How Green Are Trees? — Using Life Cycle Assessment Methods to Assess Net Environmental Benefits[1]

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Abstract

This study used life cycle assessment methods (LCA) to assess the carbon footprint of an urban tree from propagation to disposal, expanding on recent works focused primarily on inventorying the inputs for woody ornamental nursery production. Urban forest managers from the Chicago metropolitan area were surveyed on their plant selection, planting, maintenance, removal, and disposal practices to generate the model inputs. Alterations to management practices such as the pruning cycle can significantly reduce the age at which a tree changes from being a carbon emitter to being carbon neutral. Highly mechanized tree care practices extend the time to 33 years whereas less mechanized scenarios are 26 years. An annual windshield survey conducted by many municipalities will extend this period by two to three years. Results of this work offer a more accurate assessment of ecosystems services offered by urban forests and serve as a first step in identifying tree care practices which offer an optimal environmental return on investment.

Index words: carbon balance, costs and benefits, life cycle assessment, tree maintenance.

Species used in this study: red maple (*Acer rubrum* L.).

Significance to the Horticulture Industry

As components of green infrastructure programs, trees are planted because of their utility in reducing urban heat islands, controlling stormwater runoff, and sequestering carbon. Trees are an investment and as such require routine maintenance such as pruning and watering in order to increase their health and longevity. However, as trees sequester carbon over time, maintenance practices produce carbon emissions. Understanding the carbon balance is critical for understanding the environmental value of urban forest systems. Sequestration curves show that tree species sequester carbon differently over their course of life. Understanding emissions information associated with establishment, maintenance, and removal of a tree helps determine when a tree reaches carbon neutrality. Furthermore, mortality and decomposition rates help determine how much carbon one tree needs to sequester to make up for other losses. Development of this knowledge will help influence what species trees are planted, which planting and maintenance practices are adopted, and where trees are sited within the landscape (right tree in the right place).

Introduction

Greater than 50% of the global population inhabits cities, a number expected to grow to 66% by 2050, placing further stress on urban resources and regional ecosystems (UN 2014). This demand is expected to contribute over 70% of anthropogenic CO_2 emissions (IEA 2008), resulting in warmer global temperatures related to climate change (IPCC 2014). Impacts of rising temperatures are expected to have a concentrated effect on cities where low albedo surfaces contribute to an urban heat island effect (UHI) and growing population density will increase concentrations of anthropogenic pollutants and heat (Dorer et al. 2013, Carter et al. 2015). The use of trees in urban context extends beyond aesthetics to their ability to influence and reduce these impacts. Trees are considered one of the most effective and least energy intensive approaches to reducing UHI and mitigating greenhouse gas emissions (Stone et al. 2012). Studies by Norton et al. (2015), Masson et al. (2014), and McPherson et al. (1997) show that tree canopy contributes substantially to the reduction of UHI. The utility of trees for carbon sequestration is demonstrated by McPherson et al. (2015), Ingram (2012), and Nowak and Crane (2002). While urban growth continues at unprecedented rates, scholars and policymakers are also looking at the application of trees to ameliorate issues of noise, carbon pollution, soil erosion, and habitat loss (Sudipto et al. 2012). The growing interest in urban trees for addressing environmental issues warrants a closer look at the sustainability of trees. While the apparent benefits of trees are quite tangible and well-documented, far fewer works have investigated the environmental costs associated with the production, care, and removal of urban trees (Nowak et al. 2002).

Previous life cycle assessment studies. Carbon sequestration by urban trees can be offset by urban forestry management practices that concurrently release carbon to the atmosphere. Several studies quantified greenhouse gas emissions during nursery tree production (Ingram 2013, Ingram and Fernandez 2012, Ingram 2012, and Kendall and McPherson 2012). However, only recently are studies emerging that consider the life cycle of the tree once planted in the landscape. A study of emissions associated with commercial arboriculture practices in the United Kingdom illustrates the impact of mechanized tree care practices, showing that the arboriculture industry releases seven times more CO_2e per year than other similar sized industries (Luck et al. 2014). Carbon emissions associated with urban arboriculture practices in Los Angeles were evaluated by McPherson and

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Kendall (2014) and McPherson et al. (2015). The importance of understanding the lifecycle post-planting is to ensure that forest ecosystems do not eventually become net emitters of carbon (Nowak 2002).

In a cradle-to-gate analysis, container nursery production of a #5 (nominally a 19-L or 5-gal) tree was found to be a net greenhouse gas (GHG) emitter, with an estimate of 4.6 kg (10.1 lb) of CO_2e (Kendall and McPherson, 2012). A similar study builds on this work by including the post-nursery management of urban trees in a cradle-to-grave analyses of *Acer rubrum* 'October Glory' (Ingram 2012). This work, which was based on results from survey data estimating that carbon footprint of *A. rubrum* to be 8.213 kg (18.1 lb) CO_{2e} before leaving the nursery site, emphasizes the importance of the nursery production process. The author postulates that if the tree were to live 60 years in a favorable, suburban landscape in the Lower Midwest and undergo minimal maintenance, after accounting for 92.9 kg (204.8 lb) CO_2e for take down and disposal at end of life, the net carbon sequestered would be approximately 800 kg (1,763.7 lb) CO_2e (Ingram 2012). Post-nursery management, however, is estimated using assumptions of minimal tree care. Nowak (2002) provided insight on the carbon impact of mechanized urban tree care management practices on the resultant carbon budget of a tree, showing that maintenance could significantly reduce or eliminate carbon sequestration benefits, potentially causing trees to become net carbon emitters. A more recent study highlights emissions and sequestration under varying management scenarios for California sycamore (*Platanus racemose* Nutt.) planted as part of the Million Trees program in Los Angeles, CA (McPherson et al. 2015). Results illustrate the broad range of outcomes, with the highly mechanized scenario as a net carbon emitter (1.204t CO_2) and the lowest emission case as a net carbon sink (–3.768t CO_2).

Research objective. The objective of this research was to quantify the post-nursery production phase of the life cycle assessment (Fig. 1) using survey data regarding tree planting and management practices. Carbon emissions from urban tree care are dependent on the nursery production practices and life cycle of management practices. A tree's lifespan can be described in six steps: nursery production, tree planting, tree growth, tree maintenance, tree removal, and tree disposal. Each phase of a tree's life requires a varying degree of energy inputs. Using survey data, this study was able to ascertain common management practices used by urban forestry programs in metro-Chicago. Building on Ingram (2012) and Nowak (2002), this study quantifies the life cycle of the tree *A. rubrum* post-nursery under varying management scenarios reflecting different degrees of mechanization.

Implications of research. The real impact of urban tree care is demonstrated through studies such as the one reported herein. The results are meant to be used as a guide for municipalities as they engage in current and future urban forestry efforts. A better understanding of the long-term care impacts is expected to guide changes in planting, maintenance, and management practices. Siting a tree in an urban area will impact its long-term management (species and relation to utilities) and appropriate design of the planting bed will impact the longevity of the tree (design and preparation of planting beds).

Goal, scope, and functional unit. The purpose of this research was to provide a more accurate assessment of the ecosystem services offered by urban forests and to serve as a first step in identifying tree care practices which offer an optimal environmental return on investment. As such, our goal was to quantify the life cycle of an average urban maple tree (the most widely planted species according to our survey) in metro-Chicago, Illinois. Specifically, we sought to calculate if and when a tree reaches a point of carbon neutrality and determine if urban trees are net carbon sinks or sources. This study evaluated the life-cycle inputs used to care for urban trees grown in three different urban settings: residential, commercial downtown, and industrial.

Materials and Methods

Initial survey of urban forestry programs. Urban foresters from the Chicago metro area were surveyed in the summer of 2013 to assess variation and commonalities in their management efforts. A web-based survey (SurveyMonkey, Palo Alto, CA) was distributed by the Northeast Municipal Foresters (NEMF, an urban forestry group based in the sample area) to its members. The survey was largely made up of open-ended questions. Prior to electronic distribution, the project was introduced though a pair of talks and a discussion session at a NEMF meeting (November 2012). The survey was refined to address questions of interest to those in attendance. The survey was also split into two parts to meet the group's preferred maximum time for completion (10 minutes). Two urban foresters from outside the study area pretested the survey to confirm anticipated time requirements and assess survey clarity. Both parts of the survey were distributed at the same time. Respondents were given a $10 gift card to an online retailer for each of the two sections successfully completed. One follow-up reminder was sent.

The scope of this analysis was a cradle-to-grave CO_2 assessment using data from previous work by Ingram (2012) for nursery production phase and data from the survey to develop the post-nursery fuel and material use inputs for planting, maintenance, and removal stages of a tree's life cycle. Survey results indicated that the most commonly planted urban tree in suburban Chicago was maple (varying species) of 5 to 7.5 cm (2 to 2.9 in) caliper. The functional unit used by Ingram (2012) in his analysis was a 5 cm (2 in) caliper red maple. Survey respondents indicated the average lifespan of *Acer* sp. to be 48 years in residential (standard deviation 17 years), and 31 (standard deviation 11 years) and 30 (standard deviation 8 years) years for commercial and industrial sites, respectively. Given the similarities between commercial and industrial tree longevity, these site types were combined and modeled separately from residential as commercial-industrial.

System boundaries and assumptions. The system boundary was defined as a 'typical' municipality in metro-Chicago where a tree was delivered by truck from the nursery, transported by truck to the planting site, planted, maintained over its life (watered initially and pruned throughout), and removed and disposed of by truck at the end of life. Figure 1 illustrates the system boundary. Forty-five urban forestry programs in suburban Chicago responded to a survey inquiring about urban forestry practices, including which nurseries they source tree stock, planting, pruning, and removal equipment types and practices, equipment horsepower and run time, and pruning and irrigation cycles. Survey results were used to establish the baseline and subsequent model scenario inputs for this study.

Emissions associated with the production of capital goods (planting and maintenance equipment) such as chainsaws, trucks, chippers, and aerial lifts were not included in this study as per PAS 2050:2011, Section 6.4.4 (PAS 2050:2011). Emissions associated with tree stabilization (T-posts and wire) and tree bags for watering (modeled after the TreeGator® Original, Spectrum Products, Inc. Youngsville, NC) were included in this analysis as per PAS section 2050:2011, section 6.4.5 (PAS 2050:2011). Because the study focuses on planting sites that are urban and suburban, land use change was not considered as part of this life cycle assessment.

This LCA was composed of seven steps: nursery production, delivery, planting, irrigation, pruning, removal, and disposal. An annual windshield survey (to assess tree survival and condition) was modeled separately to demonstrate the associated carbon impact. A baseline and three alternate scenario models were developed to study the impact of alternative management schemes on resultant carbon emissions. The baseline model assumes mostly mechanized planting, maintenance, and removal and is a representative model system reflecting the most mechanized urban forestry programs in suburban Chicago. Three alternate scenarios were provided that reflect tree care programs that rely on less mechanized practices for planting, maintenance, and disposal. Each subsequent scenario represented a slightly less mechanized strategy. Scenarios A and B were derivations of the baseline that utilize gradually smaller trucks and equipment. For example, the baseline might use a medium or heavy-duty truck whereas Scenario A would utilize a light-duty truck and Scenario B would utilize a landscape UTV for the same operation. The third scenario, Scenario C, is considered an ideal input scenario from an emission and longevity perspective. It assumes manual labor and hand tools will be used for most maintenance practices yet still includes irrigation after planting to help establish the tree and minimize mortality rates.

Light and medium-duty trucks. Two different emission rates were used in this study for light and medium-duty trucks — idling and in-use. Survey respondents provided operation times (in minutes) for the various steps within each phase. When a truck was used for a phase other than transport (irrigation, pruning, and removal), it was assumed to be idling. Estimation of vehicle idling emissions was made using EPA, DOE, and Argonne National Laboratory idle vehicle fuel consumption rates and emissions data for similarly sized vehicles (EPA 2002; Gaines et al. 2006). Light-duty trucks were assumed to consume 3.2 $L \cdot hr^{-1}$ (0.84 $gal \cdot hr^{-1}$) without a load and 4.2 $L \cdot hr^{-1}$ (1.10 $gal \cdot hr^{-1}$ with a load. Medium-duty trucks were assumed to consume 3.2 $L \cdot hr^{-1}$ (0.84 $gal \cdot hr^{-1}$) with no load and 4.31 $L \cdot hr^{-1}$ (1.14 $gal \cdot hr^{-1}$) with a load. Transport time provided by survey respondents indicated duration of trips where trees were being delivered or refuse was being discarded. A trip to and from the site was also assumed for each phase, which was estimated to average 18 minutes each way in a light-duty truck. Estimating emissions using travel time assumed an average speed of 56 kmh (35 mph) and 416 $g \cdot mi^{-1}$ CO_2 (14,560 $g \cdot hr^{-1}$) for medium duty truck (GM/Ford) and 297 $g \cdot mi^{-1}$ (10,395 $g \cdot hr^{-1}$) for light duty truck (GM/Ford). Emission rates were developed using the average emissions per mile for medium and light-duty trucks from 2009 to 2011 as provided by EPA/DOT National Highway Traffic Safety Administration Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards (Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 2010).

Tree production. This study builds on emissions results from a previous LCA study conducted by Ingram (2012) for nursery tree production. Our analysis assumes that as the tree

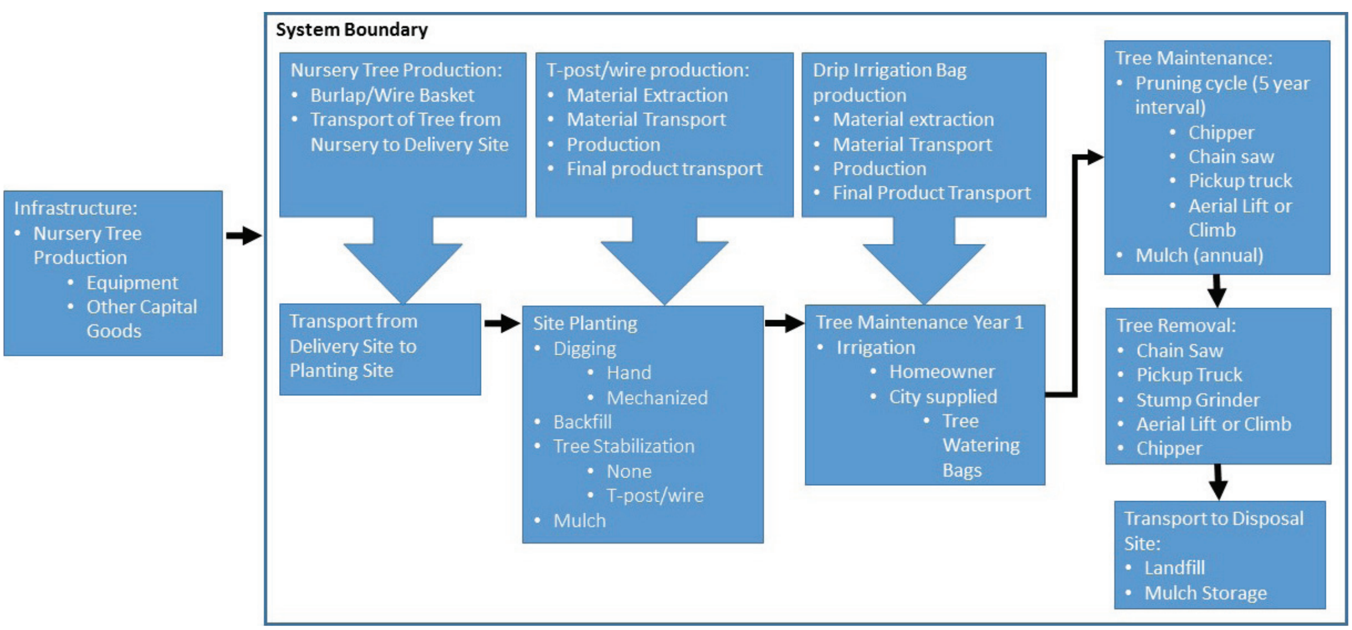

Fig. 1. Cradle-to-grave Life Cycle Assessment System Boundary for *A. rubrum*.

leaves the nursery, it has a carbon balance of 8.213 kg (18.1 lb) CO_2e (Ingram 2012). Refer to Ingram (2012) for description of nursery production process and associated inputs.

Delivery. Survey respondents provided names of the three most used nurseries from which they source trees. The distance from each nursery to the municipality was mapped in Google Maps to establish shipping distance. The average shipping distance from a nursery was 61 km (38 miles) using a medium duty truck for transport to the delivery site. A delivery weight of 136 kg (300 lb) per tree was used to establish the ton-km for a SimaPro (Simapro, PRé North America, Inc., Washington, DC) model simulation of the medium-duty truck. The delivery phase of the model also accounted for emissions associated with transport of the tree from the delivery site to the planting site. Survey respondents provided travel time for this trip, the average being 18 minutes. The vehicle type used to transport the tree from the delivery location to the planting site is modeled as a medium-duty truck for the base-case, light-duty truck for Scenario A, skid steer for Scenario B, and hand cart for Scenario C. Respondents using methods found in Scenario C reported that they have trees delivered directly to the planting site (Table 1).

Planting. The planting phase was composed of four steps: excavation, backfilling, tree stabilization, and mulching. Summarizing survey responses, the most frequently used equipment for excavation included the backhoe, auger, stump grinder, and/or tractor. Manual digging with a shovel was also commonly practiced. Operation time and horsepower (HP) varied by equipment. Emission information for off-road equipment (chippers, skid steer, aerial lifts, etc.) was derived using the EPA Motor Vehicle Emissions Simulator (MOVES) (EPA 2014). MOVES provides emissions data for off-road equipment in terms of $g{\cdot}hp^{-1}{\cdot}hr^{-1}$. MOVES data combined with survey results (HP and operation time) were used to create the model components in SimaPro LCA analysis software version 8.05. Backfilling was often done by hand, though some respondents indicated use of a skid steer or tractor. Tree stabilization, when done, called for three 1.8 m (6 ft) rail steel tee posts with aluminum anchoring wire and rubber hose. These items were modeled using SimaPro LCA analysis software, which includes manufacturing and processing of rail steel and the production and extrusion of aluminum wire and rubber hose. Production weights for these materials were assumed based on shipping weights of similar commercially available products. An 8 cm (3 in) depth of mulch was typically applied to newly planted trees by all municipalities. Because municipalities indicated that they use recycled mulch from tree pruning and removal, additional emissions for this step were not accounted for as they would be created in the pruning and removal stages of another tree's life. It is assumed that when the tree is planted, mulch was transported along with the tree to the planting site. The final step in this phase was the installation of a tree watering bag. The emissions associated with the creation of the tree bag material were developed in the SimaPro LCA modeling software using polyethylene production and extrusion processes. The baseline simulation utilized a backhoe (excavation); tractor (move tree and backfill around it); tee posts, wire, and rubber hose for stabilization; and tree bag for watering. Scenario A inputs were left the same as the base-case model. Scenario B utilized a grinder for excavation, skid steer for backfilling, a tree watering bag, and no stabilization materials. Scenario C utilized manual labor and shovels for excavation and backfill and a tree bag, with no tree stabilization (Table 2).

Irrigation: Tree watering, when done by the municipality, was repeated approximately ten times following the tree planting (once per week until the fall season). Some municipalities relied on residents to water the tree after planting. The baseline and subsequent scenarios were modeled based on the assumption that the municipality maintained watering of trees after planting. Equipment commonly used in the irrigation process included a light or medium-duty truck with a pump or a landscape UTV (such as John Deere® Gator) with water tank and pump. The landscape UTV was modeled using the SimaPro database that included machine operation with similar horsepower, 20 HP. Watering was not commonly done after the initial planting year. Therefore, the model assumed no watering after establishment in the planting season. The base-case scenario was modeled using a medium-duty truck and supplemental pump. Scenarios A and C were modeled using a light-duty truck and supplemental pump. Scenario B was modeled using a landscape UTV and supplemental pump. Scenario C was modeled using a light-duty truck because distance would likely preclude use of a landscape UTV (Table 3).

Pruning. Survey respondents indicated chippers, chainsaws, and a light truck were commonly used by all municipalities for tree pruning. Additional equipment used to get into the tree included a bucket truck (Baseline), aerial lift (Scenario A, B), or tree climbing with rope and saddle (Scenario C) (Table 4). A 5-year pruning cycle was most common among municipalities, though some respondents indicated a longer interval of around 10 to 15 years. The longer pruning cycle led to a longer equipment run time as indicated by respondents, which resulted in a negligible impact on carbon emissions (343 kg vs 318 kg [756.2 lb vs 701.1 lb]). Therefore, the modeled scenarios were analyzed using a 5-year pruning cycle. SimaPro LCA software includes chainsaw operation as a process, which is based on the EPA non-road emissions data for 2008. This process was used for the analysis. Remaining equipment inputs were created in SimaPro using emissions information provided by the EPA MOVES model for non-road equipment.

As noted previously, trees grown in urban and industrial areas do not live as long as those in residential areas. This reduced lifespan would only impact the pruning phase of the tree's growth since it results in fewer pruning cycles. As such, the pruning cycle was modified to reflect a shorter lifespan for the urban and industrial tree planting life cycles. A reduction in age also impacts the number of windshield surveys conducted during the tree's life, which was reduced.

Removal. Tree removal includes three pieces of core equipment: chipper, chainsaw, and light-duty pickup truck. Additional equipment used in tree removal can include a stump grinder (Baseline), log loader (Baseline), and a lift (aerial [Scenario A, B], bucket [Baseline], or rope and saddle [Scenario C]) (Table 5). Emissions outputs for all equipment except the truck and chainsaw were developed using EPA MOVES model. Chainsaw emissions exist in the SIMAPRO database and are based on the EPA non-road emissions data

Table 1. Equipment used for tree transport from delivery site to planting site as estimated for 4 different situations. The baseline represents highly mechanized tree care practices with each subsequent scenario representing a gradually lower level of mechanization.

					Scenario		
Tree growth phase	**Equipment type**	**HP**	**Fuel use**	**Base case**	**A**	**B**	**C[z]**
Delivery (18 minutes)	Hand cart	—	—	x	x	x	x
	Medium-duty truck	350	Diesel	x			
	Light-duty truck	200	Diesel		x		
	Skid steer	66	Diesel			x	

[z]*Respondents using methods found in Scenario C reported that they have trees delivered directly to the planting site.

Table 2. Equipment and materials comparison for tree planting. The baseline represents highly mechanized tree care practices with each subsequent scenario representing a gradually lower level of mechanization.

					Scenario		
Tree growth phase	**Equipment type**	**HP**	**Fuel use**	**Base case**	**A**	**B**	**C**
Planting	Excavation						
	Hand	—	—				x
	Backhoe	75	Diesel	x			
	Auger	63	Diesel				
	Grinder	78	Diesel		x	x	
	Tractor to move and/or backfill	115	Diesel	x	x		
	Backfilling						
	Hand	—	—				x
	Skid steer	66	Diesel		x	x	
	Tree stabilization						
	None	—	—			x	x
	6' T-post and wire	—	—	x	x		
	Mulching						
	3" wood chips	—	—	x	x	x	x

Table 3. Equipment compared for tree irrigation. The baseline represents highly mechanized tree care practices with each subsequent scenario representing a gradually lower level of mechanization.

					Scenario		
Tree growth phase	**Equipment type**	**HP**	**Fuel use**	**Base case**	**A**	**B**	**C**
Irrigation (10× first season)	None (homeowner)	—	—				
	Tree bag	—	—	x	x	x	x
	Light-duty truck	200	Diesel		x		x
	Heavy-duty truck	350	Diesel	x			
	Gator	20	Diesel			x	
	Small pump	5	Gas	x	x	x	x

Table 4. Equipment compared for cyclical maintenance pruning. The baseline represents highly mechanized tree care practices with each subsequent scenario representing a gradually lower level of mechanization.

					Scenario		
Tree growth phase	**Equipment type**	**HP**	**Fuel use**	**Base case**	**A**	**B**	**C**
Pruning (over life)	Chipper	200	Diesel	x	x	x	x
	Chain saw	5	Gas	x	x	x	x
	Pickup truck (light)	200	Diesel	x	x	x	x
	Aerial lift[z]	40	Diesel		x	x	
	Bucket	242	Diesel	x			
	Climb						x
	5 yr pruning cycle			x	x	x	x

[z]Pruning using a bucket truck is most common. Aerial lift has been included for comparison purposes.

Table 5. Equipment compared for tree removal and disposal phases. The baseline represents highly mechanized tree care practices with each subsequent scenario representing a gradually lower level of mechanization.

					Scenario	
Tree growth phase	**Equipment type**	**HP**	**Fuel use**	**Base case**	**A/B**	**C**
Removal	Chipper	200	Diesel	x	x	x
	Chain Saw	5	Gas	x	x	x
	Pickup Truck (Light)	200	Diesel	x	x	x
	Stump Grinder	78	Diesel	x		
	Log Loader	75	Diesel	x		
	Aerial Lift[z]	40	Diesel		x	
	Bucket	242	Diesel	x		
	Climb	—	—			x
Disposal	To Landfill (Truck)	210	Diesel	x		
	To Mulch Storage Site (Truck)	210	Diesel		x	x

[z]Removal using a Bucket Truck is most common. Aerial lift has been included for comparison purposes.

Table 6. Equipment HP and run times (includes in-use and idle run time) used for each model scenario. The baseline represents highly mechanized tree care practices with each subsequent scenario representing a gradually lower level of mechanization.

						Scenario		
Tree growth phase	**Equipment type**	**HP**	**Fuel use**	**Run time**	**Base case**	**A**	**B**	**C**
Delivery (18 minutes)	Hand cart	—	—					x
	Medium duty truck	350	Diesel	18	x			
	Light duty truck	200	Diesel	18		x		
	Skid steer	66	Diesel	18			x	
Planting	Excavation							
	Hand	—	—	0				x
	Backhoe	75	Diesel	28	x			
	Auger	63	Diesel	4				
	Grinder	78	Diesel	8		x	x	
	Tractor to move and/or backfill	115	Diesel	5	x	x		
	Backfilling							
	Hand	—	—					x
	Skid steer	66	Diesel	15		x	x	
	Tree stabilization							
	None	—	—					x
	6' T-post and wire	—	—		x	x		
	Mulching							
	**3" wood chips	—	—		x	x	x	x
Irrigation (10× first season)	None (homeowner)	—	—					
	Tree bag	—	—		x	x	x	x
	Light duty truck	200	Diesel	44		x		x
	Medium duty truck	350	Diesel	44	x			
	Gator	20	Diesel	44			x	
	Small pump	5	Gas	4	x	x	x	x
Pruning (over life)	Chipper	200	Diesel	15	x	x	x	x
	Chain saw	5	Gas	16	x	x	x	x
	Pickup truck (light)	200	Diesel	30.5	x	x	x	x
	Aerial lift	40	Diesel	26		x	x	
	Bucket	242	Diesel	26	x			
	Climb			0				x
	5 yr pruning cycle				x	x	x	x
Removal	Chipper	200	Diesel	48	x	x	x	x
	Chain saw	5	Gas	74	x	x	x	x
	Pickup truck (light)	200	Diesel	66	x	x	x	x
	Stump grinder	78	Diesel	30	x			
	Log loader	75	Diesel	37	x			
	Aerial lift	40	Diesel	58		x	x	
	Bucket	242	Diesel	120	x			
	Climb	—	—	0				x
Disposal	To landfill (truck)	210	Diesel	18	x			
	To mulch storage site (truck)	210	Diesel	18		x	x	x

for 2008. A summary of equipment HP and run time for the complete life cycle can be found in Table 6.

Disposal. Following removal, trees were disposed of, typically, by being processed into mulch for re-use within the community. Some respondents indicated that trunks were given to local mills for processing into lumber or that after mulching and cutting into logs, wood and mulch were left for the community to take and use. Some respondents indicated wood was taken to the local dump. The baseline model assumes wood was taken to the dump whereas all subsequent scenarios assume re-use as mulch. A travel time of 18 minutes each way was used for transporting waste or woodchips to and from a dumping site (either landfill or a mulch storage area).

Additional Inputs: Most municipalities indicated that an annual windshield survey of trees was conducted to assess damage. However, the particular type of vehicle used for the annual survey was not asked in the survey. Therefore, the model assumed that a light duty truck was used. This input was modeled separately from the baseline and subsequent scenarios to further illustrate the disaggregation of process impacts.

Sequestration. SimaPro was used to model the emissions. The Center for Urban Forest Research (CUFR) Tree Carbon Calculator (US Forest Service, 2015) was used to estimate carbon sequestration. Carbon is sequestered by trees at varying rates. The nursery production phase used in this study used results from a previous life cycle assessment of *Acer rubrum* 'October Glory' (Ingram 2012). CUFR provides sequestration by year of growth for *A. rubrum*. When establishing the point of carbon neutrality, where emissions were close but not equal to sequestration for a given year, the following year was used to establish the age at which the tree changes from being a carbon emitter to being carbon neutral.

Results and Discussion

Using SimaPro LCA software version 8.05, the baseline and three subsequent scenarios were modeled to establish global warming potential of a single tree. There is no doubt that mechanization simplifies tree care practices and that it is necessary for certain tree care phases. However, the use of smaller trucks and manual labor can significantly reduce carbon emissions. As expected, species of tree and planting site (residential vs commercial-downtown and industrial) influence the age at which a tree becomes carbon neutral. Different species sequester carbon at different rates and, as identified in the survey data, location within the city (residential, urban-commercial, and industrial) impacts lifespan of the tree.

Machinery. The use of machinery for maintaining trees is necessary for certain phases of a tree's life. When possible, use of hand tools over mechanized equipment contributes to a reduction in emissions. Utilizing manual labor for planting and avoiding tree stabilization could eliminate emissions associated with planting (aside from tree delivery), resulting in a reduction in emissions of 121 kg (266.8 lb) CO_2e per tree. Using light-duty equipment in lieu of heavy equipment in the removal phase is expected to reduce emissions by 396 kg (873 lb) CO_2e. Similar impacts are seen for pruning and removal. Pruning practices had the most significant reduction on carbon emissions in the model. Minimizing use of machinery for pruning would result in a reduction of 1,026 kg (2,262 lb) CO_2e. Literature tends to suggest that a 5-year pruning cycle is best (Churack et al. 1994, Miller and Sylvester 1981). However, Ryder's (2013) study shows that pruning may have the greatest impact on tree health if conducted when trees are young, which reduces the need for heavy equipment, reduces the need for heavy pruning as the tree matures, and corrects issues that lead to decay and tree failure later in life.

Irrigation. The irrigation scenarios' impacts on emissions were not significantly changed from the baseline. A shift from a medium truck to a light truck reduces irrigation emissions by 27 kg (59.5 lb) CO_2e. Irrigation is viewed as an important step for tree establishment and essential for minimizing mortality rates. Because of this, we assumed that the municipality would oversee tree watering in all scenarios rather than rely on residents and utilize drip irrigation bags.

When does a tree attain carbon neutrality? Figure 2 provides a summary of the scenario results. The baseline scenario for residential trees, representing highly mechanized tree care practices, would emit an estimated 2,919 kg (6,435.3 lb) CO_2e. Scenario A, the moderately mechanized residential scenario, produced 1,725kg (3,803 lb) CO_2e. For residential trees, Scenarios B and C (the ideal scenario), which relied on manual labor when possible and light irrigation to establish the tree, would reduce emissions to 1,693 and 1,340 kg (3,732.4 and 2,954.2 lb) CO_2e respectively. These values were compared to the sequestration curves of *A. rubrum* to determine at which point in the tree's life it becomes carbon neutral under the varying management regiments. In the baseline scenario, *A. rubrum* achieves carbon neutrality at 33 years. An annual windshield survey extends the point of carbon neutrality out two years. However, the CUFR calculator shows the maximum carbon sequestered at 33 years. The moderate and low mechanized scenarios for residential trees indicate this time can be reduced to around 26 years for *A. rubrum*. Figure 3 illustrates carbon emissions over the lifespan of a tree for a residential tree. Similarly, when emissions associated with the windshield survey are added, this time is extended two to three years from an additional 392 kg (864.2 lb) CO_2e. Note that some municipalities may use hybrid cars for conducting windshield surveys, which would greatly lower associated emissions and its impact on the point at which the tree attains carbon neutrality (McPherson et al. 2015).

Figure 2 provides a summary of the scenario results. During their functional life, production, transport, transplanting care and removal of trees grown in urban-commercial and industrial areas emit 2,127, 1,296, 1,264, and 1,034 kg (4,689.2, 2,857.2, 2,786.6 and 2,279.6 lb) CO_2e for the baseline, moderately mechanized (Scenario A), slightly mechanized (Scenario B), and ideal scenarios (Scenario C), respectively. The average lifespan for trees planted in these two environments is approximately 30 years. Given this reduced lifespan, there are also reduced emissions (although over the full lifespan of the tree, less carbon is sequestered, as well). Similar to residentially grown trees, *A. rubrum* attains carbon neutrality at 30 years for baseline and 24 years

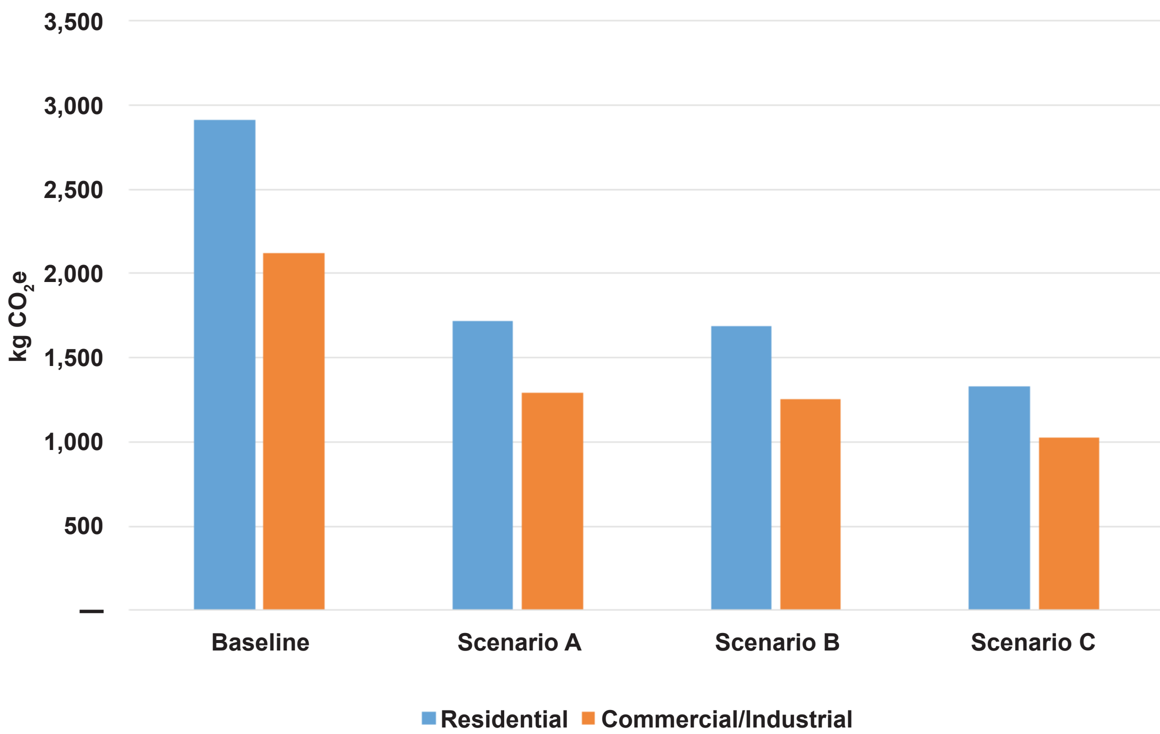

Fig. 2. Carbon emissions by scenario for residential and commercial/industrial trees over the tree lifespan (48 years residential and 30 years commercial/industrial).

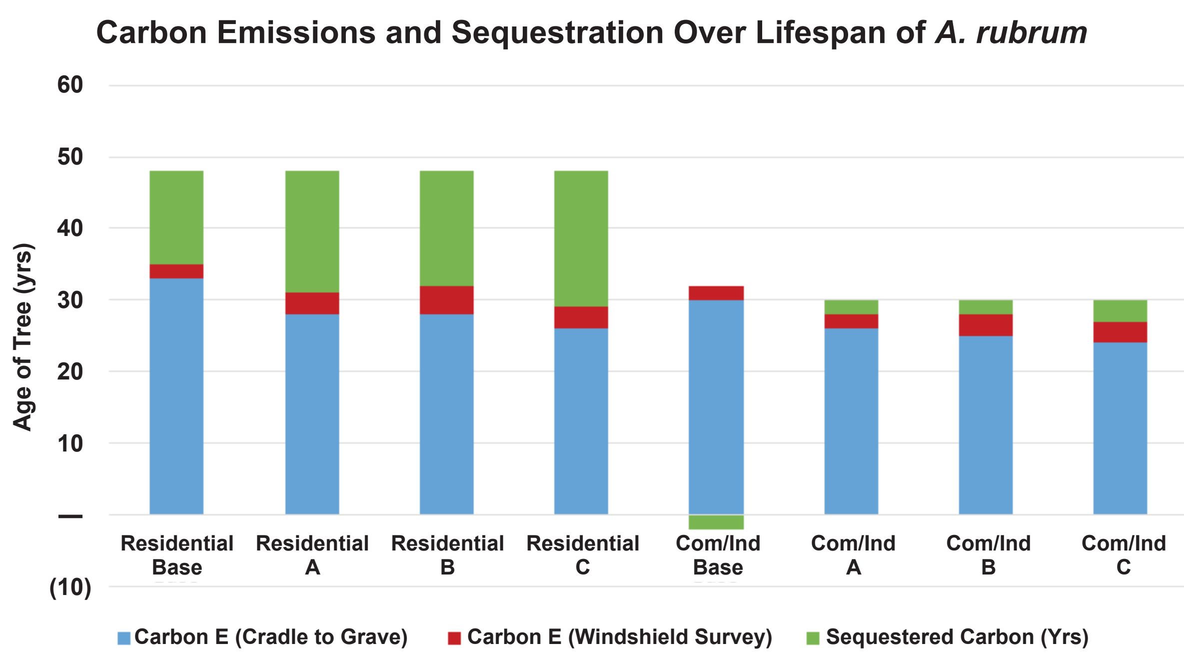

Fig. 3. Cradle-to-grave carbon emissions and sequestration potential for residential and commercial/industrial trees. Bars represent years as a carbon emitter during the tree's life span (Carbon E cradle to grave), years as a carbon emitter during the driving survey (Carbon E windshield survey) and number of years sequestering carbon during the 48 year average lifespan of a residential tree and the 30 year lifespan of a commercial/industrial tree.

in Scenario C. Figure 3 illustrates carbon emissions over the lifespan of a tree for a commercial/industrial tree. The addition of a windshield survey extends this age by one to two years from an additional 242 kg (533.5 lb) CO_2e.

The ideal scenario, Scenario C, reduces emissions relating to tree care by 1,578 kg (3,478.9 lb) CO_2e compared to the baseline for a residential tree and 1,093 kg (2,409.7 lb) CO_2e for an urban/industrial planted tree. The reduction illustrates the impact less mechanized planting, pruning, and removal processes have on carbon emissions for a single tree.

For this study, emissions data associated with nursery production were taken from Ingram (2012). Kendall and McPherson (2012) conducted a similar analysis for a #5 and #9 tree estimating 4.6 and 15.3 kg (10.14 and 33.7 lb) CO_2e per tree respectively. Despite differences in production methods and geographic location of the studies, the calculated difference in emissions in the tree nursery is relatively small when compared to the total for the complete life cycle. Given the purpose of this study, to establish when (at what age) a tree attains carbon neutrality, the difference is insignificant.

Including a windshield survey, results were considerably lower than those calculated by McPherson et al. (2015) where similar equipment and life-cycle phases were used to study carbon life cycle of *Platanus racemosa* in Los Angeles. However, this is largely due to the fact that McPherson included decomposition of mulch and discarded woody material from trimming and removal. Additionally, this study uses longer transport distances, more intensive irrigation, and different methods for calculating equipment emissions. McPherson et al. (2015) also included several different methods for handling tree waste, including bio-energy production. Watering and estimates and biogenic carbon emissions lead to the most significant differences between studies. Given the occurrence of drought in California, it is expected that irrigation would become a significant contributor of carbon emissions over the course of a tree's life. In Illinois, common practice is to irrigate the first season to establish the tree and then cease irrigation. Note that biogenic emissions associated with woody biomass decomposition (from mulch) were not taken in to account for the life-cycle of *A. rubrum* in this study.

Trees sequester carbon at varying rates depending on species. *A. rubrum* is a slower growing maple, which means that it sequesters carbon slower compared to *A. saccharinum*, for example, which would attain carbon neutrality in half the time required for *A. rubrum*. *A. platanoides* and *A. saccharum*, other relatively fast growing maples, similarly would attain carbon neutrality approximately ten years earlier. The point at which urban trees become carbon neutral depends nearly as much on the species planted as the equipment used to maintain. However, these faster growing trees may not always be the best choices for urban residential, downtown, and industrial landscape trees. Faster growing species are often characterized by weaker wood and require more maintenance over the course of lifetime, which is shorter. This presents a tradeoff between GHG emissions associated with increased maintenance and sequestration potential.

For the baseline and three scenarios, each species of maple would attain carbon neutrality if it reached the anticipated lifespan. However, tree mortality rates were not considered. Surviving trees should be expected to sequester enough carbon to offset the trees that did not survive after planting. McPherson et al. (2015) estimates that of the trees planted as part of the Million Trees Los Angeles program, approximately 67% of planted trees did not survive. A study by Nowak (1990) found that 34% of trees died after the first two years of planting. These losses increase the carbon footprint of planting efforts which have not been accounted for in previous tree LCA studies. Assuming a 30% mortality rate for 200 newly planted trees, the point of carbon neutrality would be extended by approximately 3 years for each maple species.

Additionally, it is unclear if the sequestration curves provided by CUFR account for the reduction in stored carbon associated with decay resulting in biogenic carbon emissions. Recent works by Koeser et al. (2015) and Luley et al. (2009) show similar results, illustrating that approximately 50 to 60% of standing trees have some level of internal decay. Luley et al. (2009) focused decay research specifically on maple street trees in New York, finding that silver maple tended to display the greatest severity of decay. This not only impacts sequestration rates but also tree lifespan. Ryder and Moore (2013) notes that a small amount of formative pruning when trees are young reduces many problems associated with mature tree failure, which also reduces need for tree pruning efforts over the life of the tree.

In summary, while all maple trees that survive are expected to achieve carbon neutrality over their functional life in residential, urban, and industrial environments, additional sequestration benefits could be realized if modifications are made to planting, maintenance, and removal practices. The greatest impact comes from changes to pruning practices, which reduce GHG emissions by 1,026 kg (2,262 lb) CO_2e per tree. This provides support for the idea of the 'right tree in the right place' planting practices and irrigation to help reduce mortality and need for pruning. Additionally, developing an alternative method of conducting windshield surveys would also provide significant reduction in overall GHG emissions. As McPherson et al. (2015) suggested, a hybrid vehicle could be used. An alternative strategy relying on public feedback, crowdsourcing information, or merging this task with other municipal duties could eliminate the need for the annual windshield survey.

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