Carbon Footprint and Related Production Costs of System Components of a Field-Grown *Cercis canadensis* L. 'Forest Pansy' Using Life Cycle Assessment[1]

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Abstract

Life cycle assessment (LCA) was utilized to analyze the global warming potential (GWP), or carbon footprint, and associated costs of the production components of a field-grown, spade-dug, 5 cm (2 in) caliper *Cercis canadensis* 'Forest Pansy' in the Lower Midwest, U.S. A model production system was determined from interviews of nursery managers in the region. Input materials, equipment use and labor were inventoried for each production system component using international standards of LCA. The seed-to-landscape GWP, expressed in kilograms of carbon dioxide emission equivalent (CO_2e), was determined to be 13.707. Equipment use constituted the majority (63%) of net CO_2-e emissions during production, transport to the customer, and transplanting in the landscape.

The model was queried to determine the possible impact of production system modifications on carbon footprint and costs to aid managers in examining their production system. Carbon sequestration of a redbud growing in the landscape over its 40 year life, weighted proportionally for a 100 year assessment period, was calculated to be –165 kg CO_2e. The take-down and disposal activities following its useful life would result in the emission of 88.44 kg CO_2e. The life-cycle GWP of the described redbud tree, including GHG emissions during production, transport, transplanting, take down and disposal would be –63 kg CO_2e. Total variable costs associated with the labor, materials, and equipment use incurred in the model system were \$0.069, \$2.88, and \$34.81 for the seedling, liner, and field production stages, respectively. An additional \$18.83 was needed for transport to the landscape and planting in the landscape and after the 40 year productive life of the tree in the landscape, another \$60.86 was needed for take-down and disposal activities.

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

Species used in this study: redbud (*Cercis canadensis* 'Forest Pansy').

Significance to the Nursery Industry

Knowing the carbon footprint of production and distribution components of field-grown trees will help nursery managers understand their system and evaluation potential modifications to reduce GHG emissions and costs. During their useful life, trees have significant, positive impact on atmospheric GHG and these data can be used to communicate to the consuming public the value of trees in their landscape, along with producers' efforts to minimize GHG emissions during production.

Introduction

The environment is impacted by the production, distribution and use of products. One measure of that impact is global warming potential (GWP), which relates to greenhouse gas emissions (GHG) throughout the life cycle of individual products. GHGs, primarily CO_2, N_2O and CH_4, are expressed in relation to the GWP potential of CO_2 in a standard 100 year assessment period (3, 9). The GWP of CO_2 is set as 1. The GWP of products or services is often referred to as their carbon footprint. Therefore, the carbon footprint is expressed in kilograms CO_2 equivalent (CO_2e). Consumption of fossil fuels is a major contributor to the increase in atmospheric CO_2 concentration (9). Nursery-produced trees have a carbon footprint. However, comprehensive information on such environmental impacts of nursery crops in lacking and will be an important expression of sustainability for the industry (13, 17).

Reliable, reproducible, research-based information is required by nursery managers and the consuming public in a time of unfounded claims and lack of standardized labels relative to product environmental impact. However, the marketplace is placing increased importance on environmental impact of products even when those impacts are broadly defined (5, 28, 29).

The scientific community has developed and continues to refine international standards for defining environmental impacts and the tools for assessing them. One such tool, life cycle assessment (LCA), is a systematic process of accounting for environmental impacts of interrelated input components and processes of a product during its life cycle (1). LCA protocols are governed by international standards (10). The three primary life phases of a product include the production, use and post-life phases. However, the boundaries of a LCA may include the complete life cycle, cradle-to-grave, or something less that a complete life cycle, such as cradle-to-gate.

LCA has been used to determine the propagation-to-landscape carbon footprint of red maple and Colorado blue spruce. Ingram reported that the propagation-to-landscape carbon footprint of 5 cm (2 in) caliper, spade-dug red maple and Colorado blue spruce to be 8.2 kg CO_2e (6) and 13.6 kg CO_2e (7), respectively. Kendall and McPherson (11) reported that 4.6 and 15.3 kg CO_2e were emitted in the production and distribution of container-grown trees in #5 and #9 containers, respectively. Ingram accounted for carbon sequestration during production and Kendall and McPherson did not.

The cost of individual components of production systems and the impact of potential changes in those components on cost is also important to nursery managers. Understanding

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costs and how they are distributed within the overall business enterprise enables growers to improve the efficiency of management and production practices.

Nursery production system protocols vary greatly between regions, plant products and individual nurseries. To systematically assess the GWP of the production system components for a range of nursery crops throughout their life cycle, redbud (*Cercis canadensis*) was chosen as a representative flowering tree. There are significant differences in the growth habit among redbud cultivars, and 'Forest Pansy' was chosen for this study as it is propagated via chip budding and is a popular cultivar.

Methods and Materials

The functional unit for this LCA study was a field-grown, 5 cm (2 in) caliper *Cercis canadensis* 'Forest Pansy' in the Lower Midwest. There is significant variation in production system protocols in the region but a model system was described following interviews with several nursery managers. The model production system in this study would include seedling production in a specialized nursery using in-row, field production encompassing one growing season. Seed would be purchased from a nearby collector. The field would be planted with a cover crop during a fallow year every fourth year then prepared for sowing of redbud seed. The resulting seedlings from the first nursery would be transported 48 km (30 mi) to a second nursery that would grow the plants in rows on 20 cm (8 in) centers in the spring. 'Forest Pansy' buds would be chip-budded onto the seedlings in August. Plants would be staked and trained throughout that growing season before a December to February harvest after the second growing season. The resulting 1.5–1.8 m (5–6 ft), lightly-branched, bare root liners would be shipped 402 km (250 mi) to a third nursery where they would be transplanted in the field in March or April following a fallow year with a cover crop. After three growing seasons, the trees would be harvested as a 5 cm (2 in) caliper, spade-dug finished product. The tree would be shipped an average of 386 km (240 mi), 120 trees per tractor-trailer transporter, and transplanted into a favorable landscape site.

This LCA study followed published standards of the International Organization for Standardization [ISO (Geneva, Switzerland)] (10), and PAS 2050 guidelines by BSI British Standards (3). Equipment use and input products were inventoried and their individual GHG emissions were determined, converted to kg CO_2e per functional unit and summed. 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 (3). 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 and equipment use in seedling production. Material and equipment use and variable costs for seedling production were inventoried based on the described model system. Land would be fallowed every fourth year with a cover crop, sudex (*Sorghum bicolor* (L.) Moench × *S. sudanense* (P.) Staph.). Land preparation included plowing, applying agricultural lime and disking before seeding. The sudex would be mowed twice during the summer and turned under the fall of the fallow year. Redbud seed purchased from a local collector would result in insignificant GHG emissions. Growers expect 30,865 live seed per kg (14,000 per lb) and at least 85% germination. Seed would be scarified with sulfuric acid (14 liters per ha; 1.5 gal per A) before sowing in April. Sawdust was used to cover the seed at a rate of 151 m^3 per hectare (8 yd^3 per A). The soil would be rototilled before sowing. Rows 1.1 m (42 in) apart would be laid off with a tractor and the seed sown by hand at a rate of 1.2 M per ha (492,000 per A). Following germination and early seedling growth, 684 kg per ha (600 lbs per A) of 13N-5.7P-10.8K (13-13-13) fertilizer would be banded using a tractor and side dresser. Herbicides, Surflan (oxyzalin) and Baracade (prodiamine), would be applied 4 times as a tank mix at recommended rates. The field would be cultivated seven times with a small cultivation tractor. Drip irrigation using a T-tape system with a 5-hp electric pump would be applied 48 times. Seedlings would be harvested in the fall and winter using a tractor and band digger. Dug seedlings would be picked-up by hand, stored in a barn until graded and sorted by hand and prepared for shipment. An average lot of 20,000 seedlings would be transported 48 km (30 mi) from the seedling nursery to the liner nursery in a pickup truck. Energy use (electricity and gasoline) not assigned to a specific operation was inventoried and the associated GHG emissions were designed as overhead and apportioned to each marketable seedling.

Input materials and equipment use in liner production. Material and equipment use and variable costs for liner production were inventoried based on the described model system. A fallow year would occur after two, 2-yr crop cycles as described above. Following disking, seedlings would be transplanted in early spring using a tractor with transplanter and a crew of five at a 20 cm (8 in) in-row spacing in rows 1.8 m (6 ft) apart (25,700 per ha; 10,400 per A). Most liner nurseries sow a cover crop between rows. The seedling transplants would be cultivated 3 times. This study assumed that crimson clover (*Trifolium incarnatum*) would be sown 182 $kg{\cdot}ha^{-1}$ (160 $lbs{\cdot}A^{-1}$) in the summer following transplanting and mowed once. The rows would be hoed twice per year. Bud wood of 'Forest Pansy' would be taken from nursery trees and chip budded to the seedlings in August by a contractor. The production model assumed a budding success rate of 70% but the unsuccessful ones would be re-budded the following spring with a 70% success rate. The original shoot would be removed. A fiberglass stake would be inserted by each plant and plants trained and taped to the stake periodically. Fertilizer would be applied three times per year at a 114 kg N per ha (100 lbs $N{\cdot}A^{-1}$) rate with 13N-5.7P-10.8K (13-13-13) using a tractor and side dresser. Irrigation would be provided 24 times using drip irrigation through a T-tape system powered by a 5-hp electric pump covering 2 ha (5 A) at a time. Orthene (acephate) and Tempo (cyfluthrin) would be applied three times each at recommended rates with an air-blast sprayer. Surflan would be banded in the row twice per year and either tank mixed with Baracade or Gallery (isoxaben) at recommended rates using a tractor and boom sprayer. Stakes would be removed before harvesting the liners following the second growing season using a tractor and shaker/digger. The liners would be transported to a barn for grading and stored. Liners would be transported to field nurseries an average of 402 km (250 mi) in a tractor/trailer. The impact of overhead energy use was apportioned as previous described.

Input materials and equipment use in field nursery production. Material and equipment use and variable costs for field production of the finished tree were inventoried based on the described model system. Following a fallow year with sudex as described above, the field would be disked twice and tilled once before transplanting 1.5–1.8 m (5–6 ft), lightly branched liners on a 1.8 m (6 ft) spacing in rows 3 m (10 ft) apart using a tractor and transplanter. It would take a 4-person crew 1 hr to plant an acre (2.5 hrs per ha). Fescue (*Festuca arundinacea*) would be sown between rows, leaving 0.9 m (3 ft) clear in each row. Middles would be mowed four times per year. In-row cultivation would be performed four times during the field production phase. Although some nurseries do not stake 'Forest Pansy', a 1.8 m (6 ft) bamboo sake inserted by each plant was assumed and plants were pruned and trained periodically (8 hrs per ha; 20 hrs per A). Irrigation would be provided by a traveling gun three times over the production cycle. Fertilizer (15N-6.6P-12.4K; 15-15-15) would be banded in rows with a tractor and side dresser at 85.5 kg N per ha per yr (75 lbs N per A per yr). In-row cultivation was performed annually. Herbicide applications would include Surflan and Goal (oxyfluorfen) tank mixed and applied annually within row with a tractor with boom sprayer. Roundup (glyphosate) would be banded in-row once per yr with a hooded sprayer on a tractor. Discus (cyflurthin) would be applied once and Bifendrin 7.9 (bifendrin) was applied twice at recommended rates for insect control. Plants would be irrigated four times over the three years by a traveling gun. Following three growing seasons, trees would be dug with a tree spade mounted on a skid steer, inserted in a burlap-lined wire basket, transported to the shipping area using a skid steer with articulating arm and tractor with wagon. Culls (10% of planted) would be removed with a skid steer with forks and tractor/wagon. The impact of overhead energy use was apportioned as previous described.

Assumptions for equipment use. The activities of motorized equipment described in the model were assumed as follows. Tractor horse power (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 and mowing fallow land, 80 hp tractor at 0.85 throttle and 0.85 load; spraying and spreading in-row 24 hp tractor at 0.50 throttle and 0.50 load; air blast sprayer, 40 hp at 0.85 throttle and 0.85 load; mowing row middles and cultivating, 24 hp tractor at 0.85 throttle and 0.85 load; transporting seeding, liners and harvested trees on the farm, 40 hp tractor at 0.50 throttle and 0.50 load; liner harvesting, 80 hp tractor at 1.0 throttle and 0.85 load; and harvesting finished trees, 75 hp skid steer with tree space or forks at 1.0 throttle and 0.85 load. The traveling irrigation gun was powered by a PTO driven pump and 80 hp tractor at 1.0 throttle and 0.85 load. The 120 hp chipper was assumed to consume diesel at the rate of a 120 hp tractor at 1.0 throttle and 0.85 load. The 5 hp electric irrigation pump was assumed to require 3.73 kWh.

Assumptions in post-harvest activities. It was assumed that the finished product would be transported to a landscaper 386 km (240 mi) away, 120 trees per heavy truck, although some product would possibly be shipped shorter distances in smaller quantities for more local sales. It was assumed that the tree would be transported 34 km (20 mi) to the planting site along with nine other trees, unloaded and set in place with a tractor with frontend loader (5 min) and transplanted by hand (1 man-hr). Following 40 years of useful life, the tree would be removed by a two-man crew working 2.5 hrs using a heavy truck traveling 38.6 km (24 mi), a chain saw (1 hr) and a 120 hp chipper (0.5 hr). The resulting chipped tree would be utilized as mulch.

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

Cost calculations. The entire production system for redbud production was modeled using an economic engineering approach. It is important to note that only variable costs of each cultural practice (activity) were included in the analysis. Facilities may vary significantly among successful operations in the industry; therefore corresponding fixed costs also vary accordingly. Because of this, fixed costs associated with land, buildings, and other structures were not included in the analysis.

For each activity, the amount of labor it took to perform the activity was tracked, as was the amount of time machinery and equipment was operated and the amount of materials that were used (e.g. fertilizers, pesticides, etc.). The Adverse Effect Wage Rate (AEWR) of \$10.81 was used, which is the average minimum wage that the U.S. Department of Labor (23) has determined for the states included in the Lower Midwest region. 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 (16). Costs of materials were valued at 2012 prices 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 \$3.63 per gallon (\$13.74/liter) represented the U.S. average as reported by the Energy Information Administration (24).

Inventory analysis and data collection. The GWP of manufacturing and transporting fertilizer was calculated by Snyder (2009) from the U.S. Dept of Energy's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model, GREET 1.8a (23), and reported by Ingram (7) to be 3.2, 1.0, 0.7 and 0.6 kg $CO_2e{\cdot}kg^{-1}$ for N (from urea), P_2O_5, K_2O and lime, respectively. Although highly variable and assuming a loss of 1% of N applied as N_2O from soils, the additional GWP was calculated to be 4.65 kg $CO_2e{\cdot}kg^{-1}$ of N applied, (8, 19).

Lal (12) reported a mean reported C emission from the production, transportation, storage and transfer of agricultural lime to be 0.160 ± 0.11 kg C (0.586 kg CO_2e), indicating the variability of this product and its associated GWP. The average CO_2e emission for a range of herbicides (23.083 kg CO_2e) and insecticides (18.687 kg CO_2e), and specifically for glyphosate (33.342 kg CO_2e), were calculated from data presented by Lal (12).

West and Marland (27) reported a carbon footprint of 1.11, 0.54 and 1.72 kg $C{\cdot}kg^{-1}$ for orchardgrass, ryegrass and red clover seed. The kg C in their paper was converted to 6.302 kg CO_2e for red clover. In the absence of data specific for sudex and fescue seed, the carbon footprint for orchardgrass (4.07 kg $CO_2e \cdot kg^{-1}$) was used for these seed. The CO_2e emissions from producing sulfuric acid was assumed to be 0.00264 kg $CO_2e \cdot kg^{-1}$ (21) and emissions lost during the use would be minimal, assuming complete reaction with organic material and subsequent percipient formation. The GWP of the wire basket was assumed to be 1.2927 kg $CO_2e \cdot kg^{-1}$ (6). The GWP for the small amount of burlap and nylon twine was not readily available and considered to have negligible impact. The GWP of sawdust was assumed to be 0.0119 kg $CO_2e \cdot kg^{-1}$ (21) plus kg CO_2e for transporting it 40 km (25 mi) from the sawmill in a heavy truck at 13.8 m^3 (18 yd^3) per load.

GWP for machinery and truck use in each operation was estimated from fuel consumption calculations. Tractor diesel use was estimated using published standards based on horse power, throttle and load for each operation (4) as previously reported (6, 7). Diesel use rates of 2.5 and 4.2 $km \cdot liter^{-1}$ (6 and 10 mpg) were assumed for heavy trucks and light trucks, respectively. The GWP factors for fuel consumption were determined based on 'well-to-wheel' emission reported in GREET1_2011 (24) as 2.9339 kg $CO_2e \cdot liter^{-1}$ for gasoline and 3.0153 kg $CO_2e \cdot liter^{-1}$ for diesel. The GWP of fluids used by tractors and trucks were calculated using GREET2_7 (2) as previously reported (7). The fuel consumption for the 5 hp gasoline-powered irrigation pump was assumed to be 1.9 $liters \cdot hr^{-1}$ (0.5 $gal \cdot hr^{-1}$). The GWP of electricity was assumed to be 0.67 $CO_2e \cdot kWh$ (18).

Carbon sequestered during production was estimated by washing, drying and weighing four finished trees. Fifty-percent of the tree dry weight was assumed to be carbon and each kg of carbon would have resulted from the uptake of 3.664 kg CO_2 (14).

Unlike most products, even agricultural products, trees continue to sequester carbon during their use phase and the amount of carbon sequestered annually follows a species-specific growth model (14). The annual sequestration of redbud grown in a suitable Lower Midwest USA landscape for 40 years was estimated using the U.S. Forest Service's Center for Urban Forestry Research (CUFR) Tree Carbon Calculator calculation method (20). Because the 40 yr tree life assumed for redbud was shorter than the 100 year assessment period, the impact of the sequestered carbon was weighted for the portion of the 100 years that it would have been sequestered from the atmosphere using protocols from PAS 2050 (3).

Results and Discussion

The estimated seed-to-landscape carbon footprint of a 5 cm caliper 'Forest Pansy' redbud in the Lower Midwest U.S. was 13.707 kg CO_2e, including carbon sequestration during production of 10.539 kg CO_2. The carbon footprint at the farm gate was estimated to be 6.61 kg CO_2e. In the assumed model production system, 17.152 kg CO_2e were emitted during production, while transport to the customer (3.891 kg CO_2e), and transporting and transplanting in the landscape (3.203 kg CO_2e) would result in an additional 7.094 kg CO_2e emissions. These emissions were similar to that reported for Colorado blue spruce (7) but were higher than values published for red maple (6). Some of the differences between the red maple values and those for the spruce and redbud can be explained

Table 1. Input material contributions to the global warming potential (GWP) in carbon dioxide equivalents (CO_2e) of redbud seedling and liner production.

Input material	Product·ha⁻¹ (kg)	Product per marketable seedling or liner (kg)	GWP (kg $CO_2e \cdot kg^{-1}$)	GWP per marketable seedling or liner (kg CO_2e)
Seedling production				
Sudex - fallow yr	15	0.000014	4.0670	0.0000588
Ag lime	760	0.000723	0.5862	0.0004239
Sulfuric acid	10	0.000045	0.0026	0.0000001
Sawdust to cover seed	8865	0.008434	0.0137	0.0001157
Fertilizer (13-13-13)	684	0.000651	1.2420	0.0008083
Irrigation; T-tape and lay-flat	118	0.000112	1.5000	0.0001682
Liner production				
Sudex - fallow year	23	0.001163	4.0670	0.0047301
Crimson clover seed	182	0.009304	6.3020	0.0586364
Fiberglass stakes (cnt.)	25,699	0.015876	2.0646	0.0327769
Irrigation; T-tape and lay-flat	64	0.003529	1.5600	0.0055048
Fertilizer (13-13-13)	684	0.034892	1.2420	0.0433353
Input material	**Product·ha⁻¹ (kg)**	**Active ingredient (a.i.) per marketable seedling or liner (kg)**	**GWP (kg $CO_2e \cdot kg^{-1}$)**	**GWP per marketable seedling or liner (kg CO_2e)**
Seedling production				
Surflan	22.8	0.000009	23.0832	0.0002023
Baracade	7.5	0.000003	23.0832	0.0000669
Liner production				
Orthene	0.6	0.000028	18.6864	0.0005292
Tempo	4.3	0.000026	18.6864	0.0004869
Suflan	11.3	0.000233	23.0832	0.0053689
Baracade	1.2	0.000041	23.0832	0.0009448
Gallery	0.8	0.000029	23.0832	0.0006645

by the fact that a more inclusive GWP for fuel (well-to-wheel emissions vs emissions only from combustion) was used in the latter two LCAs (22, 25). The production system for the spruce was a year longer in the liner phase and two years longer in the field production phase compared to the redbud and the redbud was estimated to have sequestered slightly more carbon during production.

GHG emissions associated with a liner, including seedling and liner production, contributed only 3% (0.535 kg CO_2e) of total emissions invested in the finished product at the gate (17.152 kg CO_2e). Seedling production, including its transport to the liner nursery, accounted for only 1.6% of liner GWP. The GWP of crimson clover seed, fertilizer and stakes were notable among materials used during liner production contributors (Table 1). Other input materials, including pesticides, contributed little to the liner GWP. Equipment use contributed 19% of the liner GWP. Equipment use per seedling produced was minor due to the high population density in seedling production (Table 2). Overhead energy use and transport of the liner to the field nursery were notable contributors.

GHG emissions from input materials during the field production of the finished product contributed 3.654 kg CO_2e, including the 0.675 kg CO_2e from the liner (Table 3). Of the total input material GWP, pesticides contributed 0.135 kg CO_2e or 3.7% with fertilizer and agricultural lime (52%) and the wire basket (23%) being the major contributors to input material GWP. Equipment use accounted for 71% (12.195 kg CO_2e) of the GWP during field production (Table 4). Overhead electricity and gasoline contributed 7.6% of total GWP in the field nursery. Operations involving the larger equipment for longer use times per tree occurred during harvesting, accounting for emission of 10.0 kg CO_2e with cull removal contributing an additional 0.469 kg CO_2e.

Table 2. Contributions of equipment use and energy overhead to the global warming potential (GWP) in carbon dioxide equivalents (CO_2e) of redbud seedling and liner production.

Equipment use	hrs·ha^{-1}	hrs per marketable seedling or liner	fuel per marketable seedling or liner (L)	GWP per marketable seedling or liner (kg CO_2)
Seeding production				
Chisel plow	0.82	0.000001	0.000012	0.0000377
Disk	0.41	0.000000	0.000006	0.0000189
Ag lime	0.41	0.000000	0.000006	0.0000189
Seeding sudex	1.07	0.000001	0.000016	0.0000490
Mowing	0.82	0.000001	0.000012	0.0000377
Turning plow	0.82	0.000001	0.000012	0.0000377
Disk	1.24	0.000001	0.000019	0.0000566
Rototill	1.85	0.000002	0.000028	0.0000849
Layoff rows	0.74	0.000001	0.000003	0.0000102
Sawdust to cover seed	2.47	0.000002	0.000040	0.0001222
Irrigation	47.44	0.000046	0.000648	0.0001147
Fertilizer application	16.89	0.000016	0.000041	0.0001241
Apply herbicide	1.24	0.000001	0.000003	0.0000136
Cultivate	11.53	0.000011	0.000052	0.0001590
Harvesting	2.47	0.000002	0.000010	0.0000301
Transport to barn	16.89	0.000016	0.000068	0.0002059
Transport to nursery#2		0.000050	0.001136	0.0034524
Overhead electricity (kWh)	800		0.001913	0.0012817
Overhead gasoline			0.000226	0.0006639
Liner production				
Chisel plow	2.47	0.000128	0.002009	0.0060675
Disk	1.24	0.000064	0.001004	0.0030337
Seeding sudex	1.54	0.000080	0.001256	0.0037922
Mow	1.24	0.000064	0.001004	0.0030337
Plow	2.47	0.000128	0.002009	0.0060675
Disk	2.47	0.000128	0.002009	0.0060675
Rototilling	2.47	0.000128	0.002009	0.0060675
Transplanting	7.91	0.000410	0.001022	0.0031147
Sowing clover	1.85	0.000096	0.000240	0.0007300
Mow middles	1.65	0.000085	0.000402	0.0012181
Remove seedling shoot	1.24	0.000064	0.000266	0.0008078
Staking	9.88	0.000513	0.001278	0.0038934
Cultivate	6.92	0.000359	0.000895	0.0027254
Irrigate	23.72	0.001231	0.017425	0.0030841
Apply insecticide	2.47	0.000256	0.001065	0.0064426
Apply fertilizer	2.47	0.000385	0.001065	0.0029200
Applied herbicide	7.41	0.000547	0.000959	0.0041530
Mowing roadways	10.54	0.000005	0.001363	0.0001215
Removing stakes	0.10	0.000423	0.000040	0.0053315
Harvest - shaker/digger	8.15	0.000513	0.001757	0.0262112
Transport to barn	9.88	0.000272	0.008680	0.0034332
Transport to field nursery			0.001132	0.1198764
Overhead electricity (kWh)	1384		0.177515	0.1189349
Overhead gasoline	25		0.012133	0.0365833

Table 3. **Input material contributions to the global warming potential (GWP) in carbon dioxide equivalents (CO_2e) of field production of a 5 cm (2 in) caliper, spade-dug redbud tree.**

Input material	Product·ha^{-1} (kg)	Product per marketable tree (kg)	GWP (kg CO_2e·kg^{-1})	GWP per marketable tree (kg CO_2e)
Sudex seed	46	0.025199	4.0670	0.1024861
Preplant Ag lime	2280	1.259972	0.5862	0.7386461
Fertilizer (15-15-15)	1482	0.818982	1.4325	1.1731916
Bambo stakes	1977	0.244444	0.1818	0.0444400
Fescue in middles	13	0.007087	4.0670	0.0288242
Wire basket (cnt)	1779	0.652000	1.2927	0.8428541
Cardboard trunk protector (cnt)	1779	0.011352	0.4700	0.0053353
Liner (cnt)	1977	1.111111	0.5354	0.5948369
Input material	**Product·ha^{-1} (kg)**	**Active ingredient per marketable tree (kg)**	**GWP (kg CO_2e·kg^{-1})**	**GWP per marketable tree (kg CO_2e)**
Surflan	10.3	0.002291	23.0832	0.0528751
Goal	5.1	0.001145	23.0832	0.0264375
Roundup (glyphosate)	7.7	0.001465	33.3424	0.0488309
Bifendrin	7.7	0.000507	18.6864	0.0063211
Discus	1.3	0.000738	18.6864	0.0000966

When the GWP of input material and equipment use were combined in production system activities for the field nursery, it is obvious that the majority (63%; 10.848 kg CO_2e) of the GHG emissions from the production system occurred at harvest (Fig. 1). Harvesting also contributed $16.46 (47%) of the total variable costs of field production. Other productions system components of note in terms of their contribution to GWP in production include overhead energy use, fertilization and fallow year activities. Harvest functions would then be a primary candidate to evaluate in terms of reducing GWP and cost of the finished product.

Weed control activities, including herbicide application and mowing, accounted for 0.5206 kg CO_2e (3%) and irrigation contributed 4%. Staking, pruning and insect control were minor contributors to GWP. These trends were similar to those published for spruce (7) and red maple (6).

After accounting for all labor, materials, and equipment use, total variable costs incurred in the model system were $0.069, $2.88, and $34.81 for the seedling, liner, and field production stages, respectively. An additional $18.83 was needed for transport to the landscape and planting in the landscape, thus the total variable cost from cutting to land-

Table 4. **Contributions of equipment use and energy overhead to the global warming potential (GWP) of field production of a 5 cm (2 in) caliper, spade-dug redbud tree.**

Equipment use	hrs·ha^{-1}	hrs per marketable tree	fuel per marketable tree (L)	Equipment GWP per marketable tree (kg CO_2e)
Chisel plow	4.94	0.002778	0.043527	0.1314621
Apply Ag lime	2.47	0.000694	0.010882	0.0328655
Seed sudex	1.24	0.001806	0.028293	0.0854504
Plow	3.21	0.001389	0.021764	0.0657311
Disk	2.47	0.002778	0.043527	0.1314622
Rototilling	2.47	0.001042	0.016323	0.0492983
Transport liners to field	1.85	0.000347	0.000865	0.0026362
Transplant liners	0.62	0.001389	0.021764	0.0657311
Sow fescue in middles	2.47	0.000694	0.005441	0.0164597
Stakes to field	1.24	0.000694	0.001731	0.0052723
Irrigation	1.24	0.013333	0.225671	0.6814912
Apply fertilizer (3 yr)	23.72	0.002083	0.005192	0.0158169
Cultivate (4 times in 3 yr)	3.71	0.005556	0.043527	0.1316776
Apply herbicide (3 yr)	9.88	0.005556	0.013845	0.0421784
Apply Glyphosate (3yr)	7.41	0.004167	0.010384	0.0316338
Apply insecticides (3 yr)	7.41	0.000694	0.005441	0.0493791
Mow (3 yr)	3.71	0.000769	0.065291	0.1975164
Digging with tree spade	14.83	0.066700	1.058362	3.1964104
Loading in field	118.61	0.050000	0.734526	2.2186659
Hauling from the field	88.96	0.050000	0.783495	2.3663184
Unloading and loading	88.96	0.050000	0.734526	2.2186659
Removal of culls	88.96	0.009259	0.136023	0.4108641
Haul culls from field	16.47	0.004630	0.019230	0.0583418
Overhead electricity (kWh)	720		1.000000	0.6700000
Overhead gasoline	40		0.055556	0.6341111

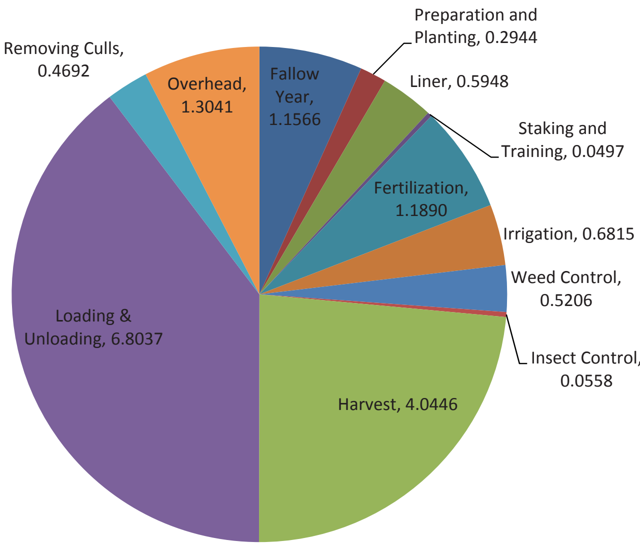

Fig. 1. Contributions of equipment use and input materials to the global warming potential (GWP) in carbon dioxide equivalents (CO_2e) of the production system components (seed-to-nursery gate) for a 5 cm (2 in) caliper, spade-dug redbud.

scape was $56.59. After the productive life of the tree in the landscape (40 years), another $60.86 was expended for take-down and disposal activities.

An important feature of a modeling system using LCA is the ability to query the system for impact of possible production system component modifications. Transporting the finished product 240 miles would result in GHG emissions of 3.831 kg CO_2e and reducing that to 120 miles would reduce the GWP by half (1.92 kg CO_2e) and the variable cost by $2.60 per tree. Clover in the middles for liner production would be expected to reduce the number of cultivations by six and eliminate three sprays of glyphosate. Six cultivations would result in emissions of 0.0054 kg CO_2e and add $0.017 to the variable cost and three glyphosate sprays would result in emission of 0.0317 kg CO_2e and add $0.04 to the variable cost. Sowing and maintaining the clover during the liner production phase would reduce erosion and allow better access during wet weather but would result in GWP of 0.060 kg CO_2e and variable cost of $0.066. Therefore, choosing clover and mowing instead of cultivation and herbicides would result in 0.023 kg CO_2e more emissions and add $0.009 to variable costs. This does not include environmental impact of reduce erosion or possible cost saving by being able to access the field during somewhat wetter conditions.

If 50% more fertilizer was used than the recommended rate, GWP would increase by 0.586 kg CO_2e and add $0.37 would be added to the variable cost of the tree. If the cull rate during the final field production phase would be 20% instead of the assumed 10%, GWP assigned to each marketable tree would increase by 1.528 kg CO_2e and increase the variable cost of each tree by $3.06. At first glance, the increase in GWP might be expected to be higher in this scenario but 63% of GHG emissions occur at harvest and culled trees would not be harvested. Increased cull rate in the seedling and liner production phases would not be as dramatic given the high population density and relatively low GWP of seedlings and liners. Increasing field production time from 3 to 4 yrs would increase the GWP by 1.18 kg CO_2e and the variable costs per tree by $0.75.

The weighted impact on atmospheric GWP during a 100 year assessment period of a redbud tree transplanted into the landscape over its 40 year life was calculated to be –165 kg CO_2e. The take-down and disposal activities following its useful life would result in the emission of 88.44 kg CO_2e. Therefore, the life-cycle GWP of the described redbud tree, including GHG emissions during production and transplanting, would be –63 kg CO_2e. This does not account for long-term storage of carbon from the tree roots left in the soil but should be the objective of additional research (15). There are many factors that could impact the sequestration of carbon during the use phase and the GHG emissions required to maintain the tree in less favorable conditions such as urban environments. The –63 kg CO_2e life-cycle impact is less than estimated for red maple (–800 kg CO_2e) and Colorado blue spruce (–431 kg CO_2e). That would be expected due to the relative sizes of the trees and the shorter life expectancy assumed for redbud.

Management implications. Life cycle assessment is an evolving quantitative tool that has the potential to be used to improve the profitability of green industry firms. The results of previous studies show that LCA can be a valuable means to identify the production steps with the highest environmental impacts during the whole production chain. The results from such a systems analysis can help growers improve the efficiency of their operations. The input costs of production processes (machinery, water, fertilizers, pesticides and energy) are a significant portion of the overall nursery operation costs. Thus, a more efficient use of environmentally sensitive inputs can reduce both the production costs for the nursery as well as the environmental risks or impacts. In this study, LCA has been shown to be an effective tool for nursery growers in understanding the inputs, outputs, and impacts of systems producing field-grown trees. Information gained from this LCA of field-grown ornamental tree production systems will help managers better understand their production system and practices and help them better articulate an improved value proposition for their products in the green industry marketplace.

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