Best Management Practices for Reducing Greenhouse Gas Emissions in Ornamental Plant Production

by

Anna-Marie Murphy

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
December 12, 2020

Keywords: carbon sequestration, nursery production, greenhouse production, container plant production, global warming

Approved by

Jeff L. Sibley, Chair, Professor of Horticulture
Stephen A. Prior, Plant Physiologist/Lead Scientist, USDA-ARS
G. Brett Runion, Research Plant Pathologist, USDA-ARS
Glenn B. Fain, Associate Professor of Horticulture
Jeremy M. Pickens, Extension Specialist
H. Allen Torbert, III, Research Leader/Soil Scientist, USDA-ARS

Abstract

In 2018, agriculture accounted for nearly 10% of total greenhouse gas (GHG) emissions in the United States. Nearly half of N_2O emissions in that 10% were attributed to the management of agricultural soils, through the application of synthetic and organic fertilizers, the cultivation of N-fixing crops, the drainage of organic soils, and irrigation practices. Other contributions include production of livestock (>25% of agricultural emissions), wetland production of rice, tillage, and burning of crop residues. The greenhouse, nursery, and floriculture industry was estimated to generate $16.7 billion in direct industry output in 2018, employing more than 134,000 people. While the plants produced generally serve as C and N sinks, the production process contributes to the increase in atmospheric GHG concentrations through its reliance on plastics, synthetic fertilizers, managed irrigation, and allied industry (electricity, transportation, etc.). The objective of this research was to evaluate GHG emissions during the plant production process as a factor of several best management practices, including irrigation method, fertilizer application method, light requirement, and use of alternative substrates. This work seeks to understand the mitigation potential of these practices in an effort to provide growers with quantitative data detailing the 'worth' of their efforts in anticipation of legislation regulating emissions, as well as any C credit trading system that could have financial benefits. In order to evaluate the impact of irrigation method (overhead impact or micro-emitted) and fertilizer placement (incorporated, dibbled), GHG emissions from the

production of Japanese boxwood (*Buxus microphylla*) grown in 3-gal containers were measured once or twice weekly over nine months. Total cumulative CO_2 emissions were unaffected by differences in irrigation or fertilizer delivery method. Emissions of N_2O were highest for plant-pot systems receiving overhead impact irrigation and utilizing incorporated fertilizer. Regardless of fertilizer placement, the utilization of drip, or micro-emitted, irrigation significantly reduced N_2O efflux over the course of the evaluation period. However, when limited to overhead impact irrigation, N_2O emissions may be mitigated through the use of dibbled fertilizer. Fertilizer placement (incorporated, dibbled, or top-dressed) was also evaluated as a factor affecting GHG emissions in the production of two perennial species [full sun-grown daylily (*Hemerocallis* × 'Stella D'Oro' L.) and shade-grown hosta (*Hosta* × 'Royal Standard', or *Hosta plantaginea* Aschers × *Hosta sieboldiana* N.Fujita). Similar to the boxwood study, plant-pot systems utilizing the dibbled fertilizer method had the lowest CO_2 and N_2O emissions over the duration of the five month study. While no differences were observed between cumulative N_2O emissions for plants fertilized with either incorporated or top-dressed fertilizer, cumulative CO_2 emissions were lower for plants top-dressed with fertilizer, as compared to plants fertilized by incorporation. In the final study, wood fiber-amended substrates were evaluated for their effects on GHG emissions in the production of three annual species [coleus (*Solenostemon scutellarioides* Thonn. 'Redhead'), vinca (*Catharanthus roseus* L. 'Cooler Grape', and impatiens (*Impatiens walleriana* Hook. f. 'Super Elfin XP White')]. Portions of peat and perlite were replaced in a traditional 80:20 peat:perlite blend to form substrates with either 20% WholeTree (80:20 peat:WholeTree) or 40% WholeTree (60:40 peat:WholeTree). No differences were observed for the main effect of species or media for either N_2O or CH_4. As expected due to its superior size, coleus had the highest cumulative CO_2 emissions over the course of the 52-day evaluation period. As a main effect, substrate had a significant impact on CO_2 emissions, as the 60:40 peat:WholeTree treatment had significantly higher cumulative CO_2 emissions as compared to the other two substrates, regardless of plant species. Treatments with only 20% WholeTree were similar to the 80:20 peat:perlite industry standard. These results suggest that the utilization of a more sustainable material such as WholeTree in a substrate designed for greenhouse crop production could yield plants that are similarly sized with no impact on GHG emissions. Data from these studies builds on previous research in the pursuit of quantifiable GHG mitigation strategies for ornamental plant producers.

Acknowledgments

Many thanks are due to a host of individuals who have made the pursuit and ultimate completion of this Ph.D. possible. Thank you first to Dr. Jeff Sibley for your vision and encouragement. I am still amazed at how you saw the potential for this when I was only a freshman, still unsure if I was in the right major! You gave my dad a ride from Paterson to Funchess in 2006 and told him that this is what I could have if I wanted it. Thank you for your patience while I figured out what it was worth to me. Thank you to Dr. and Mrs. Charles Gilliam. Dr. Gilliam first taught me how to be a scientist, and Mrs. Gail showed me faith personified through her unending steadfastness, grace and hospitality. I am additionally thankful for Drs. Glenn Fain and Jeremy Pickens for agreeing to serve on the committee of a student who almost never worked her proposed timeline! You have all been patient beyond measure.

Thank you to Drs. Prior, Runion, and Torbert with the USDA National Soil Dynamics Lab. You are each the better halves to the collaborative research efforts we share. Thank you for the plethora of ways you support me both personally and professionally. My name may be on the cover, but it is evident to all involved that the completion of this project hinged on your participation. A huge debt of gratitude is also owed to Robert Icenogle for the tedious work of project installment and data collection. I value your friendship and thank you for all your hard work. Thanks are also due to Barry Dorman and the many students who had a hand in pulling of thousands of samples!

I have a wonderful family. My parents, Richard and Farrie, and my grandmother, Evelyn (Ma-E) are without a doubt, my biggest supporters. I owe them for much more than their encouragement to pursue this Ph.D. We have been through a lot in the last decade, and you have remained constants in the chaos. You encourage me to pursue the things that matter, regardless of what others might think and against all odds. I am blessed to have your unwavering support.

Lastly, this work is dedicated to S and H. It is likely that you both will never know the impact you have had on my life. In the past year, you have taught me love and sacrifice, patience and humor, and have pressed me to closer intimacy with our Father than I have ever known. May you know that I am here for you always and proud of you forever.

'I have told you these things, so that in me you may have peace. In this world, you will have trouble. But take heart! I have overcome the world.' ~John 16:33.

Table of Contents

List of Tables

List of Figures

CHAPTER I

Literature Review

Greenhouse Gases and Climate Change Defined

Greenhouse gases (GHGs), or those gases present in Earth's atmosphere that absorb infrared radiation, consist of numerous compounds including carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), water vapor, ozone (O_3), and various other fluorinated gases (Mathez and Smerdon 2018). While 'climate' is broadly defined as a 'dynamic system' incorporating properties of our atmosphere (including GHGs), hydrosphere (oceans), cryosphere (glaciers, terrestrial ice sheets, and sea ice), biosphere (the living biomass), and lithosphere (the solid Earth itself), GHGs within the atmosphere have the unique ability to affect us most directly with respect to climate change (Mathez and Smerdon 2018).

The temperature at Earth's surface fluctuates based upon the balance of solar radiation (or incoming radiation from the sun) and terrestrial radiation (or outgoing radiation from Earth's surface). Over the past forty years, this average global air temperature has warmed at a higher rate than in the last 200 years, causing much scientific concern (IPCC 2013). Scientists generally attribute this rise in atmospheric temperature to an increase in the concentration of CO_2 and other GHGs resulting from human activities including transportation, production of electricity and heat, burning of fossil fuels in industrial efforts, agriculture, forestry, and managed land use (USEPA 2020b).

The reversal or modification of current practices leading to ever increasing concentrations of GHGs is met with a myriad of obstacles. Small changes feel intangible and are often regarded as cost prohibitive (Wilson 2020). Mathez and Smerdon (2018) note that even if GHG emissions were to be 'capped at today's levels', warming would continue for several decades due to the inertia of the climate system, which only adds to the feeling of inadequacy or unimportance of small changes.

Quantifiable Impact of Greenhouse Gases

The extent to which a given GHG contributes to global warming, and therefore to climate change, depends upon a balance between concentration and longevity in the atmosphere, as well as potency, or global warming potential (GWP) of that individual gas (USEPA 2018). In an effort to accurately compare the relative impact of GHGs in terms of their radiative efficiency and persistence in the atmosphere, each gas is assigned a GWP value (USEPA 2020a). Each value is given in CO_2 equivalents, and is 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, generally 100 years (Forster et al. 2007, USEPA 2020a). Ongoing research into the methods used to calculate GWP allow for some flexibility in the determination of GWP for each GHG, though current estimates assign a value of between 28 to 36 for CH_4, and between 265 to 298 for N_2O. Additional GHGs, including chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), among others, can have GWP values in the thousands or tens of thousands, but are much less prolific in the atmosphere than CO_2.

Sources of Greenhouse Gas Emissions

Emissions of GHGs occur from both natural and anthropogenic sources. Anthropogenic, or human-derived, refers to pools of GHG emissions resulting directly from human activities or indirectly from natural processes that have been affected by human activities (IPCC 2013). Sources of the three main GHGs (CO_2, N_2O, and CH_4) in this work are explored and discussed in the following three sections.

Sources of Greenhouse Gas Emissions – CO_2

Primary anthropogenic sources of CO_2 result from the combustion of fossil fuels for use in energy production and transportation industries, as well as certain industrial processes and major land-use changes, such as deforestation for the development of agricultural lands and growing residential and commercial areas (USEPA 2018). While managed forests and other land areas act as net sinks for CO_2 (naturally emitted as part of the C cycle), they only account for about 12% of total emissions (USEPA 2018). In 2018, CO_2 accounted for more than 80% of all anthropogenically derived US GHG emissions.

Sources of Greenhouse Gas Emissions – N_2O

A recent comprehensive quantification of global N_2O sources accounts for the gas from two primary sources between 1980 and 2016 (Tian et al. 2020). Natural sources, with no anthropogenic effects, include those associated with the nitrogen cycle among the atmosphere in collaboration with plants, animals, and bacteria both on land and in the ocean. Natural phenomena including lighting are also small sources of N_2O emissions. Major anthropogenic sources include those derived from N additions in agriculture, industry and the burning of fossil fuels, waste and wastewater, and biomass burning. In the US alone, N_2O accounts for around 6.5% of all anthropogenically derived GHG emissions (USEPA 2018).

Agricultural applications of N, in the form of either fertilizers or animal manures, to croplands account for the majority of increases to atmospheric N_2O (Tian et al. 2020). Some studies indicate that the source of N used, as well as its relative placement in the soil structure, affects N_2O loss (Eichner 1990, Mosier et al. 2003). Previous work has also shown that soil N_2O emissions are higher in organically fertilized plots versus minerally or synthetically fertilized plots (Kaiser and Ruser 2000). In addition to N source and placement, increased attention to efficiency of N fertilization (both dosage and delivery) has been shown to reduce emissions of N-containing N_2O, ammonia and NO (Kroeze et al. 1999), as well as improving water quality (Johnson et al. 2007). A reduction in the use of fertilizers through more precise dosage and delivery may have an added economic benefit, provided the labor and equipment required for the more precise application does not outweigh the economic savings observed in the decreased usage of N products. Efforts to reduce the use of fertilizers in the production of ornamental plants are met by several barriers, including but not limited to: 'lack of funding for research developing alternative products or protocols, lack of education informing users on the availability of alternatives, lack of economic or regulatory incentives for growers to implement changes, and limited consumer acceptance of aesthetic damage to plants' (Latimer et al. 1996).

In the US alone, N_2O accounted for around 6.5% of anthropogenically-driven GHG emissions in 2018 (USEPA 2018). This percentage is small in comparison to CO_2, which accounted for more than 80% of total US emissions. However, N_2O is somewhere between 265 and 298 times more 'potent' as a GHG than CO_2, a comparison made possible by assigned GWP values. While there are fewer N_2O emissions as compared to CO_2, intervention efforts focused on the N_2O mitigation may be more impactful than those aimed to mitigate CO_2 emissions.

Sources of Greenhouse Gas Emissions – CH_4

Natural sources of CH_4 include those which are generated from anaerobic respiration in wetlands, the leaking of gas from underground deposits, and the enteric fermentation of ruminant animals. However, natural processes in soil also work to remove CH_4 from the atmosphere (USEPA 2018). Anthropogenic sources of CH_4 are primarily attributed to managed livestock production, active landfills, the production of wetland crops such as rice, and the burning of biomass (Blaha et al. 1999, Cole et al. 1997, USEPA 2018).

Economic Impact of Green Industry

The term 'Green Industry' is traditionally used to describe the collective array of industries related to environmental horticulture, including, but not limited to: 1) wholesale nursery, greenhouse and sod producers; 2) landscape design, installation and maintenance companies; 3) wholesale/retail businesses including retail garden centers, big box stores with lawn and garden departments, and rewholesalers; and 4) allied trade suppliers for all related materials necessary for industry success (Hodges et al. 2015a). In 2013, the combined direct industry outputs of the Green Industry as a whole were estimated at

$136.44 billion nationally, and direct employment for the industry was at nearly 1.6 million full- or part-time jobs. With respect to the broader economy, the industry accounted for over 2 million full- or part-time jobs. As only a percentage of those industries represented, the greenhouse, nursery and floriculture sector accounted for $16.7 billion in direct industry output and the direct employment of more than 134,000 people.

In the last major economic study of Alabama's agricultural, forestry, and related industries conducted by the Alabama Cooperative Extension System, an estimated 5.1% ($239.7 million) of the state's $4.7 billion in total sales of agricultural products was generated through the state's nursery, greenhouse, and floriculture industries (ACES 2013). In a measurement of the 'contribution of an industry to regional economy' through value added, the nursery, greenhouse and floriculture industries accounted for $158.4 million. The ornamental plant production specialty crop industry was reported to have an output impact (including direct sales, indirect effects, and induced effects) of $561.6 million, while the allied landscape services industry had a total output impact of just over $1 billion. These values correlate to the employment of almost 7,000 in the ornamental plant production sector, and over 18,000 jobs in the landscape services industry. More than 600 growers have been identified in the state of Alabama (Hodges et al. 2015b).

Mitigation Incentives

Private C exchanges have slowly emerged over the last two decades despite differences in political ideologies, uncertainties regarding the value of C, and fluctuating international consensus on standardization protocols (Shrikanth 2020). Carbon prices vary greatly, and can range from less than $1 to $119 per ton of CO_2 equivalents (World Bank

2020). The World Bank reports that as of 2020, there are more than 14,500 registered crediting projects that collectively have generated nearly 4 billion tons of CO_2 equivalents. Research outcomes from this work could help growers to understand both the environmental and economic worth of their mitigation efforts.

Previous Work in Horticultural Specialty Crop Industry

Elevated CO_2 is known to increase both shoot and root growth due to increased uptake and assimilation of CO_2, as well as decreased transpiration, causing more efficient plant water relations (Prior et al. 2011). While most elevated CO_2 studies have covered agronomic crops and forest species, fewer have examined ornamental horticultural crops. For example, one study indicated that C3 plants [zinnia (*Zinnia elegans* Jacq.), petunia (*Petunia* × *hybrida* 'Grandiflorus') and Mexican marigold (*Tagetas erecta* L.)] responded more positively to increased CO_2 than C4 plants [coxcomb flower (*Celosia cristata* L.)] (Miri et al. 2017). In another ornamental study, Runion et al. (2011) reported that a perennial with a large woody root system [lantana (*Lantana camara*)] had a much greater response to CO_2 than did a plant with a fibrous root system [vinca (*Catharanthus roseus*)].

In their full and partial life cycle assessment (LCA) research focused on landscape plant production, researchers from the University of Kentucky and Texas A&M University purposed to identify management practices in plant production systems that contributed the most to increasing C emissions in an effort to narrow the focus of mitigation research (Hall and Ingram 2014, Hall and Ingram 2015, Ingram 2012, 2013, Ingram and Hall 2014, 2015, 2016, Ingram et al. 2016, 2017a, 2017b, 2018a, 2018b, 2019a, 2019b). Components of the assessments range from materials, labor, and equipment use associated with liner and plant production to transportation, transplanting, take-down and disposal associated with landscape use, and followed guidelines set forth by the International Organization for Standardization's LCA Requirements and Guidelines (2006a, 2006b). Both variable economic costs and GWP of each step in the life cycle of field-grown plants were estimated (Ingram and Hall 2015). Several case studies in Europe have also endeavored to evaluate the environmental impacts of smaller scale ornamental plant production on a nursery by nursery basis using the LCA analysis (Beccaro et al. 2014, Falla et al. 2020, Lazzerini et al. 2018, Wandl and Haberl 2017). Much of the work notes that plastics used in the propagation and subsequent container growth of plants has the highest environmental impact in the system as a whole. One study estimates that plastic accounted for nearly 80% of the total ecological footprint on the nursery, while fertilizers only accounted for 0.93% of the total footprint (Beccaro et al. 2014). Plastics are generally used in every aspect of nursery and greenhouse production, from the plastic trays and containers to shadecloth, to polyethylene or polyvinylchloride piping for irrigation.

In previous work seeking to establish specific baseline estimations of GHGs emitted in container crop production, Marble et al. (2012a) reported on CO_2, N_2O and CH_4 emissions from the container production of dwarf yaupon holly (*Ilex vomitoria* 'Nana' L.) in four container sizes [3.0 L (trade gal), 3.8 L (one gal), 7.6 L (2 gal), and 11.4 L (3 gal)] over the course of one year (2012a). Plants were grown utilizing standard best management practices for container crop production in the Southeast US. Plants were grown in a traditional 6:1 pine bark:sand substrate with incorporated amendments, including control-release fertilizer, dolomitic limestone, and micronutrients. Emissions of CO_2, N_2O and CH_4 were collected from the plant-pot system with custom chambers according to GRACEnet protocols (Baker et al. 2003). Average daily CO_2 efflux for plant-pot systems ranged from 142.10-278.02 mg·d^{-1}, and were significantly positively correlated to increasing pot size. Similarly, average daily N_2O efflux for plant-pot systems were also positively correlated with increasing pot size, and ranged from 83.76 to 767.13 μg·d^{-1}. Authors noted container trace gas efflux data did not reflect net emissions, in that they did not account for C or N sequestered in the growing plant itself, though data were important in that they offered a baseline from which to build research identifying best management practices that may be altered to mitigate GHG emissions without altering plant size and vigor.

In a follow-up study evaluating fertilizer placement as a factor affecting GHG emissions in container crop production, gumpo white azalea (Azalea X hybrid 'Gumpo White') was grown in a standard 6:1 pine bark:sand substrate with fertilizer applied either at mixing (via incorporation) or planting (via topdressing or dibble) (Marble et al. 2012b). Weekly measurements indicated CH_4 efflux was minimal throughout the study. Measurements indicated both average and cumulative CO_2 efflux was lowest for plant-pot systems utilizing the dibble fertilizer method, while systems with either incorporated or top-dressed fertilizer had similar (higher) CO_2 efflux patterns. Efflux of N_2O (average and cumulative) was lowest for dibbled and topdressed treatments, while remaining highest for plant-pot systems with incorporated fertilizer. Root and shoot dry weights were similar among all fertilized plants at study termination, indicating altering fertilization practices in an attempt to mitigate CO_2 and N_2O emissions may have no negative effect on plant growth.

While work focused on mitigation efforts in the plant production sector only, additional efforts exist to evaluate the impact on the soil carbon dynamics once container-grown plants are installed in the landscape (Marble et al. 2016). Following one year of growth in one-gal liners containing varying high wood fiber substrate amendments, three woody shrub species [cleyera (*Ternstroemia gymnanthera* Thunb. 'Conthery'), Indian hawthorn (*Rhaphiolepis indica* L.), and loropetalum (*Loropetalum chinensis* Oliv. 'Ruby')] were transplanted into native soil, and subsequently monitored with an Automated Carbon Efflux System (ACES) to continually monitor soil CO_2 efflux for one year. In addition to measurements collected with ACES, soil sampling was conducted twice to determine soil C levels, along with a plant biomass determination at study termination. Results showed that pine bark substrates decompose more slowly than higher wood fiber substrates, which may indicate that pine bark has a higher capacity for C storage potential than the other two substrates evaluated.

While the nursery and greenhouse production sector of the Green Industry may contribute to the increased levels of atmospheric GHGs (most notably through its reliance on synthetic fertilizers), it is important to realize the end product contributes to increased C sequestration and a reduction in GHGs through the abundance of biomass (Marble et al. 2011).

Best Management Practices in Ornamental Plant Production

Several key aspects of plant production, including substrate (growing media), irrigation, fertilization, and pest control (including weeds, disease and insect control), must be addressed in every operation. Oftentimes, these components of plant production vary regionally, as access to irrigation through rainfall or groundwater vary, and legislation governing fertilizer application and runoff differ from state to state. The end goal remains the same for each producer though: to produce the highest quality, and most marketable plant possible, for the least economic input.

In the southeastern United States, the primary, and most readily available, substrate used in woody plant production is pine bark. The physical structure of bark is favorable for plant growth due to its allowance of air space critical for water movement, while chemically, its inert properties are effective for nutrient management with the addition of fertilizers and micronutrients (Airhart et al. 1978, Lunt and Kohl 1956). The amendment or replacement of pine bark in container substrates has been the focus of much research over the last two to three decades in anticipation of pine bark supply interruptions (Lu et al. 2006). Researchers have evaluated numerous options, including high wood fiber alternatives. One such product is termed 'clean chip residual.' This material, generated from the biproduct of in-field harvesting of pine trees, consists largely of wood (50%), bark (40%), and needles (10%) (Boyer et al. 2008, 2009). Whole pine trees (WholeTree) from varying species of pine (*Pinus* sp.) have also been evaluated for suitability of pine bark replacements (Fain et al. 2006, Fain et al. 2008). In addition to pine, low value 'trash' trees such as sweetgum (*Liquidambar styraciflua* L.), hickory (*Carya* sp. Nutt.), and eastern redcedar (*Juniperus virginiana* L.) have been tested against industry standard bark in the production of annuals and woody ornamental crops (Murphy et al. 2011, Starr et al. 2012).

For annual and perennial plant species produced in a greenhouse setting, peat and perlite serve as industry standard substrates (Nelson 2012). While supplies of peat from bogs located across the globe are harvested annually for commercial use, its harvest is not sustainable, as the natural formation of peat takes thousands of years at a formation rate of between 0.5 to 0.6 mm per year (Hugron et al. 2013). Fluctuating fuel and shipping prices serve to amplify the need to identify a suitable alternative or replacement to peat.

Perlite is responsible for adding aeration to container substrates, and amplifying drainage while minimizing bulk density (Jenkins and Jarrell 1989, Nelson 2012). While varying grades of perlite are available, it is generally considered a nuisance due to its dusty nature. One study has linked heavy exposure of perlite to persistent reactive airway disfunction syndrome (Du et al. 2010). Another has indicated a correlation between heavy exposure to a decrease in the lung transfer factor (Polatli et al. 2001). Most recently, one review of perlite toxicology on the respiratory health of workers in US perlite mines and expansion plants reported that lung function was not adversely affected across the four-year evaluation period, though employees reported the dust as a nuisance and general irritant (Maxim et al. 2014).

Irrigation management is both an art and a science, with the ultimate goal of supplying the amount of water required by the plant at a time when the plant can utilize it, without over-irrigating. Decisions surrounding the appropriate irrigation scenario include the volume of water to be delivered, the frequency and timing of application, and the method of application (SNA 2013). Dosage and delivery of irrigation necessary for plant growth varies widely across the plant production industry as a function of operation size, budget, location, access to irrigation source, and crop species. Growers can utilize a number of delivery methods including overhead (most common) and micro-irrigation, applied manually or through the use of electronic irrigation controllers. An entire allied industry is dedicated to irrigation decision-making, installation and maintenance.

Similar to irrigation dosage and delivery, fertilization is another large component of the plant production system. Growers are faced with a number of choices affecting both product selection and application. When screening for an optimal fertilizer product, growers must consider nutrient source (such as urea or nitrate for Nitrogen), nutrient coating (or lack thereof) affecting release, longevity of product (between 3 to 12 month release depending on average temperature), and nutrient ratios (N-P-K) (SNA 2013). Some of these decisions may be affected by application method (incorporation at mixing, or topdressing or dibbling at planting) and length of growing season, in addition to simple product availability due to rising shipping costs. Consumer preference for plants produced organically, or without the addition of synthetic fertilizers or treatment with synthetic pesticides, is an additional consideration for some growers (Latimer 1996).

Conclusion

Research presented in this dissertation purposes to narrow the focus of mitigation efforts to just a few best management practices in an effort to establish baseline estimates of GHG emissions as a function of those practices. The ultimate goal of the work would be pursuit of incentive initiatives by nursery and greenhouse growers seeking monetary inducements to lessen their emissions through the altering of best management practices. This work specifically focuses on differences in irrigation delivery method (overhead vs. micro-irrigation), fertilizer placement (incorporated, topdressed, or dibbled), plant species (as a function of light requirement), and substrate (peat:perlite vs. WholeTree) as practices which affect GHG emissions.

Literature Cited

Airhart, D.L., N.J. Natarella, and F.A. Pokorny. 1978. The structure of processed pine bark. J. Amer. Soc. of Hort. Sci. 103:404-408.

Alabama Cooperative Extension System (ACES). 2013. Economic Impacts of Alabama's Agricultural, Forestry & Related Industries. Combined ANR-2012, ANR-2013, ANR-2014, ANR-2015, ANR-2016, ANR-2017, and ANR-2018. Alabama Cooperative Extension System, 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.

Beccaro, G.L., A.K. Cerutti, I. Vandecasteele, L. Bonvegna, D. Donno, and G. Bounous. 2014. Assessing environmental impacts of nursery production: methodological issues and results from a case study in Italy. J. of Cleaner Prod. 80:159-169.

Blaha, D., K. Bartlett, P. Czepiel, R. Harriss, and P. Crill. 1999. Natural and anthropogenic methane sources in New England. Atmos. Environ. 33:243-255.

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.

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.

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.

Du, C., J. Wang, P. Chu, and Y. Guo. 2010. Acute expanded perlite exposure with persistent reactive airway dysfuntion syndrome. Industrial Health 48:119–122.

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. 2006. Evaluation of an alternative, sustainable substrate for use in greenhouse crops. Proc. Southern Nursery Assn. Res. Conf. 51:651–654.

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.

Falla, N.M., S. Contu, S. Demasi, M. Caser, and V. Scariot. 2020. Environmental impact of edible flower production: a case study. Agronomy 10:4. < EBSCOhost, doi:10.3390/agronomy10040579>. Accessed 9 October 2020.

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. Marquis, M., K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, New York, NY.

Hall, C.R. and D. Ingram. 2014. Production costs of field-grown *Cercis canadensis* L. 'Forest Pansy' identified during life cycle assessment analysis. HortScience 49:622-627.

Hall, C.R. and D.L. Ingram. 2015. Carbon footprint and production costs associated with varying the intensity of production practices during field-grown shrub production. HortScience 50:402-407.

Hodges, A.W., C.R. Hall, M.A. Palma, and H. Khachatryan. 2015a. Economic contributions of the green industry in the United States in 2013. HortTechnology 25:805-814.

Hodges, A.W., H. Khachatryan, M.A. Palma, and C.R. Hall 2015b. Production and marketing practices and trade flows in the United States green industry in 2013. J. Environ. Hort. 33:125-136.

Hugron, S., H. Bussiéres, and L. Rochefort. 2013. Tree plantations within the context of ecological restoration of peatlands: Practical guide. Peatland Ecology Research Group (PERG). Laval, Québec, Canada. <http://www.gret-perg.ulaval.ca/

uploads/tx_centrerecherche/Tree_Plantation_guide.pdf>. Accessed 21 October 2020.

Ingram, D.L. 2012. Life cycle assessment of a field-grown red maple tree to estimate its carbon footprint components. Int'l J. of Life Cycle Assess. 17:453-462.

Ingram, D.L. 2013. Life cycle assessment to study the carbon footprint of system components for Colorado blue spruce field production and landscape use. J. Amer. Soc. Hort. Sci. 138:3-11.

Ingram, D.L. and C.R. Hall. 2014. Carbon footprint and related production costs of system components for a field-grown *Viburnum* × *juddi* using life cycle assessment. J. Environ. Hort. 32:175-181.

Ingram, D.L. and C.R. Hall. 2015. Life cycle assessment used to determine the potential environmental factors and water footprint of field-grown tree production inputs and processes. J. Amer. Soc. Hort. Sci. 140:102-107.

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.

Ingram, D.L., C.R. Hall, and J. Knight. 2017a. Comparison of three production scenarios for *Buxus microphylla* var. *japonica* 'Green Beauty' marketed in a #3 container on the west coast using life cycle assessment. HortScience 52:1356-1361.

Ingram, D.L., C.R. Hall, and J. Knight. 2017b. Modeling global warming potential, variable costs, and water use of young plant production system components using life cycle assessment. HortScience 52:1356-1361.

Ingram, D.L., C.R. Hall, and J. Knight. 2018a. Global warming potential, variable costs, and water use of a model greenhouse production system for 11.4-cm annual plant using life cycle assessment. HortScience 53:441-444.

Ingram, D.L., C.R. Hall, and J. Knight. 2018b. Analysis of production system components of container-grown chrysanthemum for their impact on carbon footprint and variable costs using life cycle assessment. HortScience 53:1139-1142.

Ingram, D.L., C.R. Hall, and J. Knight. 2019a. Modeling container-grown *Euphorbia pulcherrima* production system components: Impacts on carbon footprint and variable costs using a life cycle assessment. HortScience 54:262-266.

Ingram, D.L., C.R. Hall, and J. Knight. 2019b. Understanding carbon footprint in production and use of landscape plants. HortTechnology 29:6-10.

International Organization for Standardization. 2006a. Environmental management - life cycle assessment, principles and framework. ISO Rule 14040:2006. ISO, Geneva, Switzerland.

International Organization for Standardization. 2006b. Environmental management - life cycle assessment, requirements and guidelines. ISO Rule 14044:2006. ISO, Geneva, Switzerland.

IPCC. 2013. Summary for Policymakers. In: Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge Univ Press. Cambridge, UK and New York, NY. < https://www.ipcc.ch/site/assets/uploads/2018/03/WG1AR5_SummaryVolume_FINAL.pdf>. Accessed 8 October 2020.

Jenkins, J.R. and W.M. Jarrell. 1989. Predicting physical and chemical properties of container mixtures. HortScience 24:292-295.

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.

Kroeze, C., A.R. Mosier, and L. Bouwman. 1999. Closing the global N_2O budget: A retrospective analysis 1500-1994. Global Biogeochem. Cycles 13:1-8.

Latimer, J.G., R.D. Oetting, P.A. Thomas, D.L. Olson, J.R. Allison, S.K. Braman, J.M. Ruter, R.B. Beverly, W. Florkowski, C.D. Robacker, J.T. Walker, M.P. Garber, O.M. Lindstrom, and W.G. Hudson. 1996. Reducing the pollution potential of pesticides and fertilizers in the environmental horticulture industry: I. greenhouse, nursery and sod production. HortTechnology 6:115-124.

Lazzerini, G., P. Merante, S. Lucchetti, and F.P. Nicese. 2018. Assessing environmental sustainability of ornamental plant production: a nursery level approach in Pistoia District, Italy. Agroecol. and Sustain. Food Sys. 42:911-932.

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.

Lunt, O.R. and H.C. Kohl, Jr. 1956. Influence of soil physical properties on the production and quality of bench grown carnations. J. Amer. Soc. of Hort. Sci. 69:535-542.

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.

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. 2016. Species and media effects on soil carbon dynamics in the landscape. Sci. Rep. 6:25210.

Mathez, E.A. and J.E. Smerdon. 2018. Climate Change: The Science of Global Warming and Our Energy Future. 2nd Ed. Columbia University Press. New York, NY. 503pp.

Maxim, L.D., R. Niebo and E.E. McConnell. 2014. Perlite toxicology and epidemiology – a review. Inhalation Toxicology 26:259-270.

Miri, H., M. Sadaghi, A. Jafari, and M.M. Rahimi. 2017. Effect of CO2 elevation and UV-A radiation on growth responses of Zinnia, Petunia, Coxcomb, and Marigold. Acta Ag. Slovenica. 109:281-289.

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.

Nelson, Paul V. 2012. Greenhouse Operation and Management. 7th ed. Prentice Hall, Boston, MA.

Polatli, M., M. Erdinç, E.E Erdinç, and E. Okyay. 2001. Perlite exposure and 4-year change in lung function. Environ. Res. 86:238–243.

Prior, S.A., G.B. Runion, S.C. Marble, H.H. Rogers, C.H. Gilliam, and H.A. Torbert. 2011. A review of elevated atmospheric CO_2 effects on plant growth and water relations: Implications for horticulture. HortScience 46:158-162.

Runion, G.B., H.M. Finegan, S.A. Prior, H.H. Rogers, and D.H. Gjerstad. 2011. Effects of elevated atmospheric CO_2 on non-native plants: Comparison of two important southeastern ornamentals. Environ. Contr. Biol. 49:107-117.

Shrikanth, S. 2020. Carbon credit markets still have a way to go. Financial Times. <https://www.ft.com/content/3d150d3d-9b10-4e94-990a-7d2dad1666f6>. Accessed 20 October 2020.

Southern Nursery Association (SNA). 2013. Best management practices: Guide for producing nursery crops. 3rd ed. South. Nurs. Assn. Atlanta, GA. <http://contents.sna.org /bmpv30.html>. Accessed 1 September 2020.

Starr, Z.W., C.R. Boyer, and J.J. Griffin. 2012. Eastern redcedar (*Juniperus virginiana*) as a substrate component effects growth of three tree species. J. Environ. Hort. 30:189-194.

Tian, Hanqin, et al. 2020. A comprehensive quantification of global nitrous oxide sources and sinks. Nature 586:248–256. Accessed 13 October 2020. <EBSCOhost, doi:10.1038/s41586-020-2780-0>.

United States Environmental Protection Agency (USEPA). 2018. Overview of Greenhouse Gases. United States Environmental Protection Agency: Greenhouse Gas Emissions. < https://www.epa.gov/ghgemissions/overview-greenhouse-gases>. Accessed 8 October 2020.

United States Environmental Protection Agency (USEPA). 2020a. Greenhouse gas emissions: Understanding global warming potentials. < https://www.epa.gov/ ghgemissions/understanding-global-warming-potentials>. Accessed 19 October 2020.

United States Environmental Protection Agency (USEPA). 2020b. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2018 – Executive Summary. <https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-chapter-executive-summary.pdf>. Accessed 19 October 2020.

Wandl, M.T. and H. Haberl. 2017. Greenhouse gas emissions of small scale ornamental plant production in Austria – A case study. J. of Cleaner Prod. 141:1123-1133.

Wilson, M. 2020. What's at stake in the debate over climate change. Southeast Farm Press. < https://go.gale.com/ps/retrieve.do?tabID=T003&resultListType=RESULT_LIST&searchResultsType=SingleTab&hitCount=162037&searchType=BasicSearchForm&currentPosition=6&docId=GALE%7CA635415381&docType=Article&sort=Relevance&

contentSegment=ZGPP-MOD1&prodId=ITOF&pageNum=1&contentSet=GALE%7CA635415381&searchId=R3&userGroupName=naal_aub&inPS=true>. Accessed 12 October 2020.

World Bank. 2020. State and trends of carbon pricing 2020. Washington, DC: World Bank. <https://openknowledge.worldbank.org/handle/10986/33809>. Accessed 20 October 2020.

CHAPTER II

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

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*) 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.

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 7300 producers in the top 17 states, occupying approximately a half million acres (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 #1 white gumpo 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 (Eichner 1990, Mosier et al. 2003). 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 25 July 2013, 11.4 L containers were filled with a standard 6:1 PB:sand (v:v) substrate amended with 3.0 kg 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 per container (equivalent to 6.5 kg m^{-3}). Containers were watered daily with either overhead irrigation (impact sprinklers approximately 1.8 m high) or individual drip irrigation (Netafilm PC Spray Stakes; Double Spray; 6.6GPH). Both irrigation delivery methods were calibrated to deliver 6.35 mm (0.25 in) water three times daily. GHGs (CO_2, CH_4, N_2O) emitted from plants and substrate were sampled in situ for nine months (25 July 2013 to 28 April 2014) using the static closed chamber method (Hutchinson and Livingston 1993, Hutchinson and Mosier 1981). 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) 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) 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).

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 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 (5 Sept – 3 Oct 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 (Table 2).

In general, 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. 2008. Clean chip residual: A substrate component for growing annuals. HortTechnology 18:423-432.

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.

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. Marquis, M., 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. Accessed June 4, 2010. <http://www.utextension.utk.edu/hbin/greenimipact.html>.

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. <

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.

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.

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(3):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. Accessed August 6, 2011. <https://www.ars.usda.gov/ARSUserFiles/np212/chapter%203.%20gracenet%20Trace%20Gas%20Sampling%20protocols.pdf>.

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

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		
Irrigation Effect		CO_2-C (g/pot)	N_2O-N (mg/pot)	CH_4 (mg/pot)
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				Cumulative Efflux		
Irrigation Regime		Fertilizer Placement		CO_2-C (g/pot)	N_2O-N (mg/pot)	CH_4 (mg/pot)
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 (25 July 2013 - 17 April 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; 6.6GPH).

[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.

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	% Contribution CO_2 (%)	N_2O (%)	CH_4 (%)
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		GWP	% Contribution CO_2 (%)	N_2O (%)	CH_4 (%)
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 (25 July 2013 to 28 April 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.

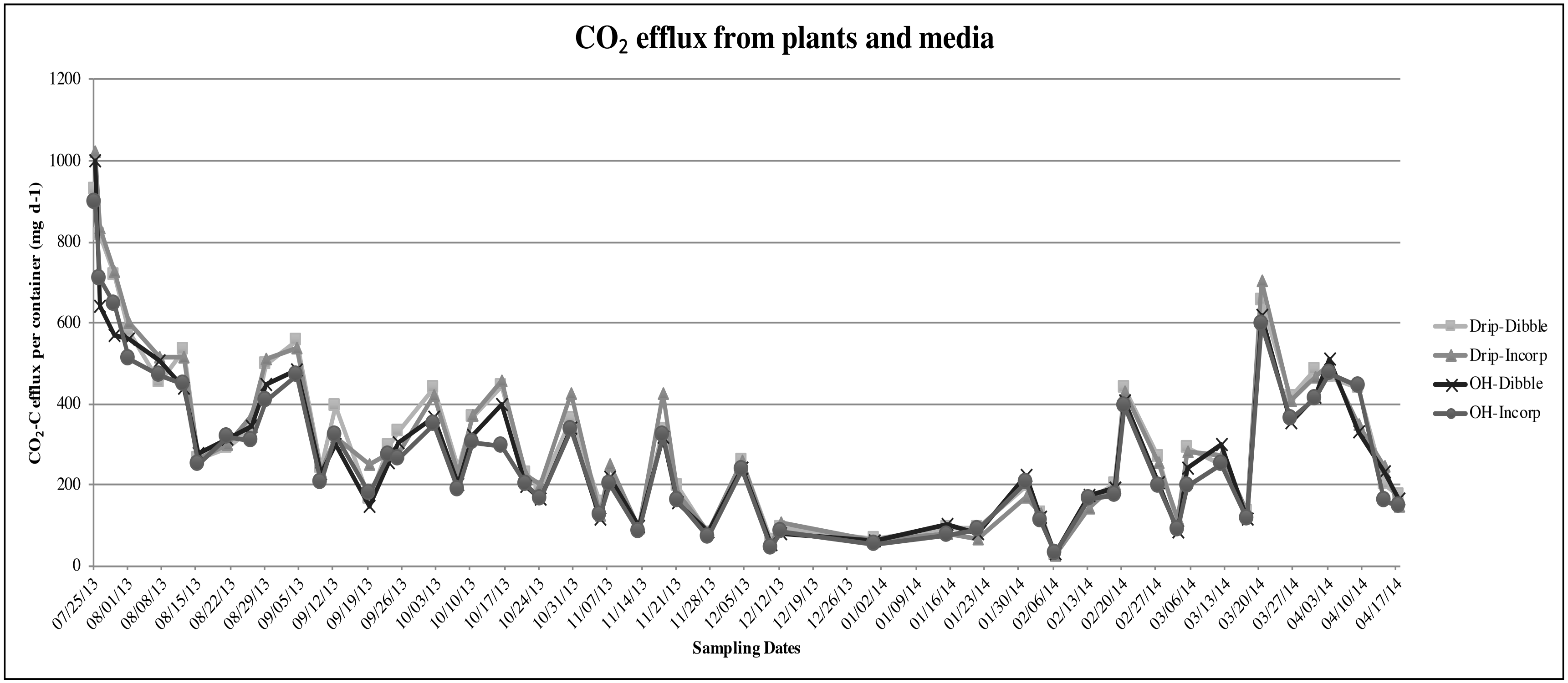

Fig. 1. CO_2-C efflux (mg d^{-1}) for boxwood irrigated with either drip or overhead irrigation, and either dibbled or incorporated fertilizer. Means are for a time period of approximately 9 months (25 July 2013 – 17 April 2014).

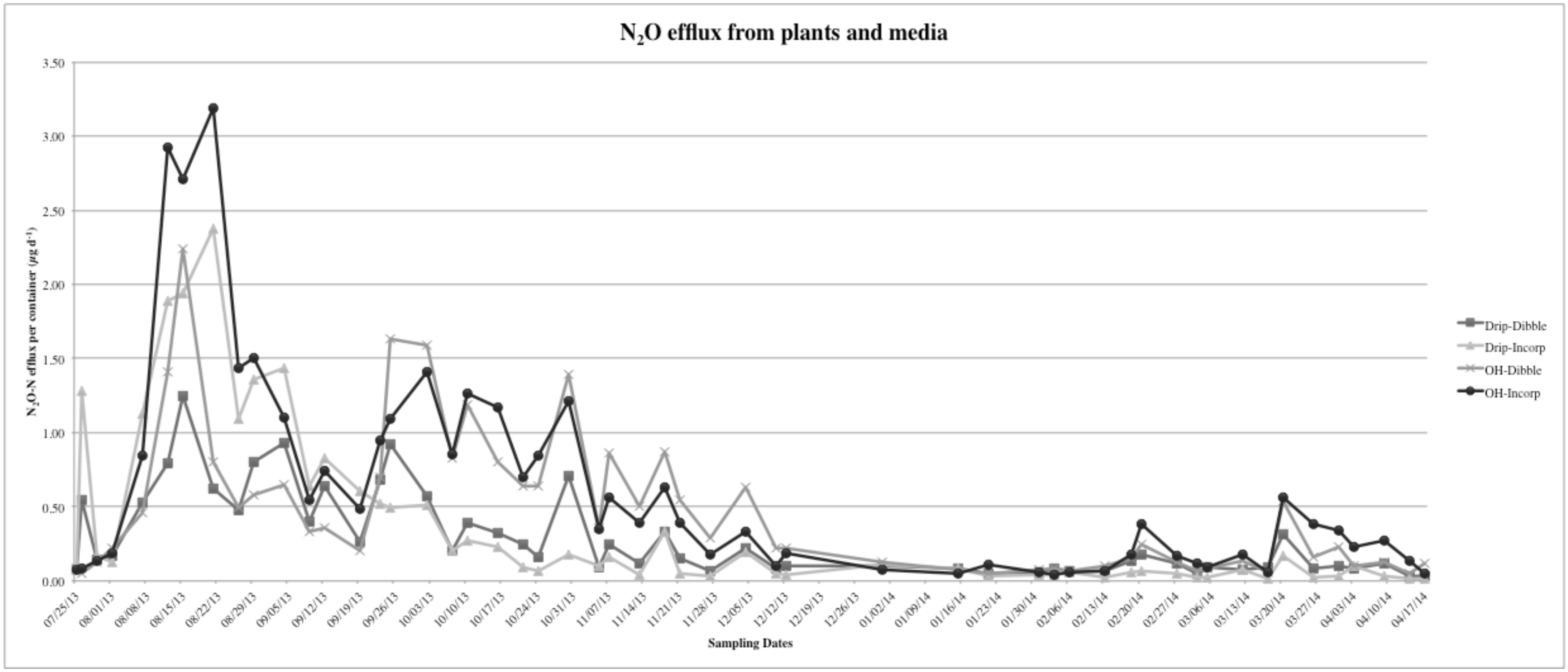

Fig. 2. N_2O-N efflux (μg d^{-1}) for boxwood irrigated with either drip or overhead irrigation, and either dibbled or incorporated fertilizer. Means are for a time period of approximately 9 months (25 July 2013 – 17 April 2014).

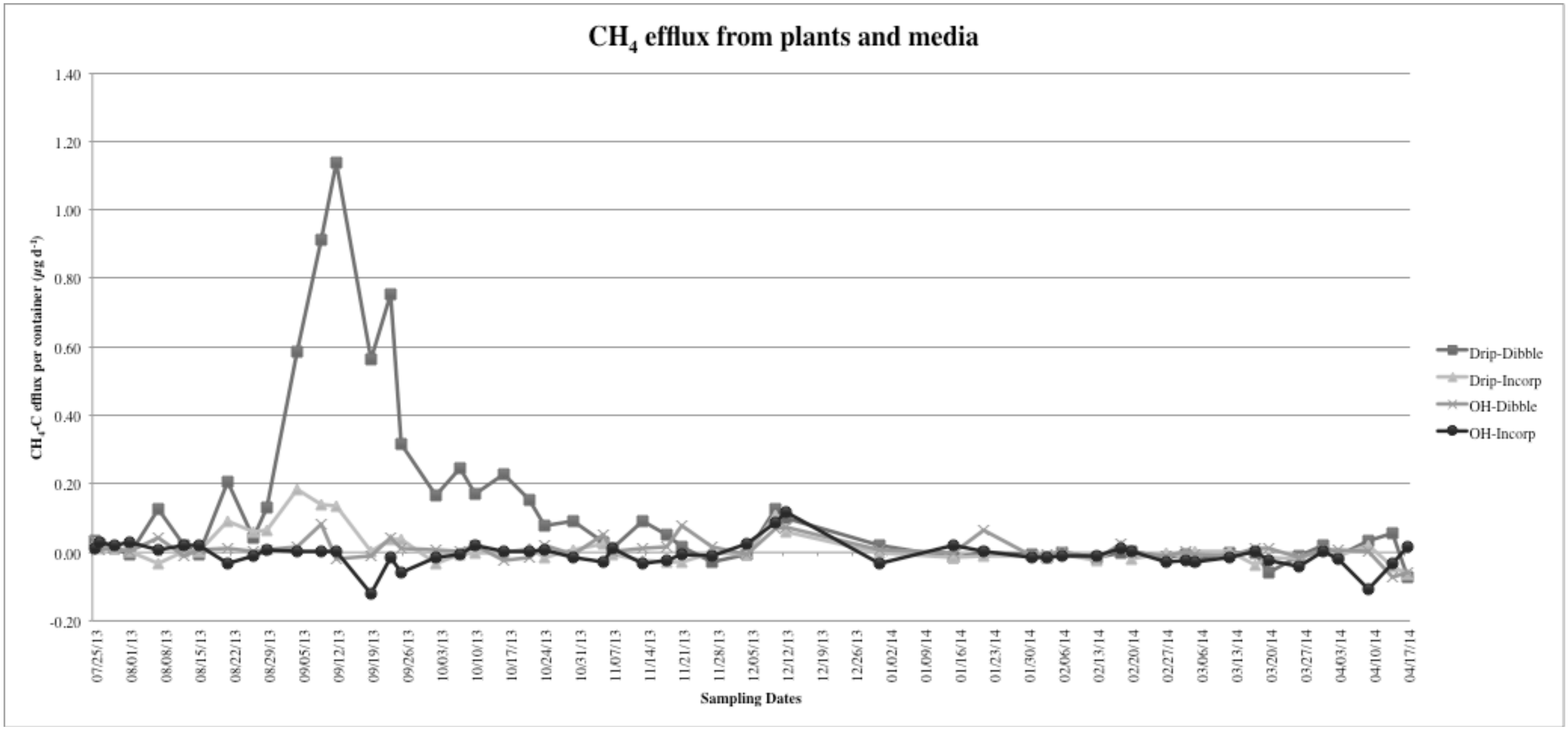

Fig. 3. CH_4 efflux (μg d^{-1}) for boxwood irrigated with either drip or overhead irrigation, and either dibbled or incorporated fertilizer.

Means are for a time period of approximately 9 months (25 July 2013 – 17 April 2014).

CHAPTER III

Effects of Fertilizer Placement on Greenhouse Gas Emissions from a Sun and Shade Grown Ornamental Crop

Abstract

The level to which ornamental plant production impacts rising atmospheric greenhouse gas (GHG) concentrations remains unknown. Research to date has focused on developing baseline estimations of GHG emissions from plant-pot production systems and their contribution to global warming potential. To date, pot size, irrigation delivery method and fertilizer application method have been evaluated in the production of common woody ornamental crops. In this study, two perennial herbaceous plants, full-sun-grown 'Stella D'Oro' daylily (*Hemerocallis* × 'Stella D'Oro' L.) and shade-grown 'Royal Standard' hosta (*Hosta* × 'Royal Standard') (*Hosta plantaginea* Aschers × *Hosta sieboldiana* N.Fujita) were grown utilizing one of three common fertilizer application methods (dibbled, incorporated or top-dressed). Plants were grown in 3.8 L (1 gal) nursery containers in a 6:1 pinebark:sand substrate with standard amendments. Gas samples were collected *in situ* according to standard GRACEnet protocols weekly for five months. Cumulative emissions for both CO_2 and N_2O were least for plant-pot systems using the dibbled fertilizer method, regardless of species. Cumulative CO_2 emissions were highest for plants fertilized by incorporation, followed by those fertilized by top-dressing. No differences were observed between N_2O efflux measurements for systems fertilized by either the incorporated or top-

dressed methods. Results suggest that dibbling fertilizer could significantly decrease both CO_2 and N_2O emission.

Significance to the Horticulture Industry

The ornamental plant production industry has the capacity to impact global climate change through a thorough review of its best management practices (BMP), and how each contributes to global warming through the emission of common greenhouse gases CO_2, N_2O and CH_4. Previous research has evaluated substrate alternatives, irrigation delivery method and fertilizer application method in an effort to determine efflux patterns associated with each BMP. The focus of this research is a continuation of those efforts, evaluating fertilizer application method (dibbled, incorporated or top-dresesed) with either a sun- or shade-grown crop. Emissions of CO_2 were highest for 'Royal Standard' hosta (*Hosta* × 'Royal Standard') as compared to full-sun-grown 'Stella D'Oro' daylily (*Hemerocallis* × 'Stella D'Oro'), which is to be expected considering the size differences in the larger shade-grown hosta as compared to daylily. By this same logic, N_2O emissions were confirmed to be lowest for shade-grown hosta, as larger plants would predictably require larger amounts of N, leaving less available for leaching. Results from this research showed that regardless of species, CO_2 and N_2O emissions were least for plant-pot systems fertilized with the dibble method. CO_2 emissions were highest for plant-pot systems fertilized by incorporation. No differences were observed between N_2O efflux measurements for systems fertilized by either the incorporated or top-dressed methods, as both were higher than N_20 emissions where the dibbled fertilizer method was used. Methane efflux throughout the study was negligible, and not significantly affected by treatments or their interactions.

Introduction

In an extensive series of reports in 2010, the greenhouse, nursery and floriculture industry in Alabama was recently valued at $629.2 million annually, supporting an estimated 7,943 jobs (ACES 2013). These nursery sales generated just over $20 million in indirect business taxes for the state. The economics are only value-added, given how the greenhouse, nursery and floriculture industries support potential C sequestration through their provision of ornamental trees and shrubs for landscape use in rural, suburban, and urban environments. Reports indicate that urban land, together with rural/suburban residential areas account for more than 150 million acres in the United States (Lubowski et al. 2006). The planting of this acreage with ornamental trees and shrubs could dynamically increase potential C sequestration.

Challenges associated with estimating the effective contribution made to climate change by the ornamental nursery and greenhouse industry are numerous. Over the past decade however, researchers have made strides in developing baseline estimates for CO_2, N_2O and CH_4 efflux patterns from a number of ornamental crops, while simultaneously evaluating the manner in which common best management practices (i.e. - pot size, alternative substrates, irrigation method, fertilizer application method) affect these emissions (Marble et al. 2012a, 2012b, 2016, Murphy et al. 2018).

GHG emissions from dwarf yaupon holly (*Ilex vomitoria* 'Nana') grown in four container sizes were reported in 2012 (Marble et al. 2012a). As expected, CO_2 and N_2O emissions were highest in the largest containers [7.6 L (2 gal) and 11.4 L (3 gal)], as compared to the two smaller containers tested [(3.0 L (trade gal) and 3.8 L (1 gal)], with a positive relationship between container size and emissions of CO_2 and N_2O. As with nearly all research evaluating GHG emissions in soilless substrates, CH_4 emissions remained low throughout the study. While CO_2 and N_2O emissions were higher in the two larger containers, the authors noted that on a per area basis, larger containers would actually emit less CO_2 and N_2O, given that less of them will fit into a given area of production.

In work assigning value to the actual contribution each GHG makes to climate change, a specific scaling factor known as global warming potential (GWP) is established for each trace gas (Forster et al. 2007). These evaluators are based on the radiative forcing from 1 kg of the gas in question to 1 kg of CO_2 over a specific interval of time. Expressed as CO_2 equivalents, the GWP for CO_2 is 1, CH_4 is 25, and N_2O is 298. N_2O is formed naturally in soils and the ocean, but is also a major by-product in agricultural and fossil fuel combustion practices (Mathez 2009). Nearly 80% of the total N_2O emissions in the US are directly attributed to N-fixation associated with the production and use of synthetic fertilizers and leguminous crops (Mosier et al. 2003). Increased efficiency of N fertilization (both dosage and delivery) has been shown to reduce emissions of N-containing N_2O, ammonia and NO (Kroeze et al. 1999). Though the bulk of previous research has focused on agronomic crops, the principles apply to soilless systems as well. Even in systems where N_2O contributes a fraction to overall GWP as compared to CO_2, identifying specific ways to mitigate N_2O emissions could have the greatest impact for the nursery and greenhouse industries. Following work evaluating differences in trace gas emissions from plants in different container sizes, Marble et al. (2012b) evaluated the growth of gumpo azalea (*Azalea* × hybrid 'Gumpo White') using one of three common fertilizer placement methods (dibble, incorporated, and top-dressed). Again, CH_4 emissions were consistently low throughout the study. CO_2 emissions were generally lowest in plant-pot systems fertilized with the dibble method, as compared to both systems utilizing the incorporated and top-dressed methods. N_2O emissions were highest with plant-pot systems utilizing the incorporated fertilizer method, with no differences observed between those utilizing either the dibble or top-dressed methods.

N loss in ornamental crop production is affected by a number of factors including N formulation, dosage, application method, temperature, and moisture (volume and delivery method). In an effort to evaluate the interactive effect of irrigation method (overhead vs drip) and fertilizer application method (dibble vs incorporated), estimates of GHG emissions from Japanese boxwood (*Buxus microphylla* Siebold & Zucc.) were measured over a nine-month period (Murphy et al. 2018). CO_2 emissions were not significantly affected by irrigation method, fertilizer placement, or the interaction of the two, though CO_2 emissions in drip irrigated plant-pot systems were reported to be 11% higher than those receiving irrigation from overhead impact risers. While statistically significant interaction effects were noted for N_2O efflux, the authors noted that delivering irrigation through micro drip emitters significantly reduced N_2O efflux over the duration of the study, regardless of how fertilizer was applied. When limited to overhead irrigation however, N_2O emissions were significantly lower for plants fertilized by the dibble method.

The objective of the current research was to continue to evaluate fertilizer placement, while simultaneously evaluating light level and its effect on GHG efflux from the plant-pot system in ornamental plant production. Unlike previous studies that examined woody ornamental species, two perennial herbaceous species (shade-grown 'Royal

Standard' hosta and sun-grown 'Stella D'Oro' daylily) were selected for the study due to their common use in the industry, as well as their economic importance.

Materials and Methods

The experiment was conducted on an outdoor nursery pad at the Paterson Greenhouse Complex on the campus of Auburn University. Two perennial herbaceous species, 'Royal Standard' hosta (*Hosta* × 'Royal Standard') and 'Stella D'Oro' daylily (*Hemerocallis* × 'Stella D'Oro'), were grown adjacently in either sun (daylily) or under 30% shade cloth (hosta). On 23 April 2015, 3.15 L (1-gal) containers were filled with a standard 6:1 PB:sand (v:v) substrate amended with 3.0 $kg \cdot m^{-3}$ dolomitic limestone. It should be noted that, since only a single species was used for each light level, it is not possible to distinguish between effects of light level from those caused by differences in species.

Fertilizer [16-5-10 Polyon – 12 month release with micronutrients (Harrell's LLC, Lakeland, FL)], at a rate of 25 g per container (equivalent to 6.5 $kg \cdot m^{-3}$), was either incorporated into, top-dressed onto, or dibbled into, substrate in each container. Dibbling was accomplished by pressing a wooden dowel with a tapered end (3.8 cm diameter) approximately 15 cm into the filled pot. Fertilizer was dropped in the hole, and a rooted cutting (daylily) or 1-2 eye bare root (hosta) was potted directly on top of the fertilizer. Irrigation events occurred three times daily, delivering 6.35 mm (0.25 in) water at each event through overhead impact irrigation risers.

Trace greenhouse gases (CO_2, CH_4, N_2O) emitted from plants and substrate were sampled weekly (in situ) for five months (23 April 2015 to 24 September 2015) using the static closed chamber method (Hutchinson and Livingston 1993, Hutchinson and Mosier 1981). Measurements were taken at the same time on each sampling day, between 9:00

and 10:00 AM CST. 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 1-gal 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. The top efflux chambers (25.4 cm inside diameter by 11.4 cm tall) were constructed of PVC, covered with reflective tape (3M™ Metallized Flexible Duct Tape 3350, 3M, St. Paul, MN), and contained a center sampling port. During gas measurements, the entire plant-pot system was placed inside the base cylinder. The top efflux chamber was placed on top, and a wide (10.4 cm) rubber band was fitted around the top-bottom interface to seal it. Gas samples were taken at 0, 20, and 40 min intervals following chamber closure, and 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 Liquid America Specialty Gases LLC (Plumsteadville, PA). Gas effluxes were calculated from the rate of change in concentrations of trace gases in the chamber headspace during the time intervals while chambers were closed (Parkin and Venterea 2010). Calculations in this study were used to express data as mg CO_2-C, μg CH_4-C, and μg N_2O-N emitted per day. Dry weights of both the above and below ground portions of the plants were measured at study termination. Shoot dry weights (SDW) (g) were determined by drying the above-substrate portion of the plant in a 76.7 C (170.0 F) forced air oven for 72 hours. Root dry weights (RDW) (g) were determined by removing the substrate from the root interface, and drying the within-substrate portion of the plant in a 76.7 C (170.0 F) forced air oven for 144 hours.

The experiment was conducted as a 2 × 3 factorial design (2 species × 3 fertilizer application methods) with six blocks (six plants per block, 3 of each species) located along the length of the outdoor nursery pad. 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 factorial 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

Statistically significant interaction effects between species and fertilizer placement were observed for cumulative efflux of both CO_2 and N_2O over the five-month sampling period (Table 1). Daylilies fertilized with the dibble method had less cumulative CO_2 emissions (22.89 g/pot) than both daylilies fertilized by either top-dressing (28.03 g/pot) or incorporation (29.90 g/pot), which were statistically similar. Similarly, cumulative CO_2 efflux was also least for hostas grown with dibbled fertilizer (22.57 g/pot), as compared to either hostas fertilized by top-dressing (35.53 g/pot) or by incorporation (39.31 g/pot). Regardless of species, cumulative CO_2 efflux for the entirety of the study was least for plants fertilized with the dibble fertilizer method (22.73 g/pot) (Table 1). An increase to 31.78 g CO_2/pot was observed for all plants top-dressed with fertilizer, while plants grown in substrates incorporated with fertilizer prior to planting had the highest cumulative CO_2 (34.61 g/pot). Differences in cumulative CO_2 efflux between species without regard to fertilizer placement were also observed (Table 1). As would be expected, shade-grown hosta, which was much larger (10.30 g SDW, 45.10 g RDW) than daylily (6.80 g SDW, 17.55 g RDW) at study termination, had higher cumulative CO_2 efflux (32.47 g/pot) than sun-grown daylily (26.94 g/pot) (Tables 1, 2). High daily CO_2 values at study initiation are consistent with results in previous studies, as high initial values are often synonymous with transplant shock (Fig. 1). As a general trend, daily CO_2 emissions were higher for shade-grown hosta than for sun-grown daylily, except for hosta grown with dibbled fertilizer. Both daylily and hosta grown utilizing the dibble fertilizer method were consistently low across all sampling dates.

Similar to results observed for CO_2 efflux, plants fertilized with the dibble method had the least cumulative N_2O efflux (12.97 mg/pot) among methods tested (regardless of species) (Table 1). No differences in cumulative N_2O emissions were observed between the incorporated (19.13 mg/pot) or top-dressed (21.27 mg/pot) fertilizer placement methods, though both were greater than values observed for the dibble method. Interaction effects within species were congruent with those observed for main effects. Daylilies fertilized with the dibble method had less cumulative N_20 emissions (13.86 mg/pot) than both daylilies fertilized by either top-dressing (25.02 mg/pot) or incorporation (22.15 mg/pot). Cumulative N_2O emissions were least for hosta grown with dibbled fertilizer 12.07 mg/pot), though emissions were statistically similar to those observed in hosta grown with incorporated fertilizer (16.12 mg/pot). Fertilizer is generally used more efficiently during the initial growth period for plants with dibbled fertilizer, given its proximity to plant roots, meaning N_2O loss is expected to be minimized in comparison to other fertilizer methods. Hosta top-dressed with fertilizer had significantly higher N_2O emissions (17.53 mg/pot) than those observed in hosta with dibbled fertilizer, but were similar to those as hosta fertilized by incorporation. As with cumulative CO_2 efflux, differences in cumulative N_2O efflux were also observed between species without regard to fertilizer placement, though emissions for N_2O were higher for daylily (Table 1). With regard to size alone, larger shade-grown hosta would predictably take up more nitrogen than smaller sun-grown daylily, resulting in less cumulative N_2O loss (15.24 mg/pot) than daylily (20.34 mg/pot). High initial values for daily N_2O values are expected and consistent with research results in prior studies, possibly exaggerated by high late spring and summer temperatures in east central Alabama (Fig. 2). Initial spikes in daily N_2O emissions were higher for sun-grown daylily than for shade-grown hosta, which contributed to higher cumulative N_2O emissions for daylily than for hosta.

Cumulative methane (CH_4) efflux, across the five-month sampling period, was minimal and not significantly affected by species/light level, fertilizer placement method, or their interaction (Table 1). Minimal to near-zero values for CH_4 loss are generally anticipated in studies occurring in well drained soilless systems, where anaerobic respiration is virtually non-existent. While negative values for net CH_4 emissions are not always observed, they are not unexpected due to the presence of methanotrophic bacteria that metabolize methane as a source of carbon (energy).

Overall global warming potential (GWP), or the total measure of the impact that CO_2, N_2O, and CH_4 each have (measured in CO_2 equivalents) was higher for hosta than for daylily, regardless of fertilizer placement (Table 3). These results are expected, again given the comparison of sheer plant size. More interestingly, fertilizer placement had a significant effect on GWP. Utilizing the dibble fertilizer method (0.0266), GWP was reduced by just over 30% from that of plants utilizing top-dressed fertilizer (0.0381), and nearly 34% compared to GWP of plants utilizing incorporated fertilizer (0.0403). Percent contribution of each GHG to GWP was also affected by treatment. Given that N_2O is 298 times as potent as CO_2 (Forster et al. 2007), it is important to note that both the dibbled and incorporated fertilizer methods were similar in their propensity to contribute to GWP (14.32% for incorporated versus 14.48% for dibble). Both contributed less to GWP than plants utilizing a top-dressed method of fertilizer application (17.04%).

Though daylily RDW was heaviest for those plants utilizing the dibbled fertilizer method (24.95 g), as compared to both those grown in substrate top-dressed (12.75 g) or incorporated (14.95 g) with fertilizer, daylily SDW was ultimately unaffected (Table 2). In contrast, hosta fertilized with the dibble method had the least RDW (36.97 g) as compared to those fertilized by either incorporation (48.67 g) or by top-dressing (49.66 g). With regard to SDW however, plants fertilized by the dibble method (8.12 g) were smaller than only those fertilized by top-dressing (12.27 g). SDW of hosta fertilized by incorporation (10.50 g) was similar to those fertilized by the dibble method. With regard to overall plant dry weight, daylilies grown with dibbled fertilizer were larger than those grown with the other two placement methods (Table 2). In contrast, hosta grown with dibbled fertilizer were smaller than those grown with either incorporated or top-dressed fertilizer. Despite these statistical differences, it is unlikely that differences in plant size would have affected marketability.

Cumulative CO_2 and N_2O efflux results for the two perennial herbaceous species, regardless of fertilizer method, are useful in developing baseline estimates for greenhouse gas efflux constructed on plant size. Practically, however, findings suggest that the use of placement of fertilizer using a dibbling method could significantly decrease both CO_2 and N_2O emissions.

Literature Cited

Alabama Cooperative Extension System (ACES). 2013. Economic impacts of Alabama's agricultural, forestry & related industries. Combined ANR-2012, ANR-2013, ANR-2014, ANR-2015, ANR-2016, ANR-2017, and ANR-2018. Alabama Cooperative Extension System, 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.

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. Marquis, M., K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, New York, NY.

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.

Kroeze, C., A.R. Mosier, and L. Bouwman. 1999. Closing the global N_2O budget: A retrospective analysis 1500-1994. Global Biogeochemical Cycles 13:1-8.

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

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.

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(3):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.

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. 2016. Species and media effects on soil carbon dynamics in the landscape. Sci. Rep. 6, 25210.

Mathez, E.A. 2009. Climate Change. Columbia University Press. New York, NY.

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. Methane and Nitrous Oxide International Workshop Proceedings. p. 273-280.

Murphy, A.M., G.B. Runion, S.A. Prior, H. Allen Torbert, J.L. Sibley, and C.H. Gilliam. 2018. Greenhouse gas emissions from an ornamental crop as impacted by two best management practices: Irrigation delivery and fertilizer placement. J. Environ. Hort. 36(2):58-65.

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.

Table 1. Total cumulative CO_2, N_2O, and CH_4 efflux[z] over five months from two herbaceous species[y] utilizing three fertilizer application methods[x].

Main Effects		Cumulative Efflux		
Species Effect		CO_2-C (g/pot)	N_2O-N (mg/pot)	CH_4 (mg/pot)
Daylily		26.94 b	20.34 a	-1.03[ns]
Hosta		32.47 a	15.24 b	-1.22
	p:	*<0.001*	*<0.001*	*0.810*
Fertilizer Placement Effect				
Dibble		22.73 c	12.97 b	-1.22[ns]
Incorporated		34.61 a	19.13 a	-1.57
Top-Dressed		31.78 b	21.27 a	-1.58
	p:	*<0.001*	*<0.001*	*0.570*

Interaction Effects			Cumulative Efflux		
Species	Fertilizer Placement		CO_2-C (g/pot)	N_2O-N (mg/pot)	CH_4 (mg/pot)
Daylily -	Dibbled		22.89 b[w]	13.86 b	-1.16[ns]
Daylily -	Incorporated		29.90 a	22.15 a	-0.47
Daylily -	Top-Dressed		28.03 a	25.02 a	-1.46
Hosta -	Dibbled		22.57 c	12.07 b	-1.28[ns]
Hosta -	Incorporated		39.31 a	16.12 ab	-0.67
Hosta -	Top-Dressed		35.53 b	17.53 a	-1.71
		p:	*0.001*	*0.171*	*0.998*

[z] Cumulative efflux for five months (23 April 2015 to 24 September 2015) was calculated using the trapezoid rule (n=6).

[y] Daylily (*Hemerocallis* × 'Stella D'Oro') and Hosta (*Hosta* × 'Royal Standard') were potted into one-gallon nursery containers filled with standard 6:1 (v:v) pinebark:sand substrate, amended with 3.0 kg m^{-3} dolomitic limestone.

[x] The same fertilizer rate (25 g per container) (16-5-10 Polyon with blended minors - 12 month release) was either incorporated into, or top-dressed or dibbled onto, the substrate in each container. Dibbling was accomplished by pressing a wooden dowel with a tapered end (3.8 cm diameter) approximately 15 cm into the filled pot. Fertilizer was then dropped in the hole, and rooted cutting or bare root was potted directly on top of the fertilizer.

[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. For interaction effects, letters designate differences within species only.

[ns] Not significantly different.

Table 2. Shoot and root dry weights[z,y] following five months of growth for two herbaceous species[x] utilizing three fertilizer application methods[v].

Main Effects		Shoot Dry Weight (g)	Root Dry Weight (g)	Total Dry Weight (g)[w]	Root:Shoot Ratio
Species Effect					
Daylily		6.80 b[u]	17.55 b	24.35 b	2.50 b
Hosta		10.30 a	45.10 a	55.39 a	4.47 a
	p:	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Fertilizer Placement Effect					
Dibble		8.03[ns]	30.96[ns]	38.99[ns]	3.93 a
Incorporated		8.41	30.71	39.12	3.31 ab
Top-Dressed		9.20	32.30	41.50	3.21 b
	p:	*0.412*	*0.862*	*0.763*	*0.052*

Interaction Effects

Species		Fertilizer Placement		Shoot Dry Weight (g)	Root Dry Weight (g)	Total Dry Weight (g)	Root:Shoot Ratio
Daylily	-	Dibbled		7.94[ns]	24.95 a	32.89 a	3.25 b
Daylily	-	Incorporated		6.33	12.75 b	19.08 b	1.94 a
Daylily	-	Top-Dressed		6.13	14.95 b	21.08 b	2.29 a
Hosta	-	Dibbled		8.12 b	36.97 b	45.08 b	4.61[ns]
Hosta	-	Incorporated		10.50 ab	48.67 a	59.17 a	4.67
Hosta	-	Top-Dressed		12.27 a	49.66 a	61.92 a	4.12
			p:	*0.001*	*0.001*	*0.001*	*0.095*

[z] Shoot dry weights (g) determined by drying the above-substrate portion of the plant in a 76.7°C (170.0°F) forced air oven for 72 hours.

[y] Root dry weights (g) were determined by removing the substrate from root interface, and drying the within-substrate portion of the plant in a 76.7°C (170.0°F) forced air oven for 144 hours.

[x] Daylily (*Hemerocallis* × 'Stella D'Oro') and Hosta (*Hosta* × 'Royal Standard') were potted into one-gallon nursery containers filled with standard 6:1 (v:v) pinebark:sand substrate, amended with 3.0 kg m^{-3} dolomitic limestone.

[w] Total dry weight = Shoot dry weight + root dry weight.

[v] The same fertilizer rate (25 g per container) (16-5-10 Polyon with blended minors - 12 month release) was either incorporated into, or top-dressed or dibbled onto, the substrate in each container. Dibbling was accomplished by pressing a wooden dowel with a tapered end (3.8 cm diameter) approximately 15 cm into the filled pot. Fertilizer was then dropped in the hole, and rooted cutting or bare root was potted directly on top of the fertilizer.

[u] Within a column, means followed by the same letter are not significantly different (p≤0.05) according to the LSMeans statement under the Proc Mixed Procedure of SAS. For interaction effects, letters designate differences within species only.

[ns] Not significantly different.

Table 3. Percent contribution to Global Warming Potential[z] of two herbaceous species[y] utilizing three fertilizer application methods[x].

Main Effects			% Contribution		
Species Effect		GWP	CO_2-C (%)	N_2O-N (%)	CH_4 (%)
Daylily		0.0330 b	82.00 b	18.09 a	-0.09[ns]
Hosta		0.0370 a	87.63 a	12.47 b	-0.09
	p:	*0.001*	*<0.001*	*<0.001*	*0.967*
Fertilizer Placement Effect					
Dibble		0.0266 b	85.65 a	14.48 b	-0.13[ns]
Incorporated		0.0403 a	85.72 a	14.32 b	-0.03
Top-Dressed		0.0381 a	83.07 b	17.04 a	-0.11
	p:	*<0.001*	*0.03*	*0.025*	*0.438*

Interaction Effects					% Contribution		
Species		Fertilizer Placement		GWP	CO_2-C (%)	N_2O-N (%)	CH_4 (%)
Daylily	-	Dibbled		0.0270 b[w]	84.87 a	15.25 b	-0.12[ns]
Daylily	-	Incorporated		0.0365 a	82.26 a	17.78 b	-0.03
Daylily	-	Top-Dressed		0.0354 a	78.86 b	21.25 a	-0.11
Hosta	-	Dibbled		0.0261 b	86.42[ns]	13.72[ns]	-0.14[ns]
Hosta	-	Incorporated		0.0441 a	89.17	10.86	-0.03
Hosta	-	Top-Dressed		0.0407 a	87.28	12.83	-0.11
			p:	*0.014*	*0.009*	*0.007*	*0.989*

[z] Global Warming Potential (GWP) is calculated on a per container basis from cumulative trace gas emissions across the entire study (23 April 2015 to 24 September 2015). 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] Daylily (*Hemerocallis* × 'Stella D'Oro') and Hosta (*Hosta* × 'Royal Standard') were potted into one-gallon nursery containers filled with standard 6:1 (v:v) pinebark:sand substrate, amended with 3.0 kg m^{-3} dolomitic limestone.

[x] The same fertilizer rate (25 g per container) (16-5-10 Polyon with blended minors - 12 month release) was either incorporated into, or top-dressed or dibbled onto, the substrate in each container. Dibbling was accomplished by pressing a wooden dowel with a tapered end (3.8 cm diameter) approximately 15 cm into the filled pot. Fertilizer was then dropped in the hole, and rooted cutting or bare root was potted directly on top of the fertilizer.

[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. For interaction effects, letters designate differences within species only.

[ns] Not significantly different.

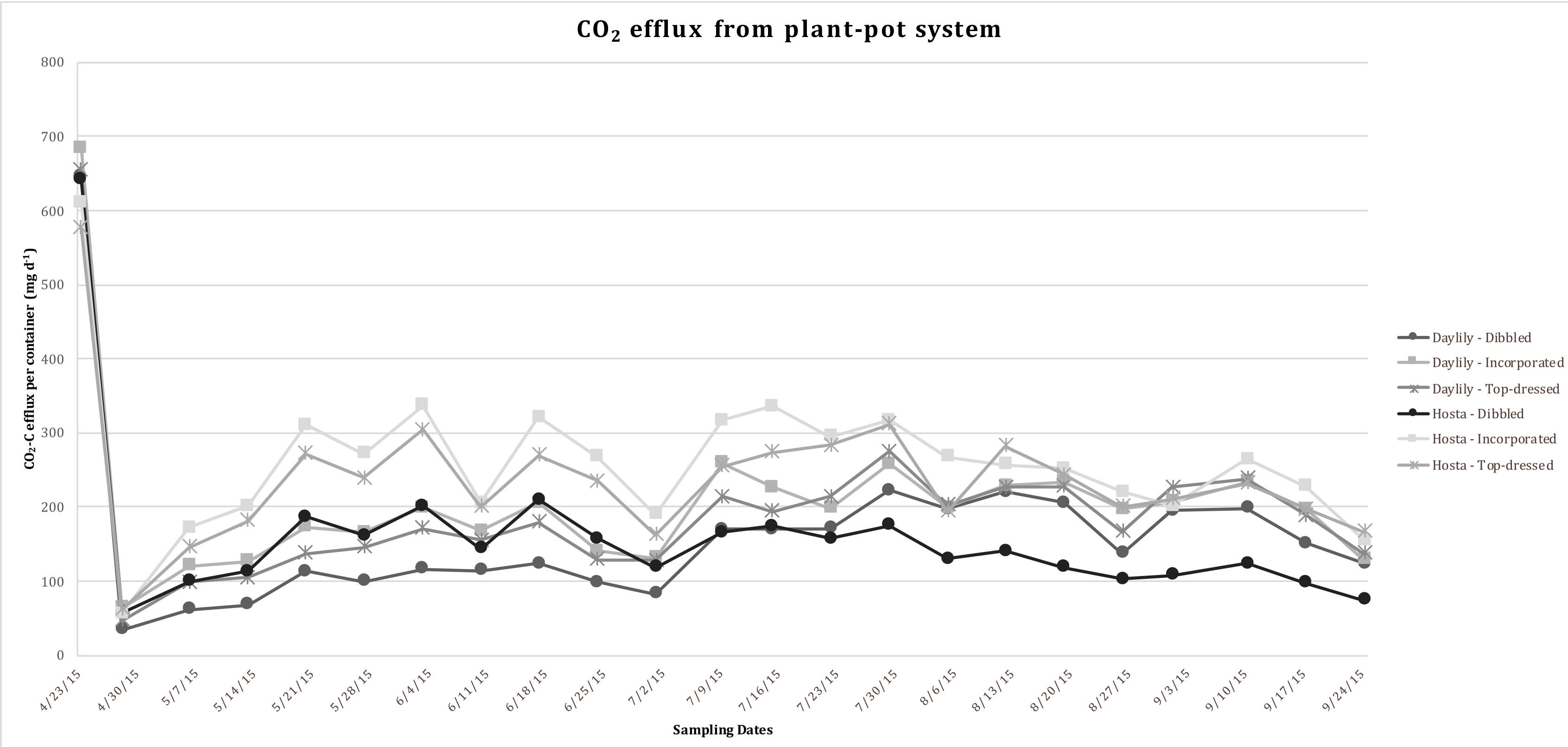

Fig. 1. Daily CO_2-C efflux for two perennial herbaceous species fertilized with one of three fertilizer application methods (either dibbled, incorporated or top-dressed). Measurements are for a time period of approximately five months (23 April to 24 September 2015).

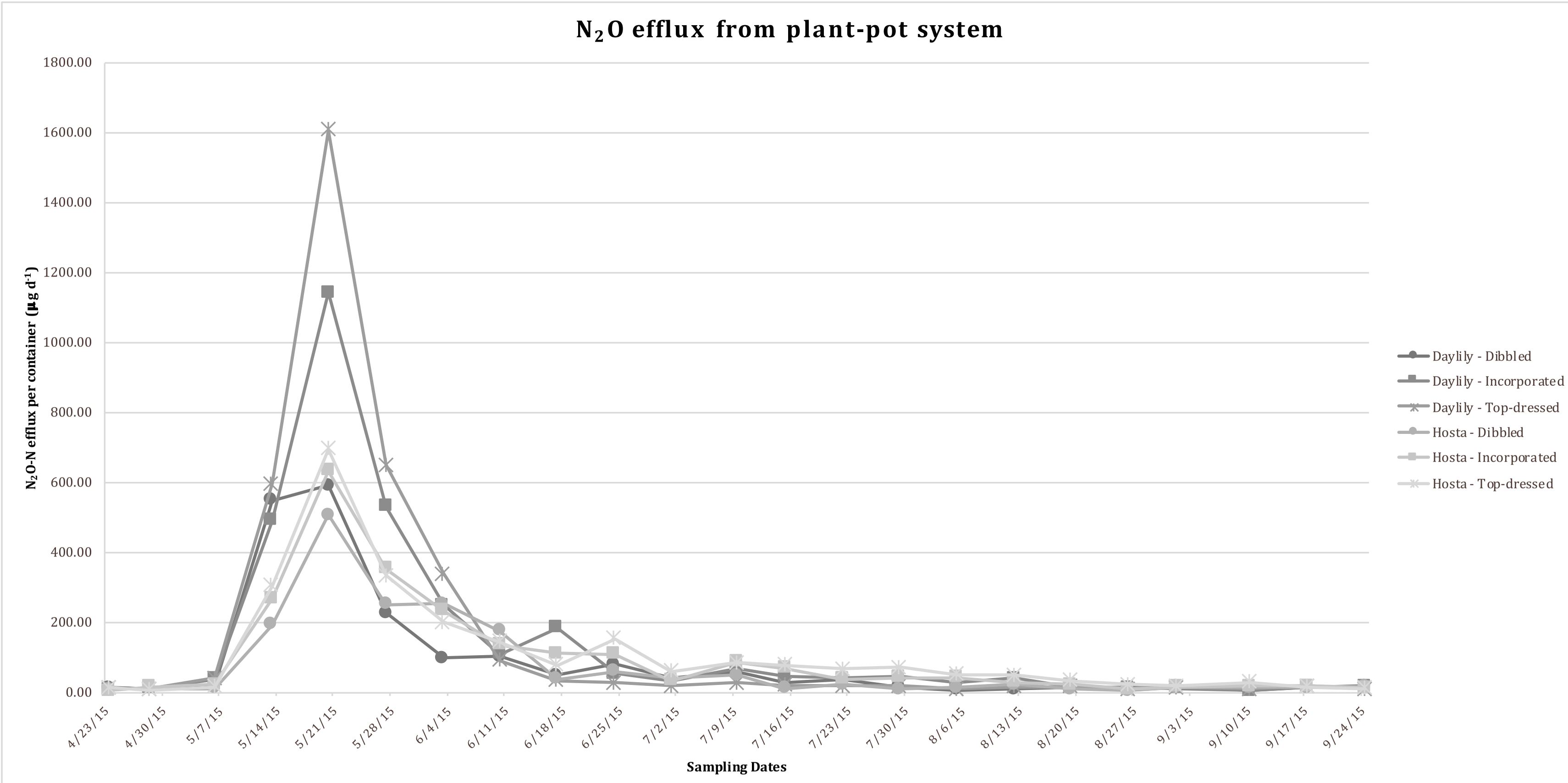

Fig. 2. Daily N_2O-N efflux for two perennial herbaceous species fertilized with one of three fertilizer application methods (either dibbled, incorporated or top-dressed). Measurements are for a time period of approximately five months (23 April to 24 September 2015).

CHAPTER IV

Effects of Growth Substrate on Greenhouse Gas Emissions from Three Annual Species

Abstract

Previous work by these authors have quantified cumulative greenhouse gas (GHG) emissions for several woody and herbaceous perennial species, in interaction with several standard best management practices (container size, fertilizer application and irrigation delivery methods, and light level). In this study, the greenhouse production of three annual species [coleus (*Solenostemon scutellarioides* Thonn. 'Redhead'), vinca (*Catharanthus roseus* L. 'Cooler Grape'), and impatiens (*Impatiens walleriana* Hook. f. 'Super Elfin XP White')] was evaluated in three substrates [80:20 peat:perlite, 80:20 peat:WholeTree (a whole pine tree-based substrate), 60:40 peat:WholeTree]. Emissions of CO_2, N_2O and CH_4 were collected over a period of 52 days. Without regard to media, coleus had the highest cumulative CO_2 efflux (statistically similar to vinca), due to its increased size in comparison with both vinca and impatiens. Without regard to species, plant-pot systems using the highest proportion of WholeTree (40%) had the most cumulative CO_2 efflux (statistically similar to those containing only 20% WholeTree). No differences were observed for the main effect of species or media for N_2O or CH_4. Results suggest that using a more sustainable high wood fiber substrate in similar proportions to that of perlite in an industry standard mix (20%) could yield similarly sized plants with no negative impact on GHG emissions.

Significance to the Horticulture Industry

As an important part of the agricultural industry as a whole, the ornamental plant production industry could impact global climate change and may reap economic benefits from potential changes in legislation or tax incentives aimed at reducing GHG emissions. In previous work, these authors have evaluated GHG emissions in the nursery container production of several woody and herbaceous perennial species as a factor of container size, irrigation delivery method (overhead vs drip), fertilizer application method (incorporated vs dibble vs topdressed), and light intensity level (sun vs shade). Previous work has focused on plants grown in a bark-based substrate, while the current study evaluated three annual species grown in a standard peat:perlite greenhouse media and two alternative substrates with varying percentages of high wood fiber. No differences were observed for the main effects of species or media for N_2O and CH_4 emissions. Results for cumulative CO_2 efflux indicated that substrates amended with up to 20% of a high wood fiber (effectively replacing perlite) had similar CO_2 emissions to that of a standard peat:perlite blend. This is promising for growers looking to identify a more sustainable substrate alternative to perlite without increasing GHG emissions.

Introduction

According to a popular press article in Business Insider in 2018, nearly half (48.8%) of millennials participating in the World Economic Forum's Global Shapers Survey chose climate change and the resulting destruction of nature as one of their top concerns facing the world's population (Loudenback and Jackson 2018). Popular opinion from America's currently largest generation (Frey 2018) coincides with the scientific community in believing that these changes are primarily anthropogenically driven, though the degree to which this is true remains unknown. Estimates of three common GHGs (CO_2, N_2O and CH_4) emitted from standard agricultural practices along with allied industries comprise nearly 20% of the annual increase in GHG emissions (Cole et al. 1997). While mitigation strategies in agriculture have focused on agronomic crops, forestry, and animal production systems, the horticulture industry, and specifically the ornamental plant production sector, has largely gone unresearched. As of 2010, the economic impact of the nursery, greenhouse and floriculture industry in Alabama was estimated at $629.2 million annually, supporting nearly 8,000 jobs (ACES 2013). Just four years earlier, the economic impact of those same industries, in addition to sod farming, was estimated at $148 billion nationally (Hall et al. 2005). The overall impact of this economically important Green Industry to GHG emissions, and ultimately climate change, is relatively unknown, though recent investigations have begun to establish baseline estimates for both individual plant-pot systems and whole production systems.

Earlier work in measuring GHG emissions in ornamental plant production has evaluated several standard production practices, including container size (Marble et al. 2012a), fertilizer placement (Marble et al. 2012b, Murphy et al. 2018, Murphy et al. 2019), irrigation delivery method (Murphy et al. 2018), and light intensity (Murphy et al. 2019). Greenhouse gas emissions observed from plant-pot systems containing dwarf yaupon holly (*Ilex vomitoria* Sol. ex Aiton 'Nana') grown in four container sizes [3.0 L (trade gal), 3.8 L (1 gal), 7.6 L (2 gal), and 11.4 L (3 gal)] understandably indicated that both CO_2 and N_2O

emissions were highest in the two largest container sizes as compared to the two smaller container sizes tested, with a positive linear relationship between container size and emissions (Marble et al. 2012a). As a follow-up, Marble et al. (2012b) evaluated the growth and GHG emissions of gumpo azalea (*Azalea* × hybrid 'Gumpo White') as a factor of three common fertilizer placement methods (dibble, incorporated, and top-dressed). Carbon dioxide emissions were highest for plant-pot systems utilizing the incorporated and top-dressed fertilizer application methods, while those using the dibble method were lowest. Results for cumulative N_2O emissions indicated that, while no differences occurred between treatments utilizing either the dibble or top-dressed methods, emissions were highest for systems using the incorporated fertilizer method. Comparable results from a study by Murphy et al. (2018) evaluating both fertilizer application method (dibble vs incorporated) and irrigation delivery method (overhead vs drip) indicated that, when limited to overhead irrigation (the most common irrigation method in standard production practice), dibbled fertilizer placement could limit N_2O emissions. Regardless of fertilizer placement, N_2O efflux was least for drip-irrigated plants. Results from the same study also indicated that cumulative CO_2 emissions over the course of the nine-month study were unaffected by differences in irrigation delivery method or fertilizer placement. Most recently, a study by the authors evaluated differences in GHG emissions from both a sun- ['Stella D'Oro' daylily (*Hemerocallis* × 'Stella D'Oro')] and shade-grown ['Royal Standard' hosta (*Hosta* × 'Royal Standard') crop, grown with fertilizer that had been either dibbled, incorporated, or top-dressed (Murphy et al. 2019). Results from this five-month study indicated that larger, shade-grown hosta had both higher CO_2 efflux and lower N_2O efflux than smaller, sun-grown daylily. Results were also in line with those observed in previous studies where plants fertilized with the dibbled fertilizer method (regardless of species) had the least cumulative CO_2 and N_2O efflux as compared to the other fertilizer application methods tested. In each of these studies, CH_4 emissions were generally low due to the well-drained nature of the bark-based substrate used for nursery container production.

Results for cumulative GHG emissions over the course of a growing season or two are beneficial in establishing baseline estimates of potential GHG mitigation as a factor of standard production practices. However, in an attempt to assign value to the actual contribution of each GHG to climate change overall, a specific scaling factor known as global warming potential (GWP) is employed (Forster et al. 2007). Expressed as CO_2 equivalents, each trace gas is assigned an evaluator based on the radiative forcing from 1 kg of the gas in question to 1 kg of CO_2 over a specific interval of time (CO_2=1, N_2O=298, CH_4=25). While N_2O is formed naturally in soils and the ocean, it is also one of the major by-products in agricultural practices, along with a number of other industries (Mathez 2009). Mosier et al. (2003) reports that an overwhelming majority (80%) of the total N_2O emissions in the US are directly attributed to the N-fixation that accompanies the production and use of synthetic fertilizers and leguminous crops. A reduction of emissions derived from N-containing N_2O, ammonia and NO can be achieved through the increased efficiency of both the dosage and delivery of N fertilization (Kroeze et al. 1999). While cumulative CO_2 emissions are often the more prevalent story, GWP values, combined with the nature of the ornamental plant production industry that relies on synthetic fertilizers, indicate that identifying specific ways to mitigate N_2O emission could have the greatest impact for the nursery and greenhouse industries.

While previous studies have evaluated plant-pot systems that primarily utilize bark as the bulk substrate component, a move to greenhouse container production necessitates use of peat and perlite-based substrates to increase water holding capacity. For more than sixty years, perlite (formed by heating siliceous volcanic rock) has served as an industry standard component in traditional greenhouse substrates (Nelson 2011). Perlite's unique characteristics allow it to add air space to otherwise dense greenhouse substrates without contributing to bulk density (Jenkins and Jarrell 1989). While the future availability of perlite remains optimistic, heavy exposure to the material has been linked to persistent reactive airway disfunction syndrome (Du et al. 2010), as well as to a decrease in the lung transfer factor, or carbon monoxide diffusing capacity (Potlatli et al. 2001). A more recent report reviewing perlite toxicology indicates that the respiratory health of workers in US perlite mines and expansion plants may not be adversely affected, though the dust is still considered a nuisance (Maxim et al. 2014). It is important to note that the studies included in the review were most often in observance of occupational exposures occurring in the perlite mining and refining industries, where respirators are commonly required. Agricultural workers can be exposed to perlite dust without any type of mask or respirator.

Previous work focused on modeling GHG emissions and associated costs of a whole nursery production system (field and pot-in-pot) for both trees and shrubs provides growers with information on the 'carbon footprint' and economic cost associated with the production of several species (Hall and Ingram 2015, Ingram 2012, 2013, Ingram and Hall 2013, 2014a, 2014b, 2016, Ingram et al. 2016, Kendall and McPherson 2011). Other than prior research completed by the authors (previously mentioned in this introduction), limited research has focused on building a foundation for estimating actual GHG emissions in container plant production as affected by changes in standard production practices. The objective of this research was to further construct baseline estimates of GHG emissions by evaluating the growth of three common annual crops (‘Redhead’ coleus, ‘Cooler Grape’ vinca, ‘Super Elfin XP White’ impatiens) in three substrates (peat/perlite industry standard, and two substrates containing increasing volumetric proportions of a wood fiber substrate alternative) in standard greenhouse container production.

Materials and Methods

This experiment was conducted on a 91.4 cm (36 in) tall steel bench in a twin-walled polycarbonate-covered greenhouse at the Paterson Greenhouse Complex on the campus of Auburn University, AL. Prior to study installation, a primarily pine-based high-wood-fiber substrate was obtained from Young’s Plant Farm in Auburn, AL on 15 June 2018; this substrate is typically referred to as Wholetree (WT) (Fain et al. 2008). Young’s Plant Farm maintains its own pine stands in Macon County, AL, and processes fresh trees through a Woodsman Model 334 Biomass Chipper (Woodsman, LLC, Farwell, MI). Following initial chipping, biomass is further processed through a 0.95 cm (0.375 in) screen in a hammermill (Meteor Mill #40, Williams Patent Crusher and Pulverizer Co., Inc, St. Louis, MO). Once processed, biomass is aged in polypropylene bulk bags (1.78 m^3 or 2.33 yd^3) in full sun, which allows this high wood fiber substrate to undergo a heating process. All substrate treatments were mixed prior to study initiation on 18 June 2018. Treatments included an 80:20 fine professional sphagnum peatmoss: coarse horticultural perlite (P:P) blend, an 80:20 peatmoss:WT blend (P:WT), and a 60:40 P:WT blend. Substrates were amended at mixing on a per cubic yard basis with 0.9 kg (2.0 lb) 8-5-12 starter nutrient charge (GreenCare Fertilizers, Kankakee, IL), 2.3 kg (5.0 lb) dolomitic limestone, and 0.5 kg (1.2 lb) Aqua-Gro G (The Scotts Co., Marysville, OH). Following mixing, 1.33 L (1.41 qt) pots (06.00 AZ TW; Dillen Products, Middlefield, OH), were filled to capacity with substrate, and potted with one of three annual species. Species included 'Redhead' coleus (one rooted cutting per pot), 'Cooler Grape' vinca (2 plugs from a 200-cell flat per pot), and 'Super Elfin XP White' impatiens (2 plugs from a 200-cell flat per pot). For the duration of the study, plants were hand irrigated with municipal water as needed depending on environmental conditions and fertigated at every third irrigation event with a 150 ppm N 20-10-20 fertilizer (GreenCare Fertilizers, Kankakee, IL).

Data collected throughout the study included twice weekly samples (*in situ*) of trace GHGs (CO_2, N_2O, and CH_4). Sampling from plant-pot systems continued for 52 days (18 June 2018 to 9 August 2018). From standards established in GRACEnet protocols, custom gas efflux chambers were constructed to collect gas samples using the static closed chamber method (Hutchinson and Livingston 1993, Hutchinson and Mosier 1981, Parkin et al. 2003, Parkin and Kaspar 2006). Polyvinylchloride (PVC) cylinders with an inside diameter of 25.4 cm (10.0 in) and a height of 38.4 cm (15.1 in) were sealed at the bottom and covered with reflective tape (3M™ Metallized Flexible Duct Tape 3350, 3M, St. Paul, MN) to form the structural base of the sampling chamber. Tops constructed of the same size PVC cylinder, at a height of 11.4 cm (4.5 in) were also covered with reflective tape and fitted with a 10.4 cm (4.1 in) rubber band that acted as a seal to join the top and base together during sampling. A center sampling port was fitted into each top. During trace gas collection, the entire plant-pot system was placed inside the base cylinder with the top sealed to the base. Gas samples were taken 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. Samples were analyzed using gas chromatography (Shimadzu GC-2014, Columbia, MD). Standard curves developed using gas standards (Air Liquide America Specialty Gases LLC, Plumsteadville, PA), along with ambient air samples at the time of sampling, were used (by comparison) to determine concentrations of each GHG. Gas effluxes for each GHG (in mg gas emitted cumulatively per pot) were calculated using the rate of change in concentrations over the forty-minute sampling period (Parkin and Venterea 2010).

Growth indices (GI) (cm) [(plant height + width1 +width2) / 3], along with shoot and root dry weights were collected at study termination for all experimental units. Shoot dry weight (SDW) (g) was determined by drying the above-substrate portion of the plant in a 76.7 C (170 F) forced air oven for 72 hours. Root dry weights (RDW) (g) were determined by removing the substrate from roots with high pressure water, and drying the entire root system in a 76.7 C (170 F) forced air oven for 144 hours. Pour-thru leachates were also obtained at study termination using the Virginia Tech PourThru technique to determine substrate pH and EC (Wright 1986).

The experiment was conducted as a 3 $\times$ 3 factorial design (3 species $\times$ 3 medias) with four blocks (9 plants per block). Plants were arranged in a randomized complete block design on one greenhouse bench. Data analysis was conducted using the Mixed Models Procedure (Proc Mixed) of the Statistical Analysis System (Littell et al. 1996). Error terms appropriate to the factorial 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

Without regard to media, cumulative CO_2 efflux for the duration of the 52 day study was highest for coleus (1641.1 mg/pot), though not statistically different from vinca (1537.5 mg/pot) (Table 1). Cumulative CO_2 efflux was least for impatiens (1470.5 mg/pot), though again statistically similar to vinca. These differences can be generally linked to plant size. By study termination, GI for all coleus in the study was significantly higher (37.92) than that of either vinca (24.95) or impatiens (25.08) (Table 2). SDW and RDW of coleus at study termination (SDW=14.83 g, RDW= 2.75 g) were also higher than that of both vinca (SDW=8.02 g, RDW=0.98 g) and impatiens (SDW=7.08 g, RDW=1.00 g).

Media, without regard to plant species, also had a significant effect on cumulative CO_2 efflux throughout the study. When averaged across all three species, plants grown in the largest amount of WT (60:40 P:WT) had the highest efflux (1,615.6 mg per pot), though not statistically different from that amended with only 20% WT (80:20 P:WT=1,550.5 mg per pot) (Table 1). The industry standard 80:20 P:P treatment had the least amount of cumulative CO_2 loss (1,483.1 mg per pot) throughout the study, though this number was statistically similar to that amended with 20% WT. The authors believe these differences are due to the presence of the high wood fiber substrate, since results from previous studies generally indicate that larger plants have greater amounts of cumulative CO_2 efflux, and values from the current study do not correspond to these prior findings (Murphy et al. 2019). While cumulative CO_2 efflux in the current study was highest for plants grown in 60:40 P:WT, GI and SDW were least for these plants (GI=26.89, SDW=8.36) (Table 2). RDW was similar for plants grown in each type of media, regardless of species. In general, data for cumulative CO_2 efflux indicate that little to no differences were observed between plants grown in an industry standard 80:20 P:P compared to those grown in 80:20 P:WT. This suggests that growers looking to phase out the use of perlite in their current greenhouse operations may be able to do so without significantly increasing CO_2 emissions. Data for daily CO_2 emissions are shown in Figure 1.

In a previous study, N_2O efflux was observed to be lower in correlation with larger plants, as larger plants would predictably take up more nitrogen (Murphy et al. 2019). However, results from the current study revealed no differences due to either main effect (species nor media), as well as interactions of the two, with regard to cumulative N_2O efflux. These results are likely due to the type of fertilizer used (10-day starter nutrient charge and 150 ppm N liquid fertilizer as needed), as well as the relatively short duration of this study (52 days) relative to previous longer-term studies (5 and 9 months) where controlled release fertilizers were used (Murphy et al. 2018, 2019). Data for daily N_2O emissions are shown in Figure 2.

As with cumulative N_2O loss, no differences were observed for cumulative CH_4 efflux, regardless of species or media, or the interaction of the two (Table 1). These results parallel findings from previous studies, as soilless media often provide sufficient drainage so that anaerobic respiration is practically eliminated. Negative values observed for cumulative CH_4 loss across the 52-day study could be the result of methanotrophic bacteria metabolizing methane in the plant-pot system. Data for daily CH_4 emissions are shown in Figure 3.

As a means of quantifying the overall impact of CO_2, N_2O, and CH_4, global warming potential (GWP) was calculated from cumulative trace gas emissions (Table 3). 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 (CO_2=1, N_2O=298, CH_4=25) (Forster et al. 2007). In the current study, GWP was highest for plants grown in 60:40 P:WT (16.56), regardless of species, though this result was only significantly higher than plants grown in the industry standard 80:20 P:P (15.20), while remaining statistically similar to plants grown in 80:20 P:WT (15.96). This main effect was primarily derived from differences within impatiens, as GWP among the three medias only differed within impatiens.

At experiment termination, the Virginia Tech PourThru technique was helpful in assessing pH and EC of leachate from media. Recommended pH levels for coleus once established are between 5.5 and 5.8 (Croxton and Kessler 2007). While coleus substrate pH (regardless of media) at study termination was observed to be 4.26 (Table 4), no common visual problems were observed. Vinca pH and EC at study termination were found to be 4.98 and 1.30 mS per cm, respectively. While pH was slightly less than the recommended value of between 5.5 and 6.0, EC levels were within an acceptable range. Kessler (1998) reported that the EC of medium used to grow vinca should not exceed 1.0 mS per cm based on the 2:1 extraction method. When comparing techniques used to evaluate pH and EC, Lutz (2014) reported that a value of 1.0 to 2.6 mS per cm based on the pour-through method is equivalent to a value of 0.3 to 0.8 observed with the 2:1 extraction method. As with both coleus and vinca, pH levels for impatiens at study termination (4.95) were also lower than recommended levels (5.5 to 6.0; Kessler 2005); again, no associated visual problems were observed. EC values for impatiens at termination (0.92 mS per cm) were at or just below recommended levels of 1.25 to 2.0 mS per cm (saturated paste method), which is equivalent to the pour through nutrient extraction method values of 1.0 to 2.6 mS per cm (Lutz, 2014).

Without regard to plant species, pH of soilless substrates at study termination were observed to be highest in the 60:40 P:WT substrate (5.80), though not significantly different from that of the 80:20 P:P (4.35) (Table 4). Additionally, EC values were also lowest for the substrate containing the highest percentage of WT substrate (0.79 mS per cm). Results for both pH and EC are comparable to results from previous work evaluating high wood fiber substrates in the production of annual species (Fain et al. 2006, 2008, Murphy et al. 2011).

While impatiens grown in a 60:40 P:WT blend were comparable in size to those grown in the industry standard 80:20 P:P, they did have less SDW and higher cumulative CO_2 efflux over the duration of the study (Tables 1 and 3). These data indicate that results may be species specific for plants grown in higher percentages of a high wood fiber substrate. However, plants grown in up to 20% WT (as a perlite replacement) are generally comparable in size and cumulative GHG efflux to those grown in 80:20 P:P. These results are promising for greenhouse growers looking to use a more sustainable resource than perlite in their substrate mixes.

Literature Cited

Alabama Cooperative Extension System (ACES). 2013. Economic impacts of Alabama's agricultural, forestry & related industries. Combined ANR-2012, ANR-2013, ANR-2014, ANR-2015, ANR-2016, ANR-2017, and ANR-2018. Alabama Cooperative Extension System, Auburn University, AL. < https://www.madeinalabama.com/assets/ 2013/01/ECON-IMPACTS-AG.pdf>. Accessed September 11, 2020.

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.

Croxton, S. and J.R. Kessler. 2007. Greenhouse production of coleus. Alabama Coop. Ext. Sys. ANR-1314. < https://ssl.acesag.auburn.edu/pubs/docs/A/ANR-1314/ANR-1314-archive.pdf>. Accessed September 11, 2020.

Du, C., J. Wang, P. Chu, and Y. Guo. 2010. Acute expanded perlite exposure with persistent reactive airway dysfuntion syndrome. Industrial Health 48:119–122.

Fain, G.B., C.H. Gilliam, J.L. Sibley, and C.R. Boyer. 2006. Evaluation of an alternative, sustainable substrate for use in greenhouse crops. Proc. Southern Nursery Assn. Res. Conf. 51:651–654.

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. P. 129-146. 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. Marquis, M., K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, New York, NY.

Frey, W.H. 2018. The millennial generation: A demographic bridge to America's diverse future. Brookings Inst. Jan. 2018. < https://www.brookings.edu/wp-content/uploads/2018/01/2018-jan_brookings-metro_millennials-a-demographic-bridge-to-americas-diverse-future.pdf>. Accessed September 10, 2019.

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

Hall, C.R. and D.L. Ingram. 2015. Carbon footprint and production costs associated with varying the intensity of production practices during field-grown shrub production. HortScience 50:402-407.

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. 2012. Life cycle assessment of a field-grown red maple tree to estimate its carbon footprint components. Intl. J. Life Cycle Assess. 17(4):453-462.

Ingram, D.L. 2013. Life cycle assessment to study the carbon footprint of system components for Colorado blue spruce field production and landscape use. J. Amer. Soc. Hort. Sci. 138:3-11.

Ingram, D.L. and C.R. Hall. 2013. Carbon footprint and related production costs of system components of a field-grown *Cercis canadensis* L. 'Forest Pansy' using life cycle assessment. J. Environ. Hort. 31:169-176.

Ingram, D.L. and C.R. Hall. 2014a. Carbon footprint and related production costs of system components for a field-grown *Viburnum* × *juddi* using life cycle assessment. J. Environ. Hort. 32:175-181.

Ingram, D.L. and C.R. Hall. 2014b. Life cycle assessment used to determine the potential environmental factors and water footprint of field-grown tree production inputs and processes. J. Amer. Soc. Hort. Sci. 140:1021-1107.

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.

Jenkins, J.R. and W.M. Jarrell. 1989. Predicting physical and chemical properties of container mixtures. HortScience 24:292-295.

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.

Kessler, J.R. 1998. Greenhouse production of annual vinca. Alabama Coop. Ext. Sys. ANR-1119.

Kessler, J.R. 2005. Greenhouse production of impatiens. Alabama Coop. Ext. Sys. ANR-1113.

Kroeze, C., A.R. Mosier, and L. Bouwman. 1999. Closing the global N_2O budget: A retrospective analysis 1500-1994. Global Biogeochemical Cycles 13:1-8.

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

Loudenback, T. and A. Jackson. 2018. The 10 most critical problems in the world, according to millennials. Business Insider. < https://www.businessinsider.com/world-economic-forum-world-biggest-problems-concerning-millennials-2016-8>. Accessed September 10, 2019.

Lutz, J. 2014. Test media pH and EC with the 2:1 technique, pour-through method and saturated media extract method. Greenhouse Grower. <https://www.greenhouse grower.com/production/crop-inputs/test-media-ph-and-ec-with-the-21-technique-pour-through-method-and-saturated-media-extract-methods/>. Accessed September 12, 2019.

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(3):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.

Mathez, E.A. 2009. Climate Change. Columbia University Press. New York, NY. 84pp.

Maxim, L.D., R. Niebo and E.E. McConnell. 2014. Perlite toxicology and epidemiology – a review. Inhalation Toxicology 26:259-270.

Mosier, A.R., G.A. Peterson, and L.A. Sherrod. 2003. Mitigating net global warming potential (CO2, CH4 and N2O) in upland crop productions. Methane and Nitrous Oxide International Workshop Proceedings. 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. 29:152-161.

Murphy, A.M., G.B. Runion, S.A. Prior, H.A. Torbert, J.L. Sibley, and C.H. Gilliam. 2018. Greenhouse gas emissions from an ornamental crop as impacted by two best management practices: Irrigation delivery and fertilizer placement. J. Environ. Hort. 36:58-65.

Murphy, A.M., G.B. Runion, S.A. Prior, H.A. Torbert, J.L. Sibley, G.B. Fain, and J.M. Pickens. 2019. Effects of fertilizer placement on greenhouse gas emissions from a sun and shade grown ornamental crop. J. Environ. Hort. 37:74-80.

Nelson, Paul V. 2011. Greenhouse Operation and Management. 7th ed. Prentice Hall, Boston, MA.

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., A. Mosier, J. Smith, R. Venterea, J. Johnson, D. Reicosky, G. Doyle, G. McCarty, J. Baker. 2003. USDA-ARS GRACEnet chamber-based trace gas flux measurement protocol. Trace Gas Protocol Development Committee, 28pp. < https://www.ars.usda.gov/ARSUserFiles/31831/2003GRACEnetTraceGasProtocol.pdf>. Accessed September 11, 2020.

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.

Polatli, M., M. Erdinç, E.E Erdinç, and E. Okyay. 2001. Perlite exposure and 4-year change in lung function. Environ. Res. 86:238–243.

Wright, R.D. 1986. The pour-through nutrient extraction procedure. HortScience 21:227-229.

Table 1. Total cumulative CO_2, N_2O, and CH_4 efflux[z] over 52 days from three container-grown annual species[y] in one of three substrate blends.

Main Effects		Cumulative Efflux		
Species Effect		CO_2-C (mg/pot)	N_2O-N (mg/pot)	CH_4 (mg/pot)
Coleus		1641.1 a[w]	0.1305[ns]	-0.1753[ns]
Vinca		1537.5 ab	0.1401	-0.0017
Impatiens		1470.5 b	0.1307	-0.3084
	p:	*0.019*	*0.840*	*0.188*
Media Effect				
80:20 Peat:Perlite		1483.1 b	0.1284[ns]	-0.0365[ns]
80:20 Peat:Wholetree		1550.5 ab	0.1320	0.2364
60:40 Peat:Wholetree		1615.6 a	0.1409	-0.0686
	p:	*0.082*	*0.788*	*0.446*

Interaction Effects				Cumulative Efflux		
Species		Media		CO_2-C (mg/pot)	N_2O-N (mg/pot)	CH_4 (mg/pot)
Coleus	-	80:20 Peat:Perlite		1585.4[ns]	0.1151[ns]	-0.3404[ns]
Coleus	-	80:20 Peat:Wholetree		1634.7	0.1396	-0.0176
Coleus	-	60:40 Peat:Wholetree		1703.1	0.1367	-0.1680
Vinca	-	80:20 Peat:Perlite		1536.4[ns]	0.1429[ns]	-0.0296[ns]
Vinca	-	80:20 Peat:Wholetree		1545.0	0.1223	0.2196
Vinca	-	60:40 Peat:Wholetree		1531.1	0.1552	-0.1951
Impatiens	-	80:20 Peat:Perlite		1327.4 b	0.1271[ns]	0.2607[ns]
Impatiens	-	80:20 Peat:Wholetree		1471.8 ab	0.1342	0.5072
Impatiens	-	60:40 Peat:Wholetree		1612.4 a	0.1309	0.1572
			p:	*0.368*	*0.854*	*0.986*

[z] Cumulative efflux for 52 days (18 June 2018 to 9 August 2018) was calculated using the trapezoid rule (n=4).

[y] 'Redhead' coleus (*Solenostemon scutellarioides* 'Redhead'), 'Cooler Grape' vinca (*Catharanthus roseus* 'Cooler Grape'), and 'Super Elfin White' impatiens (Impatiens walleriana 'Super Elfin XP White') were potted into 1.33L (1.41 qt) containers filled with one of three substrates (80:20 peat:perlite, 80:20 peat:Wholetree, or 60:40 peat:Wholetree), and amended with 1.2 $kg \cdot m^{-3}$ (2.0 $lb \cdot yd^{-3}$) 7-2-10 N-P-K starter nutrient charge, 0.6 $kg \cdot m^{-3}$ (1.2 $lb \cdot yd^{-3}$) Aqua-Gro G wetting agent, and 3.0 $kg \cdot m^{-3}$ (5.0 $lb \cdot yd^{-3}$) dolomitic limestone.

[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. For interaction effects, letters designate differences within species only.

[ns] Not significantly different.

Table 2. Dry weights[z,y] and growth indices following 52 days of growth for three container-grown annual species[x] in one of three substrate blends.

Main Effects: Species Effect		Shoot Dry Weight (g)	Root Dry Weight (g)	Total Dry Weight (g)[w]	Shoot Dry Weight as % Total	Growth Index[v]
Coleus		14.83 a[u]	2.75 a	17.58 a	84.28 b	37.92 a
Vinca		8.02 b	0.98 b	9.00 b	88.76 a	24.95 b
Impatiens		7.08 b	1.00 b	8.07 b	87.43 a	25.08 b
	p:	*<0.001*	*<0.001*	*<0.001*	*0.001*	*<0.001*
Media Effect						
80:20 Peat:Perlite		11.53 a	1.74[ns]	13.27 a	87.69[ns]	30.78 a
80:20 Peat:Wholetree		10.04 b	1.53	11.56 b	87.31	30.28 a
60:40 Peat:Wholetree		8.36 c	1.46	9.82 c	85.47	26.89 b
	p:	*<0.001*	*0.070*	*<0.001*	*0.109*	*<0.001*

Interaction Effects: Species		Media		Shoot Dry Weight (g)	Root Dry Weight (g)	Total Dry Weight (g)	Shoot Dry Weight as % Total	Growth Index
Coleus	-	80:20 Peat:Perlite		16.80 a	3.16 a	19.96 a	84.10[ns]	38.83 a
Coleus	-	80:20 Peat:Wholetree		14.41 b	2.60 b	17.01 b	84.61	39.16 a
Coleus	-	60:40 Peat:Wholetree		13.26 b	2.50 b	15.77 b	84.12	35.75 b
Vinca	-	80:20 Peat:Perlite		9.68 a	1.06[ns]	10.74 a	90.15[ns]	27.67 a
Vinca	-	80:20 Peat:Wholetree		8.55 a	1.02	9.56 a	89.30	26.17 a
Vinca	-	60:40 Peat:Wholetree		5.82 b	0.88	6.70 b	86.84	21.00 b
Impatiens	-	80:20 Peat:Perlite		8.09 a	1.02[ns]	9.11 a	88.82[ns]	25.84[ns]
Impatiens	-	80:20 Peat:Wholetree		7.15 ab	0.97	8.12 ab	88.02	25.50
Impatiens	-	60:40 Peat:Wholetree		5.99 b	1.00	6.99 b	85.44	23.92
			p:	*0.431*	*0.214*	*0.269*	*0.703*	*0.055*

[z] Shoot dry weights (g) determined by drying the above-substrate portion of the plant in a 76.7 C (170.0 F) forced air oven for 72 hours.

[y] Root dry weights (g) were determined by removing the substrate from root interface, and drying the within-substrate portion of the plant in a 76.7 C (170.0 F) forced air oven for 144 hours.

[x] 'Redhead' coleus (*Solenostemon scutellarioides* 'Redhead'), 'Cooler Grape' vinca (*Catharanthus roseus* 'Cooler Grape'), and 'Super Elfin White' impatiens (Impatiens walleriana 'Super Elfin XP White') were potted into 1.33L (1.41 qt) containers filled with one of three substrates (80:20 peat:perlite, 80:20 peat:Wholetree, or 60:40 peat:Wholetree), and amended with 1.2 $kg\cdot m^{-3}$ (2.0 $lb\cdot yd^{-3}$) 7-2-10 N-P-K starter nutrient charge, 0.6 $kg\cdot m^{-3}$ (1.2 $lb\cdot yd^{-3}$) Aqua-Gro G wetting agent, and 3.0 $kg\cdot m^{-3}$ (5.0 $lb\cdot yd^{-3}$) dolomitic limestone.

[w] Total dry weight = Shoot dry weight + root dry weight.

[v] Growth index = [(height + width1 + width2) / 3].

[u] 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. For interaction effects, letters designate differences within species only.

[ns] Not significantly different.

Table 3. Percent contribution to Global Warming Potential[z] of three container-grown annual species[y] in one of three substrate blends.

Main Effects			% Contribution		
Species Effect		GWP[x]	CO_2-C (%)	N_2O-N (%)	CH_4 (%)
Coleus		16.76 a[w]	97.95[ns]	2.31[ns]	-0.25[ns]
Vinca		15.79 ab	97.35	2.64	0.01
Impatiens		15.17 b	96.80	2.62	0.59
	p:	*0.024*	*0.134*	*0.577*	*0.170*
Media Effect					
80:20 Peat:Perlite		15.20 b	97.39[ns]	2.55[ns]	0.06[ns]
80:20 Peat:Wholetree		15.96 ab	97.15	2.46	0.38
60:40 Peat:Wholetree		16.56 a	97.55	2.55	-0.10
	p:	*0.060*	*0.769*	*0.961*	*0.545*

Interaction Effects					% Contribution		
Species		Media		GWP	CO_2-C (%)	N_2O-N (%)	CH_4 (%)
Coleus	-	80:20 Peat:Perlite		16.11[ns]	98.37[ns]	2.11[ns]	-0.49[ns]
Coleus	-	80:20 Peat:Wholetree		16.76	97.56	2.47	-0.03
Coleus	-	60:40 Peat:Wholetree		17.40	97.92	2.33	-0.25
Vinca	-	80:20 Peat:Perlite		15.78[ns]	97.32[ns]	2.69[ns]	-0.01[ns]
Vinca	-	80:20 Peat:Wholetree		15.87	97.36	2.29	0.35
Vinca	-	60:40 Peat:Wholetree		15.73	97.36	2.94	-0.30
Impatiens	-	80:20 Peat:Perlite		13.72 a	96.46[ns]	2.85[ns]	0.68[ns]
Impatiens	-	80:20 Peat:Wholetree		15.24 ab	96.55	2.62	0.83
Impatiens	-	60:40 Peat:Wholetree		16.55 b	97.38	2.37	0.25
			p:	*0.336*	*0.856*	*0.732*	*0.975*

[z] Global Warming Potential (GWP) is calculated on a per container basis from cumulative trace gas emissions across the entire study (18 June 2018 to 9 August 2018). 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] 'Redhead' coleus (*Solenostemon scutellarioides* 'Redhead'), 'Cooler Grape' vinca (*Catharanthus roseus* 'Cooler Grape'), and 'Super Elfin White' impatiens (Impatiens walleriana 'Super Elfin XP White') were potted into 1.33L (1.41 qt) containers filled with one of three substrates (80:20 peat:perlite, 80:20 peat:Wholetree, or 60:40 peat:Wholetree), and amended with 1.2 $kg \cdot m^{-3}$ (2.0 $lb \cdot yd^{-3}$) 7-2-10 N-P-K starter nutrient charge, 0.6 $kg \cdot m^{-3}$ (1.2 $lb \cdot yd^{-3}$) Aqua-Gro G wetting agent, and 3.0 $kg \cdot m^{-3}$ (5.0 $lb \cdot yd^{-3}$) dolomitic limestone.

[x] GWP values are $\times 10^{-4}$.

[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. For interaction effects, letters designate differences within species only.

[ns] Not significantly different.

Table 4. Leachate analysis[z], including pH and electrical conductivity, following 52 days of growth for three container-grown annual species[y] in one of three substrate blends.

Main Effects		pH	EC[x]
Species Effect			
Coleus		4.26[w,ns]	0.93 b
Vinca		4.98	1.30 a
Impatiens		4.95	0.92 b
	p:	*0.533*	*0.036*
Media Effect			
80:20 Peat:Perlite		4.35 ab	1.22 a
80:20 Peat:Wholetree		4.03 b	1.14 a
60:40 Peat:Wholetree		5.80 a	0.79 b
	p:	*0.047*	*0.003*

Interaction Effects					
Species		Media			
Coleus	-	80:20 Peat:Perlite		3.61[ns]	1.00[ns]
Coleus	-	80:20 Peat:Wholetree		3.81	0.79
Coleus	-	60:40 Peat:Wholetree		5.35	0.99
Vinca	-	80:20 Peat:Perlite		5.13[ns]	1.59 a
Vinca	-	80:20 Peat:Wholetree		3.89	1.52 a
Vinca	-	60:40 Peat:Wholetree		5.91	0.80 b
Impatiens	-	80:20 Peat:Perlite		4.32[ns]	1.08[ns]
Impatiens	-	80:20 Peat:Wholetree		4.39	1.10
Impatiens	-	60:40 Peat:Wholetree		6.14	0.57
			p:	*0.926*	*0.162*

[z] Leachate collected using the Virginia Tech pour-through method (Wright, 1986).

[y] 'Redhead' coleus (*Solenostemon scutellarioides* 'Redhead'), 'Cooler Grape' vinca (Catharanthus roseus 'Cooler Grape'), and 'Super Elfin White' impatiens (Impatiens walleriana 'Super Elfin XP White') were potted into 1.33L (1.41 qt) containers filled with one of three substrates (80:20 peat:perlite, 80:20 peat:Wholetree, or 60:40 peat:Wholetree), and amended with 1.2 $kg{\cdot}m^{-3}$ (2.0 $lb{\cdot}yd^{-3}$) 7-2-10 N-P-K starter nutrient charge, 0.6 $kg{\cdot}m^{-3}$ (1.2 $lb{\cdot}yd^{-3}$) Aqua-Gro G wetting agent, and 3.0 $kg{\cdot}m^{-3}$ (5.0 $lb{\cdot}yd^{-3}$) dolomitic limestone.

[x] EC = electrical conductivity (mS/cm).

[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. For interaction effects, letters designate differences within species only.

[ns] Not significantly different.

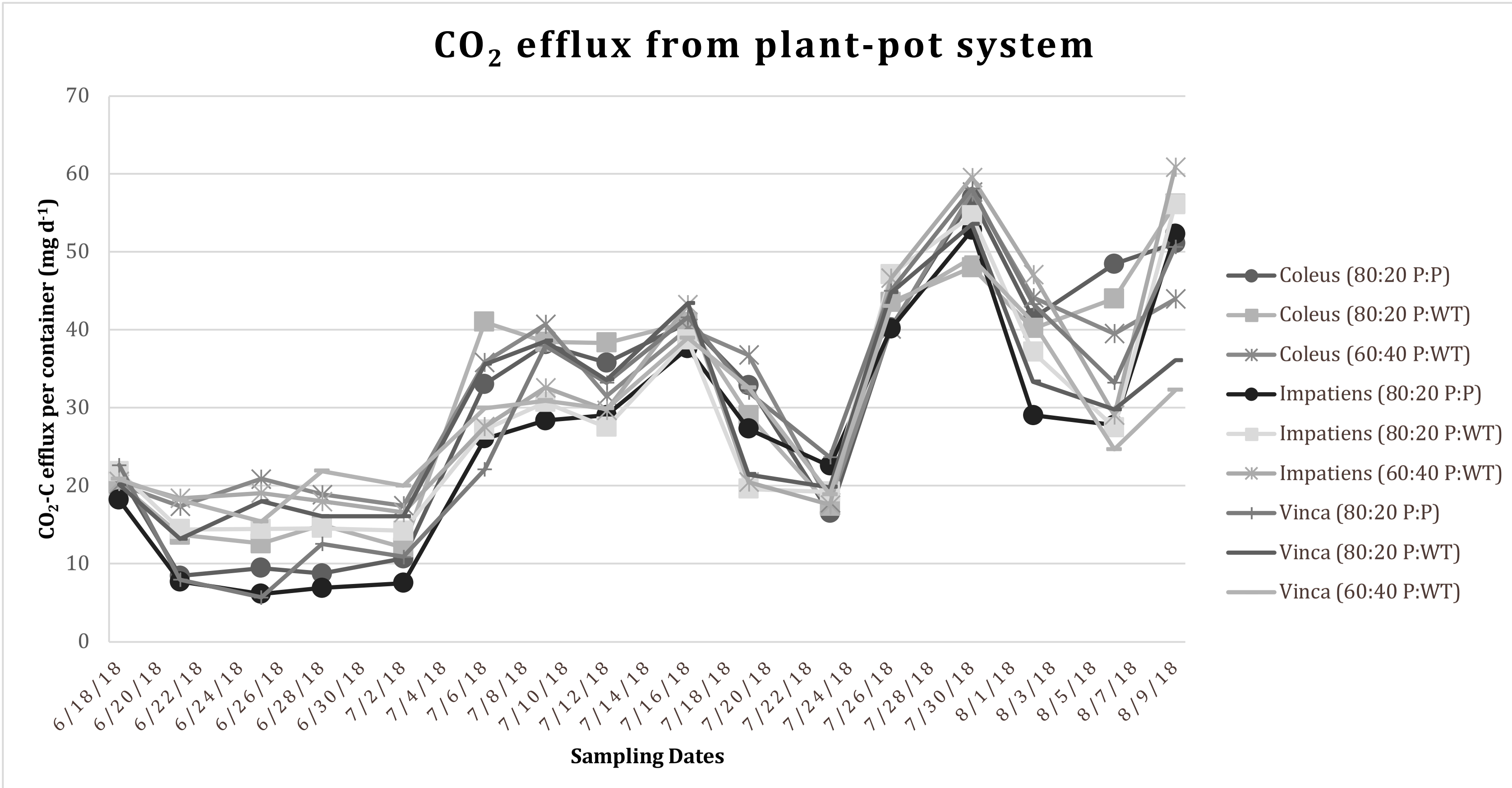

Fig. 1. Daily CO_2-C efflux for three annual species grown in three substrates. Measurements are for a time period of approximately 52 days (18 June 2018 to 9 August 2018). For substrates, 80:20 P:P = 80% peat:20% perlite, 80:20 P:WT = 80% peat:20% Whole Tree, and 60:40 P:WT = 60% peat: 40% Whole Tree.

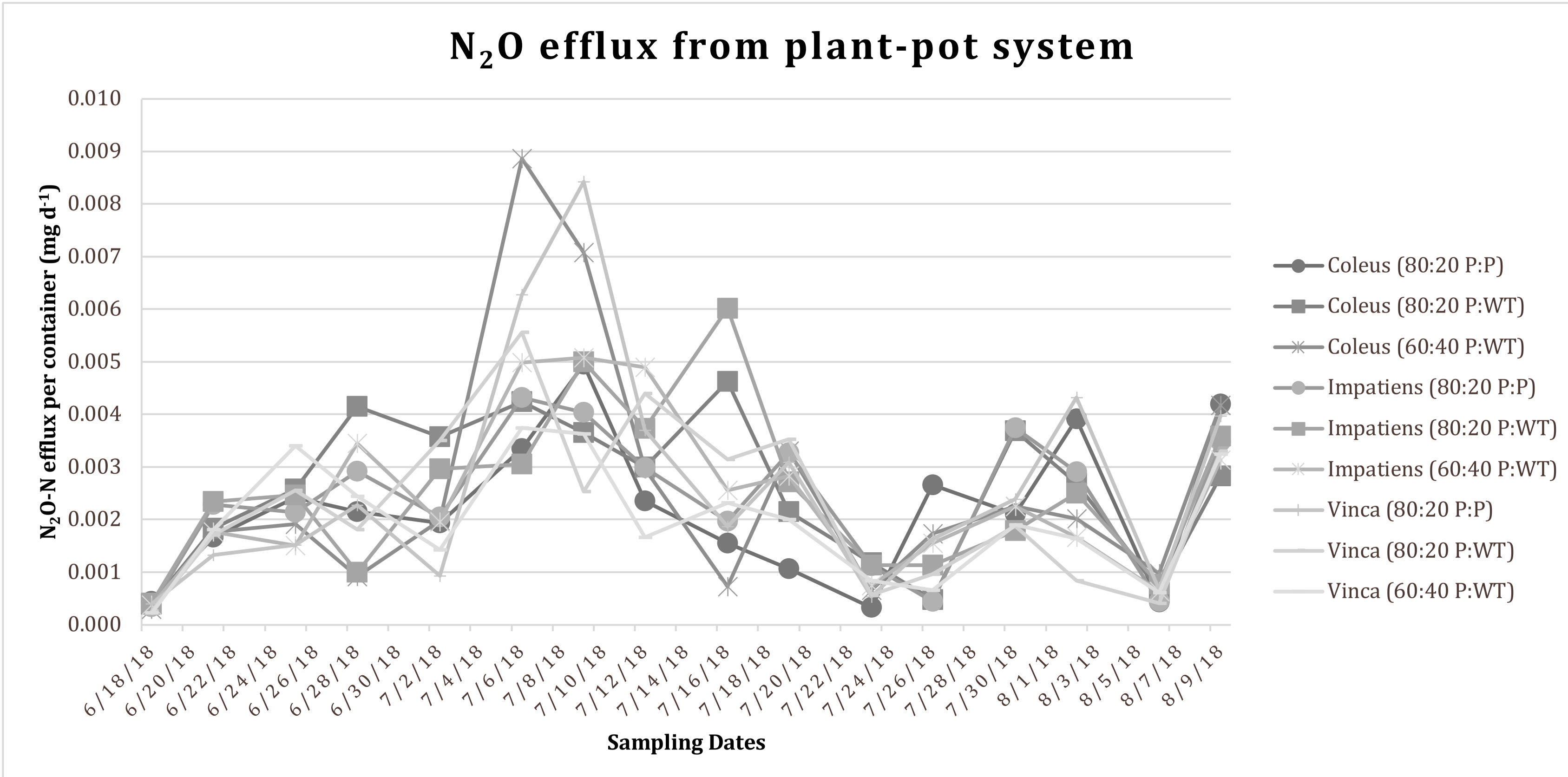

Fig. 2. Daily N_2O-C efflux for three annual species grown in three substrates. Measurements are for a time period of approximately 52 days (18 June 2018 to 9 August 2018). For substrates, 80:20 P:P = 80% peat:20% perlite, 80:20 P:WT = 80% peat:20% Whole Tree, and 60:40 P:WT = 60% peat: 40% Whole Tree.

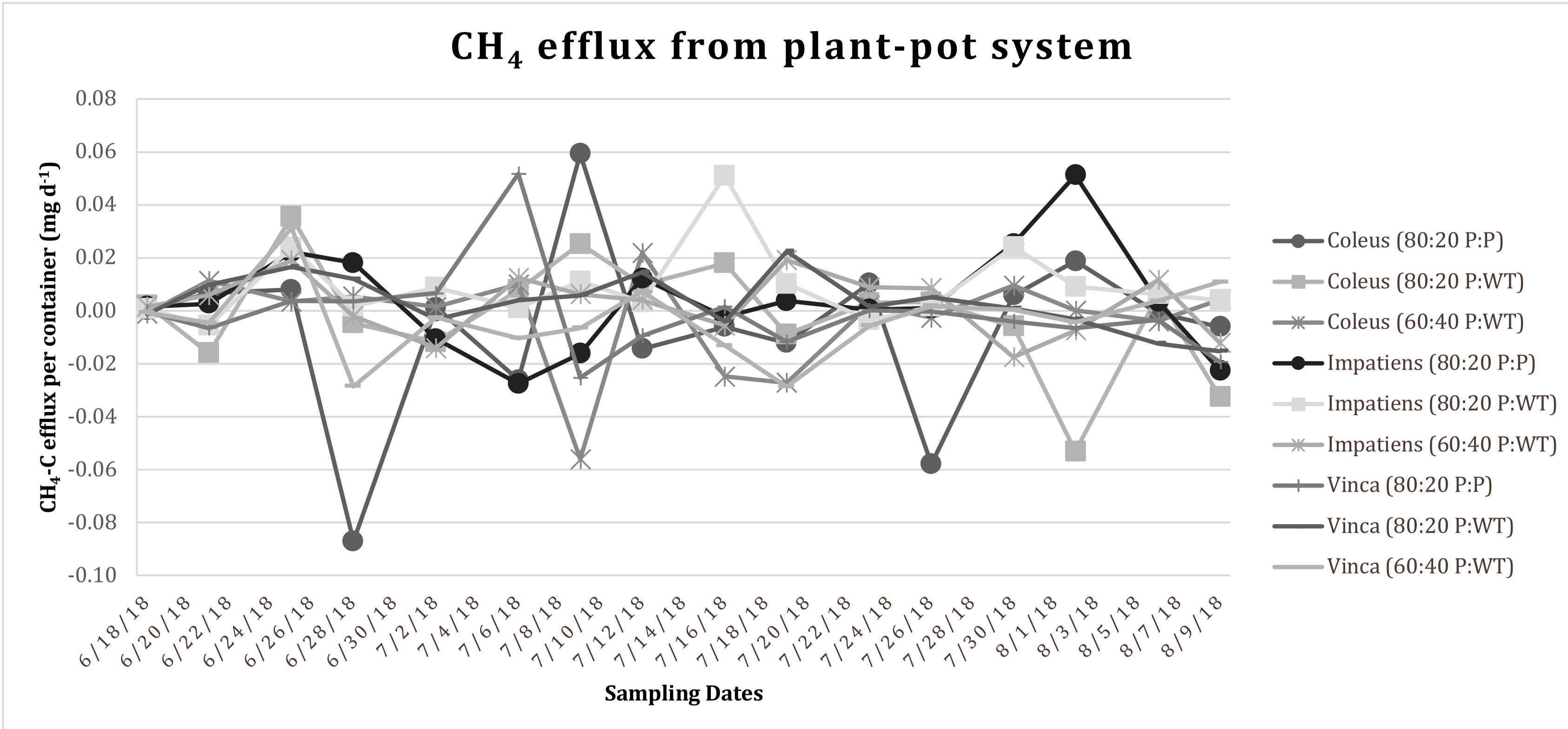

Fig. 3. Daily CH_4-C efflux for three annual species grown in three substrates. Measurements are for a time period of approximately 52 days (18 June 2018 to 9 August 2018). For substrates, 80:20 P:P = 80% peat:20% perlite, 80:20 P:WT = 80% peat:20% Whole Tree, and 60:40 P:WT = 60% peat: 40% Whole Tree.

CHAPTER V

Final Discussion

The increase in atmospheric concentrations of greenhouse gases (GHGs), including CO_2, N_2O, CH_4, O_3, water vapor, and various other fluorinated gases, is directly correlated to a rise in Earth's average temperature, and is the focus of much scientific concern and debate. While natural sources make up a percentage of annual emissions, emissions as a function of human activities are thought to be the cause of the current increased warming rate, which exceeds that of the last 200 years. In the United States, the primary categories of anthropogenically derived emissions are transportation, electricity production, industry, commercial and residential (including heat production and the handling of waste), agriculture, and land use/forestry.

In a review of the literature, we sought to summarize the sources of three of the most prevalent GHGs, including N_2O, CO_2, and CH_4, and to describe the relative impact of each gas through a description of global warming potential (GWP). Agricultural applications of synthetic and organic fertilizers account for the majority of increases to atmospheric N_2O. Previous research has evaluated efforts to reduce GHGs by attempting to dial down on the most efficient forms, dosage and delivery of fertilizer to crops, often as a response to the increasing costs of fertilizers. While N_2O accounted for around 6.5% of anthropogenically-driven GHG emissions in the United States in 2018, compared to CO_2

which accounted for more than 80%, its contribution to GWP is between 265 and 298 times that of CO_2, on a molecule-to-molecule basis. Intervention efforts focused on the mitigation of N_2O may be more impactful for the agriculture industry than those aimed at mitigating CO_2. While less than that of N_2O, agricultural emissions of CO_2 generally arise from applications of lime and urea, as well as from the clearing of land for commercial and residential settlement and agricultural purposes. Non-natural sources of CH_4 are generally attributed to livestock production, waste management, the cultivation of wetland crops, and the burning of biomass. As a part of the literature review, we summarized the previous work in the nursery, greenhouse, and floriculture industry, an industry which, in 2018, accounted for more than $16.7 billion in direct sales and the direct employment of more than 134,000 people.

Nursery, greenhouse, and floriculture producers employ a variety of best management practices in the production of ornamental plants. Growers must select appropriate substrates and amendments (fertilizers, lime, micronutrients, etc.) in their endeavor to produce marketable plants. Additionally, they must decide how to water their crops, and address any pest problems (including weeds, insects, and/or diseases). Growers may need to consider location, operation size, crop species, market, and budget in their decision-making process. Environmental regulations aimed at legislating GHGs from this industry may be forthcoming, adding additional considerations to standard production practices.

In an evaluation of fertilizer placement (incorporated vs. dibbled) and irrigation delivery method (overhead vs. micro-emitted) as factors affecting GHG emissions in nursery production, gas samples were collected from the entire plant-pot systems of boxwoods (*Buxus microphylla*) grown in 3-gal containers over a period of nine months. All containers received 76 g (equivalent to 6.5 kg/m^3, or 11 lb/yd^3) of a standard poly-coated fertilizer [Polyon 17-5-11, 5-6 month release, with micronutrients (Harrell's LLC, Lakeland, FL)] and 0.25 inch (6.35mm) irrigation three times daily, through their respective delivery methods. Gas samples were collected once or twice weekly, and analyzed with gas chromatography. Results from the study indicated that cumulative CO_2 emissions across the entire sampling period were not significantly affected by irrigation method, fertilizer placement, or their interaction. Cumulative N_2O emissions were affected by the interaction of irrigation delivery method and fertilizer placement, as plant-pot systems with incorporated fertilizer receiving overhead irrigation had the highest N_2O emissions across the study. When limited to overhead irrigation, switching from incorporated to dibbled fertilizer could significantly reduce N_2O emissions. However, regardless of fertilizer placement, plants watered through micro-emitters, had the least N_2O emissions. While the percent contribution of each GHG to GWP was affected (CO_2 and CH_4 contributed more to GWP with micro-emitted irrigation and dibbled fertilizer), overall GWP was not affected by irrigation, fertilizer placement, or their interaction.

As an extension of the research in Chapter 2, fertilizer placement (incorporated, dibbled, or top-dressed) was evaluated as a factor affecting GHG emissions in the production of two popular perennial plants in Chapter 3. Plants were chosen based on their light requirement and included sun-grown daylily (*Hemerocallis* × 'Stella D'Oro' L.) and shade-grown hosta (*Hosta* × 'Royal Standard', or *Hosta plantaginea* Aschers × *Hosta sieboldiana* N.Fujita). Gas samples for the study were collected weekly across a five month period from mid-April to mid-September. Fertilizer was applied as previously described at a rate of 25 g per container (equivalent to 6.5 kg/m^3, or 11 lb/yd^3).

Both daylily and hosta fertilized with the dibbled method had less cumulative CO_2 emissions than their top-dressed or incorporated counterparts. Larger, shade-grown hosta had higher cumulative CO_2 emissions than daylily, though that is to be expected based off of estimations associated with plant size alone. Results regarding N_2O emissions were consistent with those found in Chapter 2, as findings suggested that dibbling fertilizer could significantly decrease cumulative N_2O emissions. Again, plant size is thought to account for differences between species with regard to N_2O emissions. The much larger hosta plants would predictably assimilate more N than daylily, resulting in less cumulative N_2O loss across the duration of the study. Differences in emissions were varied enough that differences in GWP were also observed. Regardless of species, utilization of the dibbled fertilizer method resulted in a more than 30% reduction in GWP compared plant-pot systems with incorporated fertilizer. For research presented in both Chapters 2 and 3, results describing CH_4 emissions were minimal, which is to be expected in well-drained, pine bark based substrates.

Finally, work in Chapter 4 focused on substrate's effect on GHG emissions in the greenhouse production of three annual crops [coleus (*Solenostemon scutellarioides* Thonn. 'Redhead'), vinca (*Catharanthus roseus* L. 'Cooler Grape'), and impatiens (*Impatiens walleriana* Hook. f. 'Super Elfin XP White')] grown in 1.33 L (1.41 qt) containers. An industry standard substrate (80:20 peat:perlite) was compared to one amended with WholeTree instead of perlite (80:20 peat:WholeTree), and another with an increased percentage of WholeTree (60:40

peat:WholeTree). Greenhouse substrates generally have much higher water holding capacities than bark-based substrates, so irrigation was applied by hand to each individual pot as needed. Gas samples were collected twice weekly for the duration of the 52 day study. As with the perennial crop study, plant size was a determination in cumulative CO_2 emissions, as emissions of CO_2 decreased as did plant size; coleus had the highest cumulative CO_2 emissions, followed by vinca, followed by impatiens. Without regard to plant species however, substrate also had a significant effect on cumulative CO_2 emissions. Substrates with 40% WholeTree had the highest cumulative emissions (and the smallest size according to growth indices and shoot dry weights), though not significantly different from those amended with 20% WholeTree. The industry standard substrate (80:20 peat:perlite) had the least cumulative CO_2 emissions (and coincidentally, the largest growth indices and shoot dry weight), though again, values were not significantly different from those amended with 20% WholeTree. Because of this departure from previous studies where larger plants generally signified higher cumulative CO_2 emissions, elevated levels are thought to be directly affected by substrate. Due to the short duration of the study, and the relatively quick release of N forms used as fertilizer, no differences were observed for N_2O emissions due to main effect (plant species or substrate) or an interaction of the two. Results for GWP indicated no differences between the industry standard substrate (80:20 peat:perlite) and that in which the perlite was replaced with WholeTree (80:20 peat:WholeTree). Data in Chapter 4 indicated that further study may be required to make any general statements on the mitigation potential of alternative substrates in the production of greenhouse-grown annuals, and that due to the relatively short growing season, suggestions may be species specific.

Results from these studies serve to further establish the mitigation potential of altering best management practices in the horticultural production of ornamental crops.

While small changes such as fertilizer placement may seem intangible in efforts to mitigate climate change through a reduction in GHGs, it will likely be the collective body of efforts just like these, across an array of various industries, that will have an impact. In the nursery, greenhouse and floriculture industry alone, there are likely a number of obstacles to consider in mitigation efforts, of which cost is likely prevailing. Private C exchanges have proven effective at incentivizing mitigation efforts in a number of other industries, and may be effective in ornamental plant production as well, provided evidence can be offered for the quantifiable amount of GHGs certain production practices can reduce. Though additional research across additional species would presumably be required to validate results and further build a database of baseline estimations, this work sought to further understand the mitigation potential of fertilizer placement, irrigation delivery method, and substrate.