Reviews

Understanding Carbon Footprint in Production and Use of Landscape Plants

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SUMMARY. **Understanding carbon footprint (CF) terminology and the science underlying its determination is important to minimizing the negative impacts of new product development and assessing positive or negative cradle-to-grave life-cycle impacts. Life cycle assessment has been used to characterize representative field-grown and container-grown landscape plants. The dominant contributor to the CF and variable costs of field-grown trees is equipment use, or more specifically, the combustion of fossil fuels. Most of that impact is at harvest when heavy equipment is used to dig and move individual trees. Transport of these trees to customers and the subsequent transplant in the landscape are also carbon-intensive activities. Field-grown shrubs are typically dug by hand and have much smaller CFs than trees. Plastics are the major contributor to CF of container-grown plants. Greenhouse heating also can be impactful on the CF of plants depending on the location of the greenhouse or nursery and the length and season(s) of production. Knowing the input products and activities that contribute most toward CF and costs during plant production allows nursery and greenhouse managers to consider protocol modifications that are most impactful on profit potential and environmental impact. Marketers of landscape plants need information about the economic and environmental life-cycle benefits of these products, as they market to environmentally conscious consumers.**

The purpose of this article was to provide a base of understanding of CF terminology and to illustrate CF analyses using data from previous research that modeled nursery and greenhouse crop production systems and their life-cycle impact. CF relates to the efflux of greenhouse gases in the environment. The greenhouse gas emissions (GHG) of primary interest are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) and result from human and environmental activities. They warm the earth by absorbing energy and decreasing the rate at which energy escapes the earth's atmosphere to space [U.S. Environmental Protection Agency (USEPA), 2018]. In other words, greenhouse gases increase the effectiveness of the atmosphere to act as a blanket that insulates the earth. Therefore, GHG have a measurable potential for trapping energy in the earth's atmosphere.

Greenhouse gases differ in their effectiveness to absorb energy in specific wavelengths, primarily infrared. This is referred to as their radiative efficiency (USEPA, 2018). They also differ in terms of how long they stay in the atmosphere, or their lifetime. Global warming potential (GWP) was developed to categorize greenhouse gases based on their radiative efficiency and lifetime in the atmosphere. The greenhouse gas of greatest concentration is CO_2. The concentration of CO_2 in the atmosphere has also been increasing, especially since the industrial revolution, and CO_2 remains in the atmosphere for thousands of years. The combustion of fossil fuels has played a major role in this increase. Therefore, the GWP of emitted gases is expressed relative to the GWP of CO_2 for a 100-year period (GWP_{100}). The GWP_{100} of CO_2 is set as 1, the reference to which other GHGs are compared and expressed.

The CF, or GWP, of a product or activity is expressed in kilograms of CO_2-equivalent (CO_2e). CH_4 and N_2O are estimated to have a GWP_{100} of 28 to 36 and 165 to 298 times that of CO_2, respectively. CH_4 is released from animals, humans, natural wetlands, paddy rice (*Oryza sativa*) fields, fermentation, and biomass burning. Agriculture is a primary source of N_2O emissions, as are industrial activities, municipal waste landfills, and combustion of fossil fuels. Although found in the atmosphere at extremely low concentrations, chlorofluorocarbons, hydrofluorocarbons, hydrochlorofluorocarbons, perfluorocarbons, and sulfur hexafluoride can have GWPs thousands or tens of thousands of times greater than CO_2 (USEPA, 2018). These definitions were the basis for an international treaty, called the Kyoto Protocol, signed in 1997 that commits parties to reduce GHG, effective in 2005. The details of those definitions and targets for reduction have been published by the United Nations (2008). Additional related data have been published on The Intergovernmental Panel on Climate Change website of the United Nations (2018).

Tools to estimate GHG during the life cycle of a targeted product or activity have been developed over the years and

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046

have led to the development of a complex, yet systematic process called life cycle assessment [LCA (Ingram and Fernandez, 2012)]. This tool has international acceptance by the scientific community, is governed by international standards, and has application to many fields, including agriculture. Although there are periodic revisions of the standards, the authors of this article have followed the International Organization for Standardization revised standard (International Organization for Standardization, 2006) and British Standards Institution's standard (British Standards Institution, 2011). Under these standards, a functional unit of the targeted LCA is defined and all inputs are determined for the system. A functional unit may be anything from a gallon of milk or a container-grown shrub or a field-grown tree. GWP is but one environmental impact that can be measured or estimated by LCA. These potential environmental impact measures include water footprint, ecotoxicity, ozone depletion, acidification, eutrophication, and others (Ingram and Hall, 2014b). A complete cradle-to-grave LCA of a product or activity includes production, use, and post-life phases. However, a partial life-cycle impact, such as cradle-to-farm gate or seed-to-landscape, also can be defined, analyzed, and reported.

Cradle-to-gate CF of nursery and landscape plants

The CF of the components of production systems for the major crop categories for landscape plants has been modeled (Table 1), including a field-grown shade tree [red maple (*Acer rubrum*)], field-grown evergreen tree [blue spruce (*Picea pungens*)], field-grown flowering tree [‘Forest Pansy’ redbud (*Cercis canadensis*)], field-grown deciduous shrub [juddi viburnum (*Viburnum ×juddi*)], field-grown evergreen shrub [‘Densiformus’ taxus (*Taxus ×media*)], pot-in-pot shade tree [red maple (*Acer rubrum*)], container-grown evergreen shrub on the U.S. mid-Atlantic coast [‘Bennett's Compacta’ japanese holly (*Ilex crenata*)], container-grown evergreen shrub in the U.S. Pacific northwest region [‘Green Beauty’ boxwood (*Buxus microphylla japonica*)], herbaceous annual flowering plant [wax begonia (*Begonia ×semperflorens-cultorum*)], young plants (foliage plants in 72-count trays), outdoor-grown flowering potted plant [chrysanthemum (*Chrysanthemum*)], and greenhouse-grown flowering potted plant [poinsettia (*Euphorbia pulcherrima*)]. The primary purpose of this LCA modeling research was to identify inputs and processes in these production systems that contribute the most to CF and variable costs. Once these processes are identified and defined, managers know where to invest their time in seeking alternatives that would make the greatest difference in environmental impact and profitability.

Field production of trees and shrubs is still an important but decreasing portion of landscape plant production systems (Hodges et al., 2015). Analysis of production components of model systems for field-grown trees revealed that the farm-gate CF for 2-inch caliper red maple and blue spruce was 12.5 and 7.9 kg CO_2e, respectively (Table 1). The farm-gate CF for a 2-inch caliper flowering tree (redbud) model system was calculated to be 6.6 kg CO_2e. Interestingly, 71% to 77% of the GHG for these field-grown tree model systems were due to equipment use and up to 89% of equipment use per plant occurred at harvest. This is logical given the fact that heavy equipment time was focused on individual trees for these operations. Input materials and equipment use in the harvesting process contributed an average of 26% of the total variable costs for field-grown tree models studied (Ingram and Hall, 2015b).

The model systems for field-grown shrubs are characterized by hand-digging and a much higher density of plant per area than for field-grown trees. The farm-gate CF for a model system for 36-inch juddi viburnum was 0.70 kg CO_2e, whereas the model system for an evergreen shrub, 24-inch taxus, using a greenhouse propagation phase was calculated as 0.77 kg CO_2e. More than 60% of CF for these field-grown shrubs was from input materials, whereas labor accounted for 71% to 77% of variable costs.

Container production has become the system by which most landscape plants are grown and marketed. Most container-grown trees and shrubs are hardy in a region and are grown on outdoor beds with full sun or artificial shade. Winter protection of these plants is required in many parts of the country to eliminate freeze damage to roots. The farm-gate CF of #3 (11.4 L) container shrubs ranged from 1.72 to 3.36 kg CO_2e depending on the location and protocols for the model systems (Table 1). Variable costs for these model systems ranged from $2.88 to $5.73, influenced primarily by input materials and secondarily by labor, both of which varied by container size sequencing protocols.

Kendall and McPherson (2012) published the cutting-to-retail garden center CF in California for trees in #5 (14.5 L) and #9 (34 L) containers as 4.6 and 15.3 kg CO_2e, respectively. Direct fuel use contributed nearly 50% of the CF but there was no way to determine how much of this was before the farm gate from the data presented. Input materials, including the container, constituted the second largest contributor to CF.

The farm-gate CF for a 2-inch caliper red maple produced in a #25 (100 L) container in a pot-in-pot production system in the lower-midwest United States was calculated to be 10.74 kg CO_2e, of which 85% was due to input materials (Table 1). The insert or growing container contributed 30% of the input materials contributions to CF. Input materials contributed 76% of variable costs, influenced significantly by the cost of the liner.

Although equipment use was the primary contributor to the farm-gate CF of field-grown plants, the use of plastics was the primary contributor

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Table 1. Farm-gate carbon footprint [global warming potential (GWP), carbon dioxide equivalents (CO_2e)] and variable costs for landscape plant production models using life cycle assessment.

Plants modeled[z]	GWP (kg CO_2e)[y]	Variable costs ($)	Reference(s)
Red maple, B&B	12.5	36.66	Ingram, 2012; Ingram and Hall, 2015c
'Forest Pansy' redbud, B&B	6.6	37.74	Hall and Ingram, 2014; Ingram and Hall, 2013
Blue spruce, B&B	7.9	–	Ingram, 2013; Ingram and Hall, 2015c
Juddi viburnum, B&B	0.7	5.36	Ingram and Hall, 2014a
'Densiformus' taxus, B&B	0.77	5.09	Hall and Ingram, 2015
Red maple, #25 PNP	10.74	55.49	Ingram and Hall, 2015a
'Bennett's Compacta' japanese holly #3, U.S. mid-Atlantic region	2.14	3.22	Ingram et al., 2016
'Green Beauty' boxwood #3, U.S. Pacific northwest region	1.72–3.36	2.88–5.73	Ingram et al., 2017a
Wax begonia, 4.5-inch	0.14	0.67	Ingram et al., 2018a
Young plants tray (72)	2.28–4.22	24.86–25.25	Ingram et al., 2017b
Chrysanthemum, 8-inch	0.55	0.85	Ingram et al., 2018b
Poinsettia, 6-inch	0.47	1.03	Ingram et al., 2019

[z]B&B = balled and burlapped from field production system; #25 PNP = 100-L container in a pot-in-pot production system; #3 = 11.4-L container size; 4.5-inch (675 mL), 8-inch (2.9 L), and 6-inch (1.7 L) refer to container diameter; (72) refers to the number of plants in the tray; 1 L = 0.2642 gal, 1 mL = 0.0338 fl oz, 1 inch = 2.54 cm.
[y]1 kg = 2.2046 lb.

for container-grown woody plants. A research team in Italy also reported that use of plastics was a significant contributor to container-grown nursery crop CF (Beccaro et al., 2014).

Herbaceous annuals and many flowering potted plants are grown and marketed in containers. They are most often grown in greenhouses to facilitate production of these crops to satisfy spring or continuously available markets. Wax begonia produced in a greenhouse and marketed in a 4.5-inch container as part of a 12-plant shuttle tray was modeled using LCA (Table 1). The CF was calculated for this 8-week crop model as 0.14 kg CO_2e with variable costs of $0.67. Fifty-seven percent of CF and 43% of variable costs in the model were from the container and shuttle tray. Heating contributed little to CF or variable costs due to rapid turnover and a limited number of months requiring heat. The CF of a greenhouse-grown poinsettia in a 6-inch container produced in the north Atlantic U.S. coast region was modeled at 0.47 kg CO_2e, and variable costs were $1.03. The substrate, container, and fertilization contributed 30% of the CF. The unrooted cutting was 44% of the variable costs.

Young foliage plants in a 72-count propagation tray in a variety of greenhouse systems was estimated to have a CF of 2.28 to 4.22 kg CO_2e and variable costs of $24.86 to $25.25 (Table 1). Electricity and heating costs, even in the deep south United States, were the major contributors to CF (87% to 90%), and microcutting and transplanting accounted for 77% of variable costs. Outdoor production of chrysanthemum in 8-inch containers was modeled to have a CF of 0.55 kg CO_2e with variable costs of $0.85. Although the container was an important contributor to CF, substrate components accounted for 45% of CF and 12% of variable costs.

Table 2. The complete life-cycle carbon footprint [global warming potential (GWP), carbon dioxide equivalents (CO_2e)] for woody landscape plant production and use models from propagation through disposal weighted as a portion of a 100-year assessment period using life cycle assessment.

Plants modeled	GWP (kg CO_2e)[z]	Reference
Red maple	–666	Ingram and Hall, 2016
Blue spruce	–430	Ingram, 2013
'Forest Pansy' redbud	–63	Ingram and Hall, 2013
Juddi viburnum	–11	Ingram and Hall, 2014a
'Densiformus' taxus	–9	Hall and Ingram, 2015

[z]1 kg = 2.2046 lb.

Impact of nursery and greenhouse plants in the landscape

The impact of landscape plants on atmospheric CO_2 during the production and use phases contributes to the life-cycle benefits. Although GHG occur during the production phase, CO_2 is sequestered from the air and stored in the wood of plants. As CO_2 is sequestered in wood, it is not contributing to the atmospheric concentration and not affecting GWP. Although plants differ in terms of the density of their wood, ≈50% of the dry weight of wood is carbon. Carbon is sequestered in growing woody plants at a rate based on increasing dry weight accumulation. A red maple in the lower-midwest United States is estimated to sequester 3632 kg CO_2 in a 60-year life (Ingram, 2012). However, the 60-year life expectancy of a red maple is less than the 100-year assessment period, and carbon sequestered in year 1 is held for 60 years but carbon sequestered in year 50 is held for only 10 years. Therefore, the impact on GWP by carbon sequestration in each year is weighted based on the portion of the 100-year assessment period.

Greenhouse gases also will be emitted when the tree is removed from the landscape at the end of its life. These GHGs are primarily the result of gasoline and diesel combustion in chain saws, chippers, and trucks. GHGs from take down and disposal were calculated to be 214, 148, and 88 kg CO_2e for red maple, blue spruce, and redbud, respectively (Ingram, 2012, 2013; Ingram and Hall, 2013). Take down and disposal of the shrubs in this study would result in 1.25 kg CO_2e GHG.

The weighted positive impact on CF during the use phase is reduced to account for GHG during take down and disposal. The weighted life-cycle CF of modeled trees and shrubs is presented in Table 2. In the case of the red maple, the weighted life cycle CF is –666 kg CO_2e; in other words, this reduction in atmospheric CO_2 is a positive impact on tree life-cycle CF and protects the environment.

As the green industry continues to mature, differentiation is an increasingly important business strategy for green industry businesses. One such way to accomplish this is by adopting environmentally friendly behaviors and/or selling products that offer environmental benefits. Consumers' awareness and concern about environmental issues are exhibited by their interest in purchasing products that are designed to reduce long-term adverse environmental impacts. With regard to the green industry, the relationship between environmentally friendly business practices and consumer preferences suggests that nursery and greenhouse firms may realize financial benefits for their efforts toward designing environmentally sound products. In the current examples, planting shrubs and trees that more than offset the amount of GHGs that are generated during their production by the amount of CO_2 they sequester during their life span could be emphasized during firm-level marketing efforts. From a demand standpoint, recent literature has substantiated that consumers increasingly consider the potential environmental impact of green industry products (e.g., CF) when making purchasing decisions (Hall, 2010; Yue et al., 2010, 2011).

This article has summarized the life-cycle impact of landscape plants on GWP. Herbaceous plant materials have minimal impact on GWP in the landscape; however, they contribute to environmental quality in other ways. Woody and herbaceous landscape plants provide many ecosystem services, including air quality improvement, microclimate enhancement, energy conservation, noise attenuation, and storm water management. They also contribute positively to human health and quality of life and increase property value (Hall and Dickson, 2011). Additional information about ecosystem services provided by landscape plants has been summarized in an Extension publication (Knight and Ingram, 2017, 2018), documented in other publications (Hall, 2010; Hall and Dickson, 2011), and compiled online at ellisonchair.tamu.edu.

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