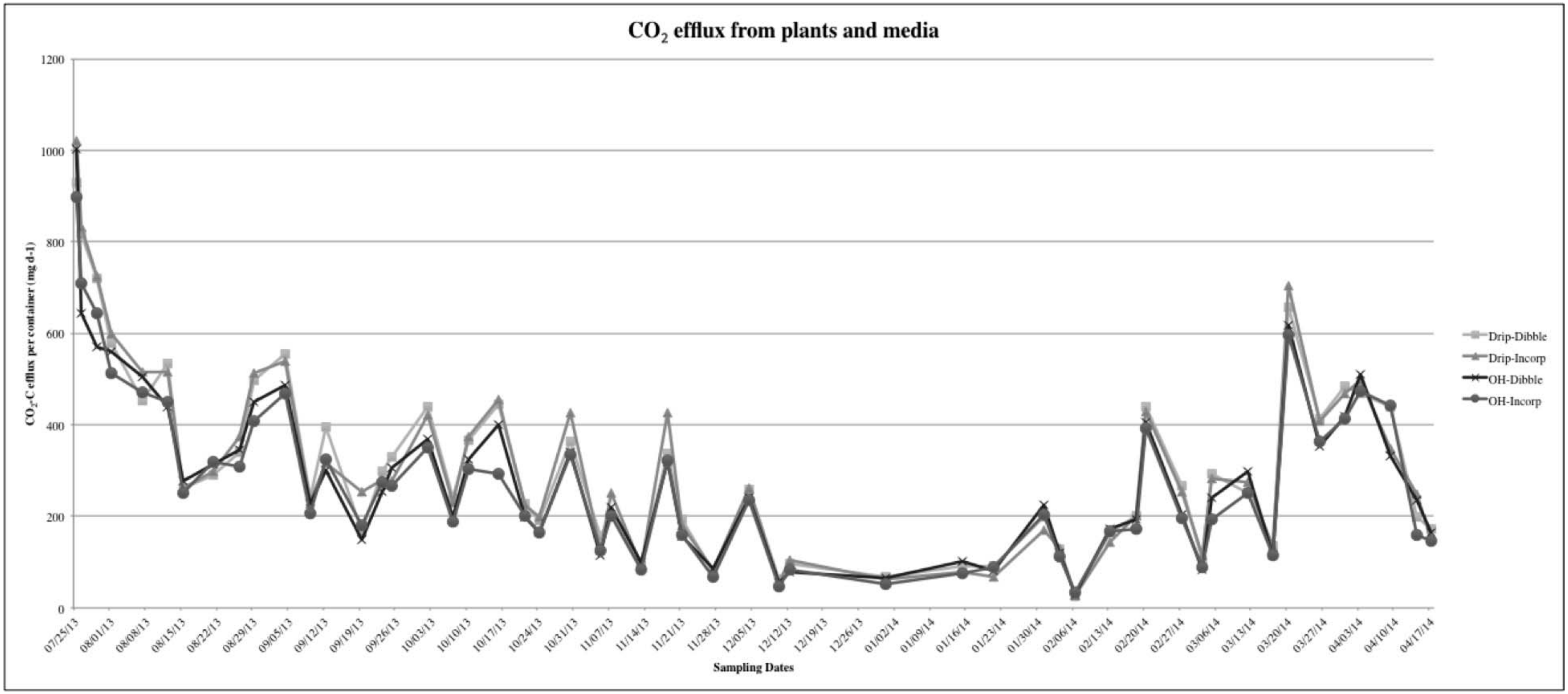

Fig. 1. CO_2-C efflux (mg d^{-1}) for container-grown boxwood irrigated with either drip or overhead irrigation, and either dibbled or incorporated fertilizer. Means are for a time period of approximately 9 months (July 25, 2013 – April 17, 2014).

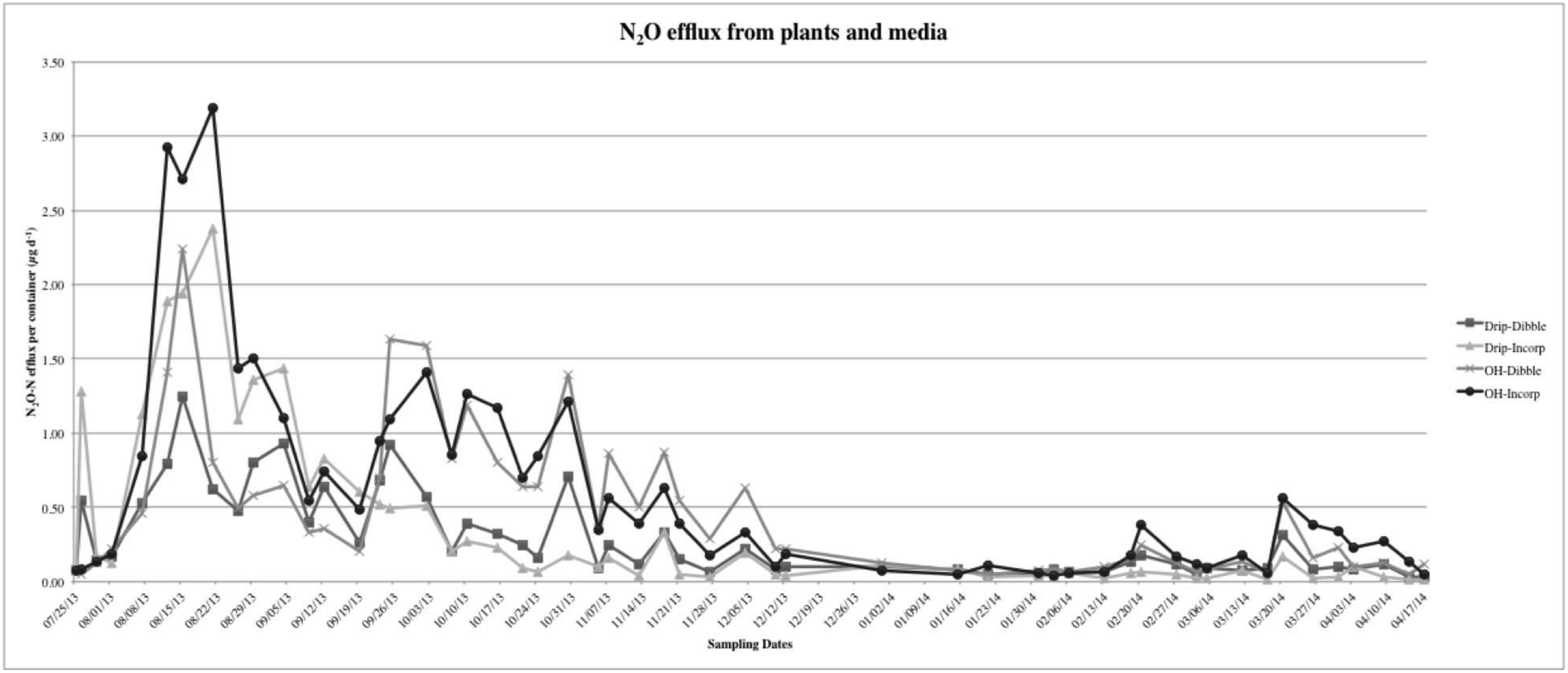

Fig. 2. N_2O-N efflux (µg d^{-1}) for container-grown boxwood irrigated with either drip or overhead irrigation, and either dibbled or incorporated fertilizer. Means are for a time period of approximately 9 months (July 25, 2013 – April 17, 2014).

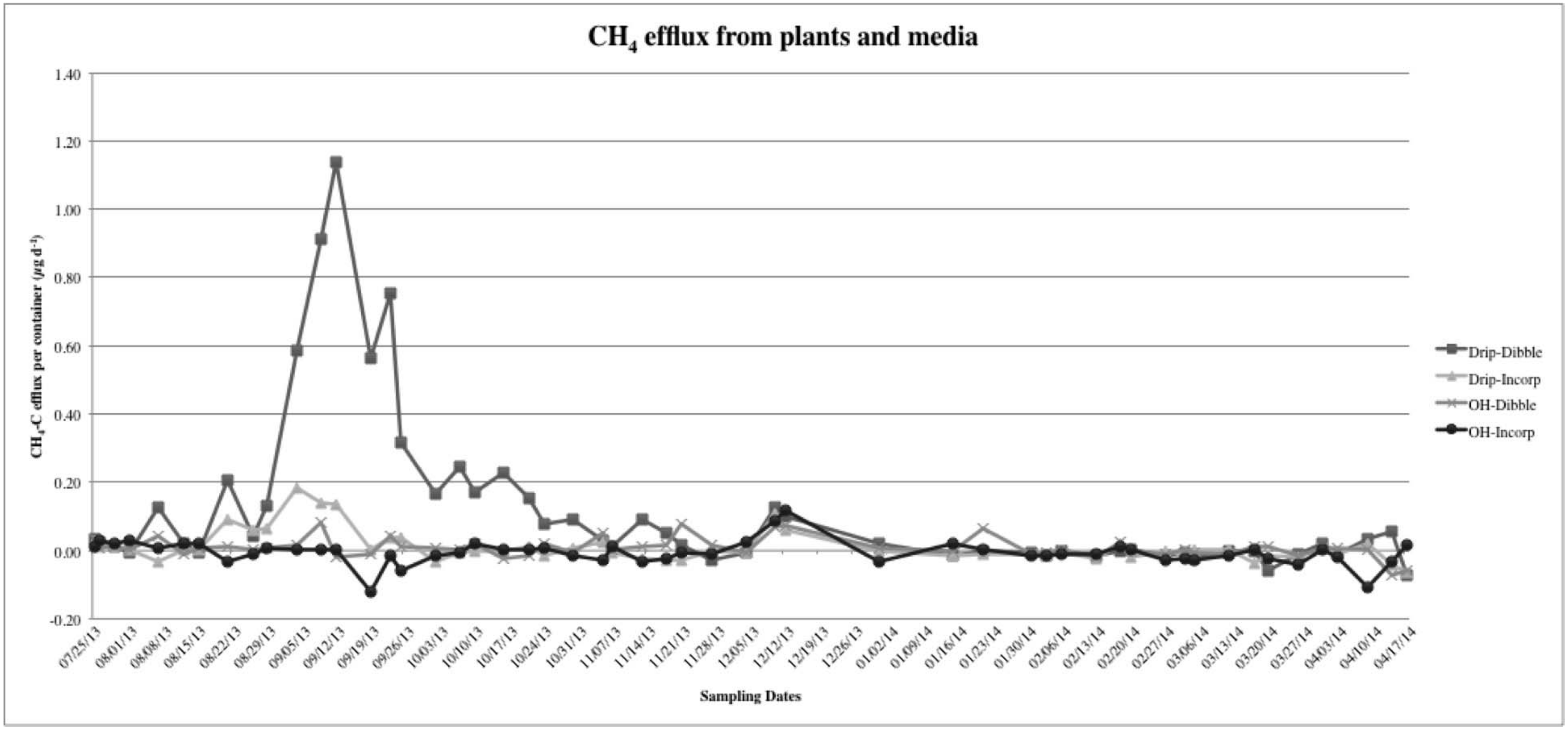

Fig. 3. CH_4 efflux (µg d^{-1}) for container-grown boxwood irrigated with either drip or overhead irrigation, and either dibbled or incorporated fertilizer. Means are for a time period of approximately 9 months (July 25, 2013 – April 17, 2014).

Table 2. **Percent contribution to Global Warming Potential[z] of boxwood[y] treated with either overhead or drip irrigation[x], and either dibbled or incorporated fertilizer[w].**

Main Effects		GWP	CO₂ (%)	N₂O (%)	CH₄ (%)
Irrigation Effect					
Drip		0.1004[ns]	74.37 a[v]	25.19 b	0.44 a
Overhead		0.1087	61.81 b	38.17 a	0.02 b
p:		*0.369*	*<0.001*	*<0.001*	*0.002*
Fertilizer Placement Effect					
Dibble		0.1013[ns]	70.65 a	28.91 b	0.44 a
Incorporated		0.1078	65.52 b	34.45 a	0.02 b
p:		*0.189*	*0.009*	*0.005*	*0.002*
Interaction Effects					
Irrigation Regime	**Fertilizer Placement**				
Drip	- Dibble	0.0977[ns]	76.17 a	23.03 c	0.80 a
Drip	- Incorporated	0.1031	72.56 a	27.36 c	0.07 b
Overhead	- Dibble	0.1050	65.13 b	34.80 b	0.07 b
Overhead	- Incorporated	0.1124	58.48 c	41.55 a	-0.03 b
p:		*0.814*	*0.342*	*0.432*	*0.008*

[z]Global Warming Potential (GWP) is calculated on a per container basis from cumulative trace gas emissions across the entire study period (July 25, 2013 - April 17, 2014). Each trace gas has an established GWP based on the radiative forcing from 1 kg of a gas to 1 kg of CO_2 over a specific interval of time. The GWP, expressed as CO_2 equivalents, of each trace gas is as follows: $CO_2 = 1$, $CH_4 = 25$, $N_2O = 298$ (Forster et al. 2007).

[y]Boxwood (*Buxus microphylla*) was potted into one-gallon nursery containers containing a 6:1 (v:v) pinebark:sand substrate, amended with 3.0 kg m-3 dolomitic limestone.

[x]The same volume of irrigation (6.35 cm or 0.25 in, three times daily) was delivered to all plants via either overhead impact sprinklers (1.8 m high) or individual drip stakes (Netafilm PC Spray Stakes; Double Spray; 6.6GPH).

[w]The same fertilizer rate [76 g of Polyon 17-5-11 with blended minors (Harrell's LLC, Lakeland, FL)] was used for both dibble and incorporated fertilizer treatments.

[v]Within a column, means followed by the same letter are not significantly different ($p \leq 0.05$) according to the LSMeans statement under the Proc Mixed procedure of SAS.

[ns]Not significantly different.

122.43 g N_2O/pot. While time [6 months observation by Marble et al. (2012b) versus 9 months observation in the current study] may be a factor, it is more likely that fertilizer rate, as a factor of pot size, accounts for the difference. A low rate of fertilizer (26 g of product) was used in the study by Marble et al. (2012b), while the same rate was used in the current study, only for a larger pot (76 g of product). The same fertilizer was used in both studies.

Methane (CH_4) emissions were highly variable, but generally low, throughout the study (Fig. 3). Drip irrigated treatments fertilized with the dibble method had the highest cumulative CH_4 efflux throughout the study (30.79 mg/pot) (Table 1) due to a spike measured over a one month period (September 5 to October 3, 2013) (Fig. 3). All other treatments had statistically lower CH_4 emissions (below 3.05 mg/pot over a nine month period), with the overhead-incorporated treatment actually acting as a net CH_4 sink (-1.48 mg/pot) (Table 1). Even with this initial spike in CH_4 efflux for drip-dibble treatments, the overall contribution of CH_4 to global warming potential (GWP), a measure of the impact of each greenhouse gas in CO_2 equivalents, was minimal (0.80% for drip-dibble treatments) (Table 2) (Forster et al. 2007).

Overall, GWP was not significantly affected by irrigation, fertilizer placement, or the interaction of these two factors (Table 2). However, the percent contribution of the various GHGs to GWP was affected by treatments. Both CO_2 and CH_4 contributed more to GWP under drip irrigation, while N_2O contributed more under overhead irrigation. Similarly, dibbling fertilizer caused CO_2 and CH_4 to have higher contributions to GWP than when fertilizer was incorporated. The opposite was true for N_2O, as dibbling fertilizer decreased N_2O contribution to GWP when compared to the incorporated fertilizer method.

In general, these findings suggest that utilizing drip irrigation could significantly decrease N_2O emissions regardless of fertilizer placement. This switch could decrease percent N_2O contribution from an average of 38.2% (for both overhead treatments) to 25.2% (an average of both drip irrigated treatments) (Table 2). However, when limited to overhead irrigation, dibbled fertilizer placement could help to mitigate N_2O emissions. Ongoing efforts are continuing to identify other best management practices for their potential to reduce GHG (CO_2, CH_4, and N_2O) emissions from container produced ornamental crops.

Literature Cited

AAES. 2009. Economic impact of Alabama's green industry: Green industry growing. Spec. Rept. No. 7. Alabama Agricultural Experiment Station, Auburn University, AL.

Baker, J., G. Doyle, G. McCarthy, A. Mosier, T. Parkin, D. Reicosky, J. Smith, and R. Venterea. 2003. GRACEnet chamber-based trace gas flux measurement protocol. Trace Gas Protocol Development Committee, March 14, pp. 1–18.

Boyer, C.R., G.B. Fain, C.H. Gilliam, T.V. Gallagher, H.A. Torbert, and J.L. Sibley. 2009. Production of woody nursery crops in clean chip residual substrate. J. Environ. Hort. 27:56–62.

Boyer, C.R., G.B. Fain, C.H. Gilliam, T.V. Gallagher, H.A. Torbert, and J.L. Sibley. 2008. Clean chip residual: A substrate component for growing annuals. HortTechnology 18:423–432.

Cole, C.V., J. Duxbury, J. Freney, O. Heinemeyer, K. Minami, A. Mosier, K. Paustian, N. Rosenburg, N. Sampson, D. Sauerbeck, and Q. Zhao. 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. Nutr. Cycl. Agroecosyst. 49:221–228.

Eichner, M.J. 1990. Nitrous oxide emissions from fertilized soils: Summary of available data. J. Environ. Qual. 19:272–280.

Fain, G.B., C.H. Gilliam, J.L. Sibley, and C.R. Boyer. 2008. WholeTree substrates derived from three species of pine in production of annual vinca. HortTechnology 18:13–17.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland. 2007. Changes in atmospheric constituents and in radiative forcing. *In:* Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M.M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, New York, NY.

Hall, C.R., A.W. Hodges, and J.J Haydu. 2005. Economic impacts of the green industry in the U.S. http://www.utextension.utk.edu/hbin/greenimipact.html. Accessed June 4, 2010.

Hutchinson, G.L. and A.R. Mosier. 1981. Improved soil cover method for field measurements of nitrous oxide fluxes. Soil Sci. Soc. Am. J. 45:311–316.

Hutchinson, G.L. and G.P. Livingston. 1993. Use of chamber systems to measure trace gas fluxes. p. 63–78 In L.A. Harper, A.R. Mosier, J.M. Duxbury, and D.E. Rolston (eds.). Agricultural Ecosystem Effects on Trace Gas and Global Climate Change. ASA Spec. Publ. 55 ASA, Madison, WI.

Ingram, D.L. and C.R. Hall. 2016. Comparison of Carbon Footprint and Variable Costs of Selected Nursery Production Systems for a 5-cm-caliper Red Maple. HortScience 51:383–387.

Ingram, D.L., C.R. Hall, and J. Knight. 2016. Carbon footprint and variable costs of production components for a container-grown evergreen shrub using life cycle assessment: An East coast U.S. model. HortScience 51:989–994.

IPCC. 2007. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.). Cambridge University Press, Cambridge, UK. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html. Accessed June 4, 2010.

Johnson, J.M., A.J. Franzleubbers, S.L. Weyers, and D.C. Reicosky. 2007. Agriculture opportunities to mitigate greenhouse gas emissions. Environ. Pollut. 150:107–124.

Kaiser, E.A. and R. Ruser. 2000. Nitrous oxide emissions from arable soils in Germany – An evaluation of six long-term field experiments. J. Plant Nutr. Soil Sci. 163, 249–260.

Kendall, A. and E.G McPherson. 2011. A life cycle greenhouse gas inventory of a tree production system. Int. J. Life Cycle Assess., doi:10. 1007/s11367-011-0339-x.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS System for Mixed Models. SAS Institute, Inc., Cary, NC. 633 p.

Lu, W., J.L. Sibley, C.H. Gilliam, J.S. Bannon, and Y. Zhang. 2006. Estimation of U.S. bark generation and implications for horticultural industries. J. Environ. Hort. 24:29–34.

Lubowski, R.N., M. Vesterby, S. Bucholtz, A. Baez, and M.J. Roberts. 2006. Major uses of Land in the United States, 2002. Economic Information Bulletin No. EIB-14. Economic Research Service, USDA. 54 p.

Marble, S.C., S.A. Prior, G.B Runion, H.A. Torbert, C.H. Gilliam, and G.B. Fain. 2011. The importance of determining carbon sequestration and greenhouse gas mitigation potential in ornamental horticulture. HortScience 46:240–244.

Marble, S.C., S.A. Prior, G.B. Runion, H.A. Torbert, C.H. Gilliam, G.B. Fain, J.L. Sibley, and P.R. Knight. 2012a. Determining trace gas efflux from container production of woody nursery crops. J. Environ. Hort. 30:118–124.

Marble, S.C., S.A. Prior, G.B. Runion, H.A. Torbert, C.H. Gilliam, G.B. Fain, J.L. Sibley, and P.R. Knight. 2012b. Effects of fertilizer placement on trace gas emissions from nursery container production. HortScience 47:1056–1062.

Mosier, A.R., G.A. Peterson, and L.A. Sherrod. 2003. Mitigating net global warming potential (CO_2, CH_4 and N_2O) in upland crop productions. Proc. Methane and Nitrous Oxide International Workshop. p. 273–280.

Murphy, A.M., C.H. Gilliam, G.B. Fain, H.A. Torbert, T.V. Gallagher, J.L. Sibley, and C.R. Boyer. 2011. Low value trees as alternative substrates in greenhouse production of three annual species. J. Environ. Hort. 29:152–162.

Parkin, T.B. and T.C. Kaspar. 2006. Nitrous oxide emissions from corn-soybean systems in the Midwest. J. Environ. Qual. 35:1496–1506.

Parkin, T.B. and R.T. Venterea. 2010. Sampling Protocols. Chapter 3. Chamber-based trace gas flux measurements, p. 3-1-3 to 39 In R.F. Follet (ed.) Sampling Protocols. https://www.ars.usda.gov/ARSUserFiles/np212/chapter%203.%20gracenet%20Trace%20Gas%20Sampling%20protocols.pdf. Accessed August 6, 2011.

USDA. 2007. U.S. Nursery crops 2006 summary. Publ. No. Sp Cr-6-3. U.S. Department of Agriculture, National Agriculture Statistics Service. 63 p.