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Modeling Global Warming Potential, Variable Costs, and Water Use of Young Plant Production System Components Using Life Cycle Assessment

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***Abstract*. The components for two production systems for young foliage plants in 72-count propagation trays were analyzed using life cycle assessment (LCA) procedures. The systems differed by greenhouse type, bench size and arrangement, rainwater capture, and irrigation/fertilization methods. System A was modeled as a gutter-connected, rounded-arch greenhouse without a ridge vent and covered with double-layer polyethylene, and the plants were fertigated through sprinklers on stationary benches. System B was modeled as a more modern gutter-connected, Dutch-style greenhouse using natural ventilation, and moveable, ebb-flood production tables. Inventories of input products, equipment use, and labor were generated from the protocols for those scenarios and a LCA was conducted to determine impacts on the respective greenhouse gas emissions (GHG) and the subsequent carbon footprint (CF) of foliage plants at the farm gate. CF is expressed in global warming potential for a 100-year period (GWP) in units of kilograms of carbon dioxide equivalents (kg CO_2e). The GWP of the 72-count trays were calculated as 4.225 and 2.276 kg CO_2e with variable costs of $25.251 and $24.857 for trays of foliage plants grown using Systems A and B, respectively. The GWP of most inputs and processes were similar between the two systems. Generally, the more modern greenhouse in System B was more efficient in terms of space use for production, heating and cooling, fertilization, and water use. While overhead costs were not measured, these differences in efficiency would also help to offset any increases in overhead costs per square foot associated with higher-cost, more modern greenhouse facilities. Thus, growers should consider the gains in efficiency and their influences on CF, variable costs (and overhead costs) when making future decisions regarding investment in greenhouse structures.**

Greenhouse production of floricultural and foliage plants in the United States is in the mature stage of its industry life cycle and increasingly hypercompetitive, with growers experiencing low profit margins despite having to incur substantial capital expenditures (Hall, 2010). In such a setting, it is desirable to maximize efficiency, yet simultaneously reduce costs. Growers can often accomplish this by introducing lean manufacturing techniques into their respective value chains. Recent literature points to the interconnectedness of efficient input use, cost savings, enhanced product quality, and the sustainable nature of production or manufacturing practices (Boston Consulting Group, 2009). In other words, sustainable practices are now viewed as profitable strategic imperatives rather than mere environmental regulatory adherence (Rankin et al., 2011).

For green industry firms, sustainable production means using best management practices that enhance plant quality and simultaneously reduce environmental impacts (Southern Nursery Association, 2013). Evaluating the triple-bottom-line aspects of their business (people, planet, and profits) can also help to differentiate their firms in the marketplace (Hall, 2010). Life cycle assessment is a tool that has been used to evaluate the environmental portion of the triple-bottom-line of products from cradle to grave or defined subsets of their life cycle.

Greenhouse gas emissions and the subsequent CF have been reported for nursery crop production systems in the U.S. (Hall and Ingram, 2014, 2015; Ingram, 2012, 2013; Ingram and Hall, 2013, 2014a, 2014b, 2015a, 2015b; Ingram et al., 2016; Kendall and McPherson, 2012). CF is expressed in GWP in units of kilograms of carbon dioxide equivalents (kg CO_2e). In addition to analyzing the environmental impacts of the detailed input products and activities during nursery production, these studies have estimated carbon sequestration from the atmosphere during the life of the plant, weighted over a 100-year assessment period.

Protocols for plant production in containers are significantly different from field-production systems (Ingram and Hall, 2015a). Nursery production systems for shrubs, trees, perennials, etc. are also markedly different from greenhouse systems used for producing propagative stock (young plants), potted flowering plants, bedding plants, and foliage plants. To date, however, the literature regarding the environmental aspects of greenhouse crop production using LCA procedures is sparse. Thus, our objective in this study was to analyze the environmental impact potentials of greenhouse plant production using young foliage plants grown in the southern Unites States as a case study.

This information should be appealing to consumers who are becoming increasingly aware of the potential environmental impact(s) of the products they purchase, including green industry products and services (Yue et al., 2016). Greenhouse growers also need information about the potential impact of specific production protocols to make informed decisions (Ingram and Hall, 2015b) regarding input use and cultural practice selection. This study should help fill that void.

Materials and Methods

Two systems (entitled System A and System B) were modeled for a 12-week production system for young foliage plants in 72-count propagation trays (0.15 m^2) to be marketed to greenhouse growers for finishing to a marketable size. The protocols for both model systems were based on interviews with producers in the deep south of the United States and access to their records to determine input products, equipment use, heating and cooling requirements, water use, and labor hours for each operation or cultural practice. The average daily temperature in this region is 21.3 °C. The substrate typically used contains 80% peat and 20%

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perlite by volume. The young plants would be transplanted as tissue-cultured microcuttings, misted for 4 weeks and grown an additional 8 weeks before being marketed. Because the modeled facilities were closed systems, the irrigation and misting would result in no runoff from the greenhouses.

In both systems, microcuttings would be misted 60 times per day at 98 mL·m^{-2} for 4 weeks which required a 3.73 kW submersible pump operating 0.05 h·d^{-1} per bench. It was assumed that microcuttings would be purchased at $0.20 each, their CF would be insignificant, and there would be 10% shrinkage. The crop would be drenched with a biological fungicide (*Bacillus amyloliquefaciens*) four times at 0.001 kg of product per tray and sprayed with an insecticide five times at 0.0004 kg of product per tray. A sprayer with a 5-kW gasoline engine would be used a total of 0.01 h/tray for pest management per crop. Trays would be graded and consolidated into full trays at the rate of 60 trays per person per 8-h day. One person would move graded trays 40 at a time on a cart into a delivery truck every 10 min.

Water would be used for evaporative cooling through fan and pad systems operating 9 months per year for an average of 8 h·d^{-1}. Based on grower interviews, water use for evaporative cooling was assumed to be 3.4 and 5.2 L·m^{-2}·d^{-1} for System A and B, respectively.

System A and System B differed by greenhouse type, bench size, and arrangement, rainwater capture, and irrigation/fertilization method. System A was modeled as an older, gutter-connected, rounded-arch 5574 m^2 greenhouse without a ridge vent, a double layer of polyethylene film on the roof, biwall polycarbonate sidewalls, and a 3-m gutter height. Shadecloth was installed inside the house. The 58-m^2 benches would be stationary and hold 365 72-cell trays each. Movement of trays from the potting area to the mist benches and from the mist benches to production houses using a manual trolley system would require 0.5 labor hours per 60-tray load.

Irrigation in System A would be provided via overhead spray nozzles applying 757 L per bench per irrigation. Irrigation would be driven by a 3.73-kW pump drawing water from a well. The fan and pad evaporative cooling system would operate an average of 8 h·d^{-1}. Fertilization would be provided with each watering with 150 mg N/L from a 20N–4.3P–16.6K water-soluble fertilizer. The benches would be irrigated 28 times for 10 min. each for a total of 64.5 L per tray during the 8 weeks of production. The System A greenhouse would be heated by a natural gas boiler combusting an average of 134 m^3 of natural gas per bench per crop. Electricity for the greenhouse and support areas would average 4 kWh per marketable tray, not including electricity for pumping which is accounted for separately. Much of the labor is accounted for in each operation, however, it was assumed that there would be 0.04 h of unallocated labor per tray in System A.

System B was modeled as a more modern gutter-connected, Dutch-style greenhouse using natural ventilation with roof vents and retractable shade interior to the house using an integrated environmental control system. The roof and sidewalls were covered with bilayer polycarbonate and the gutter height was 3.6 m. The 10,220 m^2 greenhouse would be designed with a gutter system to capture rainfall and store it in 1900 m^3 tanks.

Sixty-nine trays would be placed on each moveable 10 m^2 bench and pushed by hand to the desired location for misting, production, and preparation for shipping. Water captured from the roof would be treated and used in an ebb-flood system contained in the individual moveable tables. It was assumed that 242 L were required to flood each bench for 26 irrigations and 80% would be returned to the reservoir/tank. Water in the storage tank and supplemental well water added to the system, would be treated with calcium hypochlorite tablets (0.057 kg per bench per crop) to maintain 1 mg·L^{-1} free chlorine. A 5.60 kW electric pump would be used to pump irrigation water to the production benches for a total of 0.17 h per bench per crop. In addition, a 1.49-kW electric pump would

Table 1. Global warming potential (GWP) and variable costs of production components for System A for greenhouse production of young foliage plants in a 72-cell tray in the southern United States.

	Materials			Equipment use			Labor	Total	
Activity/Components	kg or unit/tray	GWP (kg CO_2e)	Costs ($)	h/tray	GWP (kg CO_2e)	Costs ($)	Costs ($)	GWP (kg CO_2e)	Costs ($)
Substrate	0.0032	0.0010	0.488	0.0000	0.0000	0.000	0.000	0.0010	0.488
Microcutting and t ransplanting	72.0000	0.0000	16.000	0.0000	0.0000	0.000	3.223	0.0000	19.223
Transfers in greenhouse	0.0000	0.0000	0.000	0.0000	0.0000	0.000	0.235	0.0000	0.235
Tray	0.0778	0.2038	1.606	0.0000	0.0000	0.000	0.000	0.2038	1.606
Misting	0.0000	0.0000	0.000	0.0021	0.0054	0.010	0.010	0.0054	0.020
Irrigation/water management	0.0000	0.0000	0.000	0.0265	0.0181	0.019	0.010	0.0181	0.029
Fertilization	0.0484	0.1505	0.055	0.0000	0.0000	0.000	0.000	0.1505	0.055
Pest management	0.0142	0.0437	0.965	0.0025	0.0002	0.013	0.040	0.0439	1.018
Grading and loading on truck	0.0000	0.0000	0.000	0.0000	0.0000	0.000	1.563	0.0000	1.563
Heating (natural gas)	0.0000	0.0000	0.000	0.4354	1.0448	0.137	0.000	1.0448	0.137
Electricity (kWh)	0.0000	0.0000	0.000	4.0307	2.7570	0.368	0.000	2.7570	0.368
Unallocated grower/labor	0.0000	0.0000	0.000	0.0000	0.0000	0.000	0.509	0.0000	0.509
Totals per tray	72.1436	0.3990	19.114	4.4972	3.8256	0.548	5.080	4.2246	25.251

Table 2. Global warming potential (GWP) and variable costs of production components for System B for greenhouse production of young foliage plants in a 72-cell tray in the southern United States.

	Materials			Equipment use			Labor	Total	
Activity/Components	kg or unit/tray	GWP (kg CO_2e)	Costs ($)	h/tray	GWP (kg CO_2e)	Costs ($)	Costs ($)	GWP (kg CO_2e)	Costs ($)
Substrate	0.0032	0.0010	0.488	0.0000	0.0000	0.000	0.000	0.0010	0.488
Microcutting and transplanting	72.0000	0.0000	16.000	0.0000	0.0000	0.000	3.223	0.0000	19.223
Transfers in greenhouse	0.0000	0.0000	0.000	0.0000	0.0000	0.000	0.235	0.0000	0.235
Tray	0.0778	0.2038	1.606	0.0000	0.0000	0.000	0.000	0.2038	1.606
Misting	0.0000	0.0000	0.000	0.0021	0.0060	0.011	0.009	0.0060	0.020
Irrigation/water management	0.0000	0.0000	0.000	0.0190	0.0276	0.034	0.010	0.0276	0.044
Fertilization	0.0138	0.0078	0.016	0.0000	0.0000	0.000	0.000	0.0078	0.016
Water treatment	0.0010	0.0007	0.006	0.0000	0.0000	0.000	0.000	0.0007	0.006
Pest management	0.0141	0.0435	0.960	0.0056	0.0004	0.029	0.089	0.0440	1.078
Grading and loading truck	0.0000	0.0000	0.000	0.0000	0.0000	0.000	1.563	0.0000	1.563
Heating (natural gas)	0.0000	0.0000	0.000	0.2582	0.6196	0.081	0.000	0.6196	0.081
Electricity	0.0000	0.0000	0.000	1.9958	1.3651	0.182	0.000	1.3651	0.182
Unallocated grower/labor	0.0000	0.0000	0.000	0.0000	0.0000	0.000	0.316	0.0000	0.316
Totals per tray	72.1098	0.2568	19.075	2.2807	2.0188	0.338	5.129	2.2755	24.857

run 12 h per day or 0.76 h per bench for the 8 weeks to push returning water through a filter system and circulate water in the reservoir where the chlorine would be added. Fertilizer (20N–4.3P–16.6K) would be added to the water reservoir to maintain 130 mg N/L.

Recommended fertilizer concentration for ebb-flood systems is lower than for plants receiving overhead irrigation due to differential leaching and thus salt accumulation (Liu et al., 2012). Greenhouses in System B would be heated by two natural gas boilers, combusting an average of 15.3 m^3 of natural gas per bench per crop. Electricity for the greenhouse and support areas would average 0.87 kWh per marketable tray, not including electricity for pumping water which was accounted for separately. Much of the labor was accounted for in each operation, however, it was assumed that there would be 0.025 h of unallocated labor per tray in System B.

Inventory analysis and data collection. All input products, equipment use and other activities were recorded using life cycle inventory procedures for a functional unit of one 72-cell tray of foliage plants. LCA protocols were applied to the inventory following international standards, including the International Organization for Standardization (2006) (Geneva, Switzerland) and PAS 2050 guidelines by BSI British Standards (2011). GHG were determined for each input and activity, converted to kilograms CO_2e 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.

GWP of 9.7, 1.0, and 0.7 kg CO_2e/kg for N from NH_4NO_3, P_2O_5, and K_2O fertilizers, respectively, were assumed as previously published (Snyder et al., 2009; Wang, 2007). The U.S. life cycle inventory (USLCI) database (U.S. Dept. Energy, 2016) and SimaPro (Pre' North America, Inc., Washington, DC) were used to calculate a GWP of input products, including manufacturing processes and transportation. It was assumed that N was from NH_4NO_3. Although probably not totally representative of organic substrates, a 1% loss of applied N as N_2O was assumed based on research with field soils and resulted in an estimated GWP of 4.65 kg CO_2e/kg of N applied (Intergovernmental Panel on Climate Change (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 CO_2/m^3 and 0.684 kg CO_2e/kWh, respectively, from USLCI data through SimaPro. Electricity for individual activities was calculated, and remaining electricity use was determined by consulting grower records for overall use and expressed as overhead electricity.

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 CO_2e/kg, of which 0.100 kg CO_2e was from peat (0.945 kg) and 0.217 kg CO_2e was from perlite (0.121 kg), which included mixing and transportation. The GWP of peat was based on a German model adjusted for U.S. energy by Ecoinvent database (Ecoinvent Centre, 2015) accessed through SimaPro and the GWP of perlite was obtained from the USLCI database. A GWP of the trays manufactured from polystyrene using a blow-mold technology was calculated to be 2.620 kg CO_2e/kg, assuming a transported distance of 200 km and landfill disposal of used material. The average CO_2e emission for a range of fungicides (12.50 kg CO_2e/kg) and insecticides (18.69 kg CO_2e/kg) were calculated from data presented by Lal (2004). Calcium hypochlorite tablets were the source for chlorine with a GWP of 1.09 kg CO_2e/kg (U.S. Dept. Energy, 2016).

Costs of inputs, equipment use, and labor were determined for the model systems based on the life cycle inventory. Labor requirements for operating equipment were calculated as 1.25 times the equipment operation hours to account for preparation and clean-up time. Labor contributes significantly to costs but does not contribute directly to the GWP of the product. The Adverse Effect Wage Rate as determined by the U.S. Dept. of Labor (2016) was used to set the hourly wage

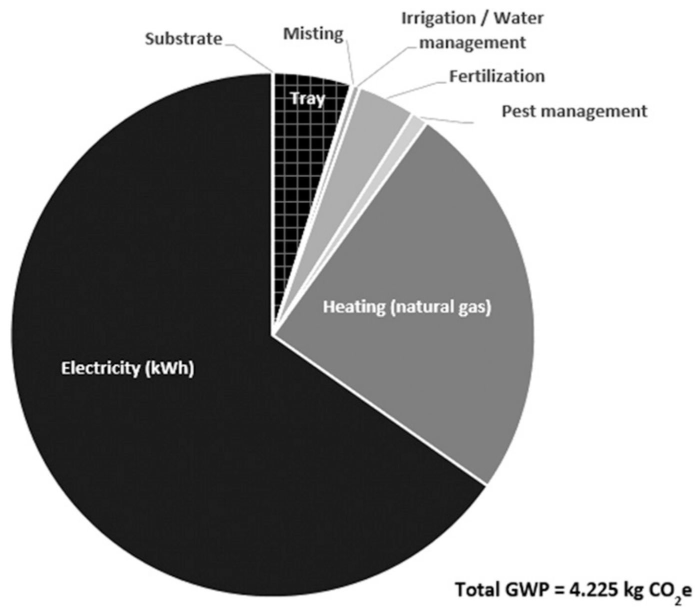

Fig. 1. Global warming potential for production components and activities for a 72-count tray of young foliage plants modeled as a 12-week crop in a gutter-connected, rounded-arch greenhouse without a ridge vent, and covered with double-layer polyethylene and having stationary benches (System A).

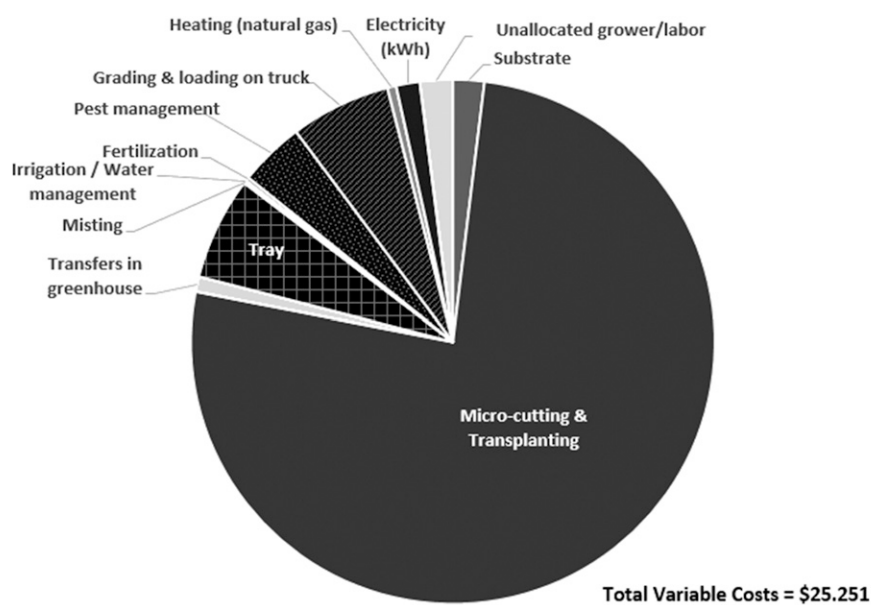

Fig. 2. Variable costs for production components and activities for a 72-count tray of young foliage plants modeled as a 12-week crop in a gutter-connected, rounded-arch greenhouse without a ridge vent, and covered with double-layer polyethylene and having stationary benches (System A).

rate of \$12.69. This represents the wage level that must be offered and paid to migrant workers by agricultural employers of non-immigrant H-2A agricultural workers. This rate was used because it acts as a price floor for labor engaged in agricultural or horticultural enterprises. Equipment costs per hour were representative of those reported in regional enterprise budgets for horticultural crops. Natural gas and electricity prices were established as \$0.386/m^3 and \$0.091/kWh through grower interviews.

Results and Discussion

The GWP due to the GHG from production, distribution, and use of input products, use of equipment and environmental control, and other activities for production of young foliage plants in 72-count trays were calculated to be 4.225 and 2.276 kg CO_2e for Systems A and B, respectively (Tables 1 and 2). Total variable costs per tray of these systems were calculated as \$25.251 and \$24.857, respectively.

Electricity and natural gas use were by far the greatest contributors to GWP of the finished tray of young foliage plants in both systems, but neither was a major contributor to the variable cost (Figs. 1–4). The primary cost item for both System A and B was the microcutting from tissue culture and the cost of transplanting those into the 72-count trays (\$19.223). However, the contribution of the microcutting to GWP was insignificant. This differs from field production of trees and shrubs where the items contributing to GWP were also primary contributors to the variable costs, principally due to equipment use on individual plants (Hall and Ingram, 2014, 2015; Ingram, 2013; Ingram and Hall, 2013, 2014a, 2014b).

The GWP of most inputs and processes were similar between the two systems. Generally, the more modern greenhouse in System B could be characterized as being more efficient in terms of space utilization for production, heating and cooling, fertilization, and water use. The substrate, microcutting, misting, and labor-intensive processes such as transplanting, transferring within the greenhouse, grading, order pulling, and loading each contributed no more than 0.001 kg CO_2e to the GWP of System A or B (Tables 1 and 2). The 72-count tray contributed 0.204 kg CO_2e which was only 5% and 9% of the total GWP for Systems A and B, respectively.

The 46% lower GWP for System B compared with System A was due primarily to differences in electricity, heating, and fertilization (Figs. 1 and 3). For System A, electricity and heating contributed 2.757 and 1.045 kg CO_2e whereas they contributed 1.365 and 0.620 kg CO_2e for System B, respectively (Tables 1 and 2). Electricity and heating with natural gas contributed \$0.368 and \$0.137 to the costs in System A whereas they contributed \$0.182 and \$0.081 for System B, respectively. Electricity and natural gas accounted for 90% of the GWP of the tray of young plants in System A and 87% in System B and 1.9% of the variable costs in both systems (Figs. 1–4). The greater potential for natural ventilation in System B would be expected to result in decreased electricity use for exhaust fans and evaporative cooling than System A. The polycarbonate covering in System B would also result in less heat loss than the double-layer polyethylene covering in System A (U.S. Dept. of Agriculture, Agricultural Research Service, 2017). System B also has a slightly lower space use (4.5 trays/m^2; benches occupy 72% of greenhouse area) than System B because of the moveable benches (5.7 trays/m^2; benches occupy 86% of greenhouse area) and the difference in space use efficiency would impact the heating and cooling requirements for a tray. This would potentially impact the allocation of overhead costs on an area basis although this LCA did not consider differences in

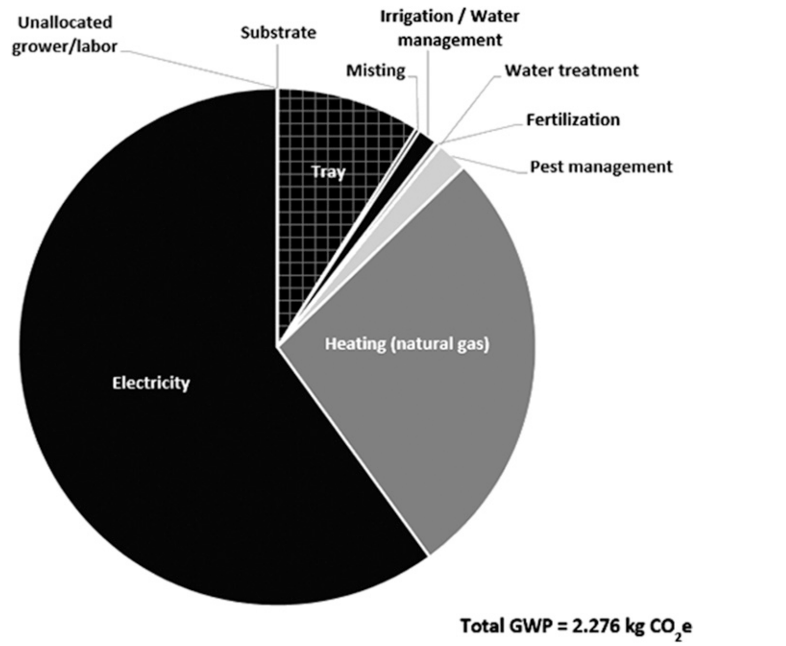

Fig. 3. Global warming potential for production components and activities for a 72-count tray of young foliage plants modeled as a 12-week crop in a more modern gutter-connected, Dutch-style greenhouse using natural ventilation and moveable ebb-flood production tables (System B).

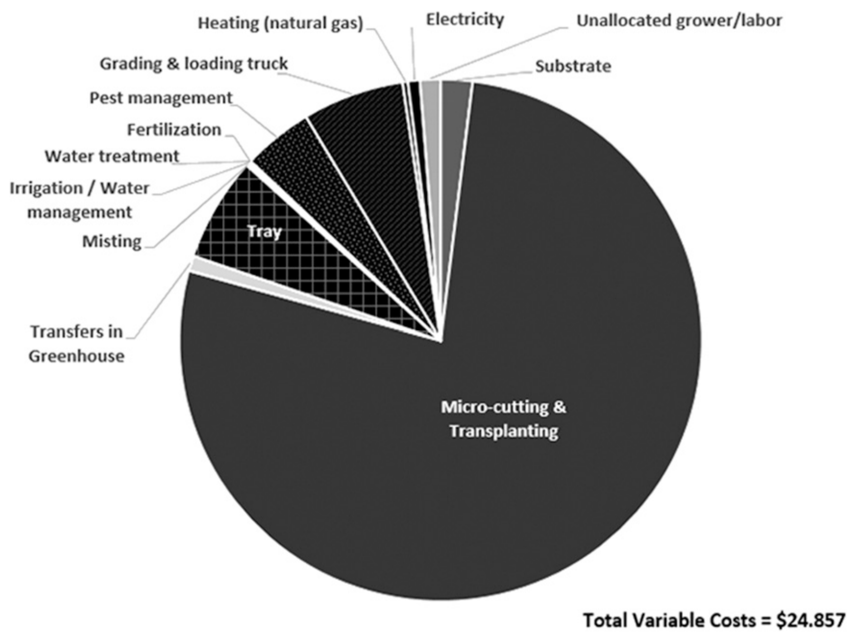

Fig. 4. Variable costs for production components and activities for a 72-count tray of young foliage plants modeled as a 12-week crop in a more modern gutter-connected, Dutch-style greenhouse using natural ventilation, and moveable ebb-flood production tables (System B).

capital investments, nor the overhead costs associated with them.

Fertilization accounted for 0.150 and 0.008 kg CO_2e of the GWP and \$0.055 and \$0.016 of variable costs for Systems A and B, respectively (Tables 1 and 2). Irrigation, water management, and water treatment together contributed 0.018 and 0.028 kg CO_2e to the GWP and \$0.029 and \$0.044 to the cost of the product in Systems A and B, respectively. Less fertilizer was required for the subsurface irrigation method in System B than the overhead sprinkler irrigation in System A because of the lack of leaching and salt accumulation in subsurface irrigation systems (Liu et al., 2012; IGE Staff, 2016). Also, recycling of the water also recycles nutrients but adds GWP and cost for pumping, filtering, and treating recycled water. Electrical pumps for irrigation, water management, and water treatment added 0.018 kg CO_2e to the GWP of the product and \$0.029 to variable costs in System A compared with 0.028 kg CO_2e and \$0.034 for System B. Misting during the rooting stage of the micro cuttings only contributed 0.005 and 0.006 kg CO_2e and \$0.020 and \$0.020 to variable costs for Systems A and B, respectively. The total GWP of water management, including pumping water from the source, movement of water within the nursery, misting, and irrigation for Systems A and B were calculated as 0.024 and 0.034 kg CO_2e, respectively.

Water use also differed between the two systems. Although water use for misting was similar between the systems at ≈25 L per tray, production water use was greater in System A than in System B. This would be expected given the recycling of water in the ebb-flood system of System B. About 64 L of water per tray is applied in irrigation for System A while only 21 L are added to the system per tray in System B model. Interestingly, the water requirements for evaporative cooling were greater than for irrigation in these models. Water use for evaporative cooling was estimated at 53 and 64 L per tray in Systems A and B, respectively.

These results point to the need for growers to consider the differences in efficiencies and their resulting impact on CF and costs (both variable and overhead) when evaluating structures for greenhouse construction. Historically, sunk costs (those already made) have had too much influence on grower decision-making regarding potential investments, particularly regarding structures (Hall, 2010). When making investment decisions as to which system to implement, a net present value analysis of future or prospective costs would be an appropriate tool to use. Although outside the scope of this analysis, we hypothesize that given the variable cost structure found in this study, System B would more likely lead to greater cost savings and/or increases in revenue for the greenhouse operation and would thus be the more favorable option. Interestingly, the use of System B also leads to a smaller carbon (and potentially water) footprint.

As far as the impacts of these results on consumers, previous studies have shown a segment of consumers have a willingness to pay more for plants that are grown using environmental-friendly techniques. Yue et al. (2016) found that, compared with conventional plants, environmental-minded consumers (about 14% of the respondents surveyed) were willing to pay \$0.18 more for bedding plants grown in a "sustainable" method, \$0.46 more for plants grown with energy-saving methods, and \$0.22 more for plants grown with water-saving methods. Compared with plants in conventional plastic containers, they were willing to pay \$0.37 more for plants in compostable containers, \$0.43 for plants in plantable containers, and \$0.14 more for plants in recyclable containers. They liked local plants and plants grown in the United States and were willing to pay \$1.99 more for locally-grown plants and \$1.73 more for domestically grown plants compared with their imported counterparts. Because the results of this study indicate that foliage plants grown using System B are more energy- and water-saving, one might surmise that this would weigh favorably for this segment of consumers.

Unlike woody landscape plants, however, young (and even mature) foliage plants do not contribute to long-term carbon sequestration due to the lack of wood production and their shorter life expectancy. However, in addition to their esthetic value, they do provide selected ecosystem services through improved air quality (including removal of volatile organic compounds), enhanced biodiversity, and storm water management. Recent research also points to the numerous health and well-being benefits of foliage plants including increased productivity, higher levels of employee satisfaction, reduced absenteeism, reduced stress, faster attention deficit recovery, and other biophilic design benefits (Hall and Dickson, 2011). These benefits should appeal to the aforementioned environmental-conscious consumers, as well as those who value health and well-being.

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