

Global Warming Potential, Variable Costs, and Water Use of a Model Greenhouse Production System for 11.4-cm Annual Plants Using Life Cycle Assessment

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Abstract. Life cycle assessment (LCA) was used to analyze the global warming potential (GWP) and variable costs of production system components for an 11.4-cm container of wax begonia (*Begonia* × *semperflorens-cultorum* Hort) modeled in a gutter-connected, Dutch-style greenhouse with natural ventilation in the northeastern United States. A life cycle inventory of the model system was developed based on grower interviews and published best management practices. In this model, the GWP of input products, equipment use, and environmental controls for an individual plant would be 0.140 kilograms of carbon dioxide equivalents (kg CO₂e) and the variable costs would total \$0.666. Fifty-seven percent of the GWP and 43% of the variable costs would be due to the container and the portion of a 12-plant shuttle tray assigned to a plant. Electricity for irrigation and general overhead would be only 13% of GWP and 2% of variable costs. Natural gas use for heating would be 0.01% of GWP and less of the variable costs, even at a northeastern U.S. location. This was because of the rapid crop turnover and only heated for 3 months of a 50-week production year. Life cycle GWP contributions through carbon sequestration of flowering annuals after being transplanted in the landscape would be minor compared with woody plants; however, others have documented numerous benefits that enhance the human environment.

Production of annual bedding plants providing seasonal color in the landscape is the primary profit center for many greenhouse operations. However, the increasingly hyper-competitive markets and decreasing profit margins of these enterprises have required the continual analysis of production and marketing systems (Hall, 2010). Also, a key success factor for these industries is to examine the inseparable factors of efficient input use, cost savings, enhanced product quality, and the sustainable nature of production or

manufacturing practices (Boston Consulting Group, 2009; Rankin et al., 2011).

For greenhouse growers, sustainable production means applying best management practices to enhance plant quality and reduce negative environmental impacts (Southern Nursery Association, 2013) while sustaining or increasing profits (Hall, 2010). Life cycle assessment is a tool used to analyze the sustainable nature of production system components from cradle to grave or defined subsets of their life cycle.

The goal of this research was to model and analyze production systems using LCA procedures for major environmental horticulture crop groups. Greenhouse gas (GHG) emissions and the subsequent carbon footprint (CF) have been reported for representative trees and shrubs produced in field operations and in container production systems (Hall and Ingram, 2014, 2015; Ingram, 2012, 2013; Ingram and Hall, 2013, 2014a, 2014b, 2015a, 2015b; Ingram et al., 2016, 2017a; Kendall

and McPherson, 2012). Young foliage plant production systems in two distinct greenhouse types have also been compared using LCA (Ingram et al., 2017b). CF is expressed in GWP due to GHG emissions for a 100-year period in units of kg CO₂e. Thus, our objective in this study was to add to the knowledge about the range of nursery and greenhouse production systems, by analyzing the environmental impact potentials of a model production system in the northeastern region of the United States for finished annual color plants in 11.4-cm containers. In addition to providing detailed impact information of the individual components of production systems, so that growers can find ways to increase production efficiency and minimize GHG emissions, information gained from these studies should be appealing to environmentally conscious consumers (Yue et al., 2016).

Materials and Methods

A production system model for greenhouse production of an 11.4-cm wax begonia plant (*Begonia* × *semperflorens-cultorum* Hort) was based on the best management practices for the northeastern United States. Grower interviews were conducted to validate production life cycle, input products, equipment use, heating and cooling requirements, water use, and labor hours for each operation or cultural practice. The system model consists of purchasing plugs in 288-count trays, transplanting them to 11.4-cm containers in 12-plant shuttle trays, and growing them for 8 weeks before marketing. General greenhouse operations and energy use not specifically assigned to an operation, input, or process were designated as overhead and calculated for an 8-week portion of a 50-week cropping year and assigned to an individual plant. The greenhouse was modeled as a gutter-connected, Dutch-style house with roof and side ventilation, horizontal circulating fans, bilayer polycarbonate covering, 3.6-m sidewalls, and no evaporative cooling, in the northeastern United States. Although supplemental lighting may be used for some portion of the year, it would not be used for other portions of the year. Therefore, the GWP and cost of lighting was not separated from the estimated overhead electrical energy consumption. The average daily temperature in this region is 12 °C (U.S. Climate Data, 2017).

The 150,000 m² of heated greenhouse space would be designed with a gutter system to capture rainfall and store it in 1000 m³ tanks. It was assumed that 6.6 plants were produced on each square meter of a concrete floor and plants were irrigated using an overhead, traveling boom.

Heating of the greenhouse would be required for 3 months and consume 5 m³ of natural gas per 1000 m² according to the records of growers interviewed. The expected overall annual electricity use of the facility minus electricity allocated to specific operations, such as pumping water for treatment

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and irrigation, constituted unallocated electricity and was calculated to be 0.047 kWh/plant in this model. In addition to the labor assigned to each operation, it was assumed that an additional 560 h of labor per 10,000 plants was invested in overall operations, such as facility management and office personnel, and proportionally assigned to an individual plant.

The substrate typically used contains 80% peat and 20% perlite by volume. It was assumed that plugs would be purchased at \$0.107 each, their CF would be insignificant, and there would be 1% plant loss during production (Ingram et al., 2017b). Three applications of a fungicide (pyraclostrobin, tetrachloroisophthalonitrile, and iprodione in rotation) would be made per crop using a sprayer with a 5-kW gasoline pump to apply 0.00004 kg of product per plant and requiring 20 min per 10,000 plants per application. A plant growth regulator, 3.5 L of product containing 0.026% ancymidol, would be applied twice using a sprayer with a 5-kW gasoline pump for 20 min per 10,000 plants.

Preparing substrate and plugs, filling pots, transplanting using a transplanter, and moving plants to the greenhouse floor was assumed to cost \$0.03 per plant and use 80 man-hours and 20 equipment-hours per 10,000 plants based on grower interviews. The transplanter and conveyer system would require 18 kW of electric motors. An electric cart would pull carts of plants from the transplanting area to the greenhouse floor at the rate of 10,000 plants in 18.3 h. Pulling orders and loading trucks for delivery would require labor costs of \$0.043 per plant and consume 0.004 kWh of electric cart (5.2 kW).

Irrigation would be provided by an overhead, traveling boom delivering a total of 120,000 L in 24 irrigations. A 37.3-kW electric pump would be required. Two man-hours per 10,000 plants would be invested in monitoring irrigation. Irrigation water would be pumped from a storage tank filled with rainwater capture and from a well. Irrigation water would be continuously filtered and ozonated to supply 2 mg ozone/L and require

36 kWh of electricity per 10,000 plants. Filtration and ozonation was assumed to cost \$0.05 for each 3785 L or \$0.00002 per plant based on Raudales et al. (2016). Treatment of wastewater would require 19 kWh of electricity per 10,000 plants and use a bacteria filter at a cost of \$0.02 per 3785 L gallons. Fertilization would be provided with irrigation each week at 200 mg N/L from a 14N–6.1P–11.6K water-soluble fertilizer with ammonium nitrate-based nitrogen sources.

Inventory analysis and data collection. Life cycle inventory procedures were used to record all input products, equipment use, and other activities for a functional unit of an 11.4-cm begonia plant in a 12-plant shuttle tray. LCA protocols were applied to the inventory following international standards, including the International Organization for Standardization [ISO (2006) (Geneva, Switzerland)] and PAS 2050 guidelines by BSI British Standards (2011). GHG emissions were determined for each input and activity, converted to kg CO₂e per functional unit and summed. Emissions from the manufacturing of capital goods, such as buildings and machinery, were not included in this study as per PAS 2050, Section 6.4.4.

The GWP of applied nitrogen from NH₄NO₃, P₂O₅, and K₂O fertilizers were 9.7, 1.0, and 0.7 kg CO₂e/kg for, respectively, as previously published (Snyder et al., 2009; Wang, 2007). A GWP of each input product, including manufacturing processes and transportation, was calculated from the U.S. life cycle inventory (USLCI) database (U.S. Department of Energy, 2017) and SimaPro (Pre' North America, Inc., Washington, DC). A 1% loss of applied N as N₂O was assumed based on research with field soils and resulted in an estimated GWP of 4.65 kg CO₂e/kg of N applied (IPCC, 2006; Snyder, et al., 2009; West and Marland, 2003). The GWP of natural gas combusted in an industrial boiler and the GWP of electricity in the region were set as 2.40 kg CO₂/m³ and 0.438 kg CO₂e/kWh, respectively, from USLCI data through SimaPro.

The substrate consisted of 80% peat and 20% perlite by volume considering a 5%

shrinkage during mixing. GWP was calculated to be 0.317 kg CO₂e/kg, of which 0.100 kg CO₂e was from peat (0.945 kg) and 0.217 kg CO₂e was from perlite (0.121 kg), which included mixing and transportation as previously published (Ingram et al., 2017a). A GWP of the 12-plant shuttle trays manufactured from polystyrene using blow-mold technology was calculated to be 0.037 kg CO₂e/kg per marketable plant. This was calculated using SimaPro, assuming a material transported distance of 200 km and landfill disposal of used containers (Ingram et al., 2017a). The GWP of the 11.4-cm pot was similarly calculated to be 0.043 kg CO₂e/kg per marketable plant. The average CO₂e emission for a range of fungicides (12.50 kg CO₂e/kg) from data presented by Lal (2004). The average CO₂e emissions from the use of growth regulators was calculated as 9.45 kg CO₂e/kg using SimaPro.

Although labor does not contribute directly to a product's GWP, it contributes significantly to product variable costs. Labor requirements for operating equipment were calculated as 1.25 times the equipment operation hours to account for preparation and cleanup time. The Adverse Effect Wage Rate as determined by the U.S. Department of Labor (2017) was used to set the hourly wage rate of \$12.69. This represents the wage level that must be offered and paid to migrant workers by agricultural employers of nonmigrant H-2A agricultural workers. Equipment costs per hour were representative of those reported in regional enterprise budgets for horticultural crops. Natural gas and electricity prices were established as \$0.286/m³ and \$0.10/kWh (U.S. Energy Information Administration, 2017).

Results and Discussion

A GWP for an 11.2-cm wax begonia plant was calculated to be 0.140 kg CO₂e from GHG emissions due to production protocols of the model system including the use of input products, use of equipment, and environmental controls (Table 1). The

Table 1. Global warming potential and variable costs of production components (labor, materials, and equipment operation costs) incurred during greenhouse production of an 11.4-cm wax begonia plant (*Begonia xsemperflorens-cultorum*) in the northeastern United States from plugs in 8 weeks.

Activity/components	Materials			Equipment use GWP			Labor	Total	
	(kg or unit/plant)	GWP (kg CO ₂ e)	Costs (\$)	(h/plant)	GWP (kg CO ₂ e)	Costs (\$)	Costs (\$)	GWP (kg CO ₂ e)	Costs (\$)
Substrate	0.0788	0.0243	0.1416	0.0000	0.0000	0.0000	0.0000	0.0243	0.1416
Plug from no. 288 and transplanting	1.0101	0.0074	0.1066	0.0000	0.0000	0.0000	0.0303	0.0074	0.1369
Transfers in greenhouse	0.0000	0.0000	0.0000	0.0006	0.0013	0.0021	0.0142	0.0013	0.0163
Container	1.0101	0.0430	0.1501	0.0000	0.0000	0.0000	0.0000	0.0430	0.1501
Shuttle tray	0.0842	0.0371	0.1346	0.0000	0.0000	0.0000	0.0000	0.0371	0.1346
Irrigation/water management	0.0000	0.0000	0.0000	0.0027	0.0012	0.0003	0.0004	0.0012	0.0007
Fertilization	0.0026	0.0059	0.0030	0.0000	0.0000	0.0000	0.0000	0.0059	0.0030
Pest management	0.0000	0.0001	0.0027	0.0000	0.0001	0.0001	0.0002	0.0001	0.0030
Plant growth regulator	0.0001	0.0000	0.0106	0.0000	0.0000	0.0001	0.0002	0.0001	0.0108
Pull orders and load truck	0.0000	0.0000	0.0000	0.0008	0.0019	0.0035	0.0427	0.0019	0.0463
Heating (natural gas)	0.0000	0.0000	0.0000	0.0001	0.0002	0.0000	0.0000	0.0002	0.0000
Electricity (overhead)	0.0000	0.0000	0.0000	0.0391	0.0171	0.0038	0.0000	0.0171	0.0038
Unallocated grower/labor	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0186	0.0000	0.0186
Total per plant	2.1859	0.1178	0.5491	0.0433	0.0218	0.0099	0.1067	0.1396	0.6657

kg CO₂e = kilograms of carbon dioxide equivalents.

total variable costs for this functional unit would be \$0.666. As expected, the GWP and variable costs of this product is significantly less than a 72-count tray of foliage plant liners (2.276 kg CO₂e and \$25.251, respectively) grown in a similar greenhouse but in the southern United States (Ingram et al., 2017b).

The container would account for 30.8% of the GWP and the 12-container shuttle tray

contributed 26.6%, primarily due to the energy required to produce these products (Fig. 1). These items would also contribute 42.8% of variable costs (Fig. 2). The substrate would contribute 17.4% of GWP and 21.3% of variable costs. Transplanting plugs from the no. 288 trays using a transplanter would result in 5.3% of the GWP (electric motors) and 20.6% of variable costs, labor in this instance.

Transferring plants from the potting area to the greenhouse floor would account for 1% of GWP and 2.4% of variable costs while pulling orders and loading trucks would account for 1.4% of GWP but 7.0% of variable costs. Compared with distributing plants to the greenhouse floor, pulling orders would require more labor because of the additional steps in locating the plants, grading as necessary, cleaning containers, etc.

Fertilization would add 4.2% of GWP but only 0.45% of variable costs. Pest management and application of growth regulators combined would contribute only 0.13% of GWP and 2.1% of variable costs.

Electricity to provide irrigation and treat the 30% runoff before discharge would contribute less than 1% of GWP and variable costs. Electricity not allocated to individual operations in the model would account for 12.3% of GWP and less than 1% of variable costs. Heating for 3 months of the 50 weeks of greenhouse production, when spread across the number of crop turnovers, would have only a minor impact on GWP and variable costs. This differs significantly from the 12-week greenhouse production of foliage plant liners where heating and electricity accounted for 77% of GWP (Ingram et al., 2017b). Some of these differences could also be due to the temperature sensitivity of foliage plants (i.e., the need to maintain a higher temperature than for begonia production) and the larger space utilization of the 72-count tray compared with an 11.4-cm container.

This production model would use 1.8 L of water for irrigation per plant. In a similar greenhouse and a stationary overhead irrigation system, the 72-count flat of foliage liners used 64 L of irrigation water (Ingram et al., 2017b). Compared on an area basis for the crops, the water use would be 17.25 L·m⁻²·week⁻¹ for this 8-week begonia model and 35.8 L·m⁻²·week⁻¹ for the 12-week foliage liner production model.

Analyzing components of a model system using LCA allows the construction of what-if scenarios that could aid in management decisions. For example, the plastic container and shuttle tray would contribute 57.4% of GWP in this model and reduce the GWP of these inputs by 10% would reduce the GWP of this begonia plant by 0.008 kg CO₂e or 5.7%. Assuming a closed water system and no related environmental impact, reducing fertilizer use by 10% would only reduce the overall plant GWP by 0.0006 kg CO₂e, or 0.4%, and reduce variable costs by \$0.0003. Reducing the cost of the substrate by 10% would reduce the total variable costs by 2% (\$0.14). Labor accounts for 18% of total variable costs in this model and increasing the labor wage rate to \$15.00 per hour (as being proposed as the minimum wage in several states), would increase the cost of the 11.4 begonia by \$0.014 or 2%. A straight 25% increase in the wage rate would result in a cost increase of \$0.02 or 3%. With a decreasing profit margin on some plants, even a small increase or decrease in an important cost item could affect profitability.

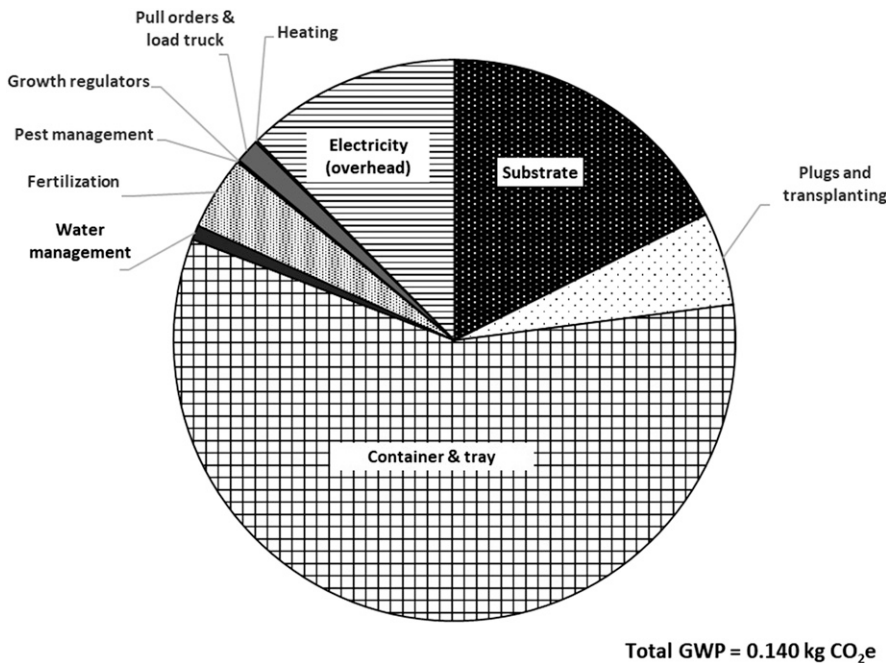


Fig. 1. Global warming potential (GWP) for production components and activities for an 11.4-cm wax begonia plant (*Begonia xsemperflorens-cultorum*) modeled as an 8-week crop from plugs in a greenhouse range in the northeastern United States.

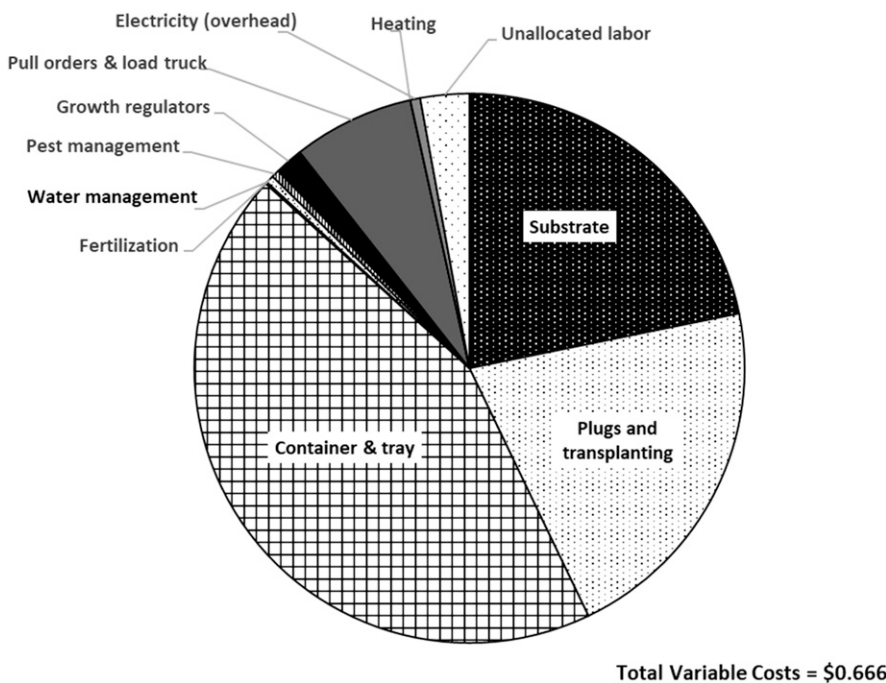


Fig. 2. Variable costs for production components and activities incurred during 8-week production from plugs of an 11.4-cm wax begonia plant in a greenhouse range in the northeastern United States.

When assessing the potential ecosystem services, such as carbon sequestration provided by plants, herbaceous annual flowering plants do not make a long-term impact compared with woody plants. However, like foliage plants, flowering annual plants do contribute to human health and well-being in other ways through their aesthetic value and ecosystem services, such as reduced storm water runoff and improved air quality (Hall and Dickson, 2011).

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