Carbon Footprint and Related Production Costs of Pot-in-Pot System Components for Red Maple Using Life Cycle Assessment[1]

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Abstract

Component input materials and activities of a model pot-in-pot (PIP) production system were analyzed using life cycle assessment methods. The impact of each component on global warming potential (GWP; kilograms of CO_2-equivalent), or carbon footprint, and variable production costs was determined for a 5 cm caliper *Acer rubrum* L. 'October Glory' in a #25 container. Total greenhouse gas emissions (GHG) of inputs and processes at the nursery gate for a defined model system were 15.317 kg CO_2e. Carbon sequestration weighted over a 100-year assessment period was estimated to be 4.575 kg CO_2, yielding a nursery gate GWP of 10.742 kg CO_2e. The major contridbutors to the GWP at the nursery gate were the substrate, production container, the 1.8 m (6 ft), branched, bare root liner, PIP system installation, and fertilization while the liner and production container also contributed significantly to the variable costs. Input materials and labor constituted about 76 and 21% of variable costs, respectively. Unlike field production systems, equipment use in PIP production accounted for only 13% of GHG emissions and 2% of variable costs.

Index words: global warming potential, sustainable systems, nursery crops, green industry.

Species used in this study: 'October Glory' red maple, *Acer rubrum*.

Significance to the Horticulture Industry

Knowing the impact of production system protocols on environmental parameters such as carbon footprint (global warming potential, GWP) and variable costs will allow managers to focus on increasing efficiency for the largest contributors. Growers will also have the necessary data to analyze the tradeoffs between costs and GWP, as well as the sensitivity of various cultural practices on costs and GWP. Findings from this research reveal that, during their useful life, trees have significantly positive impacts on atmospheric GHG. These data can be used to communicate to the consuming public the value of trees in their landscape, along with producers' efforts to minimize GHG emissions during production.

Introduction

The production and use of landscape plants have significant economic impacts, representing over $176 billion in economic contributions to the U.S. economy in 2007 (Hodges et al. 2011). Landscape plants also provide substantial ecological impacts in the form of ecosystem services including sequestering carbon dioxide (CO_2) from the atmosphere, release of oxygen, modifying the microenvironment, and many others (Marble et al. 2011, McPherson et al. 2005). The production of landscape plants and their subsequent installation in the landscape results in greenhouse gas (GHG) emissions that define the global warming potential (GWP) or carbon footprint of the product. GWP is expressed as the kilograms of CO_2-equivalent emission per functional unit of a product or activity. Nursery production systems differ in their GWP and the ecosystem service of carbon sequestration differs with plant species (Hall and Ingram 2014, 2015; Ingram 2012, 2013; Ingram and Hall 2013, 2014a, 2014b). Carbon sequestration is directly related to biomass accumulation in wood and larger woody plants sequester more carbon in their life time than smaller plants with less structural wood production.

Life cycle assessment (LCA) is systematic process accounting for environmental impacts of input products, processes and activities during a products life cycle, cradle-to-grave (ISO 2006). LCA protocols are governed by international standards and validated through published work (ISO 2006, BSI British Standards 2011).

The net GWP of field-grown, balled and burlapped landscape plants at the nursery gate determined using LCA methodology have been reported as 12.5 kg CO_2e (adjusted to an equivalent fuel and fertilizer GWP) for 5 cm (2 in) caliper 'October Glory' red maple (*Acer rubrum* L.), 6.6 kg CO_2e for 'Forest Pansy' redbud (*Cercis canadensis* L.), 8.1 kg CO_2e for blue spruce (*Picea pungens* Englm.), 0.71 kg CO_2e for a 0.9 m (36 in) Judd viburnum (*Viburnum × juddi* Rehder), and 0.77 kg CO_2e for a 0.6 m (24 in) 'Densiformis' yew (*Taxus × media* Rehder) model systems (Hall and Ingram 2014, 2015; Ingram 2012, 2013; Ingram and Hall 2013, 2014a). Kendall and McPherson (2012) reported the GWP from a LCA study of the production and distribution of container-grown trees in # 5 and # 9 containers was 4.6 and 15.3 kg CO_2e, respectively.

The purpose of this study was to utilize LCA to analyze the GWP of the components of a pot-in-pot (PIP) production system in the Lower Midwest USA for a 5 cm caliper 'October Glory' red maple in a #25 container. Although the focus was on the cutting-to-nursery gate portion of the life cycle, impact of post-harvest activities, function in the landscape, and the end-of-life phase were also analyzed.

Methods and Materials

The functional unit for this LCA study was a 5 cm caliper red maple produced in a PIP system (Fig. 1). The model system was based on interviews with four nursery managers and guided by published protocols (Halcomb and Fare

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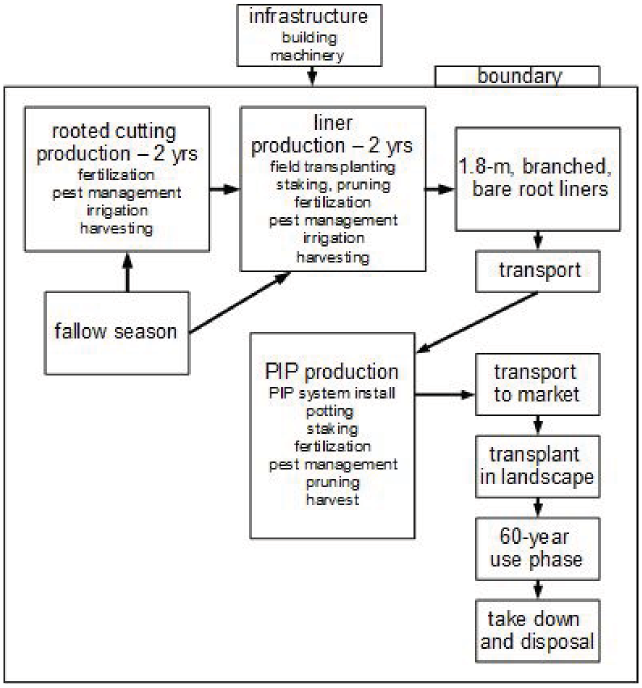

Fig. 1. Schematic of production system components of an *Acer rubrum* 'October Glory' in a #25 container from a pot-in-pot system.

2009, Hall et al. 2002, McNiel 2000). The boundaries for this model assumed cuttings would be taken from current nursery stock in early summer and stuck in ground beds amended with sand. Intermittent mist would be provided until cuttings rooted. After 2 years in the bed, rooted cuttings would be transplanted in rows in the field and grown for 2 years at which time 1.8 m (6 ft), branched, bare root liners would be harvested and transported to the PIP nursery for finishing in #25 containers in two growing seasons. Finished trees would be pulled from the socket pots and loaded on a tractor-trailer truck for transport to the customer and transplanted into the landscape. A 60 year functional life would be followed by tree removal and disposal to compete the life cycle.

LCA standards were followed, including the International Organization for Standardization [ISO (Geneva, Switzerland)] (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 emissions were determined, converted to kilograms CO_2e 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. It was assumed that the farms have been in agricultural production for at least 50 yrs and in nursery production for at least 20 yrs, therefore, no impact from land use change was included.

Input materials, labor and equipment use for bed-production of rooted cuttings. It was assumed that the crop sequencing for both the raised bed liner production and field production of the finished liners would include a fallow year with a 45.6 kg·ha^{-1} (40 lbs·A^{-1}) sudex [*Sorghum bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf.] cover crop every fourth year as previously described (Ingram and Hall 2013). Sand was transported 38 km to the nursery and placed on 1 m by 9.1 m (40 in by 30 ft) ground beds following tilling. One individual would take and stick an average of 312 cuttings·hr^{-1}. It was assumed that two applications of the insecticide bifenthrin and one application each of acephate and malathion would be made annually. Thiophanate-methyl, chlorothalonil, and mancozeb would each be applied two times per year for disease control using a backpack sprayer. Intermittent mist would be provided a total of 15 min per day for 180 days after which it was assumed that beds would be irrigated weekly. Winter protection was provided the first winter by covering welded wire mesh with 6-mil white polyethylene (assumed to last 3 years). Rooted cuttings would be harvested in May following two growing seasons by undercutting the bed with a tractor and band blade (5 min per bed) and using 0.5 hrs of labor per bed. Plants harvested from the beds would be transplanted immediately into the field. Shrinkage for this stage was assumed to be 25%.

Input materials, labor and equipment use for field-production of liners. The liner field plot would be prepared by turning once with a moldboard plow, disking three times, and tilling once with a roto-tiller. Two-year-old, bed-grown liners would be transplanted on 0.5 m (1.5 ft) centers in rows 2.0 m (6.75 ft) apart (10,750·ha^{-1}; 4,350 liners·A^{-1}) and grown for two seasons. Sixteen hundred liners would be transplanted with a tractor-pulled transplanter and a 4-person crew in 8 hrs. Two-meter-long fiberglass stakes [0.3 kg (0.7 lbs)] with a life expectancy of 20 yrs would be inserted into the ground at each rooted cutting and secured with plastic bands as the trees grew. Fungicides and insecticides would be applied at the middle of the recommended rate range with an airblast sprayer (280 L of spray·ha^{-1}, 30 gal·A^{-1}). Fungicides would include two applications each of chlorothalonil and mancozeb per year. Three annual applications of bifenthrin, acephate, and malathion and two applications of carbaryl insecticides were assumed. The herbicides oryzalin, isoxaben, glyphosate, and sethoxydim would each be applied once per year in 3 total sprays. Hoeing escaped weeds would require 44 hrs·ha^{-1} (16 hrs·A^{-1}) per year. Row middles and the roadway would be mowed (1.4 hr·ha^{-1}; 0.5 hr·A^{-1}) 4 times per year and cultivated (41 min·ha^{-1}; 15 min·A^{-1}) 4 times per year with a 24 hp tractor. Twelve irrigations per year via a drip irrigation system requiring a 5-hp electric pump at 1 hr·ha^{-1} (2 hrs for 5 A) at a time was assumed. Trees would be fertilized twice per year with 13N-5.7P-10.8K (13-13-13) at a 114 kg N·ha^{-1} (100 lbs N·A^{-1}) rate banded in rows. Pruning and training would require 1 min per tree, 4 times per year.

Each plot of 4,350 trees would require 1 hr of a 175 hp tree digger, 8 hrs of an 80 hp tractor with wagon and 145 hrs of labor to harvest and haul to the barn. Twenty-five percent shrinkage was assumed in this phase. Grading, bundling, storing and pulling for orders would require an additional 190 labor hrs per block of trees. Loading 3,000 trees on a tractor-trailer would require 16.3 labor hrs and trees would be transported 400 km (250 mi) via commercial carrier. Energy required for overhead (electricity for general activities and gasoline for field truck and ATV) for the liner production nursery was assumed to have a GWP of 0.259 kg CO_2e and cost $0.08 per liner.

Input materials, labor and equipment use for pot-in-pot (PIP) production in #25 container. It was assumed that the PIP system would be installed using a 120 hp tractor and single row, shoe-type plow to insert 10 cm (4 in) diameter corrugated drainage tile (high-density polyethylene (HDPE) manufactured with injection molding technology) and open a trench for #25 socket pots. Each block of 1,000 socket pots would require 6.7 hrs of the tractor and plow, 0.5 hrs of a tractor and wagon and 100 labor hrs. Both the socket container and the insert or growing container (1.7 kg) were assumed to be manufactured using blow-mold technology from recycled HDPE. The installed PIP system was assumed to last 30 years.

A 1.8 m (6 ft) branched tree liner as described above would be transplanted in May into a #25 insert container using 0.1 m^{-3} (3.8 ft^{-3}) of a pine bark substrate. Trimming roots, tipping branches, and potting the trees would require 16 hrs of a substrate auger and pot-filling machine operation and 160 labor hrs for 1,000 plants. An additional 156 hrs of labor and 25 hrs of a 24 hp tractor and 2 tracking wagons would be required to transport the 1,000 plants to the field and place them in the socket pots. Inserting a bamboo stake would require 2 min and pruning would require 4 min per tree 3 times per year.

A 12-month-release, polymer coated fertilizer (15 N-3.9 P-10 K) would be surface applied at 520 g (1.1 lb) per container each year, requiring 3.6 hrs of labor per 1,000-plant block. Plants would be scouted for pests weekly (6.4 hrs per 1,000-plant block·yr^{-1}). It was assumed that abamectin (2 times), cyfluthrin (2 times), and permethrin (3 times) insecticides would be applied separately by an air-blast sprayer each year at manufacturer-recommended rates. Herbicide application with a backpack sprayer would include indolziflam applied to containers twice per year and a simazine plus glyphosate tank mix applied annually to the fabric surface between containers.

Irrigation would be supplied to each container through 2.5 cm (1 in) diameter polypropylene tubing [1.8 m (6 ft) per plant], two 0.9 m (3 ft) spaghetti tubes and two spray stakes, assumed to last 15 years. Underground supply lines from the water source to the block was considered to be infrastructure and not included in this analysis. Irrigation would be applied daily for 16 months of the 18-month production cycle. Two, 40 hp electric powered pumps would deliver 500 gpm to irrigate 15,000 plants·hr^{-1} and 8 labor hrs·wk^{-1} would be required to monitor and repair the irrigation system for that block of plants.

Pulling 225 plants from the socket pots and transporting them to the shipping area would require 5.6 hrs with a 24 hp tractor, 2 tracking wagons, and 35 labor hrs. It was assumed that an 8 person crew and a 50 hp liquid propane-powered forklift (5.7 L (1.5 gal)·hr^{-1}) (California Air Resources Board 2014) would load 225 plants on a tractor-trailer in 2 hrs. Shrinkage was assumed to be 10% for this phase.

Equipment use assumptions. Estimated tractor horsepower (hp) 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: land preparation, mowing fallow land, shaping the raised beds, and air-blast sprayer in PIP production, 80 hp tractor at 0.85 throttle and 0.85 load; liner harvesting, 80 hp tractor at 1.0 throttle and 0.85 load; hauling finished liners from the field and air-blast sprayer in liner production, 80 hp tractor at 0.50 throttle and 0.50 load; installing the PIP system, 120 hp tractor at 1.0 throttle and 1.0 load; transporting PIP materials to the field, 40 hp tractor at 0.50 throttle and 0.50 load; spraying/spreading in-row, between-row cultivation and transporting plants to and from the field, 24 hp tractor at 0.50 throttle and 0.50 load; mowing, 24 hp tractor at 0.85 throttle and 0.85 load; air-blast sprayer in PIP system, 80 hp tractor at 0.85 throttle and 0.85 load; and loading substrate into hopper, 75 hp skid steer at 0.85 throttle and 0.85 load. It was assumed that electric motors use 0.746 kW·hp^{-1}. Energy required for overhead (electricity for general activities and gasoline for field truck and ATV) for the PIP nursery was assumed to have a GWP of 0.260 kg CO_2e and cost $0.083 per plant.

Labor inputs. The amount of labor for each operation in the model was determined from nursery manager interviews conducted in 2014, with follow-up Delphi-method (Hsu and Sandford 2007) discussions in 2015. 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.

Post-harvest activity assumptions. It was assumed that a 225 plant load would be transported 482 km (300 mi) by commercial carrier at $2.48·$km^{-1}$ ($2.60·$mi^{-1}$). A 32 km (20 mi), 30 min trip with a 10 plant load was assumed for the landscaper and 1.9 labor hrs (Fortier 2014) would be required to plant the tree into the landscape. Following 60 years of useful life in the landscape, tree removal would require 8.1 hrs of labor and operation of a heavy truck for 0.5 hr, 3.5 hrs of chain saw use and 2 hrs of a 120 hp chipper.

Cost calculations. An economic engineering approach was used to estimate variable costs. 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 (AEWR) as determined by the U.S. Dept. of Labor (2015) for the states included in the lower Midwest region was used to set the wage rate of $11.67. The AEWR represents the wage level that must be offered and paid to U.S. and alien workers by agricultural employers of nonimmigrant H-2A agricultural workers. Costs of input materials were obtained from green 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^{-1}$ ($3.25·$gal^{-1}$) represented the U.S. average as reported by the U.S. Energy Information Administration (2014).

Inventory analysis and data collection. The GWP of inputs was taken from a variety of published sources as follows. 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). 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 kg $CO_2e \cdot L^{-1}$ and 3.0153 kg $CO_2e \cdot L^{-1}$, respectively.

As previously published, GWP of 3.2, 1.0, and 0.7 kg $CO_2e \cdot kg^{-1}$ for N from urea, P_2O_5, and K_2O fertilizers, respectively, were assumed (Ingram 2012, Snyder et al. 2009, Wang 2007). Information on the amount of polymer or the processing of coating fertilizers is not available for proprietary products. Therefore, we assumed the polymer was 5% of the weight of the input product and the processing energy use was equivalent to HDPE and blow-mold processing to calculate in a LCA software package (Simapro, PRé North America, Inc., Washington, DC) a GWP of the coating to be 0.065 kg $CO_2e \cdot kg^{-1}$ 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 $CO_2e \cdot kg^{-1}$ of N applied (IPCC 2006, Snyder, et al 2009, West et al. 2004). 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 in the fertilizer product was assumed to be insignificant and not included. The average CO_2e emission for a range of herbicides (23.083 kg $CO_2e \cdot kg^{-1}$) were calculated from data presented by Lal (2004). The GWP for sudex [*Sorghum bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf.] seed for fallow operations was assumed to be 4.067 kg $CO_2e \cdot kg^{-1}$ based on the published GWP of similar crops (U.S. Dept. Energy 2015, West and Marland 2003).

Using USLCI data (U.S. Dept. Energy 2015) and processing impacts in SimaPro the GWP of sand used was 0.00628 kg $CO_2e \cdot kg^{-1}$ including transport of 25 miles (0.4 km); wire mesh GWP, including steel, the processes of making wire and welding and landfill disposal at end-of-life, was assumed to be 2.97 kg $CO_2e \cdot kg^{-1}$; a GWP of 2.44 kg $CO_2e \cdot kg^{-1}$ was determined for drain tile manufactured from HDPE using pipe extrusion, transporting 300 km and landfill disposal at end-of-life; and fiberglass stakes and polyethylene film GWP was calculated as 2.065 and 2.970 kg $CO_2e \cdot kg^{-1}$, respectively. The pine bark substrate GWP was calculated to be 0.124 kg CO2e·kg^{-1} (3.303 kg CO_2e per finished plant), including transport from the saw mill and processing to an appropriate particle size. A bamboo stake GWP of 0.182 kg $CO_2e \cdot kg^{-1}$was previously published (Kendall and McPherson, 2012). A GWP of 2.25 kg $CO_2e \cdot kg^{-1}$ for socket and insert containers assumed being made 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. 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 $CO_2e \cdot kg^{-1}$, respectively, using USCLI data in SimaPro.

Landscape plants sequester carbon during production and during their useful life in the landscape. Carbon sequestration during production was estimated by washing, drying and weighing four representative 5 cm caliper trees (Ingram 2012). Fifty percent of the dry weight was assumed to be carbon and each kilogram of carbon required the uptake of 3.664 kg CO_2 (U.S. Dept. Agri. For. Serv. 2008). The annual sequestration of red maple grown in a suitable Lower Midwest USA landscape for 60 years was estimated using the U.S. Forest Service's Center for Urban Forestry Research (CUFR) Tree Carbon Calculator method (U.S. Dept. Agr. For. Serv. 2008). The impact on atmospheric CO_2 weighed over a 100 year assessment period was calculated as previously published for trees using PAS 2050 protocols (BSI British Standards 2011; Hall and Ingram 2014; Ingram 2012, 2013; Ingram and Hall 2013).

Results and Discussion

GHG emissions from components of the PIP production system for the #25 red maple model from cutting to nursery gate totaled 15.317 kg CO_2e. The impact of sequestered carbon in the product weighted over a 100 year assessment period was 4.575 kg CO_2e, yielding a net GWP at the nursery gate of 10.742 kg CO_2e. The nursery gate total GHG emissions for field-grown, spade-dug red maple of comparable size, but with a shorter liner production phase and longer field production phase (Ingram 2012) and adjusted to an equivalent fuel GWP, was 17.073 kg CO_2e. Components of the rooted cutting, field liner, and PIP phases of production contributed 0.081, 1.197, and 14.039 kg CO_2e, respectively, to the GWP of the product. Variable costs for the rooted cutting and liner phases were \$0.351 and \$5.386, respectively. The purchased liner by the PIP nursery from the liner nursery for \$18.00 constituted 32% of the total nursery gate variable costs of \$55.488.

Material inputs and equipment use contributed 0.030 and 0.051 kg CO_2e to the GWP of the two-year, bed-grown rooted cutting, respectively (Table 1). Bed amendments and fertilizer were the most significant components of the input material impact. The greatest impact of equipment use was during bed preparation, misting and irrigation, and overwintering activities. Labor constituted 57% of the variable cost of the rooted cutting production.

Material inputs (including the rooted cutting) and equipment use contributed 40 and 46%, respectively, of the 1.2784 kg CO_2e GWP of the 2 year production system for the field-grown, 1.8 m (6 ft), bare root liner (Table 2). Total variable costs of the liner was comprised of \$1.1321 for material inputs, \$0.643 for equipment use, and \$3.611 for labor. Fertilization, the rooted cutting, pest management, and the fiberglass stake contributed the most to liner production input material GWP and costs. Equipment activities contributing the most to GWP and variable costs included transporting to the PIP nursery, land preparation, harvesting and hauling, pest management, and energy overhead for the nursery.

The GWP calculated as the accumulative GHG emissions from the three production phases minus the sequestered carbon dioxide during production was 10.742 kg CO_2e. Input materials, other than the liner, and equipment use during the PIP phase of production comprised 77% of the GHG emissions and 44% of variable costs for the red maple in a #25 container at the nursery gate (Table 3). Material inputs, including the liner, contributed 85% or 13.0597 kg CO_2e of the total GHG emissions and 76% of variable costs. Material inputs of note included the substrate, insert/growing container, liner, fertilizer, and landscape fabric. Although equipment use contributed just 13% of the GHG emissions of the product, equipment activities for PIP installation, preparing the substrate, transporting the plants to and from the field, and overhead energy contributed the most. Variable costs for equipment use were \$1.286 and labor costs were \$11.883 per tree. Labor constituted 21% of total variable costs

Table 1. Global warming potential (GWP) from greenhouse gas emissions and variable costs associated with input products and activities for the 2-year, rooted cutting bed phase of red maple production.

	Materials			Equipment use				Total	
Activity/components	kg or unit/ cutting	GWP (kg CO2e)	Costs ($)	hrs/ cutting	GWP (kg CO2e)	Costs ($)	Labor costs ($)	GWP (kg CO2e)	Costs ($)
Take and stick cuttings	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0481	0.0000	0.0481
Prepare beds	1.2618	0.0079	0.0595	0.0008	0.0162	0.0163	0.0116	0.0241	0.0874
Misting and irrigation	0.0000	0.0000	0.0000	0.0196	0.0132	0.0478	0.0427	0.0132	0.0905
Apply fungicides	0.0000	0.0004	0.0004	0.0016	0.0033	0.0012	0.0232	0.0036	0.0248
Fertilization	0.0028	0.0152	0.0059	0.0000	0.0000	0.0000	0.0037	0.0152	0.0096
Apply insecticides	0.0000	0.0001	0.0007	0.0011	0.0022	0.0008	0.0153	0.0023	0.0169
Overwintering	0.0024	0.0068	0.0046	0.0005	0.0138	0.0116	0.0433	0.0206	0.0595
Harvesting	0.0000	0.0000	0.0000	0.0001	0.0016	0.0028	0.0112	0.0016	0.0140
Energy overhead					0.0009	0.0003		0.0009	0.0003
Total GWP and costs		**0.0304**	**0.0711**		**0.0510**	**0.0808**	**0.1992**	**0.0814**	**0.3511**

Table 2. Global warming potential (GWP) from greenhouse gas emissions and variable costs associated with input products and activities for the 2-year, field phase of red maple liner production.

	Materials			Equipment use				Total	
Activity/components	kg or unit/ cutting	GWP (kg CO2e)	Costs ($)	hrs/ cutting	GWP (kg CO2e)	Costs ($)	Labor costs ($)	GWP (kg CO2e)	Costs ($)
Fallow year + land preparation	0.0028	0.0113	0.0129	0.0037	0.1922	0.1090	0.0572	0.2035	0.1791
Transplanting	0.0000	0.1085	0.4673	0.0017	0.0127	0.0275	0.0799	0.1212	0.5746
Staking and training	0.0159	0.0328	0.1127	0.0012	0.0093	0.0094	2.0048	0.0421	2.1269
Apply fungicides	0.0024	0.0346	0.0392	0.0006	0.0290	0.0341	0.0086	0.0636	0.0820
Apply insecticides	0.0054	0.0893	0.0939	0.0011	0.0532	0.0626	0.0158	0.1425	0.1723
Apply herbicides	0.0060	0.0380	0.2047	0.0006	0.0087	0.0191	0.0086	0.0468	0.2324
Hoeing and cultivation	0.0000	0.0000	0.0000	0.0006	0.0047	0.0062	0.1193	0.0047	0.1254
Mowing	0.0000	0.0000	0.0000	0.0012	0.0175	0.0135	0.0173	0.0175	0.0308
Irrigation	0.0015	0.0083	0.0130	0.0015	0.0014	0.0004	0.0807	0.0096	0.0941
Fertilization	0.1541	0.1913	0.1885	0.0003	0.0000	0.0080	0.0043	0.1913	0.2008
Harvest and hauling	0.0000	0.0000	0.0000	0.0028	0.0959	0.0766	0.5012	0.0959	0.5778
Grading/loading	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7131	0.0000	0.7131
Transport to PIP nursery	0.0000	0.0000	0.0000	0.0000	0.1585	0.2167	0.0000	0.1585	0.2167
Energy overhead					0.1813	0.0596		0.1813	0.0596
Total GWP and costs		**0.5141**	**1.1321**		**0.7643**	**0.6426**	**3.6109**	**1.2784**	**5.3856**

Table 3. Global warming potential (GWP) from greenhouse gas emissions and variable costs associated with input products and activities for pot-in-pot production of a marketable red maple tree in a #25 container, not including sequestration of carbon dioxide during production.

	Materials			Equipment use				Total	
Activity/components	kg or unit/ cutting	GWP (kg CO2e)	Costs ($)	hrs/ cutting	GWP (kg CO2e)	Costs ($)	Labor costs ($)	GWP (kg CO2e)	Costs ($)
PIP system installation	0.1378	0.3184	0.9435	0.0119	0.9610	0.4495	1.8913	1.2794	3.2843
Irrigation system installation	0.0017	0.0433	0.0000	0.0000	0.0000	0.0000	0.0000	0.0433	0.0000
Landscape fabric	0.8675	2.4029	1.2600	0.0000	0.0000	0.0000	0.0125	2.4029	1.2725
Insert/growing container	1.7000	3.8250	11.8500	0.0000	0.0000	0.0000	0.0000	3.8250	11.8500
Substrate	26.6394	3.3033	3.9683	0.0059	0.2603	0.1230	0.0827	3.5636	4.1739
Potting liners	1.1111	1.4204	22.0000	0.0178	0.0044	0.1727	2.0048	1.4248	24.1775
Transport containers to field	0.0000	0.0000	0.0000	0.0278	0.2109	0.1919	1.9578	0.2109	2.1498
Staking and training	1.1111	0.2020	0.8000	0.0000	0.0000	0.0000	2.9237	0.2020	3.7237
Irrigation	0.0000	0.0000	0.0000	0.8707	0.2159	0.0653	0.4277	0.2159	0.4930
Fertilization	1.1556	1.4515	1.1112	0.0000	0.0000	0.0000	0.0908	1.4515	1.2020
Apply herbicides	0.0044	0.0775	0.1246	0.0033	0.0000	0.0025	0.0470	0.0775	0.1741
Scouting and apply insecticides	0.0026	0.0154	0.1790	0.0011	0.0515	0.0674	0.2158	0.0669	0.4622
Transport from field	0.0000	0.0000	0.0000	0.0278	0.2109	0.1919	1.9578	0.2109	2.1498
Loading into truck/trailer	0.0000	0.0000	0.0000	0.0089	0.0829	0.0212	0.2707	0.0829	0.2918
Energy overhead					0.2595	0.0830		0.2595	0.0830
Total GWP and costs		**13.0597**	**42.2365**		**2.2574**	**1.3685**	**11.8827**	**15.3171**	**55.4877**

with staking and pruning, potting, transporting containers to and from the field, and PIP system installation contributing the most followed by irrigation, loading on tractor/trailers, and scouting and applying pesticides. When allocated across an assumed 30 year life, the installation of the PIP system contributed 24% of GHG emissions, and 8% of variable costs for each marketable tree.

Post-harvest activities from the nursery gate to the landscape in this model would emit 4.911 kg CO_2e and cost $26.570. Transporting the tree 482 km (300 mi) to the customer, transporting the tree to the landscape site, and transplanting the tree would result in GHG emissions of 2.627, 2.284, and 0 kg CO_2e and variable costs of $3.467, $1.902, and $21.201, respectively. Ingram (2012) reported that transporting a 5 cm caliper, balled and burlapped red maple 386 km (240 mi) on a tractor/trailer to a landscaper and 32 km (20 mi) on a heavy truck to a landscape site and transplanting a field-grown, spade-dug red maple when adjusted to an equivalent fuel GWP was 8.43 kg CO_2e or 72% greater than for the #25 container plant.

As previously published (Ingram 2012), carbon sequestration by a red maple during its 60 year life weighted over a 100 year assessment period was calculated to be 901 kg CO_2. Following the 60 year use phase, the life cycle would be completed by the take down and disposal of the tree resulting in 214.282 kg CO_2e GHG emissions. The use of a heavy truck, chain saw, and chipper would constitute 21, 7, and 72% of the GWP, respectively. Therefore, the net positive impact on atmospheric CO_2 of the red maple grown in a PIP system would be a weighted 671 kg CO_2 during its life cycle. The variable costs for take down and disposal was calculated as $168.707, of which $91.627 would be for labor and $77.080 for equipment use. Variable costs for the complete life cycle of the red maple from this production system model would be $250.764.

In examining the major contributors to this model system, the installation of the PIP system, the pine bark-based substrate, and the #25 container contributed more than any other input products to the GWP of the PIP-grown tree. Pine bark substrates provide the desired properties for container production, however, other potential substrate constituents have been investigated (Altland and Locke 2011, Fain et al. 2008). A comparison of GWP and costs of alternative substrates would be needed. Future research could examine the potential impact of alternative materials and processes for containers, but a rigid container appears to be necessary for post-harvest handling. Recycling and/or reusing a greater portion of the used containers could reduce the GWP. The purchased liner contributed 40% to the cost and 9% to the GWP of the final product and transporting the liner to the PIP nursery was a large component to the liner production model system. Transport distance of the finished product to the customer is also an important factor in the GWP and variable costs but this process was only 45% as much as the GWP km^{-1} for transporting of balled and burlapped red maple (Ingram 2012).

Part of the value of developing models using these methods is that it allows for sensitivity to certain changes to be measured. For example, if 300 trees are loaded on each tractor-trailer, the GWP of 1.992 kg CO_2e and costs of $2.60 per tree are smaller on a per unit basis than if 225 are loaded onto each tractor-trailer (GWP of 2.6268 kg CO_2e and variable costs of $3.467). In addition, the effects of longer production cycles can also be assessed. For example, some growers may opt to plant a slightly smaller liner at the beginning of the PIP production and thus incur another year of growing time to reach the same saleable #25 size. This saves on the initial cost of the liner, but adds another $2.61 to the costs of each tree and increases GHG emissions by 0.7980 kg CO_2e. This does not reflect potential impact to business cash flow, etc. Similarly, a year longer in the field during the liner production stage would result in additional variable costs of $1.700 and increase GHG emissions by 0.233 kg CO_2e. Thus, growers can evaluate the tradeoffs of cost and production times given these scenarios.

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