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Carbon Footprint and Variable Costs of Production Components for a Container-grown Evergreen Shrub Using Life Cycle Assessment: An East Coast U.S. Model

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***Abstract*. The production components of an evergreen shrub (*Ilex crenata* 'Bennett's Compacta') grown in a no. 3 container in an east coast U.S. nursery were analyzed for their costs and contributions to carbon footprint, as well as the product impact in the landscape throughout its life cycle. A life cycle inventory was conducted of input materials, equipment use, and all cultural practices and other processes used in a model production system for this evergreen shrub. A life cycle assessment (LCA) of the model numerated the associated greenhouse gas emissions (GHG), carbon footprint, and variable cost of each component. The LCA also included the transportation and transplanting of the final product in the landscape as well as its removal after a 40-year useful life. GHG from input products and processes during the production (cutting-to-gate) of the evergreen shrub were estimated to be 2.918 kg CO_2e. When considering carbon sequestration during production weighted over a 100-year assessment period, the carbon footprint for this model system at the nursery gate was 2.144 kg CO_2e. Operations, combining the impact of material and equipment use, that contributed most of GHG during production included fertilization (0.707 kg CO_2e), the liner and transplanting (0.461 kg CO_2e), the container (0.468 kg CO_2e), gravel and ground cloth installation (0.222 kg CO_2e), substrate materials and preparation (0.227 kg CO_2e), and weed control (0.122 kg CO_2e). The major contributors to global warming potential (GWP) were also major contributors to the cutting-to-gate variable costs ($3.224) except for processes that required significant labor investments. Transporting the shrub to the landscaper, transporting it to the landscape site, and transplanting it would result in GHG of 0.376, 0.458, and 0 kg CO_2e, respectively. Variable costs for postharvest activities were $6.409 and were dominated by labor costs (90%).**

Producers of landscape plants are increasingly incorporating sustainable production practices to influence social acceptance of those plants in terms of their environmental, economic, and health and well-being features. Within a maturing industry, the economic portion of the triple bottom line is important (Hall, 2010) and the nursery industry has traditionally sought ways to minimize environmental impact of production. Social sustainability is reflected in the purchasing decisions made by end consumers. Understanding the environmental impacts of production system protocols could allow managers to increase efficiency and reduce potentially negative impacts of more sustainable systems. Understanding the ecosystem services of landscape plants could provide information to more effectively market these products to environmentally conscious consumers (Ingram and Hall, 2015b; Yue et al., 2011).

LCA has been used to characterize agricultural and bioenergy production systems (Davis et al., 2009; Debolt et al., 2009; Farrell et al., 2006; Hayashi et al., 2006; Koerber et al., 2009; Liebig et al., 2008; Payraudeau and van der Werf, 2005) including landscape plant production (Beccaro et al., 2014; Ingram 2012). LCA has been used to describe environmental impacts of the nursery industry in the Piemonte region (Beccaro et al., 2014) and the Pistoia plant production district (Lazzerini et al., 2016; Nicese and Lazzerini, 2013) of Italy on an area basis. The carbon footprint of a product or activity is a measure of the associated GHG and expressed as the GWP of those gases. The GWP for the production and distribution of trees in nos. 5 and 9 containers in the United States was reported by Kendall and McPherson (2012) as 4.6 and 15.3 kg CO_2e, respectively. Ingram and Hall (2015a) conducted a LCA of a pot-in-pot production system of a red maple in a no. 25 container and reported GHG of 15.317 kg CO_2e and a cutting-to-gate GWP of 10.742 kg CO_2e. Some of these published studies have focused on the details of operational protocols and their impact on GWP, or the products' carbon footprint. The propagation-to-landscape GWP for field-grown, 5-cm-caliper *Acer rubrum* L. (red maple), *Picea pungens* Engelm (colorado blue spruce), and *Cercis canadensis* L. (redbud) and 0.9-m Judd viburnum (*Viburnum* ×*juddi* Rehder) and a 0.6-m 'Densiformis' yew (*Taxus* ×*media* Rehder) shrubs were reported as 20.9 (adjusted for more inclusive fuel and weighted sequestration during production), 13.6, 13.7, 3.16, and 3.22 kg CO_2e, respectively (Hall and Ingram, 2015; Ingram, 2012, 2013; Ingram and Hall, 2013, 2014a, 2014b, 2015a). These studies have also estimated carbon sequestration from the atmosphere during the life of the plant, weighted over a 100-year assessment period. Protocols for shrub production in containers are significantly different from field production systems and production of trees in larger containers. The objective of this study was to determine the GHG and variable costs of production system components for an evergreen shrub in a no. 3 container on the east coast of the United States.

Methods

Goal, scope, and functional unit

The functional unit for this LCA study was an evergreen shrub, such as *Ilex crenata* 'Bennett's Compacta', in a no. 3 container on the mid-Atlantic coast of the United States. A life cycle inventory for the model production system was based on interviews with nursery managers in the region and guided by published best management practices (Southern Nursery Association, 2013) (Fig. 1). The boundaries for this model assumed cuttings would be taken from current nursery stock in February and stuck 2 cuttings per 8-cm cell in a flat and placed in a Quonset greenhouse with bottom heat. The liner would be transplanted to a no. 3 container in September or October and grown for 24 months on an outdoor gravel bed covered with a ground cloth. Finished plants would be transported by tractor-trailer to

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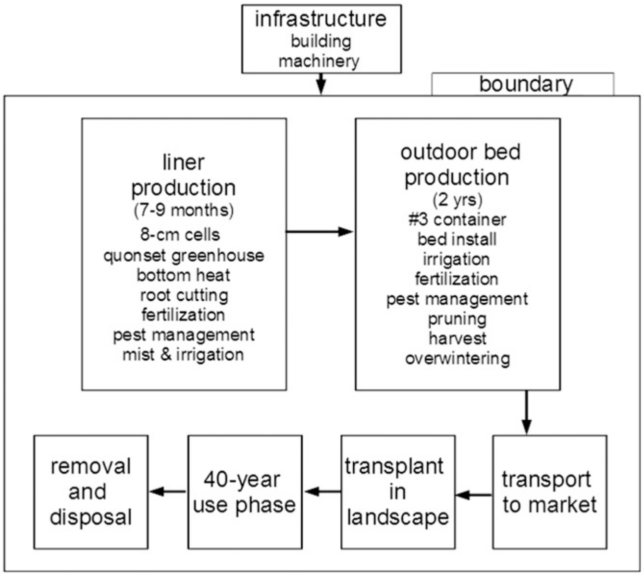

Fig. 1. System diagram and boundaries.

a landscape company, transported to the customer, and transplanted into the landscape. The shrub would reach a size of 1-m high and 1.4-m wide during a 40-year functional life, followed by shrub removal and disposal to compete the life cycle. This LCA study will focus on the GWP and variable costs of production system components.

LCA standards were followed, including the International Organization for Standardization (ISO, 2006) and PAS 2050 guidelines by BSI British Standards (2011). Input products, equipment use, and labor were inventoried for the activities in each production phase. GHG were determined, converted to kilograms CO$_2$e per functional unit, and summed. Costs of inputs, equipment use, and labor were determined for the model system. 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.

Input materials, labor, and equipment use for greenhouse production of liners

The substrate would consist of 85% aged pine bark, 15% perlite, and 5% peat by volume, amended with 2.3 kg of dolomitic limestone and 3 kg of 12-month-release, polymer-coated controlled-release fertilizer (CRF; 15N–3.5P–10.0K) with micronutrients per cubic meter. A paddle mixer with 7.46-kW (1 hp = 0.746 kW) motor would mix 3 m^3 of substrate in 5 min and require a 48.5-kW tractor with front-end loader and two people for 15 min. The substrate would be conveyed with a 1.5-kW motor from the mixer to containers placed on a wagon, ≈3 min per batch. Flats would be used for four crops and hold 18-count, deep-cell inserts used only for one crop. Plants would be moved by a 17.9-kW tractor and wagon to a 5.2 × 19.8 m Quonset structure with galvanized bows, covered with double-layer clear plastic and 50% shadecloth, 618 flats per greenhouse.

Bottom heat necessary to maintain 21C substrate temperature would be supplied by circulating water heated by a 15-kWh tankless water heater with a 746-W electric circulating pump per house through polyvinylchloride pipe on the fabric-covered gravel surface. Bottom heat was assumed to contribute 48% of heat necessary to maintain a 21C air temperature February to May with forced air heaters using propane to provide the remaining heat requirement. The heating requirements and fuel consumption of 122.4 L of propane per crop were determined using Virtual Grower, a calculator for greenhouse heating requirements developed and maintained by the Agricultural Research Service, U.S. Department of Agriculture (2015).

Cuttings would be misted until rooted then irrigated as needed. An average of 0.64 cm of irrigation was assumed to be applied daily for 32 weeks or 146 m^3 per house. Irrigation would be pumped from surface water and chlorine would be injected at 6 mg/L from sodium hypochloride (15% chlorine) to yield 1–2 ppm free chlorine at the nozzle. One full-time employee would control and monitor irrigation of 600,000 liners. Fungicides (pyraclostrobin plus boscalid, mancozeb, hydrogen dioxide plus peroxyacetic acid, and thiophanate-methyl) would be rotated in a weekly spray schedule for 24 weeks, using a 100-gallon sprayer with 3.7-kW gasoline engine pulled by a 17.9-kW tractor. One person would invest an average of 3 min per house per spray. The rooting cuttings would also receive three drenches with mefenoxam plus thiophanate-methyl using a 600-gallon sprayer with 5-kW gasoline engine pulled with the 17.9-kW tractor and require 10 min with one person per greenhouse. Shrinkage for the propagation phase was assumed to be 10%. Liners would be pruned twice with a gasoline-powered shearer requiring a total of 1 h per house.

Energy required for overhead (electricity for general activities and gasoline for field truck and ATV) for the liner production phase was calculated from the consumption of electricity at 73 kWh·ha^{-1} and gasoline at 76 L·ha^{-1} as previously published (Hall and Ingram, 2015; Ingram and Hall, 2014a).

Input materials, labor, and equipment use for production in no. 3 container

The 21.7 × 73.2-m outdoor beds would be covered with 134 × 10^5 kg·m^{-3} of gravel covered with a woven polypropylene ground cloth (0.14 g·cm^{-2}). Gravel was assumed to be transported 40 km and replenished only after 20 years. The ground cloth was assumed to last 15 years. The no. 3 container was assumed to be made using high-density polyethylene (HDPE) in a blow-mold process and weigh 0.158 kg.

The substrate would consist of aged pine bark delivered to the nursery in 41.3-m^3 loads. Each load would require 45 min of a 56.0-kW loader and 30 min of a 93.2-kW tumbler/screener to blend 5.97 kg·m^{-3} of a 12 to 14-month CRF (18N–2.2P–7.5K) with micronutrients and dolomitic limestone (2.97 kg·m^{-3}) to prepare the substrate for potting. Each cubic meter would fill 91 no. 3 containers. A 7.5-kW electric motor would operate a potting machine requiring a 15-person crew and 3 17.9-kW tractors and two tracking wagons to pot and transport 12,000 plants to the field in 8 h. Containers would be placed can-tight initially, 12,000 per bed until spaced in the spring at 6,000 per bed, requiring 48 h of labor and 3 17.9-kW tractors and wagons per 12,000-plant bed. For the second winter, the 6000 plants per bed would be placed container-to-container from November to March (16 man-hours per bed) and covered with 50% polypropylene shadecloth, assumed to last 10 years, in November and removed in March. Covering a bed of plants would require 1.5 labor hours and uncovering would require 2 h and 20 min of a 17.9-kW tractor. Plants would be pruned two times per year using gasoline-powered shearers (45 min per bed) and two times using hand pruners (14 labor hours per bed).

A 12- to 14-month CRF with minor elements (18N–2.2P–7.5K) would be surface applied at potting at 70 g per container, requiring 5.5 labor hours per bed and reapplied the second year of production. Soluble fertilizer (10N–0.9P–5K) would be applied through the irrigation system 16 times during each growing season, beginning 6 months after potting.

Based on previous work, 19 mm of water was assumed to be applied 280 times per year to the bed via overhead irrigation (Warsaw et al., 2009). A 44.8-kW pump would supply 22.7 m^3·min^{-1} to 10 beds at a time. The amount of applied water per plant would be based on plant population per bed, i.e., plant spacing. Runoff irrigation would be captured for reuse. Warsaw et al. (2009) reported that 60% of applied water from overhead irrigation to no. 3 containers spaced 45 cm on-center ran off the bed. Monitoring and controlling irrigation per bed would require 11.25 h per year.

Chlorine would be injected at 6 mg·L^{-1} as described above.

Weed control was assumed to involve four applications of granular herbicides per year, rotating between oxyfluorfen and indaziflam, requiring 10 min per bed and 5 min of a 24-kW tractor per application. Hand weeding escapes was assumed to require 6 h per bed each year.

Spring and fall applications of horticultural oil spray with copper hydroxide (70%) at 0.6 g·L^{-1} plus one spray in June with a tank mix of mancozeb (1.7 kg·ha^{-1}) and thiophanate-methyl (1.1 kg·ha^{-1}) was assumed. A 100-kW tractor with 1900-L air-blast sprayer would be used 0.5 h per bed per application.

Pulling orders and loading trucks was assumed to take 78 h of labor and 3 h of a 17.9-kW tractor with two tracking trailers for each 6000 finished no. 3 container plants. Shrinkage of 5% was assumed for the outdoor production phase.

Equipment use assumptions

Estimated tractor power (1 hp = 0.746 kW) requirements for each function were determined through nursery manager interviews. The portion of maximum tractor throttle and load for each operation was assumed to be loading substrate components in mixer, 48.5 kW at 0.5 throttle and 0.5 load; transporting plants on wagons, pulling sprayers, and transporting other materials to the field, 17.9-kW tractor at 0.50 throttle and 0.50 load; spreading gravel on field beds, 40-kW tractor at 0.50 throttle and 0.50 load; loading pine bark in tumbler/screener, 55.9-kW loader at 0.85 throttle and 0.85 load; tumbler/screener for substrate preparation, 93.2 kW at 1.0 throttle and 1.0 load; and air-blast sprayer, 74.6-kW tractor at 0.85 throttle and 0.85 load.

The 3.7-kW gasoline-powered spray was assumed to consume 1.25 L·h^{-1}. Gasoline-powered shearers were assumed to consume 0.63 L·h^{-1}. Electric motors were assumed to use 0.746 kW·hp^{-1}. Energy required for overhead for the container production phase was calculated on an area basis as described above.

Labor inputs

The model included labor requirements for each operation through nursery manager interviews conducted in 2015, with follow-up Delphi-method (Hsu and Sandford, 2007) discussions. Labor requirements for operating equipment were calculated as 1.25 times the equipment operation hours to account for preparation and cleanup time. Labor contributes significantly to costs but does not contribute directly to the GWP of the product.

Postharvest activity assumptions

A 1500-plant load was assumed to be transported 362 km by commercial carrier at \$2.48/km. A 32-km, 30-min trip with a 50-plant load was assumed for the landscaper and 0.5 labor hours (Fortier, 2014) would be required to plant the shrub into the landscape. Following 40 years of useful life in the landscape, shrub removal would require 0.5 h of labor and 15 min of a 10-plant load in a pickup truck. This was also compared with shredding on site and composting for mulch, requiring 3 min of a gasoline shredder using 1.9 L·h^{-1}.

Cost calculations. Variable costs were estimated using an economic engineering approach for production system components defined through the life cycle inventory (LCI). Fixed costs associated with buildings, land, and general overhead are highly variable between nurseries in the industry and were not included in this analysis, but range from 48% to 52% of total costs. The Adverse Effect Wage Rate as determined by the U.S. Department of Labor (2015) for the states included in the lower midwest region was used to set the wage rate of \$11.67. This represents the wage level that must be offered and paid to migrant workers by agricultural employers of nonimmigrant H-2A agricultural workers. This wage also tends to act as a floor for nonmigrant wage levels as well. Costs of input materials were obtained from nursery industry wholesale distributors and manufacturers in 2014. Equipment costs per hour were representative of those reported in enterprise budgets for horticultural crops produced in the lower midwest region. The gasoline price of \$0.858/L represented the U.S. average as reported by the U.S. Energy Information Administration (2015).

Inventory analysis and data collection

The GWP of inputs was taken from a variety of published sources as follows. The GWP for gasoline and diesel consumption was determined based on “well-to-wheel” emission reported in GREET1_2011 (Vyas and Singh, 2011) as 2.9339 and 3.0153 kg CO_2e/L, respectively. The GWP of fluids used by tractors and trucks were calculated using GREET2_7 (Burnham et al., 2006) as previously reported (Ingram, 2013). Fuel consumption was used to determine the GWP of machinery and truck use for each operation. Heavy and light truck diesel consumptions were based on 2.5 and 4.2 km·L^{-1} (6 and 10 mpg), respectively. Published standards for diesel consumption by tractor horsepower, throttle, and load (Grisso et al., 2010) were used for each operation as previously reported (Hall and Ingram, 2014, 2015; Ingram, 2012, 2013; Ingram and Hall, 2013, 2014a, 2014b, 2015a).

GWP of 3.2, 1.0, and 0.7 kg CO_2e/kg for N from urea, P_2O_5, and K_2O fertilizers, respectively, were assumed as previously published (Snyder et al., 2009; Wang, 2007). U.S. LCI data (U.S. Department of Energy, 2015) and SimaPro (Pre’ North America, Inc., Washington, DC) were used to calculate a GWP of input products, including manufacturing processes and transportation. Information on the amount of polymer or the processing of coating fertilizers is not available for proprietary products. Therefore, we assumed the polymer was 10% of the weight of the input product and the processing energy use was equivalent to polyol, a precursor to polyurethane, and blow-mold processing calculated from manufacturing data in SimaPro, to yield a coating GWP of 0.065 kg CO_2e/kg of fertilizer. This is likely an overestimate of the GWP. A 1% loss of applied N as N_2O was assumed, which would result in an estimated GWP of 4.65 kg CO_2e/kg of N applied (IPCC, 2006; Snyder et al., 2009; West and Marland, 2003). However, this assumption may not apply directly when using polymer-coated N and could overestimate the potential N_2O loss impact. The GWP of micronutrients as constituents of fertilizer product was assumed to be insignificant and not included. The average CO_2e emission for a range of herbicides (23.083 kg CO_2e/kg) and limestone (0.5862 kg CO_2e/kg) were calculated from data presented by Lal (2004).

The pine bark substrate for the container-production phase and the propagation substrate GWP was calculated to be 0.115 kg CO_2e/kg, assuming the bark was sourced from a saw mill in the southeastern United States (0.0674 kg CO_2e/kg) and transported by tractor/trailer 500 km (0.0474 kg CO_2e/kg). The pine bark would also be processed by a tumbler/screener that added 0.00957 kg CO_2e/kg. The propagation substrate GWP was calculated to be 0.145 kg CO_2e/kg, of which 0.104 kg CO_2e was from pine bark (0.83 kg), 0.018 kg CO_2e was from perlite (0.15 kg), and 0.023 kg CO_2e was from peat (0.02 kg). The GWP of peat was based on a German model adjusted for U.S. energy by Ecoinvent database (Ecoinvent Center, 2015) accessed through SimaPro.

A GWP of 2.25 kg CO_2e/kg for no. 3 containers assumed manufacturing from 100% recycled HDPE pellets using blow-mold processing, the products being transported 200 km and 50% of used containers would be sent to a landfill. A GWP of the propagation trays and inserts manufactured from polystyrene using a blow-mold technology was calculated to be 2.601 kg CO_2e/kg, assuming a transported distance of 200 km and landfill disposal of used material. Polypropylene tubing manufactured from low-density polypropylene using pipe extrusion technology and woven polypropylene fabric from granules and extrusion into sheets and including transport of materials and disposal in landfill was calculated as 2.81 and 2.77 kg CO_2e/kg, respectively.

Sensitivity analysis was conducted to evaluate the relative impact of input variable errors as well as the impact of each input variable on the total kg CO_2e investment in the shrub. Each input variable within each life phase was in turn increased by 10%, whereas other variables were unchanged in model simulations. The maximum percentage change in total kg CO_2e investment in the shrub was used to assess the sensitivity of the model to each variable. The sensitivity of CO_2 sequestration during production, use, and end-of-life phases was calculated separately using the same procedures. Sensitivity for each phase was expressed relative to the final carbon footprint. A Monte Carlo analysis with 1000 iterations was also employed using SimaPro to estimate the variability of the calculated GWP of this product.

The impact on atmospheric CO_2 as previously published for shrubs using PAS 2050 protocols (BSI British Standards, 2011). Carbon sequestration during production was determined from the average dry weight of three no. 3 *Ilex crenata* 'Bennett's Compacta' (1.03 kg) and the accumulated dry weight during the plant's 40-year life, weighed over a 100-year assessment period, was calculated to be 9.78 kg using methods previously published (Hall and Ingram, 2014, 2015; Ingram and Hall, 2014a, 2014b).

Results and Discussion

GHG from input products, cultural practices, and other processes during the production (cutting-to-gate) of an evergreen shrub in a no. 3 container on the east coast of the United States were estimated to be 2.918 kg CO_2e. Carbon sequestration in the wood of this plant during production, weighted over a 100-year assessment period, would result in a positive impact of −0.774 kg CO_2 on atmospheric carbon. The resulting carbon footprint for this model system at the nursery gate would be 2.144 kg CO_2e. This value was significantly smaller than for field-grown trees (6.6 to 12.8 kg CO_2e) and somewhat larger than for field-grown shrubs (0.70 to 0.77 kg CO_2e) (Hall and Ingram, 2015; Ingram, 2012; Ingram and Hall, 2013, 2014a).

The liner produced in the 80-mm container contributed 0.455 kg CO_2e to the carbon footprint of the finished plant, after considering a 5% loss during production in the no. 3 container. Greenhouse heating and bottom heating for the propagation trays contributed 84% (0.362 kg CO_2e) of the GHG during liner production. Mist and irrigation, the propagation tray and insert, and the temporary greenhouse structure contributed 7%, 5%, and 3% of liner production GWP, respectively. All other processes and inputs had minimal contributions to GWP of the liner.

GHG attributed to materials during the production of the finished plant in the no. 3 container in this model was 2.328 kg CO_2e while equipment use contributed only 0.546 kg CO_2e (Table 1). Major contributors to emissions due to materials would include fertilizers (0.687 kg CO_2e), the container (0.468 kg CO_2e), the pine bark (0.211 kg CO_2e), the gravel surface and ground cloth (0.222 kg CO_2e), and herbicides (0.121 kg CO_2e) and account for 74% of the GHG from material inputs. The most equipment use, although minor, was for applying pesticides, spacing containers, and preparing the substrate and transplanting the liners. The impact of equipment use was shown to be the predominant contributor to the GWP of field-grown trees (Ingram, 2012, 2013; Ingram and Hall, 2013) and shrubs (Hall and Ingram, 2015; Ingram and Hall, 2014a). Overhead energy use accounted for 1.5% (0.044 kg CO_2e) of GHG during production.

When examined from an operations perspective, which combined the impact of material and equipment use, a few operations contributed most of the GHG during production (Fig. 2). Fertilization (0.707 kg CO_2e), the liner and transplanting (0.461 kg CO_2e), the container (0.468 kg CO_2e), gravel and ground cloth installation (0.222 kg CO_2e), substrate materials and preparation (0.227 kg CO_2e), and weed control (0.122 kg CO_2e) accounted for 76% of the GHG.

Contribution of postharvest activities on GWP reflected equipment use (0.833 kg CO_2e). Transporting the shrub 362 km to the landscaping company, transporting 32 km to the landscape site, and transplanting would result in GHG of 0.376, 0.458, and 0 kg CO_2e, respectively. As expected due to differences in product size and weight and the number of plants per load, the propagation-to-landscape carbon footprint for this container-grown plant (2.337 kg CO_2e) is much smaller than for the larger field-grown trees (8.2 to 13.7 kg CO_2e) and shrubs (3.16 and 3.22 kg CO_2e) referenced above. Postharvest activities for a 5-cm-caliper red maple tree from a field production system contributed 72% more than that tree produced in the pot-in-pot system due to its lower weight and more trees per load (Ingram and Hall, 2016).

Removal from the landscape and disposal at the end of life contributed 0.115 kg CO_2e to the life cycle of this shrub. All of that was from use of a pickup truck. If the shrub was shredded on site with a gasoline-powered shredder, the activities at the end of life would have been 0.092 kg CO_2e.

Although the life of a plant in the landscape can vary greatly due to planting site, human activities, and maintenance requirements, estimating the impact of the plant during its useful life in the landscape and disposal of the plant at the end of its life is necessary for a life cycle view of the product. The accumulated, weighted impact of annual sequestration of carbon by this shrub over its 40-year life was calculated to be −4.537 kg CO_2. When summing the positive and negative impacts of the complete life cycle of this evergreen shrub, the life cycle GWP was estimated to be −1.445 kg CO_2e. This value is much smaller than the life cycle GWPs of −800, −431, and −63 kg CO_2e previously published and updated for field-grown, 5-cm-caliper red maple (Ingram, 2012), blue spruce (Ingram, 2013), and redbud (Ingram and Hall, 2013) trees, as well as the −11.3 and −8.2 kg CO_2e for field-grown viburnum (Ingram and Hall, 2014a) and yew (Hall and Ingram, 2015) shrubs, which reach a larger mature size than the holly in this study.

Seldom do LCA studies include system component costs; however, detailed production protocols include the majority of cost contributors except for labor. By adding labor to the LCI development phase of the study and assigning a cost to materials and equipment use from published sources, total variable costs can be determined for each operation and related to GWP. In this study and previous studies (Hall and Ingram, 2015; Ingram and Hall, 2013, 2014a), the major contributors to GWP were also major contributors to the variable costs except for processes that required significant labor investments (Table 1) rather than materials and/or equipment usage.

Liner production costs contributed \$0.292 to the total variable costs of the finished no. 3 shrub, considering 5% shrinkage. Labor was

Table 1. Contribution of individual production system components on global warming potential (GWP) and variable costs (\$) for an evergreen shrub, such as *Ilex crenata* 'Bennett's Compacta', in a no. 3 container grown in an east coast U.S. nursery.

	Materials			Equipment use			Labor	Total	
Activity/Components	kg or unit/shrub	GWP (kg CO_2e)	Costs (\$)	h/shrub	GWP (kg CO_2e)	Costs (\$)	Costs (\$)	GWP (kg CO_2e)	Costs (\$)
Substrate	1.8395	0.2115	0.3759	0.0003	0.0150	0.0115	0.0040	0.2266	0.3914
Dolomitic limestone	0.0341	0.0200	0.0135	0.0000	0.0000	0.0000	0.0000	0.0200	0.0135
Container	0.1663	0.4684	0.7123	0.0000	0.0000	0.0000	0.0000	0.4684	0.7123
Irrigation	0.0000	0.0000	0.0000	0.7771	0.4795	0.0527	0.0445	0.4795	0.0972
Chlorination	0.1134	0.1350	0.0182	0.0000	0.0000	0.0000	0.0000	0.1350	0.0182
Transplant liners	0.0000	0.4555	0.2924	0.0014	0.0058	0.0117	0.1187	0.4613	0.4228
Spacing	0.0000	0.0000	0.0000	0.0014	0.0106	0.0108	0.1187	0.0106	0.1295
Gravel surface	3.7349	0.0687	0.0504	0.0000	0.0004	0.0004	0.0028	0.0692	0.0536
Ground cloth	0.0552	0.1529	0.0802	0.0000	0.0004	0.0004	0.0026	0.1532	0.0832
Overwintering	0.0021	0.0059	0.0617	0.0001	0.0007	0.0002	0.0104	0.0065	0.0723
Fertilization	0.3462	0.6872	0.5152	0.0000	0.0000	0.0000	0.0109	0.6872	0.5261
Apply herbicides	0.0053	0.1213	0.2631	0.0001	0.0007	0.0007	0.0187	0.1220	0.2826
Hand weeding	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0950	0.0000	0.0950
Insecticides/fungicides	0.0001	0.0015	0.0077	0.0004	0.0259	0.0272	0.0062	0.0275	0.0411
Pruning	0.0000	0.0000	0.0000	3.0000	0.0033	0.0009	0.1167	0.0033	0.1176
Pulling orders and loading	0.0000	0.0000	0.0000	0.0005	0.0040	0.0036	0.1543	0.0040	0.1580
Energy overhead					0.0441	0.0095		0.0441	0.0095
Total GWP and costs		2.3279	2.3907		0.5903	0.1295	0.7034	2.9182	3.2237

46% of total variable costs during liner production ($0.278), followed in importance by materials (37%) and equipment (17%).

The variable costs from cutting to gate totaled $3.224. During outdoor production of the finished shrub in a no. 3 container, materials comprised 74% of total variable costs, followed by labor (22%) and equipment (4%) (Table 1). Operations (and associated inputs) identified as contributing most to the variable costs at the farm gate included the container (22%), followed by fertilization (16%), substrate materials and preparation (12%), the liner (13%), and weed control (12%) (Fig. 3). Cost of overwintering and spacing (6%), labor for pulling orders and loading trucks (5%), and gravel and ground cloth (4%) were of secondary importance. Insecticide applications, overhead energy, irrigation, and pruning had the least impact on total variable costs. Variable costs for postharvest activities, including transport and transplanting, totaled to $6.409 per shrub and were dominated by labor costs (90%).

The sensitivity analysis for GWP revealed at least a 1% increase in total GHG with a 10% increase in five of the 28 operational variables and for variable costs in four of those five operations in the production phase. Assessed from cutting to gate, a 10% increase in the GWP of the fertilization, container, irrigation, and liner had more than a 1% impact on total GHG. The same was true for variable costs except for irrigation, which accounted for 3% of total variable costs but 16% of GWP. The Monte Carlo analysis of the GWP production protocols revealed a standard deviation of 0.161 kg CO_2e at the 95% probability level, revealing a relatively high confidence in the overall assessment.

Models such as the one developed in this LCA study can be used as important tools to address questions about impact of potential operation modifications on GWP and cost. For example, if fertilizer use could be reduced by 10%, the cutting-to-gate GWP would be reduced by 0.0687 kg CO_2e or 3% to 2.076 kg CO_2e and save $0.052. If the process for container manufacturing could reduce the GWP of the no. 3 container by 10%, the cutting-to-gate GWP would be reduced by only 0.047 kg CO_2e or 2.2% to 2.098 kg CO_2e. Reducing the GWP of several operations in the production model, including irrigation, pulling orders, and loading trucks, would have negligible impact on the cutting-to-gate GWP.

If only 75% of the plants sold in the fall and 25% were maintained for six additional months and sold in the spring, 0.653 kg CO_2e GHG and $0.478 in variable costs would be added to each of those carried-over plants. However, if those GHG were spread across the total plants sold, the increase would be 0.163 kg CO_2e (5.6%) and $0.120 per plant (3.7%).

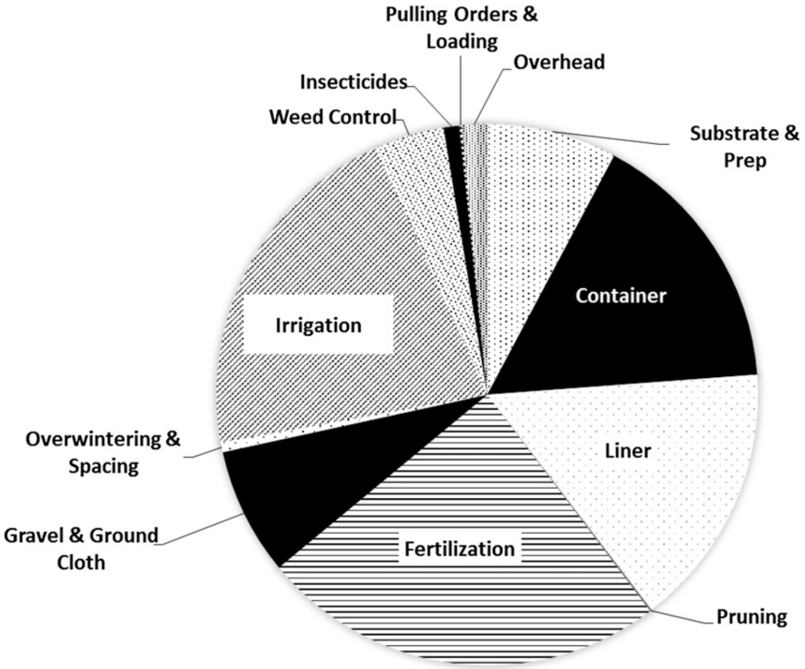

Fig. 2. The impact on global warming potential of greenhouse gas emissions during the production system components (materials, equipment use, and energy overhead) for a broadleaf evergreen shrub, such as *Ilex crenata* 'Bennett's Compacta', in a no. 3 container in an east coast U.S. nursery.

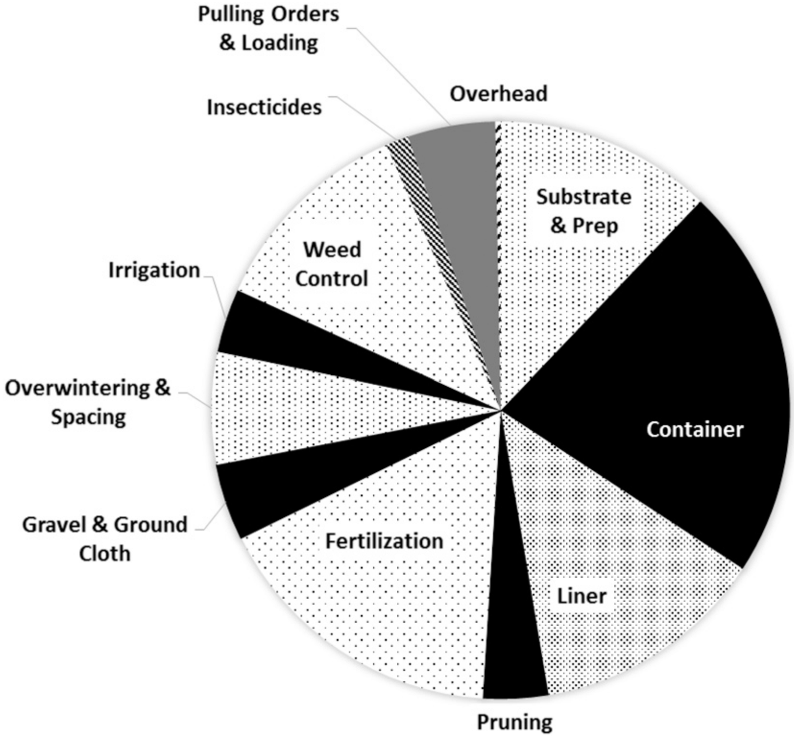

Fig. 3. Variable costs of production system components (material, equipment use, and labor) for a broadleaf evergreen shrub, such as *Ilex crenata* 'Bennett's Compacta', in a no. 3 container in an east coast U.S. nursery.

Conclusions

Analysis of nursery crop production systems using LCA has resulted in a greater understanding of the major contributing factors to GWP and variable costs. The cutting-to-gate GWP of a container-grown evergreen shrub was estimated to be less than the accumulated, weighted impact of annual carbon sequestration. Such information will inform nursery managers and equip them for making better decisions on production protocols, market area, and ways to communicate the economic and environmental value of their products to the consuming public.

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