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Biocontainer Use in a *Petunia ×hybrida* Greenhouse Production System: a Cradle-to-gate Carbon Footprint Assessment of Secondary Impacts

Andrew K. Koeser[1]
Department of Environmental Horticulture, Center For Landscape Conservation and Ecology, IFAS, University of Florida–Gulf Coast Research and Education Center, 14625 County Road 672, Wimauma, FL 33598

Sarah T. Lovell
Department of Crop Sciences, University of Illinois at Urbana–Champaign, 1009 Plant Sciences Laboratory, 1201 S. Dorner Drive, Urbana, IL 61801

Aaron C. Petri
Smart Energy Design Assistance Center (SEDAC), University of Illinois at Urbana–Champaign, 1 Saint Mary's Road, Champaign, IL 61820

Robin G. Brumfield
Department of Agricultural, Food, and Resource Economics, Rutgers University, 55 Dudley Road, New Brunswick, NJ 08901

J. Ryan Stewart
Department of Plant and Wildlife Sciences, Brigham Young University, 167 WIDB, Provo, UT 84602

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***Abstract*. This study assessed the material and energy inputs required to produce a *Petunia ×hybrida* plant from initial propagation to delivery at a regional distribution center. Impacts were expressed in terms of their contribution to the carbon footprint or global warming potential (GWP) of a single finished plant in a ≈10-cm diameter container. Beyond this baseline assessment, the study investigated the secondary impacts (e.g., irrigation demand) associated with container type used. Life cycle assessment data were sourced from interviews, published literature, propriety data sources, direct metering at the greenhouse facility, and original findings from a series of university greenhouse experiments. Results show that a traditional plastic container accounts for ≈16% of overall CO_2e emissions (0.544 kg) during petunia production. Although the container was a significant contributor to GWP, electrical consumption for supplemental lighting and irrigation during plug production proved to be the leading source of CO_2e emissions (over 47%) in our model system. Differences in GWP when considering secondary impacts associated with the various biocontainers were minor, especially when compared with the other elements of production. Our results demonstrate that biocontainers could potentially be as or more sustainable than plastic pots once pot manufacturing and end-of-life data are considered. However, use of more efficient supplemental lighting sources may ultimately have the greatest impact on overall GWP for the production system assessed.**

Environmentally conscious consumers are generally willing to pay higher prices for sustainably produced goods and demonstrate loyalty to the retailers supplying them (Dennis et al., 2010; Krug et al., 2008; Yue et al., 2011). However, not all efforts to reduce the environmental impacts associated with commercial horticulture production have resulted in positive perceptions by the plant-buying public. For example, a recent study demonstrated that the adoption of organic fertilizers offered no significant marketing advantage for floriculture crops (Yue et al., 2011). In this same study, plants labeled as "organic" were actually viewed unfavorably by trial participants, although no explanation was given for this finding.

In contrast to organic labeling, the adoption of biocontainers (plant material-based, biodegradable pots) as an alternative to the use of conventional plastic containers can be a significant driver of consumer interest. Yue et al. (2011) found that biodegradable, compostable, and recycled pots had the greatest impact on consumer preference, outranking other sustainable production practices not seen directly at the garden retail center (e.g., efficient use of wholesale production space). Similar conclusions were drawn by Hall et al. (2010), who found container type contributed most to consumers' interest in sustainably produced plants, outranking other highly influential considerations such as price and carbon footprint.

Despite their perceived environmental benefits and appeal as alternatives to petroleum-based plastic pots, biocontainers have not been assessed to determine their overall impact on commercial greenhouse sustainability. In this regard, biocontainers have one obvious advantage over conventional plastic pots; they are not discarded and transported to a landfill after use. Rather, most biocontainers are designed to be planted directly into the landscape or composted in a home compost bin. Some bioplastics, however, may require commercial composting conditions to fully break down (David Evans, personal communication).

Although recycling plastic pots is an option for some consumers with access to collection facilities, containers used for greenhouse and nursery production are less likely to be reclaimed given the potential for chemical contamination and photodegradation (Garthe and Kowal, 1994). In the United States, overall, plastic recycling rates are estimated to be only 8% [U.S. Environmental Protection Agency (EPA), 2011]. Within this aggregation, not all plastics and plastic products are recycled equally. More ubiquitous and desirable products such as bottles and jars have recycling rates ranging from 21% to 28% (US EPA, 2011). Lesser-valued agricultural plastics are generally buried or burned and are likely reclaimed at rates much lower than the overall average (Garthe and Kowal, 1994).

Beyond end-of-life considerations, container selection can have a number of impacts on the overall sustainability of greenhouse production. Biocontainers vary in their material and overall strength (Evans et al., 2010; Evans and Karcher, 2004), and they can be less resilient to the rigors of mechanization and transport (Koeser et al., 2013a). As such, overall production efficiency may decline as a result of losses linked to unacceptable container damage. For potted plants that successfully navigate through mechanized transplanting and handling processes, plant growth rate and water use in greenhouse-growing spaces can vary given differences in container design and porosity (Koeser et al., 2013b). Moving beyond issues associated with production, purchased plants introduced into the landscape may have different establishment and growth rates depending on the combination of species and plantable pot used (Kuehny et al., 2011).

This study offers a first look at the overall sustainability of biocontainers as part of

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[1] To whom reprint requests should be addressed; e-mail: akoeser@ufl.edu.

a greenhouse production system. Hall et al. (2009) noted in their survey work that greenhouse growers believed sustainability in their operations was important. Additionally, the researchers found that decisions regarding sustainable practices were largely based on this belief and not an expectation of economic reward from environmentally conscious consumers. As such, our work adopts a grower's perspective and focuses on the environmental impacts of container use during the plant production phase (cradle-to-gate).

One of the main difficulties in any life cycle assessment (LCA) is the collection of quality data from manufacturers and contractors (Boustead, 1996). Although this is true even for in-house assessments, the transparency and potential scrutiny that come with publishing results in a peer-reviewed journal can be an added barrier to full cooperation. In this assessment, only the secondary impacts occurring during the greenhouse production of plants (e.g., differences in irrigation demand, peat use, etc.) associated with each container are compared. These secondary impacts were directly measured through a series of applied research trials and represent differences in inputs growers would note in their operations. The results of this work can be used to guide future research by identifying promising containers for future assessment (i.e., determining the carbon footprints for their manufacturing). Furthermore, providing container manufacturers with preliminary results from a relevant example of the LCA process may reduce their apprehension and encourage future participation.

Biocontainers as a whole are marketed as a means of making the horticultural industry more sustainable. This article aims to provide one piece of the puzzle in evaluating these claims by identifying the extent to which each container impacts the carbon footprint of petunia production. The results of this work will help commercial growers identify secondary environmental impacts associated with their decision to adopt green packaging in their production systems.

Methods

Goal, scope, and functional unit. This article assesses the inputs and impacts of a short-rotation greenhouse crop, *Petunia ×hybrida* (petunia), from initial propagation to plant and container delivery at a retail center. This study is the first to establish a baseline, cradle-to-gate life cycle inventory of this annual floral commodity. Additionally, our article serves as an initial screening of nine commercially available biocontainers (Table 1; Fig. 1), which may be selected for a more thorough life cycle assessment that includes manufacturing inputs and environmental impacts in future research.

As a model system, our assessment is based on production practices of a large, semi-mechanized wholesale greenhouse that supplies retailers throughout the midwestern United States (Mid-American Growers, Granville, IL). This extensive 29-ha operation provides plant material for (among other clients) the nation's largest brick and mortar retail center in a 320-km to 480-km distribution range, which includes the Chicago, St. Louis, Indianapolis, and Milwaukee metropolitan areas (Flack, personal communication). GWP linked to carbon emissions was selected as the primary environmental impact estimated to allow for comparison with past life cycle assessment works in horticultural production (Aldentun, 2002; Ingram, 2012, 2013; Kendall and McPherson, 2012). The functional unit is a single petunia plant and its container (≈450-cm^3 volume, although volume was somewhat variable because of size availability for the containers assessed).

System boundaries and assumptions. The boundary for this cradle-to-gate LCA began with propagation through seed at the commercial greenhouse (Fig. 2). Actual seed production and transport were not included within the system boundary given limitations of available data and because past work has shown this process contributes very little to the overall impacts of production (rounded to 0%; Kendall and McPherson, 2012). After germination, seedlings in our model system are grown in indoor greenhouse space until they are large enough to be transplanted from their initial plug tray cell to a larger, final container for outdoor production. Once plants are market-ready (i.e., a point at which a plant is in flower and above-ground growth is sufficiently filling the container), they are transported to a garden retail center for sale.

The scope of this assessment does not consider emissions associated with the production of capital goods (e.g., the greenhouses facilities and mechanized equipment) used to produce the functional unit. This conforms to international guidelines outlined in PAS2050-2011 and follows methods adopted by past LCA work in ornamental horticulture (British Standards Institute, 2011; Ingram, 2012; Kendall and McPherson, 2012).

Life cycle inventory and data collection. Data for this LCA came from a variety of

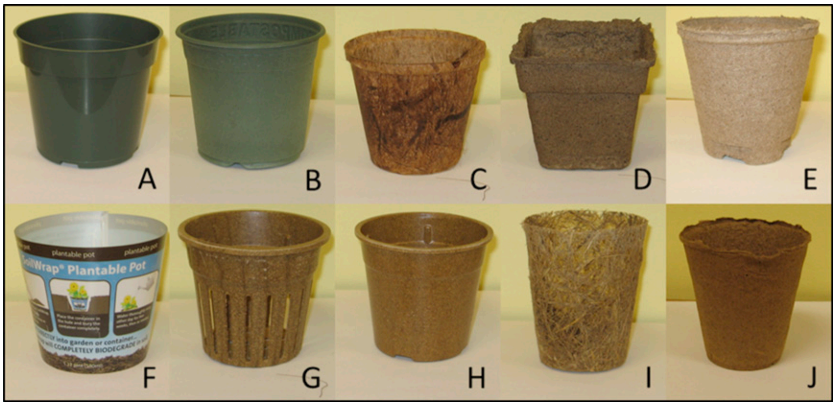

Fig. 1. Containers assessed in the life cycle assessment included (**A**) plastic control, (**B**) bioplastic, (**C**) coir, (**D**) manure, (**E**) peat, (**F**) sleeve, (**G**) slotted rice hull, (**H**) solid rice hull, (**I**) straw, and (**J**) wood fiber.

Table 1. Container type, product name, approximate volume, and manufacturer information for nine biocontainers and a conventional plastic container use for this life cycle assessment.

Container type	Product name[z]	Volume (cm^3)	Manufacturer
Plastic	Dillen 04.00 Standard Thinwall Green	480	Myers Industries Lawn & Garden Group, Middlefield, OH
Bioplastic	TerraShell™ 10-cm H Wheat Pot	473	Summit Plastic Company, Akron, OH
Coir	Coir 4.0″ Std Fiber Gro Pot	406	Dillen Products, Middlefield, OH
Manure	#4 Square CowPot	450	CowPots Manufacturing and Sales, East Canaan, CT
Peat	4″ Jiffy Pot	379[y]	Jiffy Products of America Inc., Lorain, OH
Bioplastic sleeve (Sleeve)	4.5″ Standard Assembled SoilWrap®	709[y]	Ball Horticultural Company, West Chicago, IL
Slotted rice hull	4.5″ NetPot	591	Summit Plastic Company, Akron, OH
Solid rice hull	Rice Pot 4″	473	Summit Plastic Company, Akron, OH
Straw	N/A	646[y]	Ivy Acres, Baiting Hollow, NY
Wood fiber	10 × 10-cm round individual Fertilpot	430[y]	Fertil SAS, Boulogne Billancourt, France

[z] As indicated in manufacturer's online/print catalog.

[y] Not included in manufacturer specifications. Volume approximated.

N/A = not applicable.

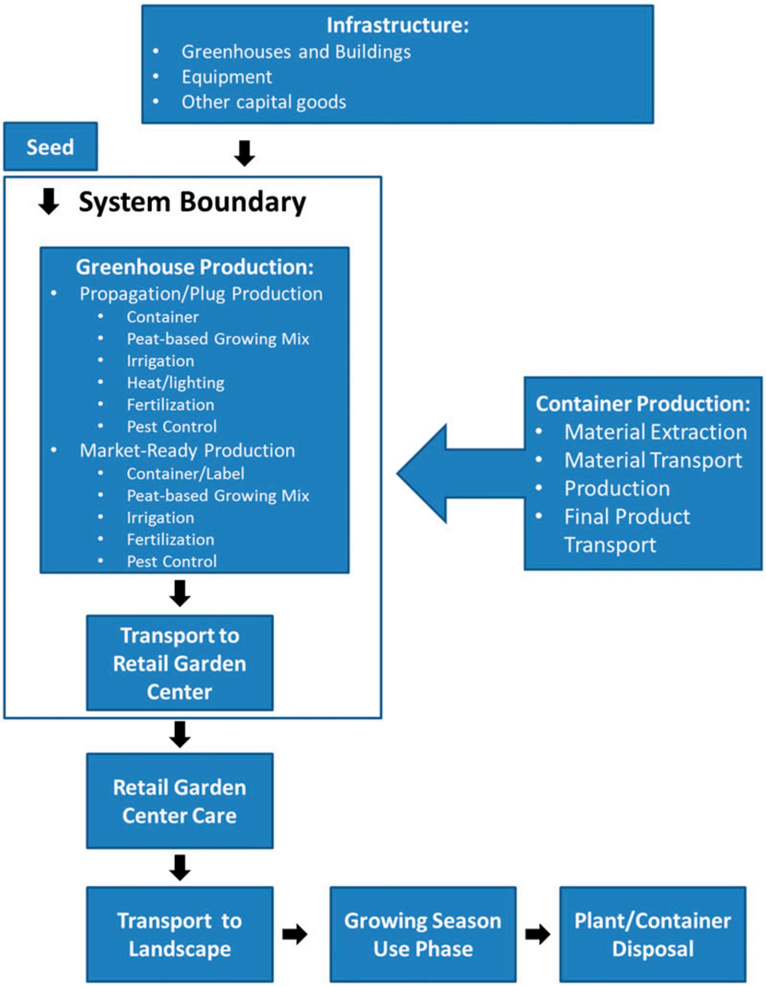

Fig. 2. Life cycle of a greenhouse-produced petunia plant. The system boundary for this cradle-to-gate assessment is outlined.

sources. General production practices for plug and final plant production were identified through a series of telephone and e-mail interviews with six production managers at Mid-American Growers. These communications were supported by direct meter readings from the greenhouse's boiler system, metering of the various electrical systems used in production, information from product labels, and interviews with horticultural equipment manufacturers. Direct experimentation from a series of independent greenhouse trials provided container-specific growing requirements. Basic material data came from past literature, the U.S. Life Cycle Inventory Database (National Renewable Energy Laboratory, 2012) and a North American-adapted version of the Ecoinvent Database (US-EI Version 2.2, Earthshift Inc., Huntington, VT; Earthshift, Inc., 2009). Electricity source information specific to the study area was obtained from the U.S. EPA's Emissions and Generation Resource Integrated Database (eGRID) model (U.S. EPA, 2009). All processes and data sources for the life cycle inventory were managed through the SimaPro LCA software tool (SimaPro 7.3.3; PRé Consultants bv, Amersfoort, The Netherlands) and are listed in Table 2.

Inputs and assumptions associated with propagation and plug production. The growers interviewed in the study estimated overall cull rate during plug production at 10% as a result of non-germination or poor seedling quality. All input values for plug production have been adjusted to account for this cull rate. Petunia plants are typically started from seed and grown for 4 weeks in a 200-cell polystyrene plug tray. Each cell is filled with ≈2.45 g of a 65:35 peat:perlite growing mix (Fafard 2; Conrad Fafard Inc., Agawam, MA). Overhead irrigation occurs every other day for the first 14 d. For the last 2 weeks, watering occurs daily. The total volume of water applied to a given plant is 52.2 mL. All water used is pumped from on-site surface water sources.

Plants are fertilized at each watering (through overhead spray irrigation) with a 14N–2P–20K fertilizer mixed at a rate of 100 ppm nitrogen. A fungicide spray/drench (Pageant; BASF, Research Triangle Park, NC) is applied as needed, typically once per crop at a rate of 0.45 mL of stock solution per liter of water. Approximately 2 weeks into the production process, plants are sprayed with 500 ppm solution of the plant growth regulator, ethephon (Florel; Lawn and Garden Products, Inc., Fresno, CA), to promote secondary branching and create a bushier appearance. Around this same time, a 1- to 3-ppm solution of paclobutrazol (Piccolo; Fine Agrochemicals, Ltd., Walnut Creek, CA) is sprayed on the plants to reduce stem elongation and limit legginess.

Plug plants are grown in an enclosed double-polypropylene greenhouse space. Supplemental lighting is provided by 600-W high-pressure sodium grow lamps covering an area of 10.5 m^2 each. Lamps are set so they were on during early mornings and weekends (24 $h \cdot d^{-1}$) for a total run time of 73 h per week. Three wood boilers using chipped industrial wood scrap maintain minimum greenhouse temperatures of 22 to 24 °C. Thirty-year average outdoor highs and lows during the modeled petunia production period are shown in Figure 3.

Inputs and assumptions associated with final greenhouse production (plastic container scenario). Plugs are mechanically transplanted into larger 10-cm polypropylene pots after the initial 4-week plug production phase. During transplanting, empty pots are placed in a 10-cell polystyrene filling tray and run through a mechanical potting mix filling machine (KV-L Filler; Agronomix, Oberlin, OH). Each container is filled with ≈68.4 g of a 85:15 peat:perlite soil-less mix (mixed on-site). After filling, plugs are hand-transplanted into the larger containers, and the trays (with pots and plants) are moved by hand cart outside for the final 5 weeks of production.

Once outside, plants are fertigated using an overheard spray irrigation system every 2 to 3 d with a 100 ppm nitrogen 14N–2P–20K fertilizer solution. Average water use for plants grown in plastic containers (without trays) was calculated to be 2162 mL during an independent growth trial intended to mimic this stage in production (Koeser et al., 2013b). This value was adjusted to reflect water savings (6%) associated with tray use (Evans et al., unpublished data).

During the final production stage, petunia plants are typically treated once with a fungicide (Banrot; Scotts-Sierra Crop Protection Company, Marysville, OH) at a rate of 0.60 g of wettable powder per liter of water. They are also sprayed once with the fungal-derived insecticide NoFly (Natural Industries, Inc., Spring, TX) at 2.3 $kg \cdot ha^{-1}$ to prevent thrip damage and again with the insecticide Mallet (Nufarm Americas, Inc., Burr Ridge, IL) at a rate of 0.12 $g \cdot L^{-1}$ to prevent aphid damage. The petunia plants are also sprayed one to two times with a 5 to 6 ppm paclobutrazol growth regulator solution to maintain a compact, full form. Cull rate at this production stage was estimated at 2% by the interviewees.

Container type-influenced production inputs (secondary impacts). Secondary impacts of container type fall into one of two general categories: impacts related to container size and impacts related to container-related irrigation demand. Differences in container size directly translate into differences in peat and perlite use during the final production

Table 2. Life cycle inventory for both the plug and final plant product stages.[z]

Product Stage	Input	Per plant	Unit	Source(s)
Plug	Electricity	0.083	MJ	US-EPA eGRID
Plug	Waste wood heat	0.240	MJ	US-EI 2.2—heat, hardwood chips from industry
Plug	Growing mix (65:35 peat:perlite)	0.002	kg	Cleary et al., 2005 US-EI 2.2—expanded perlite
Plug	Perlite transport	0.124	kg·km^{-1}	NERL USLCI—diesel truck transport
Plug	Plug tray	0.001	kg	US-EI 2.2—polystyrene PlasticsEurope Industry Data 2.0—polystyrene thermoforming
Plug	Plug tray transport	0.8050	kg·km^{-1}	NERL USLCI – diesel truck transport
Plug	14N–2P–20K fertilizer	9.072×10^{-4}	kg	US-EI 2.2—urea, as N US-EI 2.2—ammonium nitrate as N US-EI 2.2—triple superphosphate as P_20_5 US-EI 2.2—potassium chloride as K_20
Plug	Ethephon (Florel)	1.228×10^{-6}	kg	US-EI 2.2—growth regulators
Plug	Paclobutrazol (Piccolo)	4.950×10^{-9}	kg	US-EI 2.2—growth regulators
Plug	Pyraclostrobin/boscalid (Pageant)	3.143×10^{-7}	kg	US-EI 2.2—fungicides
Plug	Chemical transport	0.001	kg·km^{-1}	NERL USLCI—diesel truck transport
Plug	Irrigation	0.052	L	US-EI 2.2—agricultural irrigation
Final	10-cm plastic pot	0.014	kg	US-EI 2.2—polypropylene US-EI 2.2—polypropylene injection molding
Final	Plastic pot transport	10.1	kg·km^{-1}	NERL USLCI—diesel truck transport
Final	Plastic tray	0.013	kg	US-EI 2.2—polystyrene PlasticsEurope Industry Data 2.0—polystyrene thermoforming
Final	Plastic tray transport	9.89	kg·km^{-1}	NERL USLCI—diesel truck transport
Final	Growing Mix (85:15 peat:perlite)	0.068	kg	Cleary et al., 2005 US-EI 2.2—expanded perlite
Final	Perlite transport	1.528	kg·km^{-1}	NERL USLCI—diesel truck transport
Final	Etridiozole/thiophanate–methyl (Banrot)	0.8×10^{-5}	kg	US-EI 2.2—fungicides
Final	Paclobutrazol (Piccolo)	8.874×10^{-7}	kg	US-EI 2.2—growth regulators
Final	(NoFly)	2.360×10^{-6}	kg	US-EI 2.2—insecticides
Final	(Mallet)	1.885×10^{-5}	kg	US-EI 2.2—insecticides
Final	Chemical transport	0.014	kg·km^{-1}	NERL USLCI—diesel truck transport
Final	Final product transport	60.95	kg·km^{-1}	NERL USLCI—diesel truck transport
Final	Irrigation	2.073	L	Koeser et al., 2013a Evans et al., unpublished data US-EI 2.2—agricultural irrigation

[z] Data sources included.
N = nitrogen.

stage and ultimately shipping weight. A 10-cm diameter container size was chosen as a standard given its wide availability among container types. However, two containers, the bioplastic sleeve and the slotted rice pot, were only available in 11.5-cm sizes. Similarly, the manure pot was available in a 10-cm square only (not a round like the other nine containers). Lastly, the straw pot, although 10 cm in diameter, had a larger volume than most containers given its above-average height.

Water use, although tied in part to container volume, is also influenced by container geometry (i.e., slender vs. stout), absence or presence of drain holes, and container wall porosity. Differences in water demand influence the amount of electricity required to run irrigation systems. Additionally, all fertilization, pesticide, and growth regulator applications were administered in conjunction with normal irrigation. As such, the amount of chemical applied would vary slightly by container depending on the amount of water dispensed in a given watering.

Inputs and assumptions for transportation. All pesticides, fertilizers, and the commercially produced plug growing mix were assumed to have come from the nearest major greenhouse supplier (110 km from the study site; BFG Supply Company, Joliet, IL). The horticultural peat material data used for the two growing media mixes included an estimate for average delivery in North America (Cleary et al., 2005). However, the expanded perlite component of this mix did not include a transportation component (US-EI 2.2). As such, perlite was assumed to be sourced and delivered from the nearest processing plant (148 km to study site; Silbrico Corporation, Hodgkins, IL). Finally, transportation for the plastic containers and trays was assumed to be the distance to the manufacturer (740 km to study site; Meyers Industries, Middleton, OH). For all inputs, transportation by diesel truck was assumed.

Plants are transported only minimally during greenhouse production. Throughout the entire process, plants are moved ≈0.75 km by lawn tractor or by person (latter assumed). Mid-American Growers provides floral materials to a wide range of major retailers within 480 km of the production site. The largest market in this distribution area is the Chicago, IL, metropolitan area (174 km from Chicago to the production site). This was the assumed destination for the final product.

Impact assessment and life cycle assessment. In addition to assessing the overall GWP of a petunia plant produced in a conventional plastic container, GWP values were estimated for the 10 different container production scenarios using the U.S. EPA's TRACI 2 impact assessment model [Version 4.00 (US EPA, 2012)]. Only processes contributing 0.5% or more toward the overall environmental impact of a petunia are included in the result summaries.

Sensitivity analysis was conducted to see how the overall GWP impact results changed with the inclusion of a given container parameter (Björklund, 2002; ISO 14044, 2006). Overall differences of 15% to 30% in an impact category (GWP in this case) are considered significant by LCA practitioners when identifying influential inputs (Harnoor Dhaliwal, personal communication).

Results and Discussion

Baseline assessment of petunia production. GWP for all of the main contributing inputs are expressed as kilograms of carbon dioxide equivalents (kg CO_2e) in Table 3. For plug production, the overwhelming majority of kg CO_2e was linked to electrical consumption. The majority of the electricity used to propagate and grow petunia seedlings was used for supplemental lighting.

Wood heating was a minimal contribution to GWP (Table 3). Of the three boilers used, only two were needed intermittently to heat an area of 8 ha. When in operation, the boilers heated a large buffer tank, which helped limit temperature fluctuations as nighttime temperatures dropped. The fuel source used by the boilers also served to limit over GWP. All

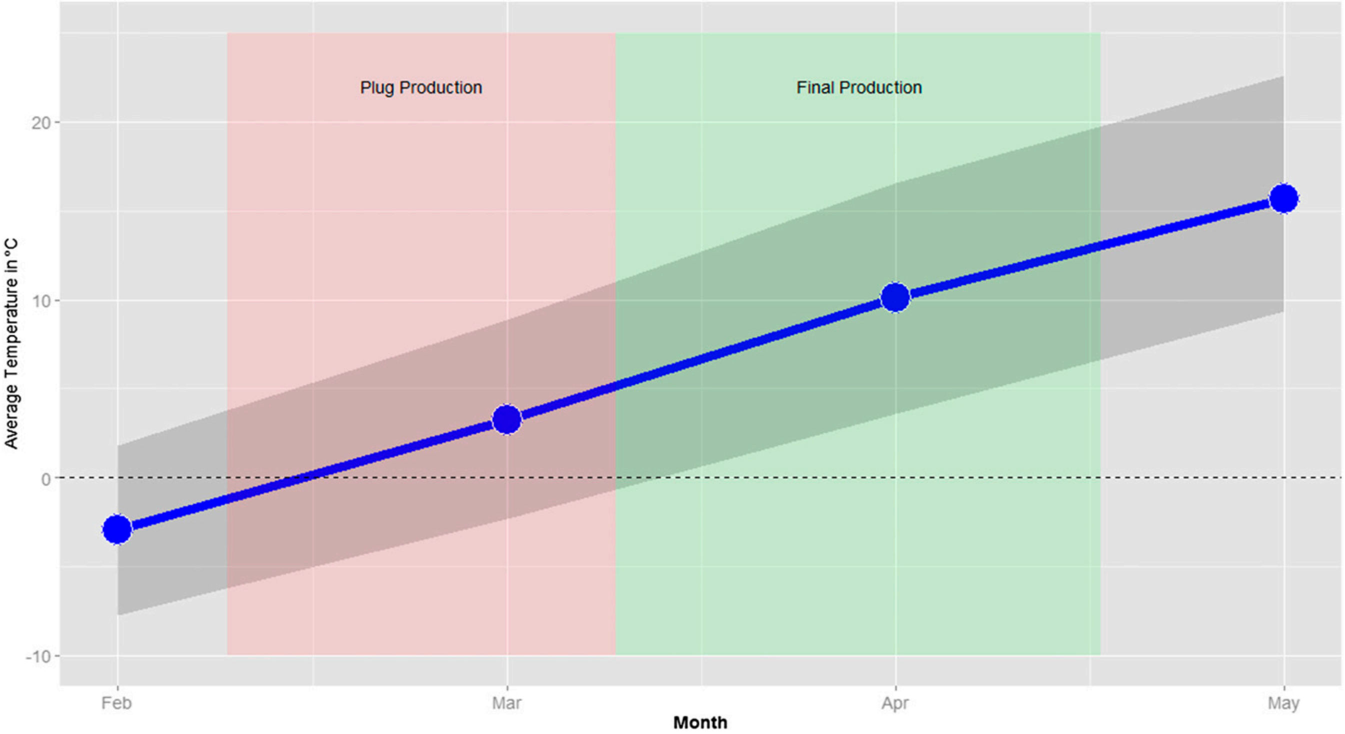

Fig. 3. Monthly average temperatures for Granville, IL, study site (data represent mean 30-year highs, averages, and lows recorded at a nearby weather station in nearby Peru, IL) during the assumed production period.

Table 3. Base-level inputs, transportation requirements, and their associated CO_2e emissions per petunia plant grown in a plastic container.

Product stage	Input[z]	kg CO_2e	Percent contribution to total GWP
Plug	Electricity (lighting and irrigation)	0.254	94.8
Plug	Waste wood heat	0.003	1.1
Plug	Growing mix	0.002	0.7
Plug	Plug tray	0.009	3.4
	Plug total	0.268	100.00
Final	Finished plug	0.268	49.3
Final	Transportation—truck	0.017	3.1
Final	Horticultural peat	0.042	7.7
Final	Expanded perlite	0.012	2.2
Final	Fertilizer solution	0.009	1.7
Final	Plastic container	0.087	16.0
Final	Plastic shuttle tray	0.109	20.0
	Plant total (including plug)	0.544	100.00

[z]Only inputs contributing 0.5% or more toward the emissions for a given production stage are included. GWP = global warming potential.

woodchips were sourced locally as industrial byproducts from pallet and other manufacturing processes (nearest supplier 30 km away).

The remainder of the inputs had minimal impact given the diminutive size of the plant and plug tray cell. Only horticultural peat and polystyrene (materials with processes noted for their CO_2e emissions) were present in sufficient quantities (by mass) to register as noteworthy contributors to GWP.

Plug production in the controlled greenhouse space accounted for nearly half of the final plant's carbon footprint (Fig. 4). Other notable inputs in petunia production included: tray (20.0% of total GWP); container (16.0% of total GWP); and peat (7.7% of total GWP). Lesser contributors to the overall impact included: transport (3.1% of total GWP); perlite (2.2% of total GWP); and the fertilizer (1.7% of total GWP).

These results offer a comparison with past cradle-to-gate carbon footprint assessment of container woody ornamental production (Kendall and McPherson, 2012) and tree seedling production (Aldentun, 2002). In the first study, a total of 4.6 kg CO_2e was emitted during the production of a typical #5 (13.5-L capacity) container tree. Like with petunia production, the researchers noted that inputs were more intensive during propagation and seedling production. Although grown over several seasons, the latter stages of tree production, like petunia production, occur outdoors in uncontrolled environments. Kendall and McPherson (2012) also note containers, growing media, and fertilizer as significant material inputs during final production. Aldentun (2002) calculated CO_2e emissions ranging from 0.045 to 0.133 kg per seedling with the variation linked to nurseries surveyed. Again, lighting, peat, and tray were identified as significant contributors to overall GWP.

Secondary impacts associated with biocontainer use. Although past research has shown biocontainer use can have significant impacts on inputs like irrigation (Koeser et al., 2013a), this variability did not translate into significant differences in GWP. In assessing the various container parameters, GWP differed by 14.4% between the lowest and highest ranked container types: sleeve and peat (Fig. 5). Although close to the more conservative 15% significance level mention in the "Methods," one could argue this difference is confounded with container size. Petunias grown in the six 10-cm diameter biocontainers had nearly identical GWP values as a petunia grown in the conventional plastic pot (also 10 cm in diameter).

The three most noticeable differences in GWP associated with secondary impacts of containers are seen with the sleeve, slotted rice, and straw containers (Fig. 5). These are also the three most voluminous pots (Table 1). All containers are filled to capacity by the mechanical filling machine. As such, differences in peat use and final shipping weight drive the elevated GWP for these three containers. Other inputs such as irrigation, fertilization, and pesticides appear to have a lesser influence on GWP, because their use was reduced (compared with plastic) in the sleeve and slotted rice containers, yet overall

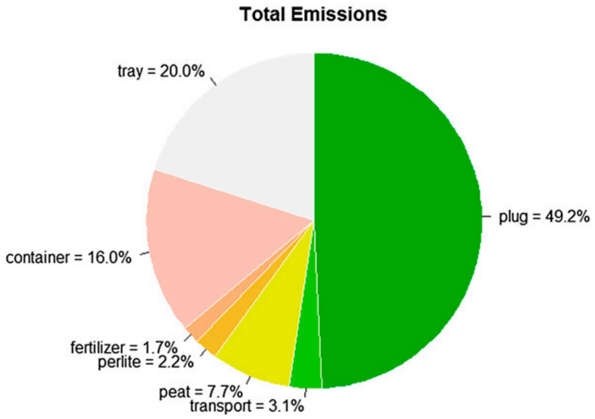

Fig. 4. Percentage of greenhouse gas emissions associated with petunia production system components with a conventional plastic container. Only inputs contributing 0.5% or more are included.

Fig. 5. Comparison of petunia production global warming potential (GWP) when using one of nine biocontainers or a conventional plastic container (CO_2e for sleeve set at 100%). Differences reflect only secondary impacts and do not include CO_2e emissions associated with the production of the biocontainers themselves.

carbon emission was still elevated for these two pots.

In conducting this assessment, we chose each biocontainer manufacturer's closest alternative to the common 10-cm plastic pot. If a grower switched from this size to one of the three larger biocontainers, the differences noted below could warrant further investigation. However, it seems likely that if all container sizes were identical, the differences in GWP would have been negligible.

Conclusion

The results of this work should be encouraging for growers and manufacturers looking to increase sustainability through the use and development of biocontainers. Although biocontainers have been linked to reduced performance in plant growth, filling speed, shipping success, and irrigation demand trials, these differences do not have a dramatic effect on production sustainability from a GWP perspective.

Furthermore, variability in plant size may be tolerated by consumers and growers as long as plant appearance remains unaffected. Other factors will likely become less of an issue as biocontainers are fully embraced by the horticultural industry. With widespread use comes innovation and adaptation of conventional greenhouse practices that will overcome past documented pitfalls.

Although future LCA research investigating the impacts of the containers and their production would lead to a more accurate assessment of petunia production GWP, the overall impact may not be very dramatic. In our baseline life cycle inventory, container accounted for $\approx$16% of total CO_2e emissions. If a given container was found to have half the GWP of our standard plastic control, the overall reduction in CO_2e emissions would be $\approx$8%.

Supplemental lighting, which accounts for nearly 47% of total GWP, is the most important factor contributing to GWP. The use of more energy-efficient light sources such as light-emitting diode lamps, although not something that would be necessarily noticed by a consumer in a retail garden center, would have the greatest impact on lowering CO_2e emission. Production systems similar to our model site have the potential to reduce both the real and perceived environmental impacts associated with greenhouse-grown petunias by adopting more efficient lighting and biocontainers in their operations.

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