Comparison of Three Production Scenarios for *Buxus microphylla* var. *japonica* 'Green Beauty' Marketed in a No. 3 Container on the West Coast Using Life Cycle Assessment

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Abstract. Three scenarios for production of *Buxus microphylla* var. *japonica* [(Mull. Arg.) Rehder & E.H. Wilson] 'Green Beauty' marketed in a no. 3 container on the west coast of the United States were modeled based on grower interviews and best management practices. Life cycle inventories (LCIs) of input products, equipment use, and labor were developed from the protocols for those scenarios and a life cycle assessment (LCA) was conducted to determine impact of individual components on the greenhouse gas emissions (GHGs) and the subsequent carbon footprint (CF) of the product at the nursery gate and in the landscape. CF is expressed in global warming potential (GWP) for a 100-year period in units of kilograms of carbon dioxide equivalents (kg CO_2e). The GWP of the plant from Scenario A (propagation to no. 1 to 3 container) was 2.198 kg CO_2e with variable costs of $4.043. Scenario B (propagation to field to no. 3 container) would result in a GWP of 1.717 kg CO_2e with variable costs of $2.880 and take a year longer in production than the other two models. The GWP of Scenario C (propagation to no. 1 to no. 2 to no. 3 containers) would be 3.364 kg CO_2e with variable costs of $5.733. Containers, transplants/transplanting, irrigation, and fertilization input products and associated activities accounted for the greatest portion of GHG and variable costs in each scenario. Pruning, assembling/load trucks, pesticides, and chlorination were other important components to variable costs of each scenario but had little impact on GWP. Otherwise, the major contributors to GWP are also major contributors to cost.

Landscape plant producers become increasingly aware of the triple bottom line as profit margins decrease in a maturing industry and the desire to be environmentally sustainable (Hall, 2010). Nursery managers have been pursuing best management practices (SNA, 2013), which seeks to maximize efficiency and limit negative environmental impacts from production. Nursery managers have also increased their understanding of expected contributions of ecosystem services from these plants in the landscape (Hall and Dickson, 2011). Consumers are also becoming more conscious of the potential environmental impact of the products they purchase, including nursery crops (Yue et al., 2011). Both the commercial producer and the consumer of landscape plants need more information about the potential impact of specific production protocols to make informed decisions (Ingram and Hall, 2015b).

Life cycle assessment is a tool that has been used to characterize the environmental impact of products from cradle to grave or defined subsets of their life cycle, including agricultural products (Debolt et al., 2009; Koerber et al., 2009; Payraudeau and van der Werf, 2005). Greenhouse gas emissions and the subsequent CF of nursery crops have been reported for production systems in the United States (Ingram, 2012) and Europe

(Beccaro et al., 2014; Lazzerini et al., 2016; Nicese and Lazzerini, 2013). 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 to have propagation-to-landscape CF of 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). In addition to analyzing the GWP of the detailed input products and activities during production, some of these studies have estimated carbon sequestration from the atmosphere during the life of the plant, weighted over a 100-year assessment period.

Kendall and McPherson (2012) reported the GWP for the production and distribution of trees in no. 5 and 9 containers in the United States as 4.6 and 15.3 kg CO_2e, respectively. A LCA study of a pot-in-pot production system of a red maple in a no. 25 container found GWP of 15.317 kg CO_2e and a cutting-to-gate GWP of 10.742 kg CO_2e (Ingram and Hall, 2015a). Protocols for shrub production in containers are significantly different from field-production systems and production of trees in larger containers (Ingram and Hall, 2015a). The cutting-to-gate GWP of a model system for production of an evergreen shrub (*Ilex crenata* 'Bennett's Compacta') in a no. 3 container on the east coast of the United States was determined to be 2.144 kg CO_2e (Ingram et al., 2016).

In observing container-production systems for an evergreen shrub for a marketable product in a no. 3 container on the west coast of the United States, the diversity of production systems protocols was striking. The objective of this study was to study the production system components of three distinct production systems for *B. microphylla* var. *japonica* 'Green Beauty' marketable in a no. 3 container on the west coast of the United States in terms of GWP and variable costs. Nursery production systems on the west coast tend to differ from the rest of the United States because of soil and climatic conditions, so it was hypothesized that GWP and variable costs will differ accordingly.

Methods

Goal, scope, and functional unit. The functional unit for this LCA study was an evergreen shrub such as *B. microphylla* var. *japonica* 'Green Beauty' in a no. 3 container produced on the west coast of the United States. Three scenarios for boxwood production were defined through interviews with several nursery managers in the Pacific northwest and following general best management practices. A detailed protocol, a LCI, of input products and activities associated with each operation was defined. Of course there are many combinations of production protocols that could be modeled for boxwood production,

but these three combinations were chosen to be representative (Fig. 1) of the most common west coast nursery production techniques.

Scenario A consisted of sticking cuttings in September directly in 40-cell flats in a greenhouse under mist, moved to a plastic covered hoop house the following spring, and grown for 11 months before being transplanted into no. 1 containers in the spring of year 2. They would be transplanted to no. 3 containers in the spring of year 3 and grown for 18 months before being marketed in the spring/summer of year 4.

Scenario B involved sticking cuttings in community trays under mist in September, transplanting rooted cuttings to 38-cell flats after 6 months and grown for 18 months before being transplanted to the field during the fall of year 2 and grown for 3 years before being dug bare root in the fall of year 5 and transplanted into no. 3 containers. They would be grown for 1 year in no. 3 containers before being marketed in the fall of year 6.

Scenario C involved sticking cuttings in community trays under mist in September, transplanting rooted cuttings to 38-cell flats after 6 months and grown for 12 months before being transplanted to no. 1 containers in the spring of year 2 and grown for 19 months, including two growing seasons.

Plants would be transplanted from no. 1 containers to no. 2 containers in the fall of year 3, growing for 18 months before being transplanted into no. 3 containers, and marketed the following spring (year 6) after 12 months. In all scenarios, 80% of the marketable crop would be sold in a target market window as noted above and 20% sold 6 months later.

The study was conducted in accordance with LCA standards, including the International Organization for Standardization [ISO (Geneva, Switzerland)] (2006) and PAS 2050 guidelines by BSI British Standards (2011). Activities for each phase for the three production scenarios were inventoried in terms of input products, equipment use, and labor. GHG 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.

In all scenarios, trays, no. 1 and 2 containers were used four times, requiring steam cleaning three times for 1 h each using a boiler (20.68 L of propane) and 1.5 h of labor per 7000 flats, 8600 no. 1, or 6500 no. 2. Bottom

heat to maintain an average substrate temperature of 21 °C during the winter propagation periods would be provided by a propane-fueled boiler circulating heated water through tubes under the trays as calculated for previous studies (Hall and Ingram, 2014). Well water use was assumed in propagation and the impact of pumping per liner was negligible. Irrigation during production on gravel beds or in the field was assumed to be from surface reservoirs. Rooted cuttings would be pruned while in the flat using mowing equipment with a 3.73-kW engine. Fungicides would be applied 10 times in Scenario A and 5 times in Scenarios B and C during propagation only, using a 3.73-kW sprayer for 10 min per application per greenhouse. Hoop houses were assumed to be constructed of galvanized tubing and covered with a poly film. The structure would have a 20-year useful life and were included in the GWP and cost analysis. Propagation substrate consisted of 70/15/15 by volume of fir bark, perlite, and peat in Scenario A and 90/10 by volume of perlite and peat in Scenarios B and C.

The substrate in no. 1, 2, and 3 containers consisted of 100% fir bark, delivered after processing, and amended with dolomitic lime at 3 kg·m^{-3} for all scenarios. The number of plants to be transplanted per cubic meter of substrate would be 130 for propagation to no. 1 containers and 260 for transplanting from no. 1 to 2 containers or no. 2 or field transplants into no. 3 containers. All irrigation water was assumed to be chlorinated using calcium hypochlorite tablets injected at 8 ppm Cl. There would be an annual application of insecticide sprayed using an air-blast sprayer.

Although the number of times pruned in each production phase correlates to the time in a container, pruning with a mowing machine (3.73-kW-gasoline mower) was assumed to be at the rate of 12,000 per h and 250 plants could be hand pruned in 1 h. Shrinkage rates for all scenarios were assumed to be 20% for the liners, 5% for each container phase, and 20% for the field phase.

A 7.6-kW canning machine used 0.5 h with 10 labor h would be invested per 1000 plants. Although the travel distance between the potting area and gravel beds differ significantly among nurseries, it was assumed that no. 1 containers would be moved to and from outdoor gravel beds with a 29.84-kW tractor and three wagons at the rate of 1000 per h, requiring a crew of five. Plants in no. 1 containers would be transferred to no. 2 injection-molded containers (0.22 kg) using the same transplanting equipment at the rate of 1000 plants per h with a crew of 10. Transporting no. 1 container plants to the potting area to gravel beds would be at the rate of 1000 per equipment hour with a crew of five. Moving no. 2 containers between the potting area and gravel beds would be at the rate of 800 per h with a crew of five. Plants in no. 2 container or field-grown plants would be transferred to no. 3 injection-molded containers (0.27 kg) using the same transplanting equipment at the rate of 800 per h with a crew of 10. Moving no. 3 containers to
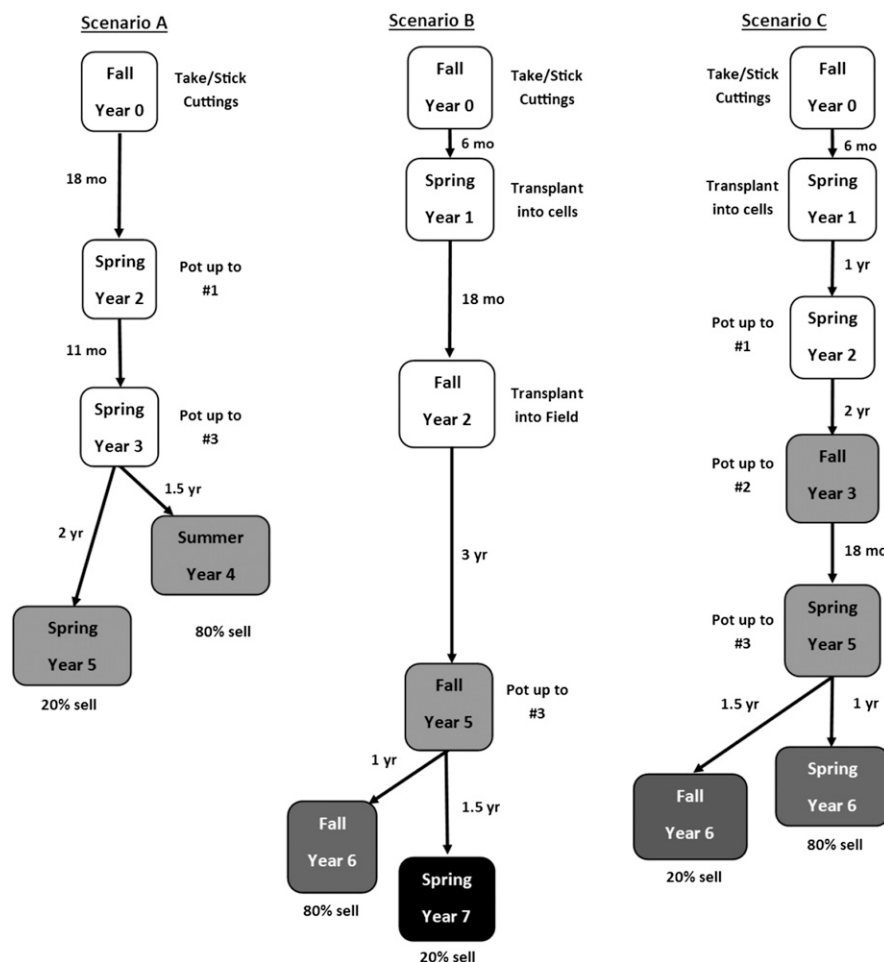

Fig. 1. System scenarios for production of *Buxus microphylla* var. *japonica* 'Green Beauty' to be marketed in a no. 3 container on the U.S. west coast.

gravel beds would be at the rate of 500 per h with a crew of five. The process of spacing containers or consolidating them on the same bed was assumed to be at 150 containers per labor hour. Pulling and assembling orders and loading trucks would require 10 people working 3 h per 1000 plants and a tractor with wagons 1.5 h and a 37.3-kW diesel fork lift running 0.25 h.

Energy required for overhead (electricity for general activities and gasoline for field truck and ATV) for each 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). The inputs impacting GWP and variable costs per functional unit are presented in Tables 1–3. Additional details specific to each scenario are presented below.

Input materials, labor, and equipment use for Scenario A. Irrigation events (124 per year) on outdoor gravel production beds were assumed to apply 2.5 cm each requiring 671 kW of pumps to cover 60-ha blocks at a time. A 37.3-kW pump was assumed to run 111 h/ha/year to recycle water from a catchment basin to irrigation reservoirs. Irrigation labor and a pickup truck use were calculated as 57 h of labor and 47 h of truck time/ha/year. Water would be purchased at $376/ha/year.

A granular herbicide would be applied to containers on the wagon following the potting process and two additional applications would be made annually to production areas using a boom sprayer and 59.68-kW tractor for 5.75 h·ha^{-1} per application. Hand weeding would average 1203 labor h/ha/year.

Table 1. Global warming potential (GWP) and variable costs of production components for Scenario A for *Buxus microphylla* var. *japonica* 'Green Beauty' to be grown and marketed in a no. 3 container on the U.S. west coast.

Liner production

Activity/components	Materials kg or unit/cutting	Materials GWP (kg CO$_2$e)	Materials Costs ($)	Equipment use h/cutting	Equipment use GWP (kg CO$_2$e)	Equipment use Costs ($)	Labor Costs ($)	Total GWP (kg CO$_2$e)	Total Costs ($)
Take and stick cuttings	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0254	0.0000	0.0254
40-cell tray	0.0005	0.0014	0.0033	0.0000	0.0002	0.0000	0.0014	0.0017	0.0046
Substrate		0.0024	0.0039	0.0000	0.0000	0.0000	0.0002	0.0024	0.0040
40-cell insert	0.0005	0.0014	0.0033	0.0000	0.0000	0.0000	0.0000	0.0014	0.0033
Fertilization	0.0022	0.0029	0.0012	0.0000	0.0000	0.0000	0.0040	0.0029	0.0052
Greenhouse structure	0.0002	0.0010	0.0006	0.0000	0.0000	0.0000	0.0011	0.0010	0.0017
Gravel	0.0252	0.0013	0.0003	0.0000	0.0000	0.0000	0.0001	0.0013	0.0004
Clear poly film	0.0004	0.0011	0.0026	0.0000	0.0000	0.0000	0.0003	0.0011	0.0029
Shadecloth	0.0001	0.0000	0.0025	0.0000	0.0000	0.0000	0.0002	0.0000	0.0027
Irrigation/chlorination	0.0001	0.0001	0.0005	0.0000	0.0000	0.0000	0.0119	0.0001	0.0124
Moving plants	0.0000	0.0000	0.0000	0.0000	0.0003	0.0004	0.0066	0.0003	0.0070
Greenhouse heating	0.0000	0.0000	0.0220	0.0000	0.1163	0.0141	0.0000	0.1163	0.0360
Pesticides	0.0000	0.0002	0.0002	0.0000	0.0001	0.0001	0.0005	0.0003	0.0008
Pruning	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0002	0.0000	0.0003
Overhead energy and labor					0.0068	0.0007	0.1195	0.0068	0.1202
Total GWP and costs		0.0118	0.0402		0.1239	0.0154	0.1713	0.1357	0.2269

No. 1 container production

Activity/components	Materials kg or unit/shrub	Materials GWP (kg CO$_2$e)	Materials Costs ($)	Equipment use h/shrub	Equipment use GWP (kg CO$_2$e)	Equipment use Costs ($)	Labor Costs ($)	Total GWP (kg CO$_2$e)	Total Costs ($)
Gravel surface	0.0000	0.0070	0.0079	0.0000	0.0002	0.0004	0.0005	0.0071	0.0088
Substrate	0.6842	0.1013	0.2079	0.0002	0.0078	0.0052	0.0040	0.1091	0.2171
Container	0.0132	0.0703	0.0658	0.0000	0.0143	0.0005	0.0008	0.0846	0.0671
Transplanting	0.0000	0.1429	0.2383	0.0005	0.0005	0.0511	0.0668	0.1433	0.3561
Moving to the field	0.0000	0.0000	0.0000	0.0021	0.0265	0.0299	0.1336	0.0265	0.1635
Irrigation	0.0000	0.0000	0.0005	0.0480	0.0451	0.0042	0.0026	0.0451	0.0073
Chlorination	0.0015	0.0016	0.0091	0.0000	0.0000	0.0000	0.0000	0.0016	0.0091
Fertilization	0.0970	0.1825	0.0407	0.0000	0.0000	0.0000	0.0000	0.1825	0.0407
Pesticides	0.0000	0.0004	0.0022	0.0001	0.0059	0.0051	0.0017	0.0063	0.0090
Hand weeding	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0591	0.0000	0.0591
Pruning	0.0000	0.0000	0.0000	0.0003	0.0029	0.0029	0.0042	0.0029	0.0071
Energy overhead					0.0034	0.0006		0.0034	0.0006
Total GWP and costs		0.5059	0.5723		0.1066	0.0997	0.2734	0.6125	0.9454

No. 3 container production

Activity/components	Materials kg or unit/shrub	Materials GWP (kg CO$_2$e)	Materials Costs ($)	Equipment use h/shrub	Equipment use GWP (kg CO$_2$e)	Equipment use Costs ($)	Labor Costs ($)	Total GWP (kg CO$_2$e)	Total Costs ($)
Gravel surface	4.2631	0.0507	0.0576	0.0001	0.0012	0.0027	0.0048	0.0519	0.0651
Substrate	1.3684	0.2025	0.4158	0.0081	0.0164	0.0062	0.0177	0.2189	0.4397
Container	0.2863	0.8021	0.8421	0.0000	0.0000	0.0000	0.0000	0.8021	0.8421
Insecticide	0.0000	0.0003	0.0012	0.0005	0.0278	0.0291	0.0075	0.0281	0.0377
Dolomitic limestone	0.0341	0.0200	0.0135	0.0000	0.0000	0.0000	0.0000	0.0200	0.0135
Transplanting no. 1 to 3	0.0000	0.6447	0.9952	0.0098	0.0088	0.0182	0.1670	0.6535	1.1804
Transporting no. 1 and 3	0.0000	0.0000	0.0000	0.0032	0.0398	0.0449	0.2004	0.0398	0.2453
Irrigation	0.0000	0.0000	0.0169	0.6492	0.6337	0.0767	0.0330	0.6337	0.1266
Chlorination	0.0200	0.0218	0.1240	0.0000	0.0000	0.0000	0.0000	0.0218	0.1240
Spacing	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0926	0.0000	0.0926
Fertilization	0.2815	0.5475	0.1338	0.0000	0.0000	0.0000	0.0286	0.5475	0.1624
Herbicides	0.0003	0.0031	0.0247	0.0003	0.0148	0.0078	0.0050	0.0179	0.0376
Hand weeding	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0457	0.0000	0.0457
Pruning	0.0000	0.0000	0.0000	0.1400	0.0029	0.0000	0.2137	0.0029	0.2137
Pulling orders and assembly	0.0000	0.0000	0.0000	0.0015	0.0189	0.0231	0.3845	0.0189	0.4076
Loading truck	0.0000	0.0000	0.0000	0.0003	0.0043	0.0006	0.0000	0.0043	0.0006
Energy overhead					0.0533	0.0089		0.0533	0.0089
Total GWP and costs		2.2928	2.6247	0.8129	0.8218	0.2183	1.2004	3.1146	4.0434

Table 2. Global warming potential (GWP) and variable costs of production components for Scenario B for *Buxus microphylla* var. *japonica* 'Green Beauty' to be grown and marketed in a no. 3 container on the U.S. west coast.

<table>
<tr><td colspan="8" align="center">Liner production</td></tr>
<tr><td></td><td colspan="3" align="center">Materials</td><td colspan="3" align="center">Equipment use</td><td>Labor</td><td colspan="2" align="center">Total</td></tr>
<tr><td>Activity/components</td><td>kg or unit/cutting</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td><td>h/cutting</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td><td>Costs ($)</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td></tr>
<tr><td>Take and stick cuttings</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0288</td><td>0.0000</td><td>0.0288</td></tr>
<tr><td>Community trays</td><td>0.0002</td><td>0.0004</td><td>0.0020</td><td>0.0000</td><td>0.0002</td><td>0.0000</td><td>0.0000</td><td>0.0007</td><td>0.0021</td></tr>
<tr><td>Substrate</td><td>0.0391</td><td>0.0438</td><td>0.0206</td><td>0.0001</td><td>0.0001</td><td>0.0000</td><td>0.0006</td><td>0.0439</td><td>0.0212</td></tr>
<tr><td>38-cell flats</td><td>0.0023</td><td>0.0061</td><td>0.0283</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0061</td><td>0.0283</td></tr>
<tr><td>Fertilization</td><td>0.0010</td><td>0.0019</td><td>0.0006</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0001</td><td>0.0019</td><td>0.0007</td></tr>
<tr><td>Greenhouse structure</td><td>0.0004</td><td>0.0019</td><td>0.0011</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0009</td><td>0.0019</td><td>0.0019</td></tr>
<tr><td>Gravel</td><td>0.0438</td><td>0.0005</td><td>0.0006</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0001</td><td>0.0005</td><td>0.0007</td></tr>
<tr><td>White poly film</td><td>0.0008</td><td>0.0024</td><td>0.0071</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0001</td><td>0.0024</td><td>0.0072</td></tr>
<tr><td>Transplant to 38-cell trays</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0003</td><td>0.0036</td><td>0.0036</td><td>0.2782</td><td>0.0036</td><td>0.2818</td></tr>
<tr><td>Irrigation/chlorination</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0108</td><td>0.0000</td><td>0.0108</td></tr>
<tr><td>Greenhouse heating</td><td>0.0002</td><td>0.0005</td><td>0.0003</td><td>0.0000</td><td>0.1321</td><td>0.0160</td><td>0.0000</td><td>0.1326</td><td>0.0162</td></tr>
<tr><td>Pesticides</td><td>0.0000</td><td>0.0001</td><td>0.0001</td><td>0.0000</td><td>0.0001</td><td>0.0001</td><td>0.0004</td><td>0.0002</td><td>0.0006</td></tr>
<tr><td>Pruning</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0001</td><td>0.0002</td><td>0.0013</td><td>0.0001</td><td>0.0015</td></tr>
<tr><td>Overhead energy and labor</td><td></td><td></td><td></td><td></td><td>0.0014</td><td>0.0002</td><td></td><td>0.0014</td><td>0.0002</td></tr>
<tr><td>Total GWP and costs</td><td></td><td>0.0576</td><td>0.0607</td><td></td><td>0.1375</td><td>0.0202</td><td>0.3213</td><td>0.1951</td><td>0.4021</td></tr>
<tr><td colspan="10" align="center">In-field production</td></tr>
<tr><td></td><td colspan="3" align="center">Materials</td><td colspan="3" align="center">Equipment use</td><td>Labor</td><td colspan="2" align="center">Total</td></tr>
<tr><td>Activity/components</td><td>kg or unit/shrub</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td><td>h/shrub</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td><td>Costs ($)</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td></tr>
<tr><td>Land preparation and fallow year</td><td>0.0071</td><td>0.0288</td><td>0.0000</td><td>0.0004</td><td>0.0196</td><td>0.0113</td><td>0.0066</td><td>0.0484</td><td>0.0179</td></tr>
<tr><td>Transplanting</td><td>0.0000</td><td>0.2439</td><td>0.0000</td><td>0.0002</td><td>0.0106</td><td>0.0053</td><td>0.0346</td><td>0.2545</td><td>0.0399</td></tr>
<tr><td>Cultivation</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0003</td><td>0.0022</td><td>0.0042</td><td>0.0046</td><td>0.0022</td><td>0.0088</td></tr>
<tr><td>Fertilization</td><td>0.1406</td><td>0.1608</td><td>0.0844</td><td>0.0002</td><td>0.0018</td><td>0.0041</td><td>0.0037</td><td>0.1626</td><td>0.0922</td></tr>
<tr><td>Weed control</td><td>0.0319</td><td>0.0018</td><td>0.1659</td><td>0.0002</td><td>0.0018</td><td>0.0041</td><td>0.0751</td><td>0.0036</td><td>0.2452</td></tr>
<tr><td>Irrigation</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0019</td><td>0.1198</td><td>0.0491</td><td>0.0059</td><td>0.1198</td><td>0.0551</td></tr>
<tr><td>Chlorination</td><td>0.0029</td><td>0.0032</td><td>0.0180</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0032</td><td>0.0180</td></tr>
<tr><td>Pruning</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0357</td><td>0.0000</td><td>0.0357</td></tr>
<tr><td>Digging</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0003</td><td>0.0200</td><td>0.0083</td><td>0.0423</td><td>0.0200</td><td>0.0506</td></tr>
<tr><td>Transport from field</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0001</td><td>0.0328</td><td>0.0393</td><td>0.0203</td><td>0.0328</td><td>0.0596</td></tr>
<tr><td>Energy overhead</td><td></td><td></td><td></td><td></td><td>0.0898</td><td>0.0149</td><td></td><td>0.0898</td><td>0.0149</td></tr>
<tr><td>Total GWP and costs</td><td></td><td>0.4385</td><td>0.2683</td><td></td><td>0.2983</td><td>0.1408</td><td>0.2288</td><td>0.7368</td><td>0.6379</td></tr>
<tr><td colspan="10" align="center">No. 3 container</td></tr>
<tr><td></td><td colspan="3" align="center">Materials</td><td colspan="3" align="center">Equipment use</td><td>Labor</td><td colspan="2" align="center">Total</td></tr>
<tr><td>Activity/components</td><td>kg or unit/shrub</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td><td>h/shrub</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td><td>Costs ($)</td><td>GWP (kg CO$_2$e)</td><td>Costs ($)</td></tr>
<tr><td>Gravel surface</td><td>3.1775</td><td>0.0378</td><td>0.0429</td><td>0.0000</td><td>0.0001</td><td>0.0002</td><td>0.0005</td><td>0.0379</td><td>0.0435</td></tr>
<tr><td>Substrate</td><td>0.6842</td><td>0.1013</td><td>0.2079</td><td>0.0017</td><td>0.0091</td><td>0.0053</td><td>0.0037</td><td>0.1104</td><td>0.2169</td></tr>
<tr><td>Container</td><td>0.2863</td><td>0.8021</td><td>0.8421</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.8021</td><td>0.8421</td></tr>
<tr><td>Insecticide</td><td>0.0000</td><td>0.0005</td><td>0.0018</td><td>0.0001</td><td>0.0031</td><td>0.0033</td><td>0.0008</td><td>0.0036</td><td>0.0059</td></tr>
<tr><td>Dolomitic limestone</td><td>0.0119</td><td>0.0070</td><td>0.0047</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0070</td><td>0.0047</td></tr>
<tr><td>Transplanting no. 3</td><td>0.0000</td><td>0.7756</td><td>0.6715</td><td>0.0010</td><td>0.0009</td><td>0.0128</td><td>0.1670</td><td>0.7765</td><td>0.8512</td></tr>
<tr><td>Transporting no. 3</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0015</td><td>0.0184</td><td>0.0208</td><td>0.0417</td><td>0.0184</td><td>0.0625</td></tr>
<tr><td>Irrigation</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.5218</td><td>0.4759</td><td>0.0471</td><td>0.0320</td><td>0.4759</td><td>0.0791</td></tr>
<tr><td>Chlorination</td><td>0.0149</td><td>0.0162</td><td>0.0926</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0162</td><td>0.0926</td></tr>
<tr><td>Spacing</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0034</td><td>0.0000</td><td>0.0034</td></tr>
<tr><td>Fertilization</td><td>0.1054</td><td>0.2983</td><td>0.0775</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0049</td><td>0.2983</td><td>0.0823</td></tr>
<tr><td>Herbicides</td><td>0.0077</td><td>0.0042</td><td>0.0752</td><td>0.0001</td><td>0.0008</td><td>0.0008</td><td>0.0053</td><td>0.0050</td><td>0.0814</td></tr>
<tr><td>Hand weeding</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0353</td><td>0.0000</td><td>0.0353</td></tr>
<tr><td>Pruning</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0641</td><td>0.0000</td><td>0.0641</td></tr>
<tr><td>Assembly and loading truck</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0018</td><td>0.0232</td><td>0.0237</td><td>0.3845</td><td>0.0232</td><td>0.4082</td></tr>
<tr><td>Energy overhead</td><td></td><td></td><td></td><td></td><td>0.0605</td><td>0.0068</td><td></td><td>0.0605</td><td>0.0068</td></tr>
<tr><td>Total GWP and costs</td><td></td><td>2.0429</td><td>2.0162</td><td>0.5279</td><td>0.5920</td><td>0.1206</td><td>0.7433</td><td>2.6350</td><td>2.8801</td></tr>
</table>

Fertility during propagation consisted of 3 kg·m^{-3} of 15N–3.5P–10K controlled-release fertilizer (CRF) incorporated during substrate preparation and weekly fertigation using 10N–0.87P–5.0K soluble fertilizer at 200 mg·L^{-1} N. For the outdoor production phase, 8.3 kg·m^{-3} of 15N–3.5P–10K CRF would be incorporated in the substrate and surface applied at the beginning of the second growing season at 66 g per container. The 20% of plants marketed 6 months later would receive an additional 66 g of this product. Fertigation would be scheduled 70 times per year during which an average of 75 mg·L^{-1} N was added to the recycled water each irrigation cycle.

Plants were mechanically pruned three times in each of the no.1 and 3 container phases and was pruned by hand three more times.

Input materials, labor, and equipment use for Scenario B. Following 18 months' growth of the rooted cuttings in the 38-cell trays, liners would be transplanted in the field in the fall (Fig. 1). Controlled-release fertilizer (18N–2.6P–10K) would be incorporated in the propagation substrate at 3.9 kg·m^{-3}. Equipment-use time and labor assumed in the model for the field production phase to subsoil, plow, disk, apply lime, and rototill during the fallow year field activities and in land preparation for planting were as previously published (Ingram,

2012, 2013). The model assumed 39,604 liners would be planted per hectare and 80% would be harvested for transplanting to no. 3 containers after 3 years in the field. A 74.6-kW tractor with transplanter would be used to transplant 7000 plants per h with a 15-member crew. A 7.5-kW tractor with rototiller would be used to cultivate the fields twice annually at 3.09 h·ha^{-1}. Herbicide would be applied twice per year using an 18-kW tractor with spreader. Fertilizer (20N–2.2P–4.2K) would be banded in rows annually at 684 kg·ha^{-1} with an 18 kW-tractor and spreader. Field-grown plants would be irrigated 20 times per year using an overhead irrigation system powered by a 74.6-kW pump

Table 3. Global warming potential (GWP) and variable costs of production components for Scenario C for *Buxus microphylla* var. *japonica* 'Green Beauty' to be grown and marketed in a no. 3 container on the U.S. west coast.

Liner production

Activity/components	Materials kg or unit/cutting	GWP (kg CO$_2$e)	Costs ($)	Equipment use h/cutting	GWP (kg CO$_2$e)	Costs ($)	Labor Costs ($)	Total GWP (kg CO$_2$e)	Costs ($)
Take and stick cuttings	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0240	0.0000	0.0240
Community trays	0.0002	0.0004	0.0020	0.0000	0.0002	0.0000	0.0000	0.0007	0.0021
Substrate	0.0391	0.0438	0.0206	0.0001	0.0001	0.0000	0.0006	0.0438	0.0212
38-cell flats	0.0023	0.0061	0.0283	0.0000	0.0000	0.0000	0.0000	0.0061	0.0283
Fertilization	0.0010	0.0019	0.0006	0.0000	0.0000	0.0000	0.0001	0.0019	0.0007
Greenhouse structure	0.0003	0.0012	0.0007	0.0000	0.0000	0.0000	0.0008	0.0012	0.0015
Gravel	0.0290	0.0003	0.0004	0.0000	0.0000	0.0000	0.0001	0.0003	0.0005
White poly film	0.0006	0.0016	0.0047	0.0000	0.0000	0.0000	0.0001	0.0016	0.0048
Transplant to 38-cell trays	0.0000	0.0000	0.0000	0.0003	0.0036	0.0036	0.2782	0.0036	0.2818
Irrigation/chlorination	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0130	0.0000	0.0130
Greenhouse heating	0.0002	0.0005	0.0003	0.0000	0.1321	0.0160	0.0000	0.1326	0.0162
Pesticides	0.0000	0.0001	0.0001	0.0000	0.0000	0.0001	0.0002	0.0001	0.0003
Pruning	0.0000	0.0000	0.0000	0.0000	0.0001	0.0002	0.0008	0.0001	0.0010
Overhead energy and labor					0.0010	0.0002		0.0010	0.0002
Total GWP and costs		0.0559	0.0576		0.1371	0.0199	0.3180	0.1930	0.3955

No. 1 container production

Activity/components	Materials kg or unit/shrub	GWP (kg CO$_2$e)	Costs ($)	Equipment use h/shrub	GWP (kg CO$_2$e)	Costs ($)	Labor Costs ($)	Total GWP (kg CO$_2$e)	Costs ($)
Gravel surface	0.7448	0.0089	0.0101	0.0000	0.0002	0.0004	0.0004	0.0090	0.0108
Substrate	0.6842	0.1013	0.2079	0.0002	0.0078	0.0052	0.0042	0.1091	0.2173
Container	0.0132	0.0703	0.0658	0.0000	0.0143	0.0005	0.0011	0.0846	0.0674
Transplanting and moving	0.0000	0.2031	0.4163	0.0004	0.0136	0.0254	0.1336	0.2167	0.5753
Spacing	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0891	0.0000	0.0891
Irrigation	0.0000	0.0000	0.0000	0.3231	0.3018	0.0311	0.0190	0.3018	0.0501
Chlorination	0.0086	0.0094	0.0534	0.0000	0.0000	0.0000	0.0000	0.0094	0.0534
Fertilization	0.0716	0.1851	0.1363	0.0000	0.0000	0.0000	0.0089	0.1851	0.1452
Insecticides	0.0000	0.0002	0.0007	0.0000	0.0012	0.0012	0.0003	0.0013	0.0022
Herbicides	0.0057	0.0031	0.0557	0.0001	0.0006	0.0006	0.0040	0.0037	0.0603
Hand weeding	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0237	0.0000	0.0237
Pruning	0.0000	0.0000	0.0000	0.0003	0.0029	0.0000	0.1636	0.0029	0.1636
Energy overhead					0.0176	0.0074		0.0176	0.0074
Total GWP and costs		0.5813	0.9462		0.3600	0.0717	0.4479	0.9413	1.4658

No. 2 container production

Activity/components	Materials kg or unit/shrub	GWP (kg CO$_2$e)	Costs ($)	Equipment use h/shrub	GWP (kg CO$_2$e)	Costs ($)	Labor Costs ($)	Total GWP (kg CO$_2$e)	Costs ($)
Gravel surface	0.1533	0.0018	0.0021	0.0000	0.0002	0.0006	0.0007	0.0021	0.0033
Substrate	0.6842	0.1013	0.2079	0.0002	0.0078	0.0052	0.0031	0.1091	0.2162
Container	0.0579	0.1289	0.1500	0.0000	0.0189	0.0006	0.0015	0.1479	0.1521
Transplanting and moving	0.0000	0.9908	1.5429	0.0041	0.0394	0.1455	0.3272	1.0302	2.0156
Spacing	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0891	0.0000	0.0891
Irrigation	0.0000	0.0000	0.0000	0.5451	0.5239	0.0594	0.0313	0.5239	0.0908
Chlorination	0.0121	0.0132	0.0752	0.0000	0.0000	0.0000	0.0000	0.0132	0.0752
Fertilization	0.0970	0.2641	0.2171	0.0000	0.0000	0.0000	0.0045	0.2641	0.2216
Insecticides	0.0000	0.0003	0.0011	0.0000	0.0019	0.0020	0.0005	0.0022	0.0036
Herbicides	0.0094	0.0051	0.0919	0.0001	0.0010	0.0010	0.0065	0.0061	0.0994
Hand weeding	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0294	0.0000	0.0294
Pruning	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0534	0.0000	0.0534
Energy overhead					0.0369	0.0061		0.0369	0.0061
Total GWP and costs		1.5056	2.2881		0.6301	0.2204	0.5470	2.1357	3.0556

No. 3 container production

Activity/components	Materials kg or unit/shrub	GWP (kg CO$_2$e)	Costs ($)	Equipment use h/shrub	GWP (kg CO$_2$e)	Costs ($)	Labor Costs ($)	Total GWP (kg CO$_2$e)	Costs ($)
Gravel surface	3.1775	0.0378	0.0429	0.0000	0.0001	0.0002	0.0005	0.0379	0.0435
Substrate	0.6842	0.1013	0.2079	0.0017	0.0091	0.0053	0.0037	0.1104	0.2169
Container	0.0526	0.8021	0.8421	0.0000	0.0000	0.0000	0.0000	0.8021	0.8421
Insecticide	0.0000	0.0006	0.0021	0.0001	0.0062	0.0065	0.0017	0.0069	0.0103
Dolomitic limestone	0.0119	0.0070	0.0047	0.0000	0.0000	0.0000	0.0000	0.0070	0.0047
Transplanting and moving	0.0000	2.2481	3.2164	0.0052	0.0546	0.0733	0.4373	2.3026	3.7270
Irrigation	0.0000	0.0000	0.0000	0.6412	0.5936	0.0580	0.0320	0.5936	0.0900
Chlorination	0.0148	0.0161	0.0920	0.0000	0.0000	0.0000	0.0000	0.0161	0.0920
Spacing	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0034	0.0000	0.0034
Fertilization	0.1173	0.3376	0.0862	0.0000	0.0000	0.0000	0.0049	0.3376	0.0911
Herbicides	0.0077	0.0042	0.0752	0.0001	0.0008	0.0008	0.0053	0.0050	0.0814
Hand weeding	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0513	0.0000	0.0513
Pruning	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0641	0.0000	0.0641
Assembly and loading truck	0.0000	0.0000	0.0000	0.0018	0.0232	0.0237	0.3845	0.0232	0.4082
Energy overhead					0.0396	0.0069		0.0396	0.0069
Total GWP and costs		3.5548	4.5696	0.6501	0.7272	0.1748	0.9887	4.2820	5.7331

running 0.5 h per application. Plants would be pruned annually by hand at 1333 plants per labor hour. Three hundred and seventy-five plants would be dug per labor hour and a 74.6-kW tractor and digger/shaker could harvest 3200 per h. Harvested plants would be transported 2000/load using a large truck with a flat-bed trailer for 0.5 h and 0.5 h of a 37.3-kW forklift would be required.

Plants dug from the field in the fall of year 5 would be transplanted to no. 3 injection-molded containers and transported to gravel beds as described above. Fertilizer (18N–2.6P–10K) would be incorporated in the substrate at mixing at 5.7 kg·m^{-3} and topdressed at 74 g per no. 3 container annually, requiring 3.5 labor h per 10,000 plants. Overhead irrigations of 1.3 cm would be applied 196 times per year using four 74.6 kW pumps running 0.56 h per 10,000 containers. In addition, a 44.8 kW-pump would run 40.5 h per year per 10,000 containers to recycle water from a catchment basin to an irrigation reservoir. Irrigation management would require 47.5 h·ha^{-1} of labor and a pickup truck running 23.8 h. Flumioxazin (0.25%) and a 2%-trifluralin + 0.5%-isoxaben mixed herbicide would each be applied once requiring 4.9 labor h·ha^{-1} and a 17.9-kW tractor and wagon for 2.5 h·ha^{-1}. Cyfluthrin (0.70%) + imidacloprid (2.94%) insecticides would be applied in one spray annually using a 74.6-kW tractor with air blast sprayer for 1.24 h·ha^{-1}. All plants would be pruned by hand once in this phase and 20% would be pruned twice due to later marketing.

Input materials, labor, and equipment use for Scenario C. Following 12 months' growth of the rooting cuttings in the 38-cell trays, liners would be transplanted to no. 1 injection-molded containers (0.272 kg) in the spring and grown for 2 years (Fig. 1). Substrate and fertilization in propagation were assumed to be the same as Scenario B.

Controlled-release fertilizer (18N–2.6P–10K) would be incorporated in the substrate at 11.4 kg·m^{-3} and topdressed at 17, 42, and 74 g per no. 1, 2, and 3 containers annually, requiring 1 h to fertilize 3000 plants. Overhead irrigations of 1.3 cm would be applied 196 times per year, herbicides would be applied twice per year. Hand weeding and one insecticide application would be as described on an area basis for Scenario B the no. 1, 2, and 3 container phases.

Pruning of no. 1 container plants would consist of one mechanical pruning and three hand prunings. Plants in no. 2 containers would be hand pruned three times, and 80% of plants in no. 3 containers would be pruned by hand once and the remaining 20% would be pruned twice.

Equipment use assumptions. Tractor power (1 hp = 0.746 kW) requirements were estimated for each function through nursery manager interviews. The portion of maximum tractor throttle and load for each operation was assumed to be: transporting plants on wagons, loading substrate components in mixer, 48.5 kW at 0.5 throttle and 0.5 load; 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 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 and herbicide boom sprayer, 74.6-kW tractor at 0.85 throttle and 0.85 load. The 3.7-kW gasoline powered sprayer was assumed to consume 1.25 L·h^{-1}. Gasoline-powered shearers were assumed to consume 0.63 L·h^{-1}. Electric motors for pumps and other equipment were assumed to use 0.746 kWh/hp. A 37.3-kW diesel fork lift at 0.50 throttle and 0.50 load would be used to load the truck for shipping.

Labor inputs. Labor requirements for each operation in the three scenarios were formulated through nursery manager interviews, with follow-up Delphi-method (Hsu and Sandford, 2007) discussions. Labor is a significant portion of costs but does not contribute directly to GHG. Equipment preparation and cleanup for each use would require 1.25 times more labor than the equipment operation hours.

Postharvest activity assumptions. A 2000-plant load was assumed to be transported 362 km by commercial carrier at $2.60/km. A 32-km, 30-min trip with a 50-plant load was assumed for the landscaper and 0.5 labor h (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.

Cost calculations. An economic engineering approach was used to estimate variable costs for production system input product and activity as defined through the LCI. Fixed costs are highly variable between nurseries firms 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. Dept. Labor (2015) for the states included in the Pacific northwest region was used to set the hourly wage rate of $12.69. This represents the wage level required for nonimmigrant H-2A agricultural workers. This wage also tends to act as a floor for nonmigrant wage levels as well. Input material costs were obtained from nursery industry wholesale distributors and manufacturers in 2016. Equipment costs per hour were representative of those reported in previous studies (Ingram et al., 2016). The gasoline price of $0.640/L represented the west coast average, not including California, 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 of machinery and truck use for each operation were determined using fuel consumption. Heavy and light truck diesel consumptions were based on 2.5 and 4.2 km·L^{-1} (6 and 10 mpg), respectively. Diesel consumption for each equipment operation were determined by tractor horsepower, throttle and load using published standards (Grisso et al., 2010) as previously reported (Hall and Ingram, 2014, 2015; Ingram, 2012, 2013; Ingram and Hall,

2013, 2014a, 2014b, 2015a). Gasoline and diesel consumption GWP was determined based on "well-to-wheel" emission reported in GREET1_2011 (Vyas and Singh, 2011) as 2.9339 kg CO_2e/L and 3.0153 kg CO_2e/L, respectively. The GWP of fluids and lubricants used by equipment was calculated using GREET2_7 (Burnham et al., 2006) as previously reported (Ingram, 2013).

GWP from the manufacturing and use of N from urea, P_2O_5, and K_2O fertilizers were determined as previously published (IPCC 2006; Snyder et al., 2009; Wang, 2007; West and Marland, 2003) and augmented by U.S. Life Cycle Inventory database (USLCI) data (U.S. Dept. Energy, 2015) and SimaPro (Pre' North America, Inc., 1001 Connecticut Ave NW, Suite 515, Washington, DC 20036) of standard and CRFs (Ingram et al., 2016). The average GWP 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 GWP of substrates were determined from their components, including their transportation and blending. Data for individual components were calculated in SimaPro, accessing USLCI (U.S. Dept. Energy, 2015) and Ecoinvent (Ecoinvent Center, 2015) databases. The GWP of fir bark substrate component for the container-production phases in all three scenarios was calculated to be 0.148 kg CO_2e/kg, assuming the bark was sourced from a saw mill in the Pacific northwest (0.0942 kg CO_2e/kg) and transported by tractor trailer 500 km (0.0474 kg CO_2e/kg). Bark would also be processed by a tumbler/screener that added 0.00647 kg CO_2e/kg. The propagation substrate GWP in Scenario A was calculated to be 0.249 kg CO_2e/kg, of which 0.110 kg CO_2e was from fir bark (0.77 kg), 0.116 kg CO_2e was from perlite (0.10 kg), 0.014 kg CO_2e was from peat (0.12 kg) and 0.0085 kg CO_2e emitted in blending. The perlite/peat propagation substrate GWP in Scenarios B and C was calculated to be 1.12 kg CO_2e, primarily due to the GWP of perlite (1.11 kg CO_2e).

GWP of production containers assumed manufacturing from 100% recycled HDPE pellets using injection-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 were assumed to be manufactured from polystyrene using a blow-mold technology, transported a distance of 200 km and landfill disposal of used material. Polypropylene tubing manufactured from low-density polypropylene using pipe extrusion technology was assumed.

The impact of sequestration on atmospheric CO_2 was determined as previously published for shrubs (Hall and Ingram, 2014, 2015; Ingram and Hall, 2014a, 2014b; Ingram et al., 2016) using PAS 2050 protocols (BSI British Standards, 2011). Carbon sequestration during production was determined from the average dry weight of three no. 3 *B. microphylla japonica* 'Green Beauty' (1.25 kg) and the accumulated dry weight during the plant's 40-year life was calculated to be 10.0 kg using methods previously published.

Carbon sequestration was expressed as the accumulated annual carbon in wood weighed over a 100-year assessment period.

Results and Discussion

The GWP resulting from GHGs related to input products, cultural practices, and other processes during the production from cutting to finished no. 3 container were calculated as 3.114, 2.632 and 4.280 kg CO_2e for defined Scenarios A, B, and C, respectively (Tables 1–3). The corresponding variable costs were estimated to be $4.043, $2.880 and $5.733, respectively. This compares to the cutting-to-gate GWP of a model system for an evergreen shrub in a no. 3 container on the east coast of the United States estimated to be 2.918 kg CO_2e with variable costs of $3.224 (Ingram et al., 2016).

Carbon sequestration in the wood of this plant during production, weighed over a 100-year assessment period, would result in a positive impact of 0.916 kg CO_2 on atmospheric carbon.

The resulting GWP for Scenarios A, B, and C at the nursery gate would be 2.198, 1.717, and 3.364 kg CO_2e, respectively. These values were somewhat higher than for field-grown shrubs (0.70 to 0.77 kg CO_2e), significantly lower than for field-grown trees (6.6 to 12.8 kg CO_2e), and similar to a no. 3 evergreen shrub produced on the U.S. east coast (Hall and Ingram, 2015; Ingram, 2012; Ingram and Hall, 2013, 2014a; Ingram et al., 2016).

Much of the differences in the nursery-gate GWP and variable costs of the finished no. 3 plants in the three scenarios were attributable to the plant that was transplanted into the no. 3 container for finishing, as would be expected given the major differences in that portion of the scenarios (Figs. 2 and 3). In Tables 1–3 and Figs. 2 and 3 the transplant GWP and variable costs from each phase represents the accumulative data for "transplant" in the subsequent phases.

In all scenarios, the propagation phase was a minor portion of the product GWP; 6% for Scenarios A and C and 11% for Scenario B. Equipment use, dominated by the impact of providing bottom heat, was the primary contributor to propagation GWP. Labor assigned to operations was the dominate component of the variable costs in this phase. Fertilization was a more important element of propagation GWP and cost in Scenario A compared with Scenarios B and C, although still a relatively small portion of GWP and cost. Rooting in a community flat and transplanting to a 32-cell flat resulted in a greater cost and GWP in Scenarios B and C compared with A. The extra growing season for liners in 32-call flats in Scenario B compared with Scenario C added little to GWP and cost.

The GWP of the transplant to no. 3 containers for Scenarios A, B, and C were 0.645, 0.773, and 2.246 kg CO_2e, respectively. The variable costs of the transplants were $0.995, $0.671, and $3.216. These represented 29%, 45%, and 67% of the nursery-gate GWP and 24%, 23%, and 56% of variable costs for the finished product. The
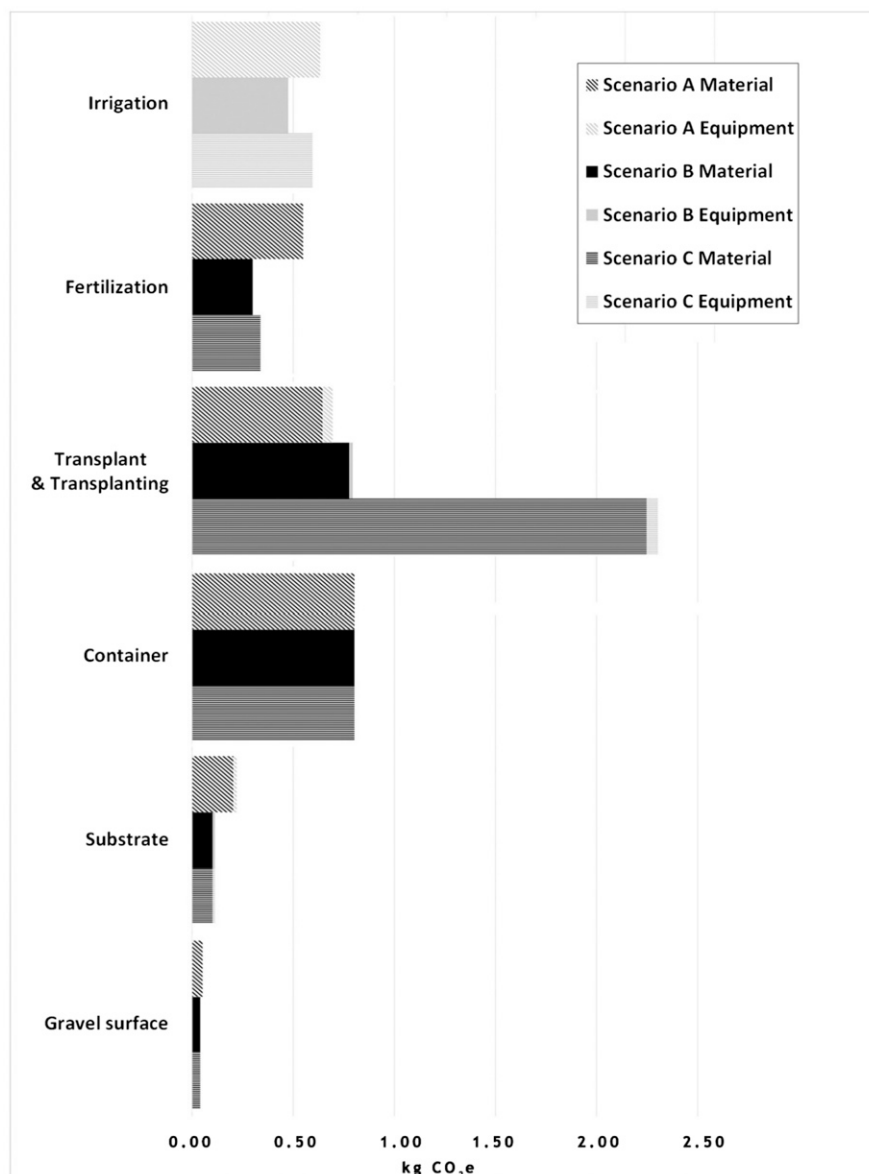

Fig. 2. Global warming potential of component input materials and equipment use for production Scenarios A, B, and C for *Buxus microphylla* var. *japonica* 'Green Beauty' to be grown and marketed in a no. 3 container on the U.S. west coast.

major inputs to GWP and costs before transplanting to no. 3 in Scenario C were the use of additional containers, substrate, irrigation, and fertilization as well as labor requirements for transplanting and transporting within the nursery for the no. 1 and 2 container phases. The transplant represented less of the nursery-gate GWP in Scenario A primarily because small plants were transplanted to no. 3 containers and the subsequent longer growth time compared with the other scenarios.

The production time in no. 3 containers for 80% of plants were 12 months in Scenarios B and C and 18 months (2 growing seasons) in Scenario A. The GWP for transplanting to no. 3 containers were similar between scenarios; however, GWP emissions for transporting transplants from the field production was allocated in the field production phase, as if they were being produced by another nursery (Table 2). As would be

expected, plants grown for two seasons in no. 3 in Scenario A required more fertilization and resulted in GWP of 0.547 kg CO_2e compared with Scenario C (0.338 kg CO_2e) and variable costs of $0.162 and $0.091, respectively. Fertilization impact for Scenario B (0.298 kg CO_2e) was slightly less due to a lower rate of incorporated fertilizer for a fall transplanting schedule. Pruning costs in Scenario A was more than 3.3 times that for Scenarios B and C but involved three more hand pruning events for the additional growing season. This increased pruning frequency could also impact product quality. Weed control with herbicides in the no. 3 container production phase resulted in a slightly higher GWP in Scenario A primarily due to higher equipment use but $0.05 less variable costs than for Scenarios B and C.

Pulling and assembling orders and loading trucks would result in a GWP of 0.232 kg
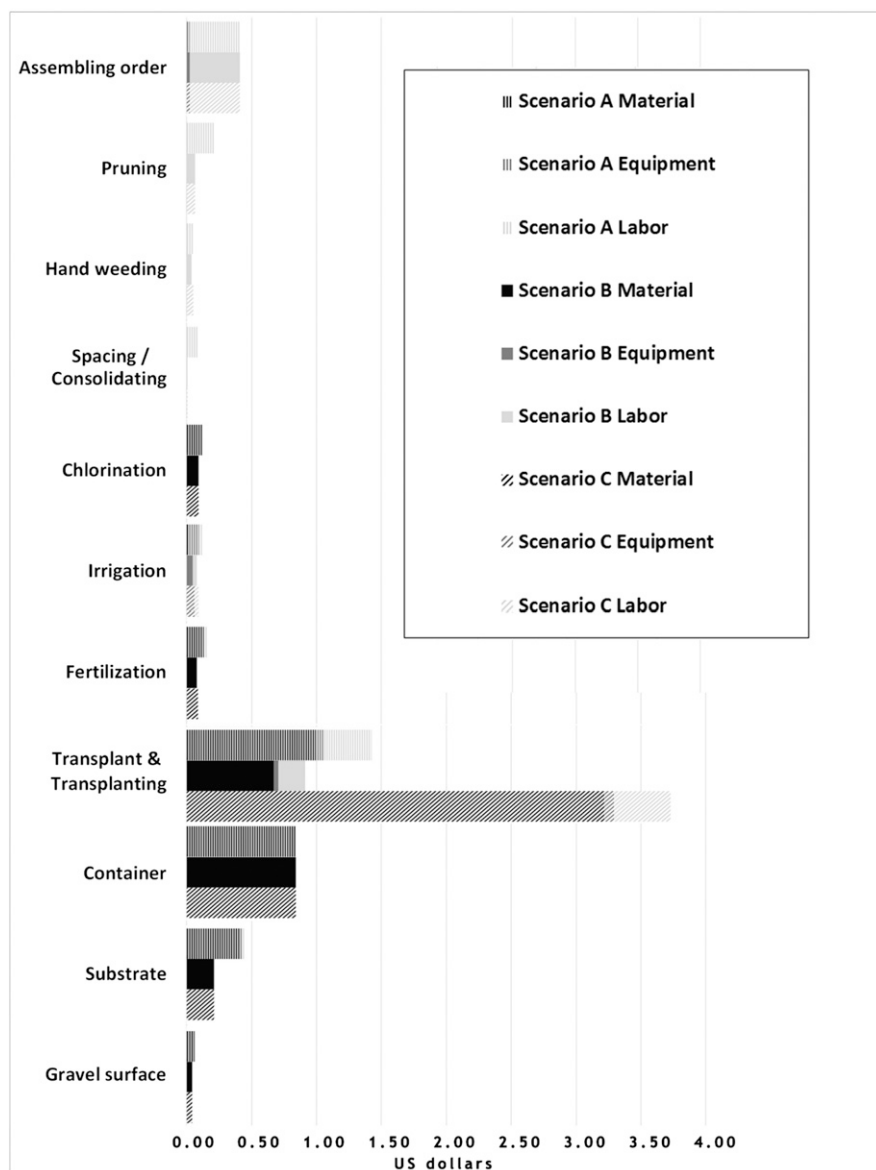
Fig. 3. Variable costs of component input materials and equipment use for production Scenarios A, B, and C for *Buxus microphylla* var. *japonica* 'Green Beauty' to be grown and marketed in a no. 3 container on the U.S. west coast.

CO_2e and cost $0.408. Transporting the product, 2000 in a load, 800 km to a customer would result in a GWP of 0.566 kg CO_2e and cost $0.650 while transporting it an additional 32 km to the landscape site would yield 0.458 kg CO_2e and cost $0.398. If the plant was to be transported from the west coast to the Midwest (3200 km), the transport GHG and costs would be four times the values above. If the plant was transported to the east coast (4825 km), the transport GHG and costs would be six times the values above. The variable costs for planting the shrub as part of a landscape project were calculated to be $6.345.

Removal from the landscape and disposal at the end of life would contribute 0.115 kg CO_2e, due to vehicle use, to the life cycle of this shrub as previously published (Ingram et al., 2016). If the shrub was shredded on site with a gasoline-powered shredder, the activities at the end of life would result in GWP of 0.092 kg CO_2e. Labor for removing the shrub was estimated to be $6.345.

The accumulated, weighted impact of annual sequestration of carbon by this shrub over its 40-year life was calculated to be –4.654 kg CO_2e. When calculating the impact on atmospheric carbon dioxide over the life cycle of this shrub, the life cycle GWP would be –1.317, –1.646, and 0.001 kg CO_2e for Scenarios A, B, and C, respectively. The published life cycle GWP for a modeled protocol for no. 3 production of an evergreen shrub grown and marketed on the east coast was –4.537 kg CO_2e (Ingram et al., 2016). As would be expected, the positive life cycle impact was estimated to be much greater for larger, longer-lived trees and shrubs (Hall and Ingram, 2015; Ingram, 2012, 2013; Ingram and Hall, 2013, 2014a).

The GWP and variable costs of water management, including irrigation and surface runoff recycling, were similar during the no. 3 production phase (Figs. 2 and 3). This is especially true given the longer production cycle for Scenario A and that Scenario B used fall transplanting. However, when the accumulated GWP and variable cost through the transplant production sequence for no. 3 container was considered, the total product GWP and variable costs for water management for Scenario A, B, and C were 0.679 kg CO_2e ($0.142), 0.593 kg CO_2e ($0.134), and 1.419 kg CO_2e ($0.230), respectively. Therefore, CF of water management for the no. 3 container-grown plant in these model systems was 22% of product nursery gate GWP for Scenarios A and B and 33% for Scenario C. Variable costs associated with water management would be 3.5%, 4.6%, and 4.0% of nursery-gate costs for Scenarios A, B, and C, respectively.

The sensitivity analysis for GWP revealed at least a 1% increase in total GWP with a 10% increase in four of the 15 operational variables and for variable costs in two of those 15 operations in the no. 3 container production phase. Assessed from cutting-to-gate, a 10% increase in the GWP of the container, transplant/transplanting, and irrigation would have more than a 2% impact on total GWP. Fertilization would have more than a 1% impact on total GWP for each of the scenarios except fertilization in Scenario C where the impact was 0.78%. These four operations accounted for 84.6%, 89.3%, and 94.2% of total GWP and 57.1%, 64.4%, and 82.88% of total variable costs for Scenarios A, B, and C, respectively. The transplant and transplant process accounted for 53.8% of total GHG and 65.0% of total variable costs for the no. 3 production phase of Scenario C. The container and transplant/transplanting had the greatest impact on total variable costs of each of the models.

Conclusions

The Scenario B model resulted in the lowest GWP and variable costs of the three options even though it required one or two more years due to the field production phase. However, availability of field production areas and equipment may not be available for many nurseries. The sequencing of production through no. 1 and 2 containers in Scenario C clearly resulted in the highest costs and GWP. Scenario A with an extended propagation phase, a brief no. 1 container phase and two growing seasons in a no. 3 resulted in intermediate GWP and costs and required one less year than Scenario C.

The sensitivity analysis identified the containers, transplant/transplanting, irrigation, and fertilization that accounted for the greatest portion of GWP and variable costs in each scenario. Managers should evaluate the potential for saving possible in each of these inputs and process as they assess production protocol efficiencies. However, these analyses did not consider that there could be differences in market window, customer preferences, or anticipated selling price between the scenarios.

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