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

Dewayne L. Ingram1,4
Department of Horticulture, N-318 Agricultural Sciences Center, University of Kentucky, Lexington, KY 40546-0091

Charles R. Hall2
Department of Horticultural Sciences, Texas A&M University, 2133 TAMU, College Station, TX 77843-2133

Joshua Knight3
Department of Horticulture, N-318 Agricultural Sciences Center, University of Kentucky, Lexington, KY 40546-0091

Abstract. The production components of an evergreen shrub (Ilex crenata ‘Bennett’s Compacta’) grown in a no. 3 container on the east coast of the United States 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 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 CO2e. 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 CO2e. Operations, combining the impact of material and equipment use, that contributed most of GHG during production included fertilization (0.707 kg CO2e), the liner and transplanting (0.461 kg CO2e), the container (0.468 kg CO2e), gravel and ground cloth installation (0.222 kg CO2e), substrate materials and preparation (0.227 kg CO2e), and weed control (0.122 kg CO2e). 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 CO2e, 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.

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2Professor and Ellison Chair in International Floriculture
3Extension Associate for Horticulture
4Corresponding author. E-mail: d-ingram@uky.edu.

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 Piedmont region (Beccaro et al., 2014) and the Pistoia plant production district (Lazzarini et al., 2016; Nicese and Lazzarini, 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 CO2e, 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 CO2e and a cutting-to-gate GWP of 10.742 kg CO2e. 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 Budd viburnum (Viburnum x blue’ Rehder) and a 1.0-m ‘Densiformis’ yew (Taxus xmedia 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 CO2e, 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...
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 CO₂e 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 m³ 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 wire, covered with double-layer clear plastic and 50% shadecloth, 618 flats per greenhouse.

**Bottom heat necessary to maintain 21°C 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 21°C 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 m³ per house. Irrigation would be pumped from surface water and chlorine would be injected at 6 mg/L from sodium hypochlorite (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 × 10³ 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-m³ 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 cantilevered 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 shearsers (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 m³·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 flavam, requiring 10 min per bed and 5 min of a 24-kW tractor per application. Hand weeding escaped 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 L·ha⁻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 assumed to take 78 h of labor and 3 h of a 17.9-kW tractor with two tracking trailers.

Cost calculations. Variable costs were estimated using an economic engineering approach for production system components and disposal in landfill was calculated as 2.81 kg CO₂e/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 CO₂e/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 CO₂e 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 CO₂e investment in the shrub was used to assess the sensitivity of the model to each variable. The sensitivity of CO₂ 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 CO₂ 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$_2$e. 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$_2$e. This value was significantly smaller than for field-grown trees (6.6 to 12.8 kg CO$_2$e) and somewhat larger than for field-grown shrubs (0.70 to 0.77 kg CO$_2$e) (Hall and Ingram, 2015; Ingram, 2012; Ingram and Hall, 2013, 2014a).

The liner produced in the 80-mm container contributed 0.455 kg CO$_2$e 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$_2$e) 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$_2$e while equipment use contributed only 0.546 kg CO$_2$e (Table 1). Major contributors to emissions due to materials would include fertilizers (0.687 kg CO$_2$e), the container (0.468 kg CO$_2$e), the pine bark (0.211 kg CO$_2$e), the gravel surface and ground cloth (0.222 kg CO$_2$e), and herbicides (0.121 kg CO$_2$e) 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$_2$e) 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$_2$e), the liner and transplanting (0.461 kg CO$_2$e), the container (0.468 kg CO$_2$e), gravel and ground cloth installation (0.222 kg CO$_2$e), substrate materials and preparation (0.227 kg CO$_2$e), and weed control (0.122 kg CO$_2$e) accounted for 76% of the GHG.

**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.

<table>
<thead>
<tr>
<th>Activity/Components</th>
<th>Materials (kg or unit/shrub)</th>
<th>Equipment Use (GWP CO$_2$e, Costs ($)</th>
<th>Labor (GWP CO$_2$e, Costs ($))</th>
<th>Total (GWP CO$_2$e, Costs ($))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>1.8395</td>
<td>0.2115</td>
<td>0.0359</td>
<td>0.0003</td>
</tr>
<tr>
<td>Dolomitic limestone</td>
<td>0.0341</td>
<td>0.0200</td>
<td>0.0135</td>
<td>0.0000</td>
</tr>
<tr>
<td>Container</td>
<td>0.1663</td>
<td>0.4684</td>
<td>0.7123</td>
<td>0.0000</td>
</tr>
<tr>
<td>Irrigation</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Chlorination</td>
<td>0.1134</td>
<td>0.1350</td>
<td>0.0182</td>
<td>0.0000</td>
</tr>
<tr>
<td>Transplant liners</td>
<td>0.0000</td>
<td>0.4555</td>
<td>0.2924</td>
<td>0.0014</td>
</tr>
<tr>
<td>Spacing</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Gravel surface</td>
<td>3.7349</td>
<td>0.0687</td>
<td>0.0504</td>
<td>0.0000</td>
</tr>
<tr>
<td>Ground cloth</td>
<td>0.0552</td>
<td>0.1529</td>
<td>0.0802</td>
<td>0.0000</td>
</tr>
<tr>
<td>Overwintering</td>
<td>0.0021</td>
<td>0.0059</td>
<td>0.0617</td>
<td>0.0001</td>
</tr>
<tr>
<td>Fertilization</td>
<td>0.3462</td>
<td>0.6872</td>
<td>0.5152</td>
<td>0.0000</td>
</tr>
<tr>
<td>Apply herbicides</td>
<td>0.0053</td>
<td>0.1213</td>
<td>0.2631</td>
<td>0.0001</td>
</tr>
<tr>
<td>Hand weeding</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Insecticides/fungicides</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Pruning</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Pulling orders and loading</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Energy overhead</td>
<td>0.0441</td>
<td>0.0095</td>
<td>0.1295</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

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$_2$e. This value is much smaller than the life cycle GWPs of −800, −431, and −63 kg CO$_2$e previously published and updated for field-grown, 5-cm-caliper red maple (Ingram, 2012), blue spruce (Ingram, 2013), and red-bud (Ingram and Hall, 2013) trees, as well as the −11.3 and −8.2 kg CO$_2$e 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

![Image of a table showing the 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.](https://example.com/table1.png)
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 CO₂e 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 CO₂e or 3% to 2.076 kg CO₂e 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 CO₂e or 2.2% to 2.098 kg CO₂e. 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 CO₂e 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 CO₂e (5.6%) and $0.120 per plant (3.7%).

**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.