Million Trees Los Angeles: Carbon Dioxide Sink or Source?

Abstract

This study seeks to answer the question, 'Will the Million Trees LA (MTLA) programme be a CO_2 sink or source?' Using surveys, interviews, field sampling and computer simulation of tree growth and survival over a 40-year period, we developed the first process-based life cycle inventory of CO_2 for a large tree planting initiative (TPI). Carbon dioxide emissions and reductions were simulated for 91,786 trees planted between 2006 and 2010, of which only 33.6% were estimated to survive to 2045. Early monitoring results suggest that the MTLA programme is achieving success in terms of tree survival and growth. MTLA was estimated to release 17,048 t of fossil CO_2 over the 40-year period, and to avoid -103,618 t of emissions from energy savings (-101,679 t) and biopower (-1,939 t). The largest sources of fossil CO_2 emissions were irrigation water (8,095 t) and equipment (4,704 t). The trees were projected to store -77,942 t CO_2 in their biomass. This amount was nearly offset by biogenic emissions from the decomposition of wood (54,293 t) and wood combustion (12,067 t). The MTLA programme will be a CO_2 sink if the projected 40-year avoided emissions from energy savings and biopower are realised. Although the trees planted by the MTLA programme are likely to be a net CO_2 sink, there is ample opportunity to reduce emissions. Examples of these opportunities include selecting drought-tolerant trees and utilising wood residue to create wood products or generate electricity rather than producing mulch.

Introduction

Mayors in a dozen of the largest US cities have launched tree planting initiatives (TPIs), together pledging to plant nearly 20 million trees (Young, 2011). Most of these TPIs are part of local climate protection programmes. Cities assume that the planted trees will help them meet greenhouse gas (GHG) reduction goals. However, there has never been a full accounting of carbon dioxide (CO_2) emissions associated with a TPI, so it is unclear whether TPIs are likely to be effective strategies (Pataki *et al*., 2011). This paper compiles data from several previously published studies to answer the question: will the Million Trees Los Angeles (MTLA) programme be a CO_2 sink or source?

By fixing carbon dioxide (CO_2) during photosynthesis and storing it as carbon (C) in aboveground and belowground biomass, trees act as a carbon sink. Also, trees reduce summertime air temperatures and building energy use for air conditioning, thus decreasing GHG emissions from power plants that generate electricity (Akbari, 2002). In winter, trees can increase or decrease the GHG emissions associated with the energy consumed for space heating, depending on the local climate, site features and building characteristics (Heisler, 1986). After trees are removed, their wood residue may be converted into mulch, with CO_2 gradually released to the atmosphere through decomposition. Carbon may continue to be sequestered for a substantial amount of time in wood products and landfill. Carbon from urban forests may also be used to provide fuel for biomass energy as a renewable form of energy.

Stone (2012) regards tree planting as the most effective and least energy-intensive approach to cooling urban environments and mitigating GHG emissions. The potential for urban trees to store CO_2, as well as to reduce GHG emissions through energy effects, has been analysed for cities around the world (Jo, 2002; Chaparro and Terradas, 2009; Yang *et al*., 2005; Strohbach and Haase, 2012; Escobedo *et al*., 2010).

Keywords:

carbon footprint,
climate change,
tree planting,
urban forestry,
urban trees

E.G. McPherson[1], A. Kendall[2] and S. Albers[2]

[1] Urban Ecosystems and Social Dynamics Program, Pacific Southwest Research Station, USDA Forest Service, USA

[2] Department of Civil and Environmental Engineering, University of California, Davis, USA

Less well studied are the GHG emissions associated with trees and their management as they grow, die and decay.

Life cycle and carbon footprint analyses have been conducted previously in two locales: Montjuic Park in Barcelona, Spain and an urban greenspace project in Leipzig, Germany. In the Montjuic Park study, the energy consumed by gardeners' vehicles and equipment accounted for only 1.2% of the total annual energy consumption (Sola *et al.*, 2007). The study in Leipzig projected carbon footprints over 50 years for several design and maintenance scenarios applied to a 2.16-ha green space (Strohbach *et al.*, 2012). Assuming slow tree growth, tree planting and maintenance, CO_2 emissions were only 4.1% and 2.2% of the total net CO_2 stored in trees after 50 years, respectively. In a study of individual trees, planting and maintenance emissions were simulated assuming different rates of tree growth and mortality, lifespans and pruning cycles (Nowak *et al.*, 2002). Annual maintenance emissions were only reported for a tree with conservative management and a short lifespan (8.4 to 34.9 kg $CO_2{}^{-yr}$).

The few studies conducted to date suggest that tree planting and maintenance emissions are relatively small; less than 10% of the amount of atmospheric CO_2 reduction from biogenic storage and avoided emissions. However, these studies do not include the full scope of emissions at each life stage.

MTLA Programme

Since MTLA's inception in 2005, approximately 407,000 trees have been planted by public agencies, non-profits, schools and residents. We categorise MTLA plantings from 2006 through 2010 as Street, Park or Residential projects.

Street tree planting includes signature projects that maximise environmental benefits and programme visibility by planting large trees (5.1 cm diameter at breast height (DBH)) along heavily travelled corridors. Street tree planting projects occur in residential areas when trees are 'adopted' by locals who agree to maintain those trees.

Residential tree planting occurs on private property. Most Residential trees are planted via tree adoption requests. These requests are parcelled out by MTLA staff to the non-profit responsible for activities in the area. The Los Angeles Conservation Corp (LACC) purchases, distributes and supervises the planting of most Residential trees. Park tree planting projects are supervised by the Los Angeles Recreation and Parks Department (RPD). The non-profit TreePeople organises and trains volunteers who participate in Park tree planting and stewardship events.

This paper describes the results of the first detailed inventory of CO_2 emissions for a TPI (McPherson and Kendall, 2014), as well as results from a recent study that combined the field sampling of tree survival and growth with the numerical modelling of future atmospheric CO_2 reductions to assess the performance of the MTLA planting (McPherson, 2014). Our goal is to determine the net CO_2 emissions attributable to the MTLA initiative.

Methods

The study area covers 1,022 km^2 of urbanised land in the City of Los Angeles, CA. Los Angeles lies within one of the largest metropolitan areas in the United States (population 3.8 million). The Mediterranean climate is characterised by hot, dry summers and cool, rainy winters from October through April. Portions of Los Angeles fall into two of sixteen US climate zones (McPherson *et al.*, 2011). Two of the city's 15 council districts (11 and 15) are in the Coastal Southern California climate zone, and the remainder are in the Inland Empire zone, hereafter referred to as the Coastal and Inland zones.

The scope of our analysis includes a cradle-to-grave CO_2 inventory of fuel use, material inputs and biogenic CO_2 flows for each life stage of the MTLA programme over a 40-year period. This time horizon corresponds to the expected lifespan of an urban tree, which, based on a meta-analysis of 16 survivorship studies, ranges from 26 to 40 years (Roman and Scatena, 2011). Park and Residential trees are likely to live longer than Street trees because their growing conditions are less harsh.

CO_2 Stored and Avoided Emissions

Information on the numbers and species of Street, Park and Residential trees planted from 2006 through 2010 came from databases maintained by MTLA, the RPD and the LACC. The methods used to model tree population dynamics and the effects on CO_2 are described in detail in a previous study. That study assumed that trees were planted in the spring, and used establishment period survival rates based on the results of two monitoring studies. Survival rates after the five-year establishment period were taken from literature-based mortality estimates. The simulations assumed that dead trees were not replaced. The results were reported for trees planted in Street, Park and Residential locations to reflect observed differences in species composition, growth and survival.

Tree-growth models were developed from data collected on predominant street tree species growing in two reference cities, Santa Monica (Coastal) and Claremont (Inland), and used as the basis for modelling tree growth (Peper *et al.*, 2001). To calculate biomass and CO_2 stored in each tree planted, climate zone, species name and DBH were used with 26 species-specific equations for trees growing in open, urban conditions (Pillsbury *et al.*, 1998; Lefsky and McHale, 2008). The marginal CO_2 stored in year *x* was calculated as the total amount stored in year *x+1* minus the total amount stored in year *x*.

Calculations of the energy effects of the Street and Residential trees on buildings were based on computer simulations that incorporated tree location and building information from the 2011 monitoring study. Climate and shading effects were modelled following the methods outlined by McPherson and Simpson (1999). Park trees were omitted from the analysis because these trees shaded very few air-conditioned buildings.

CO_2 Emissions Inventory

The Life Cycle Inventory (LCI) includes categories such as tree production, planting, pruning, sidewalk repair, removal, mulch decomposition and biopower (Figure 1). All of the data were acquired directly via interviews and from reports (McPherson and Kendall, 2014). The following section provides general descriptions of the methods for calculating emissions. Information sources, emissions factors, the equations used to calculate emissions and other technical information can be found in McPherson and Kendall (2014).

Equipment emissions occur during activities such as cutting tree wells in concrete, tree pruning and removal, chipping, stump grinding and pavement grinding. The total annual equipment emissions were calculated as the sum of the emissions per tree across climate zones, equipment types, species and locations (i.e., Street, Park and Residential). The annual run-time (RT) hours for each equipment type depended on the number of trees treated (e.g., planted, pruned, removed) and their size (DBH). Published data were used for a range of tree sizes (hours per DBH class) to

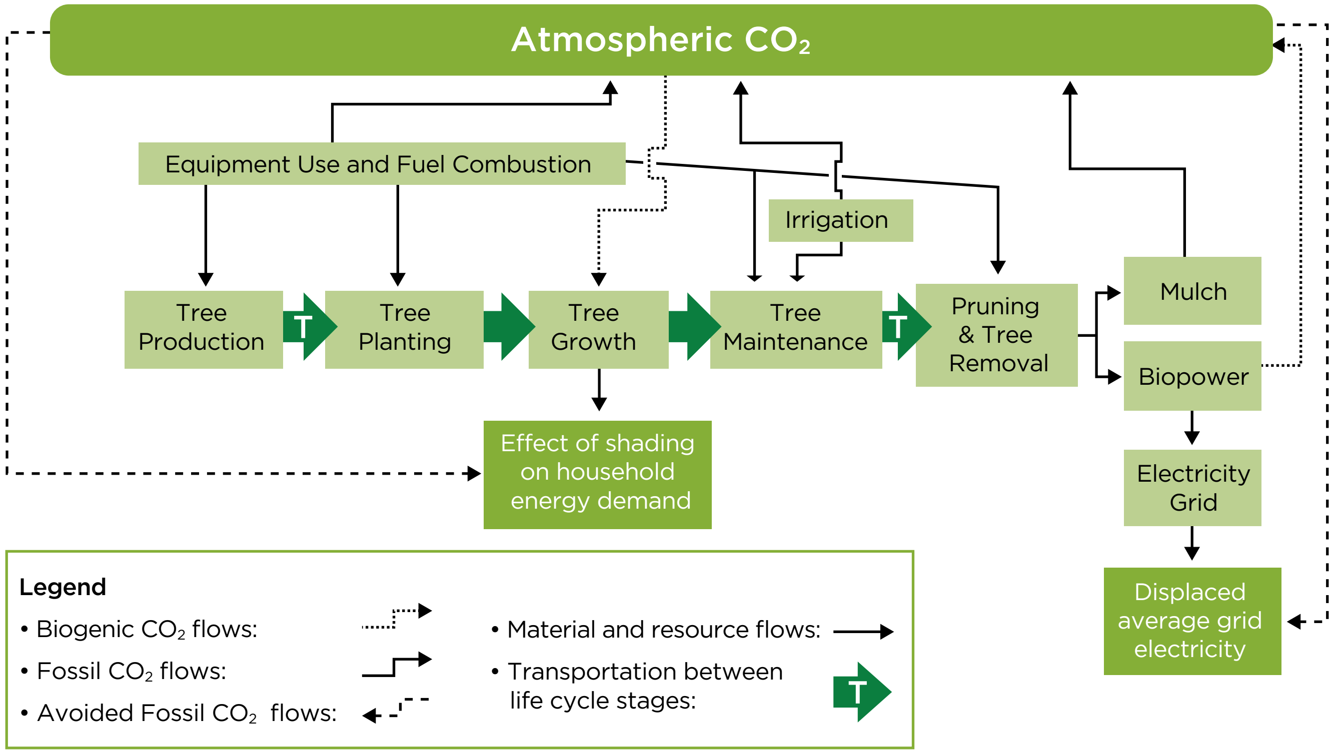

Figure 1: MTLA system diagram

calculate the RT hours per tree for each activity (e.g., prune, remove) and equipment type (e.g., chainsaw, chipper) (Nowak *et al.*, 2002).

Vehicle emissions were associated with the transport of trees, personnel, volunteers, equipment and materials to and from the tree sites. Vehicle emission constants were calculated for each vehicle type based on the distance travelled per tree (km), vehicle fuel efficiency (L^{-km}), fuel type and EFs. Total annual vehicle emissions were calculated as the sum of emissions across climate zones, vehicle types, species and locations.

Tree Production

This study applies the emission results from a previous LCI of a tree production system in California to 3.8 cm and 5.1 cm DBH trees planted in Los Angeles (Kendall and McPherson, 2012). The CO_2 emissions for 3.8 cm and 5.1 cm DBH trees were 15.3 and 32.0 kg per tree, respectively.

Planting and Initial Irrigation

From 2006 to 2010, 56,453 Street trees were planted (61.5% of all trees planted). Most Street trees (72.8%) were planted in residential areas and consisted of 3.8 cm DBH trees (77.2%). The remaining trees were planted in commercial areas and 12,844 were 5.1 cm DBH trees. Trees, shovels, rakes and other planting equipment were transported to the planting sites in a light duty truck.

LACC staff cut tree wells out of concrete pavements at 3% of all Street tree sites (1,694). Two light duty trucks transported a concrete saw and compressor to cut each tree well (1.2 m x 1.8 m) and drove the removed concrete to the recycling site.

Street trees in commercial areas were watered twice per month (56.8 l per visit) from a light duty water truck (0.8 m^3 tank) for the first two years. Residents were asked to provide 5.7 l of water per week to each residential Street tree during the first two years. After the two-year establishment period, irrigation was provided by adjacent businesses and residents and modelled using the Water Use Classification of Landscapes Species (WUCOLS) approach (Costello and Jones, 1994).

During 2006 to 2010, 12,472 Park trees (13.6% of total planted, all 3.8 cm DBH) were planted by RPD personnel and volunteers. Trees were planted by hand and native soil was used for backfill. RPD staff used light and medium duty trucks to transport trees and tools to each planting event. TreePeople staff drove a light duty truck. TreePeople organised and trained 6,661 volunteers who participated in 90 Park tree planting events and 3,931 volunteers who participated in 128 stewardship events. Approximately 55% of the volunteers drove sedans a 48.3-km round trip to these events, while the remaining 45% carpooled (assuming three people per sedan). It was assumed that Park trees received no new irrigation because most were planted in irrigated grass areas where supplemental watering was unnecessary.

From 2006 to 2010, 22,861 trees (24.9% of the total planted, all 3.8 cm DBH) were planted in Residential sites. NGOs transported trees and personnel to the planting sites in light duty trucks. Trees were planted by residents without mechanised equipment or imported soil. It was assumed that all Residential trees received supplemental irrigation, and the WUCOLS approach was applied.

Tree Irrigation

The WUCOLS approach was used to model the irrigation water applied annually to Street and Residential trees after the two-year establishment period. The projected irrigation water demand depends on evaporation (ET) losses from the soil and plant and irrigation losses. Species coefficients reflect relative ET losses that range from 0.9 to 0.1 for high and low water use plants. These values were obtained for each species planted using data for the South Coastal and South Inland Valley regions (Costello and Jones, 1994). The irrigation efficiency was assumed to be 80% in all locations. The reference ET was measured as 112.3 cm and 131.6 cm at weather stations in Santa Monica (Coastal) and Glendale (Inland). The crown projection area, or area under the tree's dripline, was calculated for each species based on crown diameter, modelled as a function of DBH. LADWP reported a CO_2 emissions rate of 0.28 t CO_2 per 1000 l for pumping and treating irrigation water.

Pruning

Pruning emissions were modelled as a function of the total annual RT for pruning each species at Street, Park or Residential locations. In any given year, this value depended on the average size (DBH) of the trees, number of live trees, percentage of trees pruned and the annual pruning cycle, defined as the probability of an eligible tree being pruned in any given year. We assumed that 15% of the woody aboveground biomass was removed during each prune.

Because of budget cuts, the LA Bureau of Street Services (LABSS) pruned Street trees on average only once during the 40-year period. Two light duty trucks transported crew and equipment (chainsaw and chipper) to the site and drove the pruned biomass to the green waste disposal site. We assumed that 15% of the residents who owned Residential trees never pruned their trees (Summit and McPherson, 1998). Contractors pruned eligible Residential trees once every ten years, transporting crews and equipment (chainsaw and chipper) in two light duty trucks. Park trees were pruned once every 20 years on average, and RPD staff drove two medium duty trucks and used a chainsaw and chipper.

Pavement Repair

Emissions associated with repairing and replacing pavement damaged by tree roots were included in our assessment for the Street trees planted in tree wells (Randrup *et al*., 2001; Costello and Jones, 2003). The city forester judged the relative potential of each tree species to heave pavements as low, moderate or high. Species rated as moderate and high were assigned a repair schedule that required pavement grinding at approximately 10, 25 and 40 years after planting, and pavement removal and replacement at 15 and 30 years after planting.

Pavement grinding (1.2-m joint per tree) required a grinder and gas generator and two light duty trucks. After the tree crowns were pruned, roots were pruned with a diesel powered stump cutter. A diesel loader was used to excavate the concrete (three 1.2 m x 1.2 m squares per tree), which was driven to the recycling centre in a heavy duty truck. A diesel powered wheel loader, crusher and screener processed concrete at the recycling centre.

Tree Removal and Stump Grinding

Because of the hazard that dead Street trees pose, the LABSS removes all dead trees the same year they die. To calculate the CO_2 for tree and stump removal, the annual RTs were determined for each type of equipment used in these activities. Variables included the average tree size and the number of dead trees. It was assumed that 100% of the aboveground biomass was removed. Stump biomass was aggregated with root biomass because grinding involved a relatively small amount of total tree biomass, and all stumps were ground into chips. The removal and chipping of trees was accomplished with a light duty truck, chainsaw and chipper. A stump grinder and two light duty trucks were used for the stump grinding. The disposal of the stump grinding debris required separate transport to the green waste processing site with a light duty truck.

In parks, approximately 75% of the dead trees were removed and 50% of the dead tree stumps were ground into chips. The same vehicles and equipment used to prune trees were used to remove trees, although a more powerful chainsaw was used for large tree removal. A medium duty truck transported the diesel-powered stump grinder.

Eighty-five per cent of all dead Residential trees were removed and chipped, and 50% of all stumps were ground and transported to the Crown Disposal site in Sun Valley. Removal operations required two light duty trucks, a chainsaw and a chipper. Stump grinding required a stump grinder and a light duty truck.

Biomass and Concrete Disposal

The emissions associated with processing woody biomass and pavement concrete were calculated on a mass basis for each year. The LABSS transported chipped Street tree biomass to the Van Norman Green Waste Site, where it was converted into mulch. A light duty truck and a medium duty diesel truck handled the material on site. The large diesel tub grinder operated 2,600 hours per year. The biomass processing constant was the sum of the equipment (12.8 kg t^{-1} DW) and vehicle (2.7 kg t^{-1} DW) CO_2 emission constants (13.5 kg CO_2 t^{-1} DW). After processing, the removed biomass was redistributed in landscaped areas maintained by the city using light duty trucks. The Park tree biomass was hauled to the Griffith Park Green Waste Site for processing, but lacking data for this facility, it was assumed that the biomass was chipped with the same emissions rates as the Van Norman Green Waste Site.

Wood chips from pruned and removed Residential trees were loaded into heavy duty trucks and transported an average 436-km round trip (approximately 600 round trips annually) to a biopower plant in Dinuba, CA. It was assumed 10% of return trips involved a return visit. The Dinuba plant sold its electricity to Pacific Gas and Electric, whose utility emission factor was 395 kg CO_2 MWh^{-1}. The total net displaced emissions were 23,768 t, or 0.295 t CO_2 t^{-1} DW of processed biomass.

Decomposition

Carbon dioxide is released through the decomposition of mulch derived from aboveground biomass and roots from removed trees. Based on a review of the literature (Cairns *et al*., 1997; Harmon *et al*., 2009; Smith *et al*., 2011; Silver and Miya, 2001; Scheu and Schauermann, 1994; Drexhage and Colin, 2001; Melillo *et al*., 1989), it was assumed that roots accounted for 22% of the total tree biomass, and that 80% of the CO_2 stored in belowground root biomass was released from dead trees to the atmosphere. The calculations conservatively assumed that 100% of the CO_2 stored in mulch was released to the atmosphere the same year that the tree was removed or pruned.

Results and Discussion

During MTLA's first five years, 91,786 trees were planted. The majority of the trees were planted in Street locations (61.5%), with 73% of these along residential streets and the remainder along commercial streets. Approximately 24.9% were planted in private residences and 13.6% in parks. The planting palette contained a diverse mix of species, with 149 taxa planted along Streets alone. However, 57 taxa had fewer than 20 individuals planted. The most abundant known species planted were *Prunus cerasifera* (6.3%), *Lagerstroemia indica* (4.6%), *Quercus agrifolia* (3.7%), *Platanus* spp. (2.5%), *Jacaranda mimosifolia* (2.2%), *Ginkgo biloba* (2.2%), *Pistacia chinensis* (2.2%), *Magnolia grandiflora* (2.1%), *Pyrus kawakamii* (2.0%) and *Cedrus spp.* (2.0%).

Growth

MTLA Street (n = 67) and Residential (n = 54) trees that were surveyed 4 to 5 years after planting had a mean DBH of 6.4 cm (standard error 0.43 cm) and 5.9 cm (standard error 0.41 cm), respectively. The average annual DBH growth across all species was 1.06 cm per year (standard error 0.30 cm) for four- and five-year-old trees. The average annual DBH growth rates for the Street and Residential trees were 1.1 cm and 0.99 cm DBH per year, respectively.

Table 1: Mean DBH (cm) and average annual DBH growth

Location	Mean	cm/year
MTLA – Street	6.4	1.10
MTLA – Residential	5.9	0.99
Gainesville[1]	0- 7.7	0.82
Gainesville[2]	7.7-15.2	1.11
Houston[3]	7.7-15.2	1.01

[1] Lawrence *et al*., 2012
[2] Escobedo, 2010
[3] Staudhammer *et al*., 2011

We compared the MTLA tree growth rates to the results for young and small trees in other subtropical cities. The mean MTLA growth rates are greater than growth rates for trees less than 7.7 cm DBH in Gainesville, FL (Table 1). They are comparable to the mean growth rates of larger trees (7.7 to 15.2 cm) in Houston, TX (1.01 cm) and Gainesville, FL (1.11 cm) (Escobedo *et al*., 2010; Staudhammer *et al*., 2011).

Survivorship

The Street tree survey found a 79.8% survivorship and a 4.4% annual mortality rate for the first five years of establishment. A 3% annual mortality rate was used for modelling thereafter, based on a recent meta-analysis of 16 street tree survival studies that found annual mortality rates that typically ranged from 3% to 5% (Roman and Scatena, 2011). Residential tree survivorship was 77.1%, and the average annual mortality rate was 4.6%. For modelling purposes, this rate was applied for the first five years, after which a 3% annual mortality rate was assumed. TreePeople's three-year survey of 225 Park trees found a 90.7% survivorship. The Park tree average annual mortality rates were modelled as 5, 4 and 2% for years 1, 2 and 3 through 5 after planting, respectively.

A constant rate of 1.5% was assumed for the remainder of the 40-year study.

The MTLA survivorship rates of 79.8%, 90.7% and 77.1% for Street, Park and Residential trees are comparable to the 78.2% reported for trees planted for three to six years in New York City (Lu *et al.*, 2010). Miller and Miller (1991) reported street tree survival rates that ranged from 58.8% to 76.5% four to nine years after planting in Wisconsin communities. Somewhat higher survival rates were found for trees planted four to five years previously in San Francisco (86.4%) (Sullivan, 2004).

The MTLA average annual mortality rates for Street (4.4%), Park (3.1%) and Residential (4.6%) trees were less than the 6.6% rate for Sacramento shade trees during the first five years (70.9% survivorship), as well as the 5.6% rate for small trees (< 7.6 cm DBH) in West Oakland, CA (Roman, 2013) (Table 2). Other studies have reported even higher average annual mortality rates for small trees: 9% in Baltimore, MD (Nowak *et al.*, 2004) and 12% (for trees 7.7 to 15.2 cm DBH) in Houston, TX (Staudhammer *et al.*, 2011).

Table 2: Tree age or DBH size class and average annual loss rate

Location	Age/Size	Loss (%/yr)
MTLA – Street	5	4.4
MTLA – Residential	5	4.6
MTLA – Park	3	3.1
Sacramento[1]	5	6.6
West Oakland[1]	< 7.7 cm DBH	5.6
Baltimore[2]	< 7.7 cm DBH	9.0
Houston[3]	7.7-15.2 cm DBH	12.0

[1] Roman, 2013
[2] Nowak *et al.*, 2004
[3] Staudhammer *et al.*, 2011

Modelled Tree Population

The modelled tree population began with 91,786 planted, of which only 30,813 (33.6%) were projected to survive to 2045 (Figure 2). The modelled Park tree population had the highest survival rate (54%) and

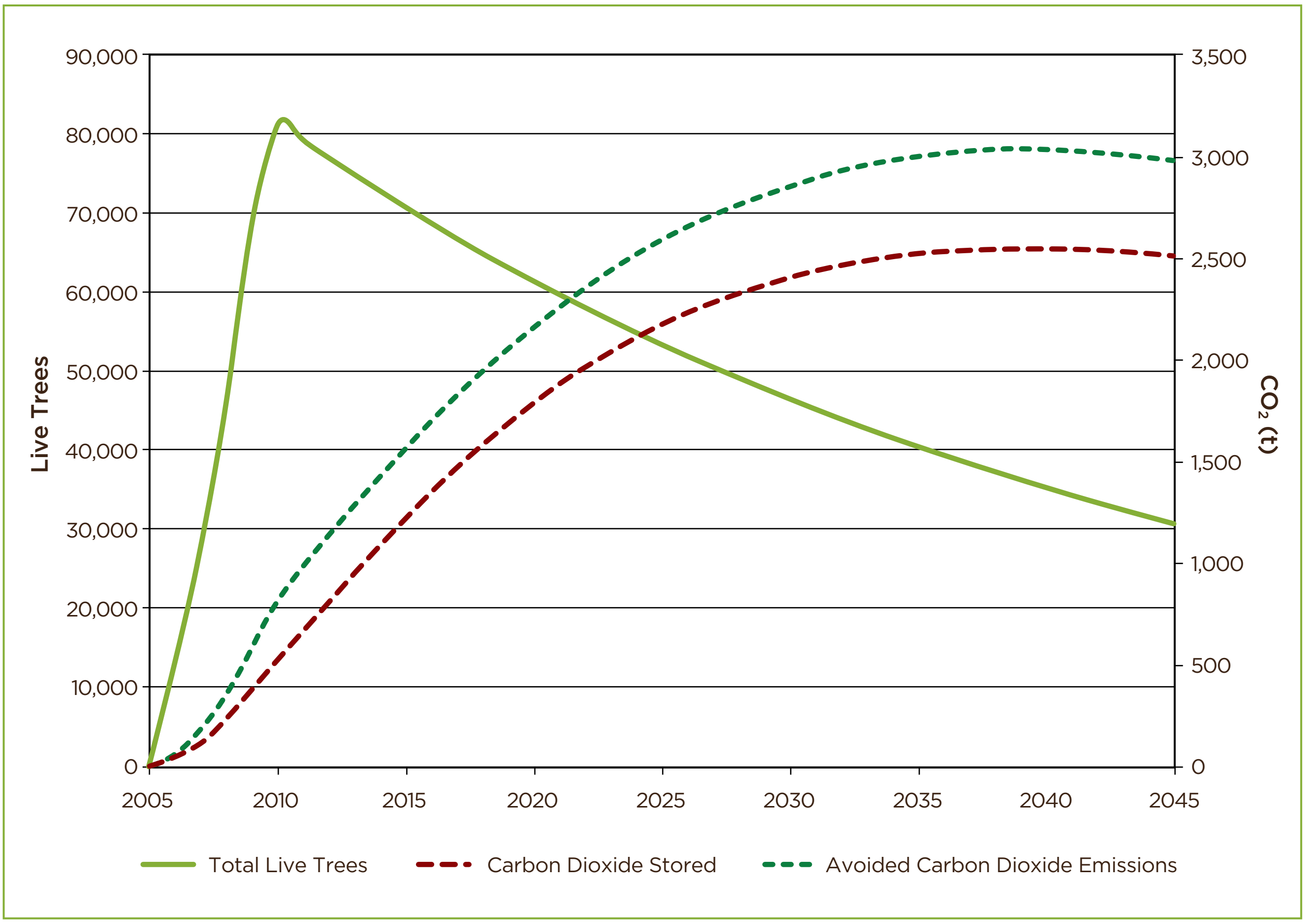

Figure 2: Projected numbers of live trees, CO_2 stored and avoided CO_2 emissions from energy savings (t) for the 40-year period.

the Residential trees exhibited the lowest (30%). After 40 years, the simulated total basal area for Street, Park and Residential trees was 31,030 m^2, 12,677 m^2 and 10,896 m^2. Although over 10,000 more Residential trees were planted than Park trees, the total basal area of the simulated Park trees exceeded that of the Residential trees after 2032. Parks were planted with relatively more large-stature trees that had higher survival rates than the simulated Residential trees.

Stored and Avoided CO_2 Emissions

The estimated amount of CO_2 stored over the 40-year period was -73,703 metric tonnes (t), valued at $1 million, assuming a price of $14 per t. Avoided CO_2 emissions attributed to the shading and climate effects of trees on building energy use were estimated to total -101,679 t over 40 years (Figure 2, Table 3). Cooling savings translated into -102,779 t of avoided CO_2 emissions. However, the trees were estimated to increase heating loads and associated natural gas consumption equivalent to CO_2 emissions of 1,101 t for 40 years. Ninety-seven per cent of the net CO_2 reductions were accrued Inland, where most of the trees were planted and air conditioning loads were greater than in the Coastal climate zone.

The projected amount of CO_2 stored per tree planted per year was -20.1 kg. The values ranged from -9.7 kg (Coastal, Residential) to -44.2 kg (Inland, Park). Emissions avoided per tree planted per year averaged -27.7 kg, and the values ranged from -7.7 kg (Coastal, Residential) to -36.2 kg (Inland, Street).

We compared the projected amounts of CO_2 stored and emissions avoided to the results from three studies that simulated biomass accumulation from tree planting over a 30- to 50-year period. In an initial study of the MTLA program, planting 1 million trees was estimated to store and reduce CO_2 emissions by -10.1 kg and -12.9 kg per tree per year, respectively (McPherson *et al*., 2011). The values from this study are about twice those reported in the initial study. One explanation for the discrepancy is that this study assumed the planting of more large-stature trees.

Kovacs *et al*. (2013) estimated net CO_2 reductions from planting 182,736 street trees in New York City over 50 years. The amounts of CO_2 sequestered and emissions avoided per tree per year varied by species, ranging from -13.2 to -52.1 kg and -25.7 to -52.1 kg per year, respectively. The sequestered CO_2 values are similar to the -20.1 kg value reported here. The avoided emissions values are somewhat higher

Table 3: Estimated fossil and biogenic CO_2 releases and removals (t) in the Street, Park and Residential locations for the 40-year period

		Street total	Per tree (kg)	Park total	Per tree (kg)	Residential total	Per tree (kg)	Grand Total	Per tree (kg)
Fossil CO2	Equipment	3,305	58.5	537	43.0	862	37.7	4,704	51.2
	Vehicles	1,599	28.3	1,657	132.9	346	15.1	3,602	39.2
	Water	5,887	104.3	0	0.0	2,208	96.6	8,095	88.2
	Tree Prod. Materials	431	7.6	76	6.1	140	6.1	648	7.1
	Avoided (Energy)	-72,853	-1,290.5	0	0.0	-28,826	-1,260.9	-101,679	-1,107.8
	Avoided (Biopower)	0	0.0	0	0.0	-1,940	-84.9	-1,940	-21.1
	Net Fossil Emissions	-61,631	-1,091.7	2,270	182.0	-27,210	-1,190.2	-86,570	-943.2
Biogenic CO2	Stored (Live Trees)	-40,379	-715.3	-20,946	-1,679.4	-12,378	-541.4	-73,703	-803.0
	Stored (Roots)	-2,657	-47.1	-657	-52.7	-825	-36.1	-4,139	-45.1
	Mulch Decomposition	37,407	662.6	7,862	630.4	0	0.0	45,269	493.2
	Root Decomposition	5,793	102.6	1,432	114.8	1,799	78.7	9,023	98.3
	Wood Combustion	0	0.0	0	0.0	12,067	527.8	12,067	131.5
	Net Biogenic Emissions	164	2.9	-12,309	-986.9	663	29.0	-11,482	-125.1
Combined*	Net Total (Fossil + Biogenic)	-61,467	-1,088.8	-10,038	-804.9	-26,547	-1,161.2	-98,053	-1,068.3

*The implication of combining these two is that the stored carbon remains stored over long time horizons, i.e., >100 years).

than the -27.7 kg reported here, in part because trees were projected to provide substantial heating savings through wind speed reductions.

McHale *et al*. (2007) estimated the amounts of CO_2 sequestered and emissions avoided over 40 years for planting in the Denver, CO region. Sequestered and avoided CO_2 ranged from -7.2 to -11.2 kg and -5.3 to -11.5 kg per tree per year, respectively. These values are somewhat less than the values reported here. The Denver region's shorter growing season is partially responsible.

Fossil CO_2 Emissions

The total fossil CO_2 emissions for the 40-year period were 17,048 t (185.7 kg per tree planted). The Street tree emissions comprised 65.8% of total fossil emissions, while the Park and Residential trees accounted for 13.3% and 20.9%, respectively (Table 3). Equipment emissions accounted for 27.6% of the total fossil CO_2 emissions. Equipment emissions were largest for the tree removal category (3,373 t), accounting for 29.4% of total fossil CO_2 emissions and 71.7% of all equipment emissions. Within this category, tree removal and stump grinding activities released the most emissions (2,764 t), primarily because powerful equipment and long RTs were involved.

Vehicle emissions accounted for 21.1% of the total fossil emissions and were most important in parks, due to travel by many volunteers, where they accounted for 73.0% of total fossil CO_2 emissions. Vehicle emissions were least important in the Residential tree locations (9.7% of total fossil emissions). Nearly 32.8% (1,642 t) of total vehicle emissions were associated with the tree removal and disposal category. Pruning (1,077 t) activities were estimated to generate more vehicle emissions than planting (622 t).

Materials contributed 51.3% (8,743 t) of the total fossil CO_2 emissions for the 40-year period. Materials emissions associated with the treatment and delivery of water to irrigate trees (8,095 t) was the single greatest source of fossil CO_2 emissions (47.5%).

Energy savings (-101,679 t) and biopower (-1,940 t) displaced fossil CO_2 emissions at power plants. The fossil emission reductions totalled -103,619 t (-1,128.9 kg per tree) for the 40-year period (Table 2), with Street trees accounting for 71.7% of the projected avoided emissions from energy savings because of their relatively large stature and strategic locations compared with the Residential trees (McPherson, 2014).

Net fossil CO_2 totalled -86,570 t (-943.2 kg per tree). Because they shaded buildings and avoided power plant emissions, the Street and Residential trees were net fossil CO_2 sinks, whereas the Park trees were projected to be net fossil CO_2 sources.

Biogenic CO_2 Emissions

Biogenic CO_2 (bCO_2) emissions totalled 66,359 t (723.0 kg per tree) for the 40-year period (Table 3). The sources were the decomposition of mulch (45,269 t) and dead roots (9,023 t), as well as wood combustion (12,067 t) during biopower production. Approximately -73,703 (-803.0 kg per tree) of bCO_2 was estimated to be stored in live trees and -4,139 t (-45.1 kg per tree) in the roots of dead trees after 40 years. Net bCO_2 totalled -11,482 t (-125.1 kg per tree). Park trees were projected to be bCO_2 sinks because of their relatively large stature and high survival rates, while Street and Residential trees were estimated to store slightly less bCO_2 than the fossil CO_2 they emit.

Net Total CO_2 Emissions

Assuming that the bCO_2 stored in woody biomass and the soil at the end of the 40-year analysis remains in situ for over 100 years, the simulated MTLA tree planting was projected to be a net reducer of CO_2 after 40 years (-98,053 t, -1,068.3 kg per tree). Residential trees were estimated to produce the greatest reduction per tree planted (-1,161.2 kg), while Street trees produced the largest total net reduction (-61,467 t).

The MTLA fossil plus biogenic CO_2 emissions were 46% of CO_2 stored in tree biomass plus avoided emissions, a high proportion compared with the 1% to 4% values previously reported for Montjuic Park and Leipzig. These previous studies did not fully account for the emissions from tree production, wood decomposition and water, all of which are important sources identified in this study. When decomposition and water emissions were omitted from this analysis, the remaining emissions were 4.9% of the projected reductions from CO_2 stored in tree biomass plus avoided emissions. This finding implies that the emissions we report for the tree production, planting, pruning and removal categories are of the same order of magnitude as those reported elsewhere. This study found that the average annual emissions per tree planted averaged -22.7 kg. This value is within the -8.4 to -34.9 kg CO_2 per year reported by Nowak *et al.* (2002).

Management Implications

The relative magnitude of emissions across categories indicates the potential to achieve reductions through management interventions. This potential is greatest for strategies that reduce decomposition, for which the values ranged tenfold from 78.7 (Residential) to 770.4 kg (Street) per tree planted. Utilising tree biomass as feedstock for biopower energy production proved to be the single most effective management practice simulated in this study. Although there is growing interest in biopower, economic, technical and environmental barriers limit its widespread application in cities (Tinus and LaMana, 2013; Nzokou *et al*., 2011). Delaying emissions by utilising removed wood in products such as benches, picnic tables and other building materials faces similar hurdles (Bratkovich, 2001). Overcoming these barriers is critical to achieving TPIs that generate substantial net CO_2 reductions in the long term.

Irrigation water emissions ranged from 0.0 (Park) to 104.3 kg per tree planted. Planting trees in areas that already receive irrigation, such as grass, can reduce or eliminate the need for supplemental irrigation. Selecting native and drought-tolerant tree species that can grow without irrigation once established is another tactic. Research on tree water use suggests that drought tolerance is highly variable across growing sites, even within the same species (Fahey *et al*., 2013; McCarthy and Pataki, 2010), so further research is needed. Other strategies to reduce tree water use include the improved management of soil moisture for root growth, improved irrigation efficiency and the harvesting of rainfall (Gill *et al*., 2007).

Tree removal and stump grinding activities (57.2 kg per tree planted) offer considerable opportunity for emission reductions. Strategies aimed at reducing equipment emissions, the primary source, include reducing the horsepower of stump grinders and chippers and limiting equipment idling and RT by working more efficiently. Vehicle emissions reductions can be achieved by concentrating jobs in one area, thereby reducing travel distances. Fleet fuel efficiency can be improved by using trucks with improved fuel efficiency, and the use of lower-carbon fuels such as CNG and biodiesel.

To maximise net CO_2 reductions, MTLA mangers could increase Residential tree planting, which produced the greatest average net CO_2 reduction per tree planted (-1,161.3 kg for 40 years). The largest reductions occurred when trees were positioned to shade west-facing walls. Storage would also be increased by selecting trees that will grow as large as the space allows, and are long-lived species with dense wood.

Conclusions

Although the number of MTLA trees planted (91,786) from 2006 to 2010 is substantially lower than the targeted 1 million or the 407,000 reported as planted in 2013, early results suggest that the programme is achieving success. MTLA is planting a relatively high number of large-stature trees compared with the availability of vacant sites for such trees. Tree growth rates compare favourably with values reported in the literature. MTLA tree survival rates are relatively high for a large city in an arid environment where transplants face extended periods of summer drought. We projected that the MTLA programme will be a CO_2 sink if 40-year avoided fossil fuel CO_2 emissions from energy savings and biopower are realised. However, opportunities exist to increase net reductions by reducing CO_2 emissions from mulch decomposition, irrigation, water, equipment and vehicles. Continued success will depend on raising awareness of proper tree care practices, strategically selecting and locating new trees, monitoring threats and adapting to challenges that arise.

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