# Effects of Growth Substrate on Greenhouse Gas Emissions from Three Annual Species[1]

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## 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 numerically 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.

**Index words:** alternative substrate, WholeTree, carbon sequestration, carbon dioxide, nitrous oxide, methane, global climate change.

**Species used in this study:** 'Redhead' coleus, *Solenostemon scutellarioides* Thonn. 'Redhead'; 'Cooler Grape' vinca, *Catharanthus roseus* L. 'Cooler Grape'; 'Super Elfin XP White' impatiens, *Impatiens walleriana* Hook. f. 'Super Elfin XP White'.

### 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.

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### 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 (1gal), 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* x 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* x 'Stella D'Oro')] and shade-grown ['Royal Standard' hosta (*Hosta* x '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 U.S. 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

**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.

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 (Parkin et al. 2003, Hutchinson and Mosier 1981, Hutchinson and Livingston 1993, Parkin and Kaspar 2006). Polyvinyl chloride (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).

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·m$^{-3}$ (2.0 lb·yd$^{-3}$) 7-2-10 N-P-K starter nutrient charge, 0.6 kg·m$^{-3}$ (1.2 lb·yd$^{-3}$) Aqua-Gro G wetting agent, and 3.0 kg·m$^{-3}$ (5.0 lb·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≤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.

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 by 3 factorial design (3 species by 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 ≤ 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

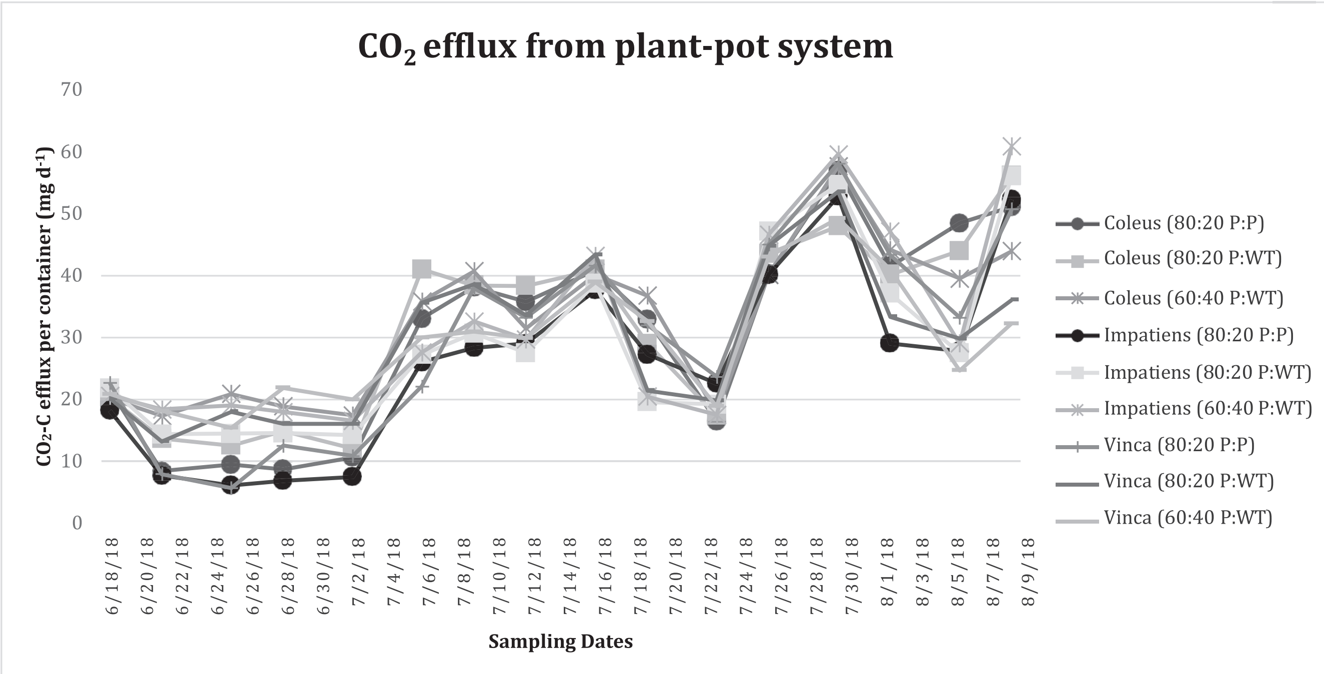


**Fig. 1. Daily $CO_2$-C efflux for three annual species grown in three substrates. Measurements are for a time period of approximately 52 days (18 June 2018 to 9 August 2018). For substrates, 80:20 P:P = 80% peat:20% perlite, 80:20 P:WT = 80% peat:20% Whole Tree, and 60:40 P:WT = 60% peat: 40% Whole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

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 cumula-

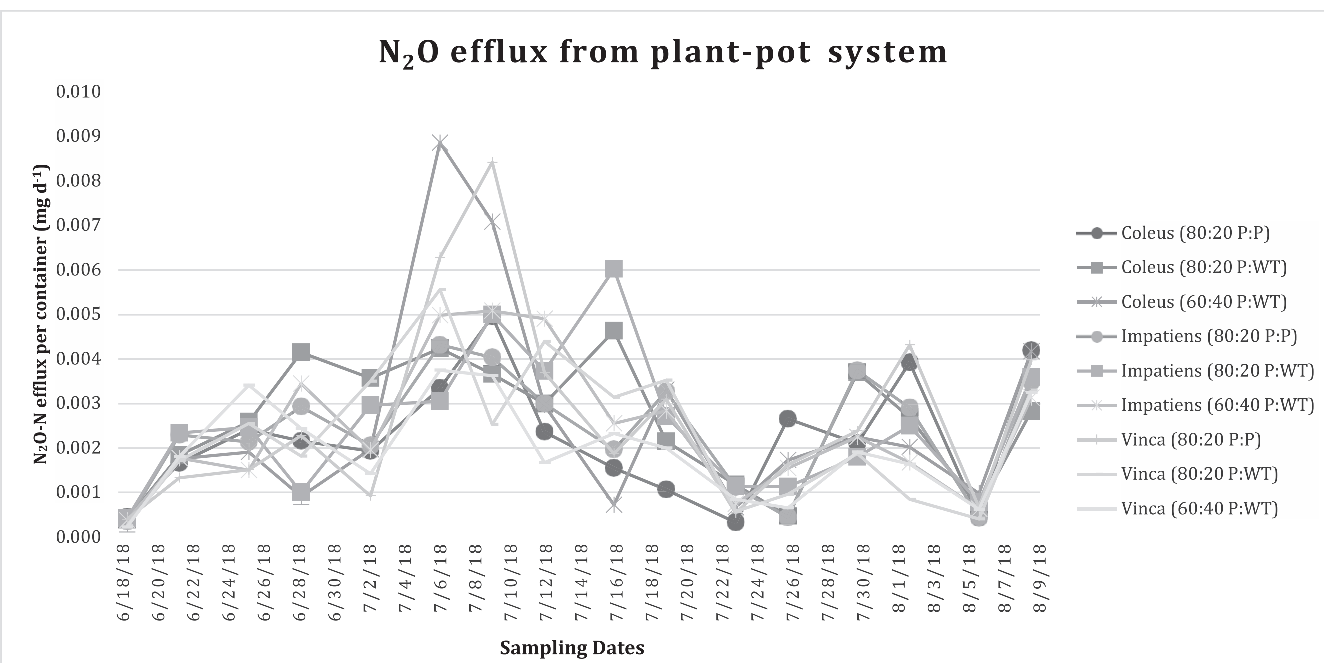


**Fig. 2. Daily $N_2O$-N efflux for three annual species grown in three substrates. Measurements are for a time period of approximately 52 days (18 June 2018 to 9 August 2018). For substrates, 80:20 P:P = 80% peat:20% perlite, 80:20 P:WT = 80% peat:20% Whole Tree, and 60:40 P:WT = 60% peat: 40% Whole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

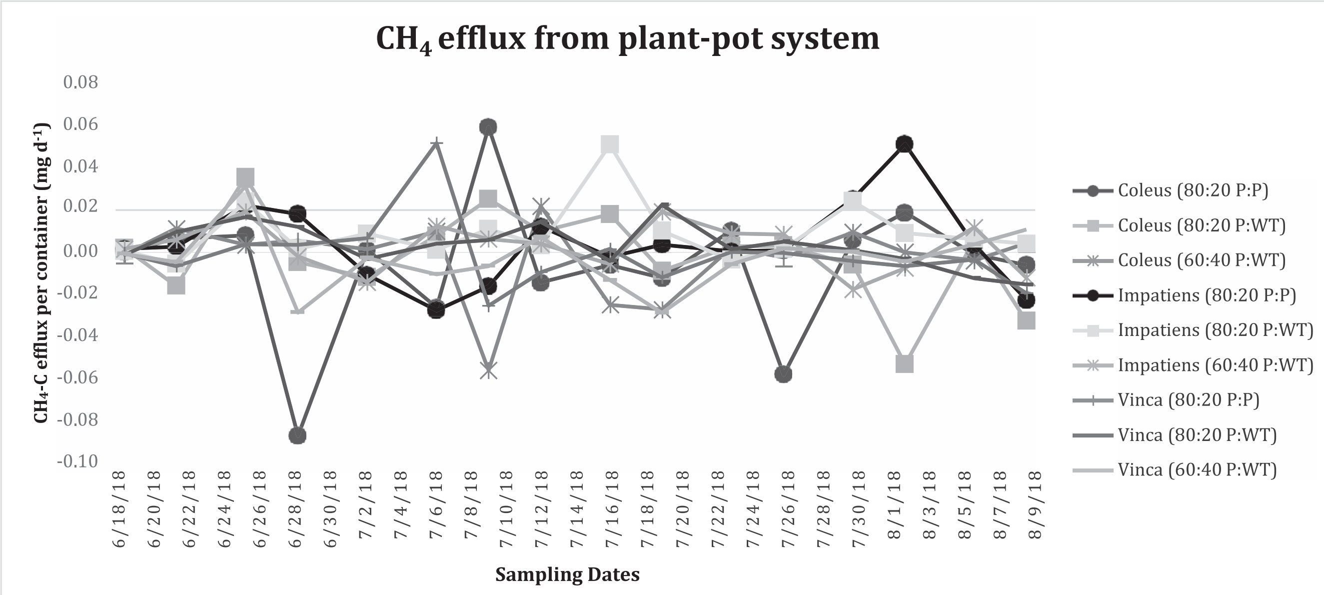


**Fig. 3. Daily $CH_4$-C efflux for three annual species grown in three substrates. Measurements are for a time period of approximately 52 days (18 June 2018 to 9 August 2018). For substrates, 80:20 P:P = 80% peat:20% perlite, 80:20 P:WT = 80% peat:20% Whole Tree, and 60:40 P:WT = 60% peat: 40% Whole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

**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 | | | | |
|---|---|---|---|---|
| **Species Effect** | | | **pH** | **EC[x]** |
| 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.

tive $CO_2$ 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 numerically 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 $mS.cm^{-1}$, 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 $mS \cdot cm^{-1}$ 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 $mS \cdot cm^{-1}$ 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 $mS \cdot cm^{-1}$ (saturated paste method), which is equivalent to the pour through nutrient extraction method values of 1.0 to 2.6 $mS \cdot cm^{-1}$ (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·cm$^{-1}$). 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.

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