Life Cycle Assessment to Study the Carbon Footprint of System Components for Colorado Blue Spruce Field Production and Use

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ABSTRACT. The contributions of interrelated production system components of a field-grown, 2-m-tall, 5-cm-caliper *Picea pungens* (colorado blue spruce) in the upper midwestern (liner) and lower midwestern (finished tree) regions of the United States to its carbon footprint were analyzed using life cycle assessment protocols. The seed-to-landscape carbon footprint was 13.558 kg carbon dioxide equivalent (CO_2e), including sequestration of 9.14 kg CO_2e during production. The global warming potential (GWP) from equipment use was the dominant contributor to the carbon footprint of production. Seventy-six percent of the GWP investments during field production occurred at harvest. Querying the model, among other things, revealed that adding one year to the field production phase would add less than 3% to the seed-to-landscape GWP of the product. The weighted positive impact of carbon (C) sequestration during a 50-year life was 593 kg CO_2e. After its useful life, takedown and disposal would result in emissions of 148 kg CO_2e, resulting in a net positive, life cycle impact on atmospheric CO_2 of ≈431 kg CO_2e.

The nursery industry is often referred to as part of the green industry. However, research to understand how system components of the production and use of landscape plants contribute to environmental impacts such as global warming potential is lacking and will determine the relative sustainability of nursery crop production (Marble et al., 2011; Prior et al., 2011). Therefore, system-level research is needed to provide reliable, reproducible information for scientists, the industry, and the general public.

Greenhouse gases (GHGs), primarily CO_2, N_2O, and CH_4, are increasing in the atmosphere and human activity is contributing to that, primarily through the use of fossil fuels [BSI British Standards, 2011; International Panel on Climate Change (IPCC), 2007]. The GWP of those gases in a standard 100-year assessment period are expressed in relation to the GWP of CO_2, which is set as 1. Although present in the atmosphere at much smaller concentrations, the GWPs of N_2O and CH_4 are 298 and 23, respectively (BSI British Standards, 2011). The production, distribution, and use of products and services result in emission of GHG and thus a carbon footprint, expressed as the GWP of that product or service in kilograms CO_2 equivalent.

Life cycle assessment (LCA) is a tool used to quantify the environmental impact of products or services. LCA is a systematic process accounting for environmental impacts of interrelated input components and processes of a product or practice during its complete life cycle, cradle to grave (Baumann and Tillman, 2004). LCA usually includes information on the three primary life phases of a product or service: production phase, use phase, and post-life phase. However, boundaries for a LCA may be referred to as cradle to grave or even cradle to gate, but defining what is the cradle and what is the grave or gate of a product or practice is an important issue. Cradle to grave refers to the

impacts of a product during manufacturing, transport, and use but ends with the impact of that product at the end of its useful life through recycling or disposal. Most published LCAs have focused on carbon footprint, but the tool can be used to assess other environmental impacts such as water footprint, toxicity potential, acidification potential, and resource depletion. International standards govern LCA protocols [BSI British Standards, 2011; International Organization for Standardization (ISO), 2006].

LCA has been used to study agriculture and biofuel production systems and their individual components (Debolt et al., 2009; Hayashi et al., 2006; Liebig et al., 2008; Nemecek et al., 2005, 2006; Williams et al., 2006). Nitrogen fertilizers have been identified as an important component of GHG emissions in agriculture as well as stimulating yield increases (Brentrup and Palliere, 2008; Hillier et al., 2009). Plastic greenhouse covers and containers represented a significant portion of the carbon footprint for floral crops in European LCA studies (Russo et al., 2008; Russo and Mugnozza, 2005; Russo and Zeller, 2008). LCA studies in Europe with forest tree seedling production have shown greenhouse heating and seedling transportation (Aldentun, 2002) and production and disposal of plastics (Cambria and Pierangeli, 2011) to be major GHG emission sources in those systems.

The cutting-to-landscape carbon footprint of a 5-cm-caliper, field-grown, spade-dug *Acer rubrum* (red maple) was calculated to be 8.2 kg CO_2e (Ingram, 2012). Unlike most products, plants take CO_2 from the atmosphere and sequester C to varying degrees in wood (U.S. Department of Energy, 1998). Trees sequester more C than shrubs and large trees sequester more C than small trees. Residential trees also provide other environmental services (McPherson and Simpson, 1999). Kendall and McPherson (2012) reported that 4.6 and 15.3 kg CO_2e were emitted in the production and distribution of trees grown in #5 and #9 containers, respectively. Their work modeled an intensive container nursery in California and did not include the impact of sequestered C during production.

Individual components of production systems result in GHG emissions to varying degrees. Ingram (2012) reported that a significant contributor to GHG emissions in the field production of red maple was fuel consumption by farm machinery and truck transport of the finished product. That report also estimated the impact of altering certain production system protocols to reduce GHG emissions. GHG emissions have been estimated for various other agricultural production systems (Lal, 2004; West and Marland, 2002a, 2002b).

The purpose of this study was to use LCA to determine the carbon footprint of a 2-m-tall, field-grown, spade-dug *Picea pungens* (colorado blue spruce) in the lower midwestern and upper midwestern United States (hardiness zones 6a to 7a) and to analyze the contributions of system components. The scope included the production system from seed to the farm gate and from the farm gate to transplanting in a landscape site. The impact of the use phase and end-of-life phase was also assessed.

Methods and Materials

The functional unit was defined as a field-grown, spade-dug colorado blue spruce with a height of 2 m, caliper of 5 cm, and a 61-cm-diameter soil/root ball with 5.0 kg plant dry weight. Production and transport protocols for evergreen trees vary widely among nurseries; therefore, a detailed model system was described following interviews with nursery managers in the region. The boundaries for this LCA include a liner produced in a nursery in the upper midwestern United States specializing in propagation and shipped to a field nursery in the lower midwestern United States for production of the finished product (Fig. 1). Seeds would be germinated in ground beds and grown for two years before transplanting them to the field for an

additional two years in the propagation nursery to produce a 50- to 60-cm-tall liner referred to as a "2 + 2 liner" in the industry. That liner would be transported to a field nursery where it would be transplanted on 1.8-m in-row spacing in rows 2.4 m apart (2224 plants/ha). The tree would be grown for five years and harvested as a 2-m-tall tree using a tree spade mounted on a skid-steer loader. The tree would be transported to a landscape contractor who would transplant it in a suburban site with favorable soil, light, and space conditions. Nowak et al.'s (2002) tree management model reported colorado blue spruce as a long-lived tree with moderate growth rate, based on Fleming (1988) and Nowak (1994), and used a 60-year life span in the landscape. However, conversations with landscape managers indicate a shorter life expectancy. Therefore, it was assumed in this LCA that the tree would live for 50 years at which time it would be removed and chipped into mulch material.

This study was conducted in accordance with the ISO (2006) published standard, and PAS 2050 guidelines by BSI British Standards (2011). The products and equipment used were inventoried and their individual GHG emissions were determined, converted to kilograms CO_2e per functional unit, and summed. Emissions associated with the manufacturing of capital goods such as buildings and machinery were not included in this study as per PAS 2050, Section 6.4.4 (BSI British Standards, 2011). Labor was assumed to have no direct impact on the carbon footprint of a product. It was assumed that the farms have been in agricultural production for at least 50 years and in nursery production for at least 20 years; therefore, impact of land use change was not included in this study as per PAS 2050.

INPUT MATERIALS AND EQUIPMENT USE IN LINER PRODUCTION. The materials (Table 1) and equipment use (Table 2) for liner production were inventoried based on the model system. Seeds would be collected from a mature stand of uniform trees. Because each cone would yield 350 to 400 seeds, the GWP impact of seed production was determined to be insignificant and not included. The field plot in sandy loam soil would remain fallow for one year with a cover crop of oilseed radish (*Raphanus sativus*) after chisel plowing and disking. The cover crop would be plowed under in the fall. In the next spring, agricultural lime and potassium as KCl would be applied as per a soil test assumed in this study to be 2242 and 373 kg·ha^{-1}, respectively. The entire plot would be disked and fumigated with methyl bromide (MeBr) applied the next spring using soil injection and covered with a 0.024-mm-thick, clear, polyethylene tarp. It should be noted that the use of MeBr is being phased out and is governed by critical-use permits for forest nursery seedling production in several states and has other environmental impact such as oxygen depletion [U.S. Environmental Protection Agency (USEPA), 2012].

Raised beds, 1.1 m wide, would be shaped between 0.7-m aisles. Seeds would be sown at the rate to yield 215 seedlings/m^2 in beds 182 m long (200 m^2/bed, 30 beds/ha). Seeds and subsequent seedlings would be irrigated up to 1 h daily through stationary pipe with a 44.7-kW, diesel-powered pump, irrigating 1.6 ha at a time. Beds would be fertilized with 19N–0P–5.0K using ammonium sulfate as the nitrogen (N) source at the rate of 224 kg·ha^{-1} N per year split into 12 applications during the summer months each year of the seedling production phase. Pesticides would be applied according to the label. A pre-emergent herbicide, oxyfluorfen (Goal; Dow AgroSciences,
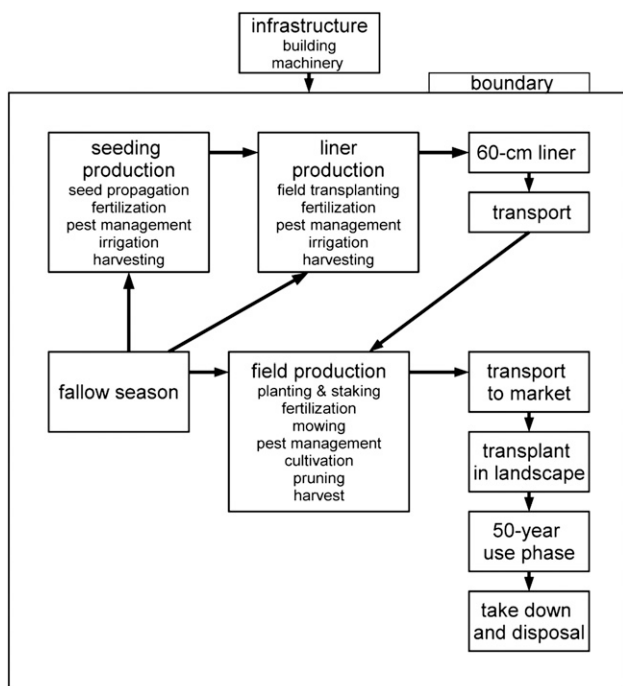

Fig. 1. Input products and process flow diagram and system boundaries for the life cycle of a field-grown, spade-dug, 5-cm-caliper colorado blue spruce in the lower midwestern United States (liner) and upper midwestern United States (finished tree).

Table 1. Contribution of material inputs to the carbon footprint [global warming potential (GWP) in kilograms CO_2 equivalent (CO_2e)] for a 60-cm-tall (2 + 2) colorado blue spruce liner.

Input material	Product (kg·ha^{-1})	Product per marketable liner (g)	Product GWP [CO_2e (kg·kg^{-1})]	GWP per marketable liner (kg CO_2e)
Seedling production				
Oilseed radish	16.81	0.006	1.8300	0.000010
Ag lime ($CaCO_3$)	2241.72	0.725	0.5900	0.000425
Pre-plant K as KCl	186.06	0.060	0.8400	0.000051
Polyethylene film	233.81	0.079	1.5000	0.000118
N as $(NH_4)_2SO_4$	273.94	0.091	7.8500	0.000711
K as KCl	71.62	0.024	0.8400	0.000020
Transplant production				
Oilseed radish	16.81	0.059	1.8300	0.000108
Ag lime ($CaCO_3$)	2241.72	7.560	0.5900	0.004432
Pre-plant K as KCl	186.06	0.060	0.8400	0.000529
N as $(NH_4)_2SO_4$	273.94	0.709	7.8500	0.005564
K as KCl	53.72	0.186	0.8400	0.000157

Input material	Product (kg·ha^{-1})	Active ingredient per marketable liner (g)	Product GWP [CO_2e (kg·kg^{-1} a.i.)]	GWP per marketable liner (kg CO_2e)
Seedling production				
Methyl bromide	392.30	0.1322	1.8530	0.000245
Oxyfluorfen	5.60	0.0004	23.0832	0.000009
Chlorothalonil	24.65	0.0067	14.2896	0.000096
Imidacloprid	0.88	0.0002	18.6864	0.000003
Transplant production				
Chlorothalonil	24.65	0.0234	14.2896	0.000334
Imidacloprid	0.88	0.0018	18.6864	0.000034
Flumioxazin	1.05	0.0019	23.0832	0.000043

K = potassium; N = nitrogen.

Indianapolis, IN), would be applied twice over two growing seasons. A fungicide, chlorothalonil (Bravo Ultrex; Syngenta Crop Protection, Greensboro, NC), would be applied six times per year and an insecticide, imidacloprid (Marathon; OHP, Mainland, PA), would be applied one time per year. Plants would be harvested in the fall of the second growing season with a tractor with a tree lifter, placed in a cooler for grading and sorting, and planted at a wider spacing in prepared beds within 2 d. A 35% cull rate would be assumed at this stage.

The field plot to receive the two-year-old seedlings would have been fallowed and prepared as described previously but would not be fumigated. Seedlings would be mechanically transplanted in the raised beds prepared as previously described at a spacing of 8.9 cm within rows 28 cm apart (12,000 per bed) and grown for two years. These beds would be fertilized as described previously except the rate would be decreased to 112 kg·ha^{-1} N per year the second year of the transplant production phase. A pre-emergent herbicide, flumioxazin (Surguard; Valent U.S.A., Walnut Creek, CA), would be applied three times over the two years; a fungicide, chlorothalonil (Bravo Ultrex), would be applied two times per year; and an insecticide, imidacloprid (Marathon), would be applied once per year. Plants would be harvested in early spring after the second growing season using a tractor with a tree lifter. The plants would be transported to a barn or cooler, sorted, and stored for ≈1 week before shipping to the field nursery. A 20% cull rate would be expected in this phase. It was assumed based on nursery manager interviews

that 60,000 transplants would be shipped 482 km to the field nursery in a tractor/trailer transporter.

INPUT MATERIALS AND EQUIPMENT USE IN FIELD NURSERY PRODUCTION. Based on the model system, the materials (Table 3) and equipment use (Table 4) for field production of the finished product were inventoried. A fallow year with a cover crop, sudex (*Sorghum bicolor* × *S. sudanense*), was assumed. Land preparation would include sub-soiling and disking before seeding. The sudex would be turned under the fall of the fallow year. Agricultural lime would be applied and the field would be disked. Fertilizer (28N–3.0P–11.6K, urea as the N source) would be banded in rows manually each year. Pesticides would be applied according to the label. A pre-emergent herbicide, prodiamine (Baracade; Syngenta Crop Protection), would be banded in-row in the spring annually the first two growing seasons. Glyphosate (Roundup Pro; Monsanto, St. Louis, MO) would be applied in-row as a directed spray three times per year. Carbonyl (Sevin; Bayer Environmental Science, Triangle Park, NC) would be applied as needed for control of bagworm (*Thyridopteryx ephemeraeformis*). It was assumed that 12.5% of the plants would be sprayed annually for bagworm with a backpack sprayer. Plants would be irrigated twice during the first year using a tractor, wagon, water tank, and a 3.7-kW gasoline water pump allowing for individual tree watering. The between-row space would be mowed four times per year. The finished product would be dug with a 61-cm tree spade mounted on a skid-steer loader and hauled to the shipping area with a tractor and wagon. A skid-steer loader with an articulating arm would be used to load wagons in the field and to load trucks for delivery. Culls (10% of crop) would be removed with a bulldozer.

ASSUMPTIONS IN POST-HARVEST ACTIVITIES. GHG emissions for transporting the finished trees to a landscape contractor were based on fuel consumption (2.55 km·L^{-1}) for 120 trees moving 241 km in a heavy truck and trailer. Ten percent of the load per tree of a light truck and trailer (4.3 km·L^{-1}) would transport the tree to a landscape site. Traveling distance was established through interviews with nursery managers and landscape contractors. Five minutes of a 26.1-kW tractor with a bucket was assumed for moving the tree from the trailer to the planting hole. The tree would be planted by hand. Based on interviews with certified arborists, it was assumed that takedown and disposal of the tree after its useful life would use a heavy truck traveling 40 km, a chainsaw for 2 h, and a 104.4-kW chipper for 1 h. The resulting material would be used for mulch.

ASSUMPTIONS FOR EQUIPMENT USE. Motorized machinery would be used in the activities described previously. Tractors

Table 2. Contribution of equipment use to the carbon footprint [global warming potential (GWP) in kilograms CO_2 equivalent (CO_2e)] for a 60-cm (2 + 2) colorado blue spruce liner.[z]

Equipment use	Use time (h·ha^{-1})	Time per marketable liner (10^{-4} h)	Fuel per marketable liner (mL)	GWP per marketable liner (kg CO_2e)
Each fallow year: seedling and transplant production fields				
Chisel plow	3.74	0.012	0.015	0.000044
Disking	1.25	0.004	0.005	0.000015
Cover crop seeding	1.25	0.004	0.005	0.000015
Dragging	1.25	0.004	0.005	0.000015
Turning plow	3.74	0.012	0.015	0.000044
Seedling production				
Broadcast ag lime ($CaCO_3$)	1.25	0.004	0.005	0.000015
Broadcast KCl	1.25	0.004	0.005	0.000015
Disking	1.25	0.004	0.005	0.000015
Fumigation	1.05	0.003	0.004	0.000012
Plastic tarp removal	1.25	0.043	0.027	0.000082
Bed shaping	2.24	0.007	0.009	0.000027
Sow seed	2.24	0.007	0.005	0.000014
Broadcast fertilizer	14.93	0.050	0.047	0.000141
Irrigation	121.90	0.407	0.517	0.001562
Herbicide application	0.75	0.003	0.002	0.000007
Fungicide application	4.52	0.015	0.014	0.000043
Insecticide application	0.75	0.026	0.002	0.000007
Harvest from bed	29.90	0.100	0.190	0.000574
Transport from field	7.47	0.025	0.016	0.000047
Transplant production				
Broadcast ag lime ($CaCO_3$)	1.25	0.043	0.051	0.000154
Broadcast KCl	1.25	0.043	0.051	0.000154
Disking	1.25	0.043	0.051	0.000154
Bed shaping	2.24	0.078	0.092	0.000277
Transplant seedlings	13.59	0.473	0.556	0.001681
Broadcast fertilizer	11.19	0.390	0.364	0.001102
Irrigation	46.02	1.603	2.035	0.006144
Herbicide application	1.13	0.039	0.204	0.000111
Fungicide application	1.51	0.052	0.049	0.000148
Insecticide application	0.75	0.026	0.024	0.000074
Harvest from bed	29.90	1.042	1.983	0.005989
Transport from field	14.95	0.521	0.324	0.000982
Transport to field nursery	NA[y]	NA	2.629	0.007928

[z]Well-to-wheel GWP of diesel fuel was assumed to be 3.01526 kg CO_2e per liter of fuel as per GREET1_2011 (Vyas and Singh, 2011).
[y]Not applicable.

with a specified power rating (kilowatts) would be matched to each operation. The portion of maximum tractor throttle and load for each operation was assumed to be: land preparation, 44.7-kW tractor at 0.85 throttle and 0.85 load; spraying and spreading in the liner nursery, high-clearance 67.1-kW tractor at 0.50 throttle and 0.50 load; transporting the plants from the field to the cooler/barn, 44.7-kW tractor at 0.50 throttle and 0.50 load; mowing, 17.9-kW tractor at 0.85 throttle and 0.85 load; liner harvesting, 67.1-kW tractor at 1.0 throttle and 0.85 load; and harvesting finished trees, 55.9-kW skid-steer loader with tree spade at 1.0 throttle and 0.85 load. The fuel consumption of a 44.7-kW diesel irrigation pump was assumed to equal that of a tractor at 1.0 throttle and 0.85 load. The fuel consumption for the 3.7-kW irrigation pump was assumed to be 1.9 L·h^{-1}. The 104.4-kW chipper was assumed to consume diesel at the rate of a 104.4-kW tractor at 1.0 throttle and 0.85 load.

INVENTORY ANALYSIS AND DATA COLLECTION. The GWP of input materials was determined as follows. The average C emission equivalent for a range of herbicides, insecticides, and fungicides was estimated by Lal (2004) to be 6.3 ± 2.7, 5.1 ± 3.0, and 3.9 ± 2.2 kg C-equivalent per kilogram a.i., respectively. Lal also reported C emission equivalents for specific pesticides as 9.1 and 3.1 kg C equivalent per kilogram of glyphosate and carbaryl, respectively. These C emissions were converted to CO_2 equivalent by multiplying by 3.664. The GWP of MeBr is 5.0, meaning it has five times the GWP as CO_2 (USEPA, 2010). According to the Montreal Protocol, 0.203 kg CO_2e would be invested in the production and distribution of each kilogram of MeBr (United Nations, 1987). Based on the Montreal Protocol, it was assumed that 33% of soil-applied MeBr would be lost directly to the environment as a result of application processes, which would add another 1.65 kg CO_2e to the GWP of each kilogram of MeBr. Therefore, the GWP was assumed to be 1.853 kg CO_2e per kilogram of MeBr.

Snyder et al. (2009) calculated from the U.S. Department of Energy's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model, GREET 1.8a (Wang, 2007), that the GWP for manufacturing and transporting N (from urea), phosphorus, potassium, and lime to be 3.2, 2.3, 0.84, and 0.6 kg CO_2e per kilogram of material, respectively. It was assumed that the GWP of ammonium sulfate was similar to that of urea, although it is a byproduct of industrial process and may have a smaller carbon footprint in some regions. Although highly variable, an additional GWP for fertilizer-induced N_2O emission from soils was calculated to be 4.65 kg CO_2e per kilogram N applied, assuming a 1% direct loss of applied N as N_2O (IPCC, 2006; Snyder et al., 2009). Lal (2004) reported a mean C emission from the production, transportation, storage, and transfer of agricultural lime to be 0.160 ± 0.11 kg C, indicating the variability of this product and its associated GWP.

GWP for machinery and truck use in each operation was estimated based on fuel consumption calculations. Diesel consumption for tractors and the irrigation pump was estimated using the American Society for Agricultural and Biological Engineers' Standard published in 2009 and applied in a Virginia Cooperative Extension Service publication (Grisso et al., 2010) adjusting for expected load and throttle for each operation for each tractor. Diesel consumption rates used for heavy trucks

Table 3. Contribution of material inputs to the carbon footprint [global warming potential (GWP) in kilograms CO_2 equivalent (CO_2e)] for a 2-m-tall colorado blue spruce assuming a five-year field production cycle.

Input material	Product (kg·ha⁻¹)	Product per marketable tree (kg)	Product GWP [CO_2e (kg·kg⁻¹)]	GWP per marketable tree (kg CO_2e)
Sudex seed	44.83	0.0224	4.067	0.091
Ag lime ($CaCO_3$)	2241.72	1.1200	0.590	0.656
Nitrogen	364.74	0.1822	7.850	1.430
Phosphorus	39.71	0.0198	2.300	0.045
Potassium	151.37	0.0756	0.840	0.064
Wire basket (count)	2002	0.6520	1.293	0.843
Cardboard truck protector (count)	2002	0.0113	0.470	0.005
Transplant (count)	2224	1.1111	0.043	0.048

	Product (kg·ha⁻¹)	Active ingredient per marketable tree (kg)	Product GWP [CO_2e (kg·kg⁻¹a.i.)]	GWP per marketable tree (kg CO_2e)
Prodiamine	1.67	0.0005	23.083	0.012
Glyphosate	39.43	0.0081	33.342	0.270
Carbonyl	0.89	0.0002	11.358	0.002

Table 4. Contribution of equipment use to the carbon footprint [global warming potential (GWP) in kilograms CO_2 equivalent (CO_2e)] for a 2-m-tall colorado blue spruce assuming a five-year field production cycle.[z]

Equipment use	Use time (h·ha⁻¹)	Time per marketable tree (h)	Fuel per marketable tree (L)	GWP per marketable tree (kg CO_2)
Subsoiling	1.85	0.0009	0.014	0.044
Disking	1.24	0.0006	0.005	0.016
Cover crop seeding	3.21	0.0016	0.025	0.076
Dragging	1.24	0.0006	0.005	0.015
Turning plow	1.85	0.0009	0.014	0.044
Spread ag lime ($CaCO_3$)	1.24	0.0006	0.010	0.029
Disking	1.24	0.0006	0.005	0.015
Transplanting	7.41	0.0037	0.031	0.093
Herbicide application	23.48	0.0117	0.029	0.089
Mow	24.71	0.0123	0.058	0.176
Irrigation (twice)	47.43	0.0237	0.083	0.252
Digging with tree spade	166.80	0.0833	1.322	4.014
Loading on wagon	100.08	0.0500	0.734	2.159
Hauling from field	166.80	0.0833	1.410	4.144
Loading on truck	66.72	0.0333	0.490	1.439
Removal of culls	18.53	0.00939	0.157	0.463

[z]Well-to-wheel GWP of diesel fuel assumed to be 3.01526 kg CO_2e per liter of fuel as per GREET1_2011 (Vyas and Singh, 2011).

and light trucks were assumed to be 6 and 4.2 km·L⁻¹, respectively. The GWP factors for fuel consumption were determined based on "well-to-wheel" emission reported in GREET1_2011 (Vyas and Singh, 2011) as 2.93389 kg CO_2e per liter for gasoline and 3.01526 kg CO_2e per liter for diesel. The GWP of fluids used by tractors during a 10,000-h life was calculated using GREET2_7 "Vehicle Fluids" (Burnham et al., 2006) for consumption and disposal of engine oil (changed every 1000 h), power steering fluid (changed one time), brake fluid (changed one time), transmission fluid (changed two times), and coolant (changed two times). The fluid GWP for the chipper

and irrigation pump engines assumed changing only engine oil and coolant and following the same frequency as for tractors. Fluid use by trucks was calculated based on general recommendations for fluid-changing schedules.

The GWP of oilseed radish seeds or sudex seeds could not be found. However, the reported GWPs of seed production for wheat (*Triticum aestivum*) and rapeseed (*Brassica napus*) were 1.5 and 1.84 kg CO_2e per kilogram, respectively (U.S. Department of Energy, 2012). West and Marland (2002b) reported GWPs for orchardgrass (*Dactylis glomerata*) seeds (1.11 kg CO_2e per kilogram) and ryegrass (*Lolium perenne*) seeds (0.54 kg CO_2e per kilogram). Therefore, this study assumed GWPs of 1.84 and 1.11 kg CO_2e per kilogram of oilseed radish and sudex seeds, respectively.

Based on a professional LCA conducted for the World Steel Association (Brussels, Belgium) (unpublished data) for the steel wire from recycled steel, the GWP of the wire basket was assumed to be 1.2927 kg CO_2e per kilogram. Although 0.638 kg of burlap and 0.045 kg of nylon twine were used in packaging the harvested tree, the GWP for these products was not readily available and considered to have a negligible impact.

The annual GWP overhead for the liner nursery and the field nursery was determined by estimating the electricity (shop, cooler, office, etc.) and gasoline use (all-terrain vehicle, small tractor, farm truck, chain saw, etc.) in general farm operations. It was assumed that a 42-ha liner nursery would consume 55,000 kW-h per year in electricity and 5148 L per year of gasoline for general operations. A 71-ha field nursery was assumed to consume 14,150 kW-h per year of electricity and 1453 L per year of gasoline. The GWP of electricity was assumed to be 0.67 kg CO_2e per kW-h (Samaras and Meisterling, 2008).

LCAs of farming operations should consider the carbon captured by the growth of the crop (Mourad et al., 2007), especially for perennial crops. It was assumed that 50% of the tree dry weight was C (McPherson and Simpson, 1999), which was multiplied by 3.664 to yield the kilogram CO_2 sequestered during production.

Carbon is sequestered by trees as they mature during their use phase (McPherson and Simpson, 1999) according to a

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normal growth model for each species. A colorado blue spruce transplanted as a 2-m tall tree into a suburban landscape in the lower midwestern United States, according to the U.S. Forest Service's Center for Urban Forestry Research (CUFR) Tree Carbon Calculator calculation method (U.S. Department of Agriculture, 2008), would sequester 2093 kg CO_2 aboveground and in the roots in 50 years. The rate of C sequestered differs over time as per a normal growth curve and not all the carbon would be sequestered for the full 50 years of useful life. The assumed 50 years of useful life is also less than the 100-year assessment period specified by international standards (BSI British Standards, 2011). Using the growth curve for colorado blue spruce in the CUFR Tree Carbon Calculator and the protocol for estimating the weighted average GWP impact of stored C described in Appendix E of PAS 2050 (BSI British Standards, 2011), the annual sequestration relative to a portion of the 100-year assessment period was calculated. This protocol accounts for the fact that CO_2 sequestered in Year 1 would be stored throughout the 50-year life of the use phase but the CO_2 sequestered in Year 40 would be stored for only 10 years of the 100-year assessment period. It was assumed that the tree would be removed from the landscape after 50 years and stored C in the truck, shoots, and roots would be released into the atmosphere relatively quickly. Although storage of carbon sequestered in roots has been reported to reside in the rhizosphere for an extended period after tree removal (IPCC, 2006; McPherson and Simpson, 1999; Mokany et al., 2006), this was not considered as a result of the lack of definitive data for spruce in the lower midwestern United States. It should be noted that CO_2 emission reduction resulting from energy savings in a building resulting from a strategically placed tree was not included in this study. Carbon investment in tree maintenance in a residential landscape would be expected to be minimal and excluded from this model.

The relative impact of input variables on total CO_2e investment in a spruce tree life cycle was determined using sensitivity analysis. Each input variable within each life phase was in turn increased by 10%, whereas other variables were unchanged in model simulations. The maximum percentage change in total kilograms CO_2e investment in the tree was used to assess the sensitivity of the model to each variable. The sensitivity of CO_2 sequestration during production, use, and end-of-life phases was calculated separately using the same procedures. Sensitivity for each phase was expressed relative to the final carbon footprint.

Results and Discussion

The estimated seed-to-landscape carbon footprint of a 2-m-tall, 5-cm caliper colorado blue spruce tree produced in the upper midwestern (liner) and lower midwestern United States (finished tree) was 13.558 kg CO_2e. This included sequestration of 9.14 kg CO_2e during production. The total CO_2e emissions invested in input materials, equipment use, and truck transportation in the production and distribution system in this model was 22.693 kg CO_2e. These values are somewhat higher than those published for red maple: 8.213 kg CO_2e carbon footprint from 12.1 kg CO_2 sequestered during production and 20.567 kg CO_2e total GWP investment in production and distribution (Ingram, 2012). These differences can partially be explained by the more rapid growth rate and larger mass of the red maple compared with the spruce offset by the two years

additional for liner production at a higher population density and one year additional required in field production for the spruce.

The carbon footprint of the liner at the farm gate was 0.035 kg CO_2e, including 0.001 kg CO_2e from overhead GWP (electricity and non-assigned fuel consumption) of the liner nursery. This did not account for sequestration of C at this stage of production. An additional 0.008 kg CO_2e was invested in transporting the liner 483 km to the field nursery. The GWP of input materials and equipment use contributed 0.013 and 0.021 kg CO_2e, respectively, to the liner carbon footprint (Table 1). Lime and fertilizer contributed 0.012 kg CO_2e to GHG emissions from materials, which was 34% of the liner carbon footprint at the farm gate. Pesticides contributed 0.0008 kg CO_2e, which was only 2% of the liner production GWP.

Equipment use in liner production contributed almost half of the liner carbon footprint (Table 2). Among the operations involving equipment use that contributed the most to the carbon footprint included irrigation (0.008 kg CO_2e), transplanting seedlings (0.002 kg CO_2e), harvesting the finished liner (0.006 kg CO_2e), and broadcasting fertilizer (0.001 kg CO_2e). Although the input materials and equipment use per hectare were similar for the seedling production and transplant production phases for the liner, the lower density of plants and lower cull rate in the transplant production phase compared with the seedling phase resulted in greater GWP impact of materials and equipment use per marketable liner.

When the combined GWP of input materials and equipment use was segregated by production system component for the liner production in the propagation nursery, similar CO_2e emissions were invested in land preparation and planting, fertilization, irrigation, harvesting, and transportation to the field nursery and combined to account for 97% of the emissions (Fig. 2). Disease, weed, and insect management contributed 3% of total GWP.

The total production system GHG emissions from material inputs, from seed to finished tree, contributed 3.467 kg CO_2e (Table 3). The GWP of the liner (0.048 kg CO_2e) contributed
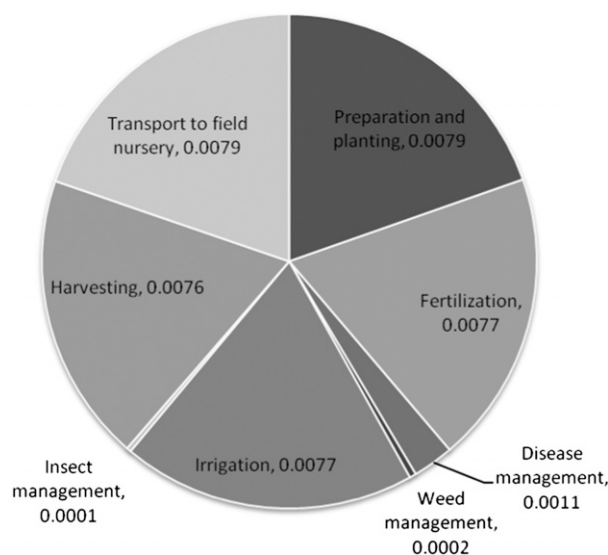

Fig. 2. Material and equipment use contributions of production system components to the carbon footprint (global warming potential in kilograms CO_2 equivalent) for a 60-cm-tall (2 + 2) colorado blue spruce liner.

only 0.28% to the GWP invested in production of the finished tree at the farm gate. Fertilizer and lime contributed 2.196 kg CO_2e, 63% of the input material GWP. The wire basket and cardboard trunk protector contributed 0.848 kg CO_2e, 24% of input materials' GWP impact. Pesticides contributed 0.284 kg CO_2e, 8% of material GWP investments.

Equipment use in the field nursery contributed 13.069 kg CO_2e to total GWP investments (Table 4), 89% of which occurred at harvest. This value is greater than that published for red maple (8.979 kg CO_2e). Much of that difference is because this study used a more inclusive value for fuel GWP from GREET, well to wheel (Vyas and Singh, 2011), whereas the red maple study used the USEPA (2005) value for GWP only from the combustion of fuels. The well-to-wheel GWP of diesel was 13% greater than the more narrowly defined GWP by the USEPA (2005). There was also less GWP invested in staking and pruning in spruce compared with red maple production. The field nursery overhead GWP from energy use not assigned to individual production components was estimated to be 0.581 kg CO_2e per tree. Other larger contributors included land preparation (0.239 kg CO_2e), mowing (0.176 kg CO_2e), transplanting (0.093 kg CO_2e), and irrigation (0.252 kg CO_2e). Equipment use contributed 3.8 times more to the farm-gate carbon footprint than input materials. Direct energy use was the largest component of the published carbon footprint of container-grown trees (Kendall and McPherson, 2012).

When the combined GWP of input materials and equipment use was segregated by operational component in the field production system, harvesting contributed 13.068 kg CO_2e to the GWP investment (Fig. 3). That is 76% of the total GWP investment at the farm gate. Fertilization (1.540 kg CO_2e), weed management (0.546 kg CO_2e), and land preparation (0.987 kg CO_2e) contributed another 18%.

Trees impact the environment by taking up atmospheric CO_2 and storing it as C in wood. Many factors affect how much C is sequestered during the useful life of a tree. The weighted positive impact of C storage of a colorado blue spruce over a 50-year useful life in a 100-year assessment period was
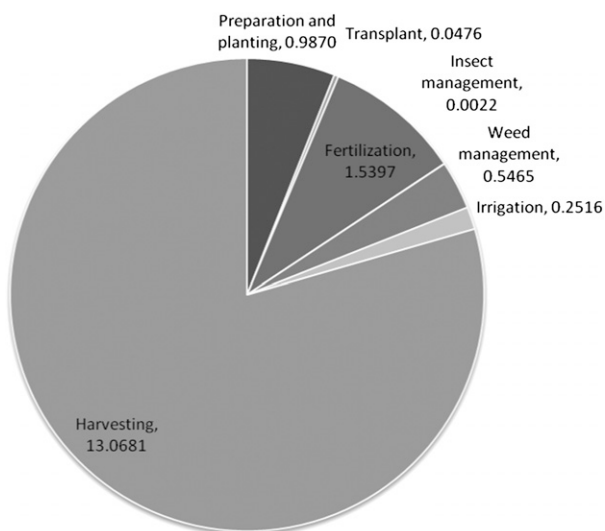

Fig. 3. Material and equipment use contributions of field production system components to the carbon footprint (global warming potential in kilograms CO_2 equivalent) for a 2-m-tall, spade-dug colorado blue spruce in a five-year production cycle.

calculated as 593 kg CO_2e. Eighty-seven percent of the direct positive impact on atmospheric CO_2 of the tree in the landscape was estimated to occur in the first 40 years. If the assumed life expectancy had been decreased by 10 to 40 years, the weighted impact of C storage would have been 78 kg CO_2e less. An assumed useful life of 60 years would have increased the positive impact by 20 kg CO_2e. At the conclusion of its useful life, takedown and disposal would result in emissions of 148 kg CO_2e. Therefore, the net positive impact through the reduction of atmospheric CO_2 during the 50-year use and end-of-life phases would be $\approx$446 kg CO_2e. Subtracting the seed-to-landscape carbon footprint (13.693 kg CO_2e) yielded an overall positive impact of the colorado blue spruce over its complete life cycle that exceeded 431 kg CO_2e. That was almost 30 times greater than the seed-to-landscape carbon footprint of the tree. The overall positive life cycle impact after 60 years in the landscape for a red maple was reported to exceed 800 kg CO_2e (Ingram, 2012). Neither the red maple LCA nor the current spruce study considered the potential long-term storage of carbon from plant roots left in the soil at the end of life, but the impact could be significant (IPCC, 2006; McPherson and Simpson, 1999; Mokany et al., 2006) and should be addressed in further research.

Sensitivity analysis of input variable GWP revealed that a 10% increase in a given variable would result in at least a 1% increase in the total GWP investment for eight of the 86 variables in the model in the production and distribution phases. A 10% increase in carbon sequestered in production would decrease the seed-to-landscape C footprint by 7%, whereas a 10% decrease in the GWP investment from digging, loading on a wagon, hauling from the field, loading the truck, and N applied in field production would yield a 3%, 2%, 3%, 1%, and 1% decrease in the seed-to-landscape carbon footprint, respectively. A 10% decrease in traveling distance to the landscaper and to the landscape site would each decrease the carbon footprint by 2%. Analysis of the aggregated components of the model showed that C sequestered in the use phase and GHG emissions invested in the end-of-life takedown and disposal and during production had the greatest impact on the life cycle carbon footprint in that order. A 10% change in C sequestration during its useful life phase would result in a 14% change in life cycle carbon footprint. Carbon sequestration during the use phase is definitely the major variable in the overall model and, therefore, the greatest potential for introduction of errors. Although the literature revealed that the GWP of agricultural lime is highly variable, a 10% increase would only result in a 0.02% increase to the carbon footprint. This illustrates the need for nursery managers and researchers to focus on possible modifications of system inputs and activities that could have the greatest impact on GWP.

The capacity to query the model system through LCA allows "what if" modification of system components to determine the overall impact of those modifications. In the current model, it was determined from nursery manager interviews throughout the region that the length of time required to produce a 2-m-tall colorado blue spruce from a 2 + 2 liner varied from four to six years. The model presented here was based on a five-year production cycle plus a fallow year with a cover crop. Querying the model revealed that adding an additional year to production in the field nursery would only add 0.412 kg CO_2e, less than 3%, to the seed-to-landscape GWP of the product. Drought conditions could result in more irrigation requirements. If four

additional irrigations were applied during field production, it would increase the seed-to-landscape carbon footprint by 0.50 kg CO_2e (3.6%). Increasing the cull rate from 20% to 30% in the second liner production phase would only add 0.004 kg CO_2e to the final product, but increasing the cull rate from 10% to 20% in the field nursery phase would add 1.085 kg CO_2e. This is primarily the result of the high-density production in the liner phase compared with the field production phase. Reducing the number of mowing passes by five (25%) during field production would decrease the GWP by 0.0439 kg CO_2e, but reducing the equipment use in harvesting by only 10% would decrease the GWP by 1.22 kg CO_2e. Reducing the transport distance of the final product by 25% would decrease the seed-to-landscape carbon footprint by 0.608 kg CO_2e (5%).

LCA has proven to be an effective tool to analyze the environmental impact of production system components and to estimate the life cycle impact of trees on the environment. Nursery managers and the consuming public can use information generated through this and other studies to make production system and purchasing decisions. Additional work is needed to determine the environmental impact of other classes of landscape plants and to link the impacts of inputs to economic and market consequences.

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