# Carbon Footprint and Related Production Costs of System Components for a Field-Grown *Viburnum × juddi* Using Life Cycle Assessment[1]

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## Abstract

Life cycle assessment was used to analyze the global warming potential (GWP) and variable costs of input materials, equipment use and labor of a model system for field production of a balled and burlapped, 0.9 m (36 in) Judd viburnum (*Viburnum* × *juddi* Rehder) shrub in the lower Midwest. The model system was defined using information obtained through interviews with nursery managers in the region. The propagation-to-gate GWP of the shrub was determined to be 0.705 kg $CO_2$ equivalent ($CO_2$e), after subtracting 0.916 kg $CO_2$e, the weighted impact of carbon sequestered during production. Estimates for propagation-to-landscape GWP (3.156 kg $CO_2$e) and variable costs ($9.19) were also calculated for the model. Material inputs during field production contributed 1.063 kg $CO_2$e to the propagation-to-gate GWP and $0.89 of the variable costs while equipment use contributed 0.558 kg $CO_2$e and $0.32 to variable costs.


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

**Species used in this study:** Juddi viburnum (*Viburnum* × *juddi* Rehder).

### 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. The estimated propagation-to-gate carbon footprint, subtracting the weighted carbon sequestration (0.916 kg $CO_2$) during production, was 0.705 kg $CO_2$e and the propagation-to-landscape carbon footprint of the model system was estimated to be 3.156 kg $CO_2$e. Material production inputs contributed 66% of the 1.621 kg $CO_2$e propagation-to-gate greenhouse gas emissions (GHG) and 17% of variable costs ($5.35) while equipment use contributed 16% to GHG and 6% to variable costs. The opposite ratio has been shown for 5 cm (2 in) caliper, field-grown, spade-dug redbud trees, which required much more equipment use in harvesting and handling. Nursery managers should focus on harvesting efficiencies in cost savings but hand digging contributed very little to the carbon footprint. Local transport distance of the product was also a significant contributor to GWP. Although significantly less than for shade trees, the estimated positive impact on GWP by $CO_2$ sequestration during complete life cycle of the shrub, weighted over a 100-year assessment pe-

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riod, was 20 times greater than its propagation-to-landscape carbon footprint. The positive life cycle impact of a shrub on atmospheric $CO_2$ reductions can be used in marketing strategies to environmentally-conscious consumers.

## Introduction

One measure of the environmental impact of a product or activity is its carbon footprint, which is commonly expressed as the global warming potential (GWP) of that product or activity. GWP is the net impact of greenhouse gas emissions (GHG) and $CO_2$ sequestration over the life of a product or activity, referenced in a 100-year assessment period. The three primary greenhouse gases are $CO_2$, $N_2O$ and $CH_4$ and their GWP is expressed in relation to that of $CO_2$; 1 kilogram $CO_2$ equivalent ($CO_2$e). The majority of $CO_2$ emissions into the atmosphere results from combustion of fossil fuels (BSI British Standards 2011, IPCC 2006, IPCC 2007).

Standards for determining environmental impacts and tools for assessing them have been developed, including Life Cycle Assessment (LCA). LCA protocols are governed by international standards and include activities and input products during production, use and end-of-life phases of a product (BSI British Standards 2011).

LCA has been used to determine the propagation-to-landscape GWP for field-grown, 5 cm (2 in) caliper red maple (*Acer rubrum* L.), Colorado blue spruce (*Picea pungens* Engelm.) and redbud. (*Cercis canadensis* L) to be 8.2, 13.6 and 13.7 kg $CO_2$e, respectively; representing a shade tree, evergreen tree and flowering tree (Hall and Ingram 2014; Ingram 2012; Ingram 2013; Ingram and Hall 2013). The GWP for the production and distribution of container-grown trees in #5 and #9 containers was reported by Kendall and McPherson (2012) as 4.6 and 15.3 kg $CO_2$e, respectively.

The impact of input products and activities on cost is also important and part of economic analyses of production systems. Costs and GWP for field production components for redbud were closely related (Hall and Ingram 2014). Understanding both the cost and environmental impact of specific operations will help nursery managers make decisions about their operations to not only increase efficiency but consider the environmental implications as well. This study adds to that knowledge base by assessing the costs and GWP of production system components of *Viburnum* × *juddi*, a representative deciduous shrub in the lower Midwest.

## Methods and Materials

The functional unit for this LCA study was a 91 cm (36 in), field-grown, hand-dug *Viburnum* × *juddi* Rehder shrub with a 30 cm (12 in) soil/root ball. *V.* × *juddi* was used as an example of typical deciduous shrub production in the Midwest. To initiate the production system, a model production system was constructed based on interviews with four nursery managers in the lower Midwest and guided by published protocols (McNiel 2000). The model assumed cuttings would be taken in early summer from current nursery stock, stuck into substrate in individual cells of plug trays, rooted under mist and overwintered in an unheated greenhouse with a gravel floor. A 95% success rate rooting the cuttings was assumed. The rooted cuttings would be transplanted in raised beds in the field the following spring. It was assumed that five percent of plants would have died during liner production or been culled at harvest.

Liners would then be harvested from the raised beds after two growing seasons and transplanted to the field in rows. Following three years of growth, plants would be dug and the root ball wrapped in burlap by hand. The model assumed that two percent of the plants during this production phase would have died or been culled before harvest. Plants would be transported to the shipping area with a tractor and wagon and immediately loaded on a truck. Finished plants would be transported to the customer using a nursery-owned truck.

Standards for an LCA were followed in this study, including the International Organization for Standardization [ISO (Geneva, Switzerland)] (2006) and PAS 2050 guidelines by BSI British Standards (2011). All activities in each production phase were inventoried, including the input products, equipment, and labor used during each activity. Individual GHG emissions were determined, converted to kilograms $CO_2$e per functional unit and summed. Costs of inputs, equipment use and labor were determined for the adopted model system but labor was assumed not to contribute to the GWP. Emissions from the manufacturing of capital goods, such as buildings and machinery, were also not included in this study as per PAS 2050, Section 6.4.4. Impact of land use change was not included in this study as 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.

*Input materials, labor and equipment use in rooted-cutting production*. The model assumed that cuttings would be taken from production plants in summer, stuck in 4.76 by 2.25 cm (1.87 by 0.9 in) cells with a peat-perlite substrate in 957 50-count trays and placed under intermittent mist in an unheated, 6.1 by 29.3 m (20 by 96 ft), Quonset-type greenhouse. The trays would be cleaned and reused four times, requiring 8 hrs for 957 trays. Sixteen man-hours would be invested in taking, prepping and sticking 10,000 cuttings. The greenhouse would be constructed of galvanized metal pipe and pressure-treated lumber and covered with opaque polyethylene film expected to last for 4 years. The only equipment use was for spreading gravel in the greenhouse (Table 1). The mist would be operated for a total of 67 hours during the production of rooted cuttings. The mist system and the municipal water use were assumed to be insignificant to this study. One application of 15-9-11 fertilizer (15N-3.9P-9.1K) was applied at 50 $g{\cdot}m^{-2}$ (0.163 $oz{\cdot}ft^{-2}$). Successfully-rooted cuttings would be planted into raised, field beds the following spring.

*Input materials, labor and equipment use in liner production.* It was assumed that the crop sequencing for both the raised bed liner production and field production of the finished product would include a fallow year with a 45.6 $kg{\cdot}ha^{-1}$ (40 $lbs{\cdot}A^{-1}$) sudex [*Sorghum bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf.] cover crop every fourth year as previously described (Ingram and Hall 2013). Equipment-use time and labor assumed in the model to plow, disk, subsoil, rototill and form raised beds during the fallow year field activities and in land preparation for planting are listed in Table 2. There would be 1,890 rooted cuttings transplanted 20 cm (8 in) on center in 101 cm (40 in) wide by 61 m (200 ft) long raised beds in the field the following spring, requiring 15 man-hours per bed. A 50 cm (20 in) aisle between beds was assumed. Plants would be irrigated an average of 10 times per year using a low-volume system with t-tape and



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Table 1. **Contributions of input materials, equipment use and labor to the global warming potential (GWP) and variable costs of Juddi viburnum rooted-cutting production in an unheated quonset-type greenhouse.**

| Activity/components | Materials | | | Equipment use | | | Labor | Total | |
|---|---|---|---|---|---|---|---|---|---|
| | kg·cutting$^{-1}$ | GWP (kg CO2e) | Costs ($) | hrs·cutting$^{-1}$ | GWP (kg CO2e) | Costs ($) | Costs ($) | GWP (kg CO2e) | Costs ($) |
| Take and stick cuttings | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0380 | 0.0000 | 0.0380 |
| 50-cell plug tray | 0.0010 | 0.0025 | 0.0079 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0025 | 0.0079 |
| Substrate | 0.0154 | 0.0122 | 0.0310 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0122 | 0.0310 |
| Clean flats for re-use | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0021 | 0.0000 | 0.0021 |
| Metal bows | 0.0005 | 0.0021 | 0.0012 | 0.0000 | 0.0000 | 0.0000 | 0.0013 | 0.0021 | 0.0025 |
| Polyethylene film | 0.0003 | 0.0009 | 0.0026 | 0.0000 | 0.0000 | 0.0000 | 0.0005 | 0.0009 | 0.0031 |
| Gravel surface | 0.0000 | 0.0019 | 0.0005 | 0.0000 | 0.0001 | 0.0000 | 0.0001 | 0.0020 | 0.0006 |
| Mist and irrigation | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0173 | 0.0000 | 0.0173 |
| Fertilize, 15-9-11 | 0.0002 | 0.0003 | 0.0007 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0003 | 0.0008 |
| Energy overhead | | | | | 0.0158 | 0.0030 | | 0.0158 | 0.0030 |
| | | | | | | | **Total** | **0.0359** | **0.1063** |

municipal water. The liners would be pruned to a uniform height in the summer of the first season and lightly pruned the next spring using gasoline-powered hedge trimmers (86 hrs·ha$^{-1}$; 35 hrs·A$^{-1}$). Fertilizer (20N-2.2P-4.2K; 20-5-5) would be applied annually at a 114 kg N·ha$^{-1}$ (100 lbs N·A$^{-1}$) rate. Pendimethalin would be applied 2 times per year for weed control, requiring 10.4 hrs·ha$^{-1}$ (4.2 hrs·A$^{-1}$). Hand weeding of escapes was assumed to be insignificant. Plants would be harvested bare root after two years using a tractor-pulled undercutter/shaker, requiring 4 hrs per 10,000 liners. Five laborers would then harvest 10,000 in an 8-hr day. Harvested liners would be transported within the nursery for field planting using a tractor and wagon.

*Input materials, labor and equipment use in field production*. Equipment-use time and labor assumed in the model to subsoil, plow, disk, apply lime and rototill during the fallow year field activities and in land preparation for planting are listed in Table 3. The model assumed that liners would be transplanted on 0.9 m (3 ft) centers in rows spaced 1.3 m (4.5 ft) apart (7,907·ha$^{-1}$; 3,200·A$^{-1}$) using a tractor and transplanter and a 6-person crew (47.4 man-hours·ha$^{-1}$; 19.2 man-hours·A$^{-1}$). Irrigation would be provided 30 times per year through a low-volume system using T-tape, requiring 15 man-hours for maintenance and operation. Fertilizer (20N-2.2P-4.2K; 20-5-5) would be banded in-row annually at a 137 kg N·ha$^{-1}$ (120 lbs N·A$^{-1}$) rate. Cultivation with a 24 hp tractor and rotovator (1.8 man-hours·ha$^{-1}$; 0.75 man-hours·A$^{-1}$) would occurred 6 times per year and the fertilizer would be applied during one of those cultivations. Pendimethalin and oxyfluorfen herbicides would be sprayed at recommended rates to in-row bands twice per year, requiring 2.5 hrs·ha$^{-1}$ (1 hr·A$^{-1}$). Manual hoeing would be performed once per year, requiring 26.4 man-hours·ha$^{-1}$ (10.7 man-hours·A$^{-1}$). Pruning would be completed once per year using gasoline-powered hedge trimmers (29.6 man-hours·ha$^{-1}$; 12 man-hours·A$^{-1}$). Following three years of production, plants would be tagged by nursery staff and contract-dug and burlapped by hand at

Table 2. **Contributions of input materials, equipment use and labor to the global warming potential (GWP) of Juddi viburnum liner production in raised field beds.**

| Activity/components | Materials | | | Equipment use | | | Labor | Total | |
|---|---|---|---|---|---|---|---|---|---|
| | kg or unit·liner$^{-1}$ | GWP (kg CO2e) | Costs ($) | hrs·liner$^{-1}$ | GWP (kg CO2e) | Costs ($) | Costs ($) | GWP (kg CO2e) | Costs ($) |
| Sow sudex — fallow year | 0.0001 | 0.0006 | 0.0007 | 0.0000 | 0.0005 | 0.0002 | 0.0001 | 0.0011 | 0.0010 |
| Chisel plow | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0008 | 0.0005 | 0.0002 | 0.0008 | 0.0007 |
| Disk | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0004 | 0.0002 | 0.0001 | 0.0004 | 0.0003 |
| Mow twice | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0004 | 0.0002 | 0.0001 | 0.0004 | 0.0003 |
| Chisel plow and subsoil | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0008 | 0.0005 | 0.0002 | 0.0008 | 0.0007 |
| Disk | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0001 | 0.0001 | 0.0002 | 0.0001 |
| Rototill | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0008 | 0.0005 | 0.0002 | 0.0008 | 0.0007 |
| Form raised beds | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0008 | 0.0005 | 0.0002 | 0.0008 | 0.0007 |
| Transplant rooted cuttings | 1.0500 | 0.0380 | 0.1116 | 0.0000 | 0.0000 | 0.0000 | 0.0950 | 0.0380 | 0.2066 |
| Shear with gas shearer | 0.0000 | 0.0000 | 0.0000 | 0.0006 | 0.0010 | 0.0017 | 0.0126 | 0.0010 | 0.0142 |
| Irrigation T-tape | 0.0010 | 0.0016 | 0.0056 | 0.0010 | 0.0014 | 0.0037 | 0.0014 | 0.0030 | 0.0107 |
| Irrigation supply line/header | 0.0000 | 0.0001 | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 |
| Irrigation operations | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0018 | 0.0000 | 0.0018 |
| Apply fertilizer (20-5-5) | 0.0072 | 0.0119 | 0.0088 | 0.0000 | 0.0004 | 0.0012 | 0.0007 | 0.0123 | 0.0107 |
| Apply Pendulum herbicide | 0.0003 | 0.0045 | 0.0025 | 0.0001 | 0.0005 | 0.0021 | 0.0010 | 0.0051 | 0.0056 |
| Harvest — shaker/digger | 0.0000 | 0.0000 | 0.0000 | 0.0021 | 0.1076 | 0.0646 | 0.0475 | 0.1076 | 0.1121 |
| Energy overhead | | | | | 0.0129 | 0.0019 | | 0.0129 | 0.0019 |
| | | | | | | | **Total** | **0.1849** | **0.3685** |



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a cost of $3 per plant. It was assumed that two percent of the plants during this production phase would have died or been culled before harvest.

*Equipment use assumptions.* The only equipment use for rooted-cutting production was in constructing the greenhouse. Transport of the greenhouse components was included in the materials cost and GWP. A truck would haul the gravel for 40 km (25 mi) and spread it. The gravel surface would be further smoothed by hand.

For liner and field production, 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 hauling finished plants from the field, 80 hp tractor at 0.85 throttle and 0.85 load; liner harvesting, 80 hp tractor at 1.0 throttle and 0.85 load; and spraying/spreading in-row, between-row cultivation, and transporting liners to the field with a wagon, 24 hp tractor at 0.50 throttle and 0.50 load. It was assumed that trimming with a gas shearer consumed 18.7 $L{\cdot}ha^{-1}$ (2 $gal{\cdot}A^{-1}$) of gasoline for each operation. A 3 hp electric irrigation pump would be used (148 $hrs{\cdot}ha^{-1}$; 60 $h{\cdot}A^{-1}$) over the two years in liner production and a 5 hp electric irrigation pump would be used for 29.6 $hrs{\cdot}ha^{-1}$ (12 $hrs{\cdot}A^{-1}$) during field production.

*Post-harvest activity assumptions.* It was assumed that 250 finished shrubs would be transported to the customer on a 7.3 m (24 ft) truck for a distance of 193 km (120 mi) and the truck would travel empty back to the nursery. The shrub would then be transported by the landscape service provider to the landscape with a light truck and trailer as part of a 50 plant load traveling 32 km (20 mi). Following 50 years of useful life in the landscape, the shrub would require 0.5 hrs of labor and 10 miles in a light truck for removal and disposal.

*Labor inputs.* Although labor is obviously part of the cost of activities and processes, it does not contribute directly to the GWP of the product. The amount of labor for each operation was determined from nursery manager interviews and used to define the model. Labor requirements for operating equipment were calculated as 1.25 times the equipment operation hours to account for preparation and clean-up time.

*Cost calculations.* An economic engineering approach was used for the entire model production system for this shrub. Only variable costs were included for each operation and fixed costs were excluded. Fixed costs associated with buildings, land and general overhead are highly variable between nurseries in the industry but range from 48 to 52% of total costs. The Adverse Effect Wage Rate (AEWR) as determined by the U.S. Dept. of Labor (2012) for the states included in the lower Midwest region was used to set the wage rate of $11.28. 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 valued at 2013 prices and were obtained from green industry wholesale distributors and manufacturers. Equipment costs per hour were representative of those reported in enterprise budgets for horticultural crops produced in the lower Midwest region. The fuel price of $13.74${\cdot}L^{-1}$ ($3.63${\cdot}gal^{-1}$) represented the U.S. average as reported by the U.S. Energy Information Administration (2012).

*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 trucks were assumed to consume 2.5 and 4.2 $km{\cdot}L^{-1}$ (6 and 10 mpg) of diesel. Published standards for diesel consumption by tractor horsepower, throttle and load (Grisso et al. 2010) were used for each operation as previously reported (Ingram 2012). Nursery manager interviews revealed that a gasoline-powered shearer consumes 0.63 $L{\cdot}hr^{-1}$ (0.167 $gal{\cdot}hr^{-1}$). The GWP for gasoline and diesel consumption was determined based on 'well-to-wheel' emission reported in GREET1_2011 (Vyas and Singh 2011) as 2.9339 and 3.0153 kg $CO_2e{\cdot}L^{-1}$, respectively.

It was assumed that the unheated greenhouse was constructed of 16-guage galvanized steel tubing weighing 419 kg (924 lbs), including 3.6 cm (1.428 in) diameter bows and purlines and 1.2 m (4 ft) stakes. It was assumed it took 100 man-hours to construct without equipment use and would last 20 years (McNiel 2000). The GWP for the galvanized steel tubing, 4.34 kg $CO_2e{\cdot}kg^{-1}$, was determined using SimaPro LCA software (Pre' North America, Inc., 1001 Connecticut Ave NW, Suite 515, Washington, DC 20036), assuming transport distance of 250 km (155 mi) and GWP for steel sheets and metal working/machine operation of 2.94 and 1.4 kg $CO_2e{\cdot}kg^{-1}$, respectively. Thirty-six tons of gravel for the ground surface, as well as the metal structure, was assumed to last 20 years. The GWP of the lumber used was insignificant and not included.

As previously published, GWP of 3.2, 1.0, 0.7 and 0.6 kg $CO_2e{\cdot}kg^{-1}$ for N from urea, $P_2O_5$, $K_20$ and lime, respectively, were assumed (Ingram 2012, Snyder et al. 2009, Wang, 2007). 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 (IPPC 2006, Snyder, et al 2009, West et al. 2004). 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 2014; West and Marland 2003). Gravel, irrigation system materials and polyethylene film GWP, including their transport, were taken from the U.S. Life Cycle Inventory database (U.S. Dept. Energy 2014) as 0.052, 1.56, and 2.86 kg $CO_2e{\cdot}kg^{-1}$, respectively. The GWP for the small amount of burlap and nylon twine was not readily available and considered to have negligible impact. Their costs were considered as part of the digging cost per plant.

The propagation substrate of peat:perlite (65:35 by vol), has a calculated GWP of 0.794 kg $CO_2e{\cdot}kg^{-1}$ (Koeser 2013). Plastic flats, manufactured from polystyrene and transported 250 km (155 mi), was determined using SimaPro to have a GWP of 2.620 kg $CO_2e{\cdot}kg^{-1}$.

Landscape plants sequester carbon during production and during their useful life in the landscape. Three representative shrubs were harvested from a field nursery in Kentucky, dried in a forced-air oven at 50C (122F), and weighed with leaves removed. The dry weight of the three shrubs averaged 1.0 kg (2.2 lb) and was used to estimate carbon sequestered during

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production. Using the relationship of plant volume index and dry weight at the liner stage and at the end of production, a dry weight of 29 kg (64 lb) at maturity was estimated based on expected plant volume index at maturity. This method has been used previously by R. Schutzki, (Michigan State University, personal communication). A sigmoidal curve with a beginning value of 1 kg (2.2 lb), a maximum of 29 kg (64 lb) at 50 years, a midpoint of 20 years and a 0.2 slope at the midpoint was used to model plant growth over the life of the plant in the landscape. Plant dry weight at the nursery gate and modelled for each year thereafter for the 50 years was multiplied by 3.664 to determine the kg of $CO_2$ uptake in photosynthesis for each kilogram of carbon in the wood and 50% of the dried wood mass was assumed to be carbon (U.S. Dept. Agri. 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, Ingram 2012).

## Results and Discussion

The propagation-to-gate GWP of a 0.9 m (36 in), field-grown, hand-dug Juddi viburnum in the lower Midwest was estimated to be 1.621 kg $CO_2$e with total variable costs of $5.35 (Table 3). Subtracting 0.916 kg $CO_2$ sequestered during production, weighted for 50 years of a 100-year assessment period, the carbon footprint at the nursery gate was estimated to be 0.705 kg $CO_2$e. Transport to the landscaper (1.993 kg $CO_2$e) and transport and transplanting to the landscape site (0.458 kg $CO_2$e) resulted in emissions of 2.450 kg $CO_2$e, significantly more than GHG emissions for the production phase. The propagation-to-landscape GWP of this shrub was calculated to be 3.156 kg $CO_2$e, much smaller than the 13.6 and 13.7 kg $CO_2$e for field-grown, 5 cm (2 in) caliper Colorado blue spruce and redbud, respectively (Ingram 2013, Ingram and Hall 2013). This could be expected due to the higher population density for shrubs during production and the lower equipment use requirement, particular at harvest. Total propagation-to-landscape variable costs would be $9.19.

The rooted-cutting production phase resulted a GWP of 0.036 kg $CO_2$e with 56% from material inputs (Table 1.). The substrate contributed 34% and overhead energy use accounted for 44% of the rooted cutting GWP. The GWP of a bed-grown liner was 0.185 kg $CO_2$e, with 0.57 kg $CO_2$e from materials and 0.128 kg $CO_2$e from equipment use and overhead energy (Table 2). Production of the rooted cutting contributed the most to the GWP of material inputs and the costs for a finished liner. A majority of equipment-use GWP occurred at harvest of the liner (0.108 kg $CO_2$e) and constituted 30% of variable costs. The field operations of fertilizer application and pruning with gasoline shears contributed the next largest amounts to GWP and costs, followed closely by irrigation and fertilization costs. Forty-four percent of the total variable costs of $0.37 for liner production was for labor.

Material inputs during the liner and field production phases contributed 1.063 kg $CO_2$e (66%) to the propagation-to-gate GWP and $0.89 of the variable costs while equipment use contributed 0.558 kg $CO_2$e (16%) and was $0.32 (6%) of the costs (Table 3). In a previous study for field-grown, spade-dug, 5 cm (2 in) caliper redbud, equipment use accounted for 71% of the seed-to-gate GWP and 34% of the costs (Hall and Ingram 2014). Overhead electricity and gasoline use for the field nursery contributed 0.299 kg $CO_2$e (18%) of GWP and $.05 to the costs. Material and equipment use for the application of lime (0.347 kg $CO_2$e) and fertilizer (0.434 kg

**Table 3. Contributions of input materials, equipment use and labor on the global warming potential (GWP) and variable costs of Juddi viburnum during field nursery production.**

| Activity/components | Materials | | | Equipment use | | | Labor | Total | |
|---|---|---|---|---|---|---|---|---|---|
| | kg or unit·shrub$^{-1}$ | GWP (kg CO2e) | Costs ($) | hrs·shrub$^{-1}$ | GWP (kg CO2e) | Costs ($) | Costs ($) | GWP (kg CO2e) | Costs ($) |
| Plow | 0.0000 | 0.0000 | 0.0000 | 0.0003 | 0.0151 | 0.0101 | 0.0045 | 0.0151 | 0.0146 |
| Subsoil | 0.0000 | 0.0000 | 0.0000 | 0.0003 | 0.0151 | 0.0096 | 0.0045 | 0.0151 | 0.0141 |
| Disk | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0075 | 0.0037 | 0.0022 | 0.0075 | 0.0060 |
| Lime application | 0.5786 | 0.3392 | 0.0128 | 0.0002 | 0.0075 | 0.0063 | 0.0022 | 0.3467 | 0.0213 |
| Sudex — fallow year | 0.0058 | 0.0235 | 0.0268 | 0.0004 | 0.0196 | 0.0094 | 0.0058 | 0.0431 | 0.0420 |
| Plow-in cover crop | 0.0000 | 0.0000 | 0.0000 | 0.0003 | 0.0151 | 0.0101 | 0.0045 | 0.0151 | 0.0146 |
| Disk | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0075 | 0.0037 | 0.0022 | 0.0075 | 0.0060 |
| Rototilling | 0.0000 | 0.0000 | 0.0000 | 0.0003 | 0.0151 | 0.0092 | 0.0045 | 0.0151 | 0.0137 |
| Transport liners to field | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0006 | 0.0012 | 0.0011 | 0.0006 | 0.0023 |
| Transplant liners | 0.0000 | 0.1887 | 0.3767 | 0.0002 | 0.0075 | 0.0048 | 0.0690 | 0.1962 | 0.4505 |
| Irrigation T-tape | 0.0111 | 0.0173 | 0.0612 | 0.0038 | 0.0096 | 0.0000 | 0.0360 | 0.0269 | 0.0972 |
| Irrigation supply line/header | 0.0007 | 0.0011 | 0.0023 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0011 | 0.0023 |
| Irrigation operation | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0027 | 0.0000 | 0.0027 |
| Apply fertilizer (20-5-5) | 0.2604 | 0.4309 | 0.3444 | 0.0005 | 0.0036 | 0.0125 | 0.0067 | 0.4345 | 0.3636 |
| Apply herbicides | 0.0074 | 0.0622 | 0.0452 | 0.0010 | 0.0073 | 0.0297 | 0.0135 | 0.0694 | 0.0884 |
| Hoeing | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.1151 | 0.0000 | 0.1151 |
| Cultivate | 0.0000 | 0.0000 | 0.0000 | 0.0036 | 0.0272 | 0.0741 | 0.0506 | 0.0272 | 0.1247 |
| Pruning | 0.0000 | 0.0000 | 0.0000 | 0.0115 | 0.0212 | 0.0344 | 0.1295 | 0.0212 | 0.1639 |
| Digging — contract | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 3.0000 | 0.0000 | 3.0000 |
| Tagging plants | 0.0000 | 0.0000 | 0.0175 | 0.0000 | 0.0000 | 0.0000 | 0.0752 | 0.0000 | 0.0927 |
| Hauling from the field | 0.0000 | 0.0000 | 0.0000 | 0.0017 | 0.0789 | 0.0475 | 0.3500 | 0.0789 | 0.3975 |
| Loading on truck | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.2707 | 0.0000 | 0.2707 |
| Energy overhead | | | | | 0.2994 | 0.0519 | | 0.2994 | 0.0519 |
| | | | | | | | **Total** | **1.6209** | **5.3558** |



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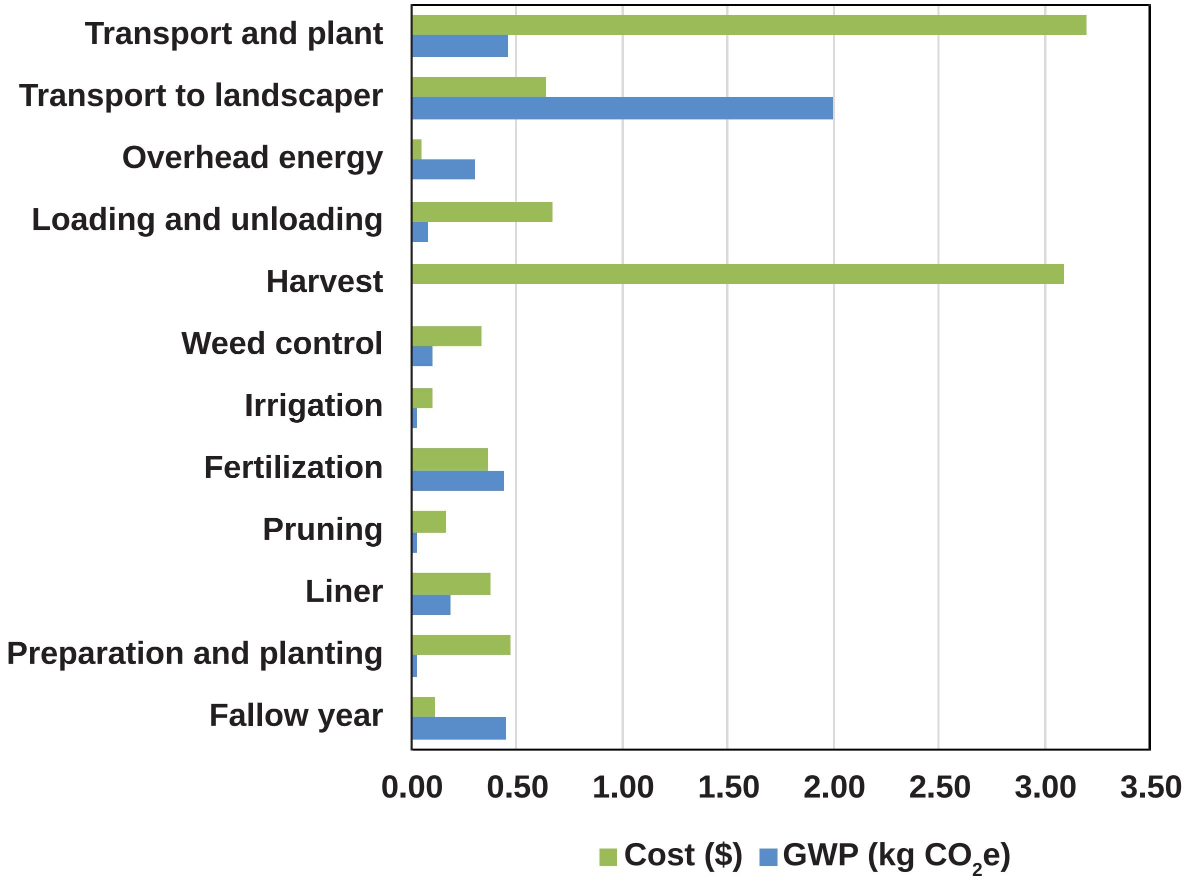


**Fig. 1. Contribution of activities, including material inputs, equipment use and labor, on the propagation-to-landscape global warming potential (GWP) and variable costs of Juddi viburnum.**

$CO_2$e) in the field production phase accounted for 48% of the GHG emission investments during production. Input materials and equipment use in the fallow year before the field production phase accounted for 27% (0.443 kg $CO_2$e) of the GWP. The liner was 12% of the propagation-to-gate GWP. Equipment use and herbicides for weed control contributed 0.097 kg $CO_2$e (6%) to the GWP and $0.15 to the costs. Shrub loading in the field, transport to the loading area and loading on a trailer contributed 0.079 kg $CO_2$e and added $0.67 to the cost, including labor. Labor accounted for $4.15 (77%) of total field nursery production costs.

Post-production activities in the model included transporting the shrub to a landscape company, transport and transplanting the shrub by the landscaper and the removal of the shrub following a 50 year useful life. Transport of the shrub 193 km (119 mi) to the landscape company would result in GHG emissions of 1.993 kg $CO_2$e and cost $0.64, including labor. Transporting to the landscape site and transplanting would add 0.457 kg $CO_2$e to the GWP and cost $3.19. It is estimated that the cost to remove and dispose of the shrub after 50 years would be $9.06, including labor ($5.64) and equipment use ($3.42), and would result in emission of 1.149 kg $CO_2$e.

The relative contribution of products and activities to the propagation-to-landscape GWP and costs for the Juddi viburnum are shown in Fig. 1. Local transporting and transplanting the shrub resulted in 60% of the GHG emissions and cost more (33% of the total) than any other operation. Harvesting accounted for another 33% of costs. The fallow year, fertilization and overhead energy contributed the next higher amounts of emissions. The GWP and costs for activities were not closely related, but was closely related for redbud production where the costs and GWP were dominated by equipment use (Hall and Ingram 2014, Ingram and Hall 2013). Viburnum propagation-to-landscape costs would be dominated by labor requirements (77%) compared to the spade-dug redbud tree (44%) primarily because the shrub would be hand dug. Due to less equipment use in field production of this shrub compared to tree production and the subsequent smaller GWP, the input materials had a proportionally greater impact on the GWP than in tree production. The lighter weight and small size of the shrub also resulted in less GWP of transportation to the customer and planting in the landscape.

The estimated sequestration of $CO_2$ during production would result in the reduction of the life-cycle GWP of the shrub over the assessment period by 0.916 kg $CO_2$e. The weighted $CO_2$ sequestered during the use phase in the landscape would be 15.6 kg $CO_2$e, or 22 times greater than the nursery gate GWP and 20 times greater than the GWP incurred up to the point where the shrub was transplanted in the landscape. An estimated 1.15 kg $CO_2$e would have been emitted during end-of-life removal and disposal.

Using the model developed in this LCA study, alternatives to the input materials and processes assumed in the model can be assessed as to their impact. Such an analysis



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would logically focus first on the major contributors, in this case, transportation activities. If the assumed distance for travel by the landscaper was increased from 32 km to 48 km (20 mi to 30 mi) the shrub propagation-to-landscape GWP would increase by 0.15 kg $CO_2$e or 5%. If the 300 plants were transported to the landscaper instead of 250 per load, the propagation-to-landscape GWP would decrease by 0.318 kg $CO_2$e or 10% and variable costs by $0.10.

These findings are consistent with previous studies in that the GWP is positive when considering the entire life cycle of the shrub from propagation to eventual removal from the landscape. Since the potential environmental impact of products is increasingly being considered in the purchasing decision of an increasing portion of the consuming public (Hall et al. 2010, Yue et al., 2011, Yue et al. 2010), these data become valuable information for them to consider as part of the purchasing decision. Often, they lack reliable, reproducible and easily understood information to guide those decisions. The data contained herein help overcome that void.

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