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WOOD AND OTHER RENEWABLE RESOURCES

A life cycle carbon dioxide inventory of the Million Trees Los Angeles program

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Abstract

Purpose This study seeks to answer the question, "Will the Million Trees LA (Million Trees Los Angeles, MTLA) program be a carbon dioxide (CO_2) sink or source?" Because there has never been a full accounting of CO_2 emissions, it is unclear if urban tree planting initiatives (TPIs) are likely to be effective means for reaching local reduction targets.

Methods Using surveys, interviews, field sampling, and computer simulation of tree growth and survival over a 40-year time period, we developed the first process-based life cycle inventory of CO_2 for a large TPI. CO_2 emissions and reductions from storage and avoided emissions from energy savings were simulated for 91,786 trees planted from 2006 to 2010, of which only 30,813 (33.6 %) were estimated to survive.

Results and discussion The MTLA program was estimated to release 17,048 and 66,360 t of fossil and biogenic CO_2 over the 40-year period, respectively. The total amount emitted (83,408 t) was slightly more than the −77,942 t CO_2 that trees were projected to store in their biomass. The MTLA program will be a CO_2 sink if projected 40-year-avoided fossil fuel CO_2 emissions from energy savings (−101,679 t) and biopower (−1,939 t) are realized. The largest sources of CO_2 emissions were mulch decomposition (65.1 %), wood combustion (14.5 %), and irrigation water (9.7 %).

Conclusions Although trees planted by the MTLA program 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 utilizing wood residue to generate electricity rather than producing mulch.

Keywords Carbon footprint · Carbon sequestration · Climate change · Life cycle inventory · Tree planting · Urban forestry · Urban trees

1 Introduction

Urbanized areas in the USA now account for 3 % of total land area and 81 % of total population in the USA, and they are growing (Nowak et al. 2013). Because large cities experience two climate change mechanisms: the global greenhouse effect and the local heat island effect, their rate of warming is 50 % greater than that of nearby rural areas (Stone 2012). Stone (2012) regards tree planting as the most effective and least energy-intensive approach to cooling urban environments and mitigating greenhouse gas (GHG) emissions. By fixing carbon dioxide (CO_2) during photosynthesis and storing carbon as biomass, trees act as a sink. Trees also reduce summertime air temperatures and building energy use for air conditioning, thus altering GHG emissions from power plants that generate electricity (Akbari 2002). In winter, trees can increase or decrease GHG emissions associated with energy consumed for space heating, depending on local climate, site features, and building characteristics (Heisler 1986). The potential for urban trees to store and sequester CO_2 as well as to reduce GHG emissions has been analyzed for cities around the world (Jo 2002; Chaparro and Terradas 2009; Yang et al. 2005; Strohbach and Haase 2012; Escobedo et al. 2010). Less well

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

1.1 Tree planting initiatives in the USA and Million Trees Los Angeles

Nine of the 12 largest US cities have launched mayoral tree planting initiatives (TPIs), pledging to plant nearly 20 million trees (Young 2011). In many cases, these initiatives are embedded within municipal climate protection plans. The implied assumption behind these TPIs is that trees are a net long-term CO_2 sink, but this has never been substantiated for a TPI. Million Trees LA (Million Trees Los Angeles or MTLA) program is one of several large-scale mayoral TPIs that promise to create more livable cities through urban forestry.

A 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 (McPherson and Simpson 1999; Sola et al. 2007; Strohbach et al. 2012). However, these studies do not include the full scope of emissions associated with vehicles, equipment, and materials at each life stage. For instance, emissions associated with tree production, site preparation, and the fate of removed biomass and fossil fuels consumed to transport, treat, and distribute irrigation water are often omitted. Because there has never been a full accounting of GHG emissions for a TPI, some claim that TPIs are not likely to be an effective means for reaching local GHG targets (Pataki et al. 2011).

1.2 Previous life cycle assessments and emission inventories for TPIs

Life cycle and carbon footprint analyses have been conducted previously for TPIs in two locales: Montjuic Park in Barcelona, Spain, and an urban green space project in Leipzig, Germany. In the Montjuic Park study, energy consumed by gardeners' vehicles and equipment accounted for only 1.2 % of 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). Scenarios included different levels of tree planting, growth, and mortality rates and lawn mowing. Included in the analysis were vehicle and equipment emissions associated with tree transport and planting (461 trees), pruning, removal, wood chip production, and transport. Processes not included were nursery tree production, site preparation, stump removal, and decomposition of wood chips. Most fuel consumption values for equipment and vehicles were obtained from secondary databases. The estimated amount of CO_2 stored in trees after 50 years ranged from 20 t ha^{-1} for a slow growth and high mortality scenario to 226 t ha^{-1} for maximum growth and low mortality. Assuming slow tree growth, tree planting and maintenance CO_2 emissions were only 4.1 and 2.2 % of total net CO_2 stored in trees after 50 years, respectively.

Though no life cycle assessments (LCAs) on TPIs have been conducted in the USA or California previously, non-LCA studies have been conducted, analyzing the emissions of urban forestry programs for the USA. A survey of 16 municipal forestry departments and 12 non-governmental organizations (NGOs) in different cities collected information on annual fuel consumption by vehicles and equipment, energy consumed for heating and cooling buildings, and the number of trees planted and managed (McPherson and Simpson 1999). Total CO_2 emissions per tree planted by NGOs averaged 2.62 kg. The average annual release of CO_2 per tree for the 16 municipalities was 0.14 kg per cm diameter at breast height (dbh, 1.37 m). However, there was substantial variability among municipalities. For example, average annual emissions for care of 97,000 municipal trees in Sacramento, CA, were 0.51 kg per cm dbh per tree. Given the location and dbh distribution of the region's six million existing trees, annual CO_2 emissions were estimated at 9,422 t (McPherson 1998). For Sacramento, emissions from tree care amounted to 3 % of the total estimated CO_2 sequestered and avoided emissions.

In a study of individual trees, planting and maintenance emissions were simulated, assuming different rates of tree growth and mortality, life-spans, and pruning cycles (Nowak et al. 2002). Annual maintenance emissions for a tree with conservative management and short life-span were (8.4–34.9 kg CO_2 year^{-1}). The authors noted that tree maintenance had a negative effect on the tree carbon budget unless it led to an increased life-span. Research has not established a strong link between maintenance levels and tree longevity.

Given growing interest in urban forestry as a climate protection strategy and uncertainty concerning its effectiveness, the purpose of this study is to answer the question, "Will the MTLA program be a net CO_2 sink or source?"

2 Methods

2.1 Study area

The study area covers 1,022 km^2 of urbanized land in the city of Los Angeles, CA. The city of Los Angeles (latitude 34° 06′ 36″ N, longitude 118° 24′ 40″ W) lies within one of the largest metropolitan areas in the USA (population is 3.8 million). The climate of Los Angeles is Mediterranean, characterized by hot, dry summers, and cool, rainy winters from October through April. Average annual rainfall is 345 mm, and the average annual and lowest temperatures recorded are 19 and

−4 °C. Los Angeles has a variety of climate zones because of its proximity to the Pacific Ocean and nearby mountain ranges. Portions of Los Angeles fall into two of 16 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 remaining 13 are in the Inland Empire zone, hereafter referred to as coastal and inland zones.

2.2 Goal and scope

The goal of this life cycle inventory (LCI) is to generate the first detailed inventory for a TPI to determine the net CO_2 emissions attributable to the MTLA initiative. We expect that this inventory will be used as a benchmark for the MTLA program and as a model for analyses of other TPIs and urban forestry management programs.

The scope of our analysis constitutes a cradle-to-grave CO_2 inventory that includes fuel use, material inputs, and biogenic CO_2 flows for each life stage of the MTLA program over a 40-year time horizon. This time horizon corresponds to the expected life-span of an urban tree; based on a meta-analysis of 16 survivorship studies, the life-span of a street tree ranges from 26 to 40 years (Roman and Scatena 2011). Park and yard trees are likely to live longer than street trees because their growing conditions are less arduous. Of course, the actual lifetime of a tree is highly dependent on its genetics; fitness to site; exposure of the site to the vagaries of cars, dogs, people, and weather; as well as the quality and timeliness of planting and stewardship practices. We did not extend the modeled lifetime beyond 40 years because of increasing uncertainty about how changes in policies and technologies will influence future vehicle and equipment emissions.

2.3 MTLA program

We categorize MTLA plantings from 2006 through 2010 as street, park, or yard projects. Street tree plantings include Signature Projects that maximize environmental benefits and program visibility by planting large trees (#24 box, 61×61×61 cm) along heavily traveled corridors. Also, street tree planting projects occur in residential areas when trees are "adopted" by locals who agree to maintain the trees planted along the street.

Yard tree plantings occur on private property. Most yard trees are planted via tree adoption requests. These requests are parceled out by MTLA staff to the non-profit responsible for activities in the area. Staffs help residents select and locate trees, coordinate planting events, provide training on planting and tree care, supervise plantings, and conduct follow-up inspections to insure that trees are irrigated. Trees planted under the supervision of the partner non-profits are reported monthly by the Los Angeles Conservation Corp (LACC), which purchases and distributes most of the trees. Also, LACC runs a residential shade tree program that delivers trees directly to homes through an application process.

Park tree planting projects are organized by the non-profit TreePeople with support from the Los Angeles Recreation and Parks Department (RPD). TreePeople organizes and trains thousands of volunteers who participate in park tree planting and stewardship events.

2.4 Life cycle inventory

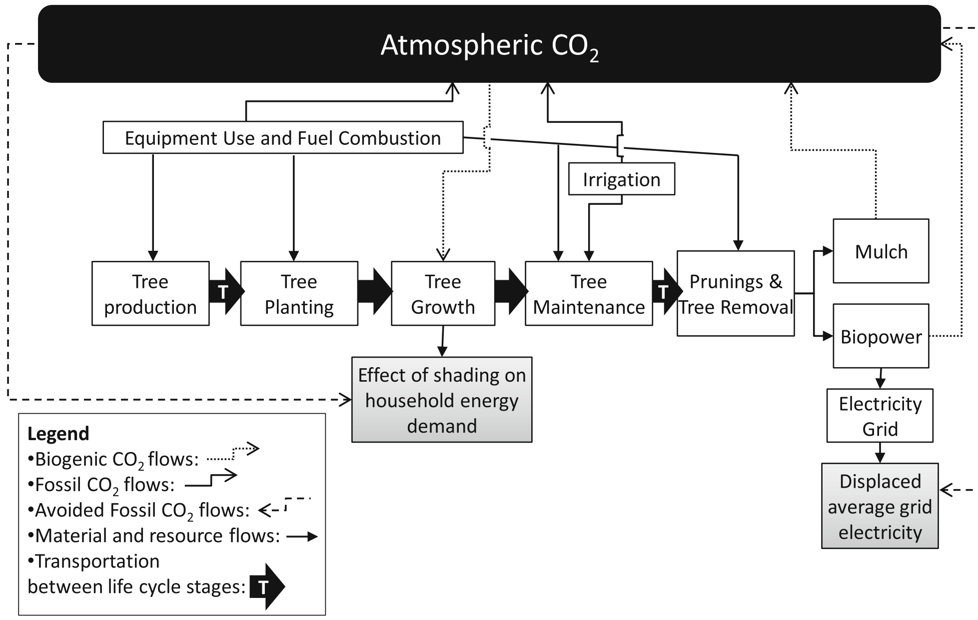
The LCI model is made up of categories shown in Fig. 1 such as tree production, planting, pruning, sidewalk repair, removal, mulch decomposition, and biopower. Categories were subdivided into activities for the purposes of developing the LCI. All data were acquired directly via interviews and from reports (Electronic Supplementary Material (ESM) Table S1). The following section describes how tree population dynamics and CO_2 reductions were modeled. General methods for calculating emissions from equipment and vehicles follow. Subsequent sections describe the emission inventories for each life stage category.

2.4.1 Tree population dynamics, CO_2 storage, energy effects, and avoided emissions

Information on the numbers and species of street, park, and yard trees planted from 2006 through 2010 came from databases maintained by MTLA, RPD, and LACC (ESM Table S1). The methods used to model tree population dynamics and effects on CO_2 are described in detail in a previous study (McPherson, 2014). 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 were used as the basis for modeling tree growth (Peper et al. 2001). Each planted species in LA was matched to one of the 20 or 22 species that were intensively studied in the reference cities. Correctly matching species and climate zone (coastal or inland) insured that the appropriate allometric and growth equations were applied to calculate biomass and annual carbon storage rates.

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. Urban-based biomass equations were developed from street and park trees measured in California (Pillsbury et al. 1998) and Colorado cities (Lefsky and McHale 2008). Volume estimates were converted to green and dry weight estimates (Markwardt 1930) and were divided by 78 % to incorporate root biomass (Nowak 1994). Dry weight biomass was converted to carbon (50 %) (Leith 1975), and these values were converted to CO_2. 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.

Fig. 1 MTLA system diagram



Calculations of energy effects of street and yard 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 modeled following methods outlined by McPherson and Simpson (1999) and McPherson (2014). Park trees were omitted from the analysis because these trees shaded very few air-conditioned buildings. Changes in unit energy consumption (UEC) due to the effects of trees were calculated on a per-tree basis by comparing results before and after adding trees. Weather data (e.g., hourly air temperature, wind speed, irradiance) for a typical meteorological year (TMY2) from Ontario International Airport (inland) and Los Angeles International Airport (coastal) were used (Marion and Urban 1995). Shading effects for each of the 20 to 22 tree species were simulated at three tree-to-building distances, eight orientations, and nine tree sizes.

The previous study (McPherson, 2014) assumed that trees were planted in the spring and used establishment period survival rates based on results of two monitoring studies. Survival rates after the first 5-year establishment period were taken from literature-based mortality estimates, and the previous simulations assumed that dead trees were not replaced. The previous study reported that from 2006 to 2010, MTLA planted a diverse mix of 91,786 trees. Assuming 33.6 % of those trees survived after 40 years, the plantings were projected to reduce atmospheric CO_2 by 175,381 t (1,911 kg per tree planted) by sequestering 73,703 t CO_2 (803.0 kg per tree planted) and avoiding emissions of 101,679 t (1,107.8 kg per tree planted) through effects on building energy use. The previous study did not account for projected CO_2 emissions associated with the MTLA program.

2.4.2 Equipment and vehicle emissions

Information on the equipment and vehicles used for each activity (i.e., model, fuel type) was obtained from municipal street and park tree managers (ESM Table S1). Information on equipment and vehicles used for yard tree planting and management was provided by a local arborist (ESM Table S1). Emission factors (EFs) were obtained for each fuel type (ESM Table S2) (Climate Action Reserve 2010). Information on each type of equipment and vehicle is presented in ESM Tables S3 and S4, respectively.

Equipment emissions occur during activities such as cutting tree wells in concrete, tree pruning and removal, chipping, stump grinding, and sidewalk grinding. Total annual equipment emissions (AEEs) were calculated as the sum of emissions per tree across climate zones (coastal and inland), all equipment types, species, and locations (i.e., street, park, and yard), as in Eq. 1 (ESM Table S5). 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 calculate RT hours per tree for each activity (e.g., prune, remove) and equipment type (e.g., chain saw, chipper) (Nowak et al. 2002). Because trees were planted over a 5-year period, a cohort of one species at any given year consisted of trees with slightly different ages and sizes. The average dbh for each species was calculated annually and used with the RT tables to calculate annual hours of use for each equipment type. Equipment load factors were assigned based on equipment type and size (US Environmental Protection Agency 2004).

Vehicle emissions were associated with transport of program 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 traveled per tree (km), vehicle fuel efficiency ($L^{-100\ km}$), fuel type, and EFs (VEC, ESM Table S5, Eq. 2). Total annual vehicle emissions (AVEs, ESM Table S5, Eq. 3) were calculated as the sum of emissions across climate zones (coastal and inland), all vehicle types, species, and locations (i.e., street, park, and yard).

2.4.3 Tree production

A LCI of a tree production system in California that supplies trees for the MTLA program found 4.6 kg of CO_2 equivalent was emitted per #5 tree (nominally 5 gal) or 0.83 kg per equivalent unit (EQU) (Kendall and McPherson 2012). EQUs are used by some nursery operations to track the costs associated with producing different products, namely, different size trees. They reflect the inputs and time required to produce each sized nursery tree. This study applies the emission results from Kendall and McPherson to #15 (nominally 15-gal container or 56.8 L) and #24 box trees planted in Los Angeles. The CO_2 emissions for #15 and #24 box trees were 15.3 and 32.0 kg per tree, respectively, based on their EQUs.

2.4.4 Planting and initial irrigation

Street trees A total of 56,453 street trees were planted from 2006 to 2010, accounting for 61.5 % of all trees planted. All 12,844 #24 box trees and 2,500 of the #15 trees were planted in commercial street sites. The remaining street sites were planted with #15 trees along streets in residential areas. Trees, shovels, rakes, and other planting equipment were transported from the staging yard to the planting sites in a light duty truck.

Tree wells were cut out of the concrete sidewalks for street tree planting by LACC staff at 3 % of all street tree sites (1,694). Two light duty trucks transported a concrete saw and compressor to cut each 1.2 m by 1.8 m tree well and hauled removed concrete to the recycling site.

Street trees in commercial areas were watered twice per month (56.8 L per visit) on average from a light duty water truck (a 0.8-m^3 tank) for the first 2 years. MTLA staff directed residents to provide 5.7 L per week of water to each residential street tree during the first 2 years of establishment. After the 2-year contract period expired, irrigation was provided by adjacent businesses and residents as needed and modeled using the Water Use Classification of Landscapes Species (WUCOLS) approach described below.

Park trees During 2006 to 2010, 12,472 trees (13.6 % of total planted, all #15) were planted in Los Angeles parks by RPD personnel and volunteers. TreePeople organized and trained 6,661 volunteers, who participated in 90 park tree planting events over the 5-year period. Trees were planted by hand and used native soil for backfill. RPD staff used a light and medium duty truck to transport trees and tools to each planting event. TreePeople staff drove a light duty truck. Approximately 55 % of the volunteers drove sedans 48.3 km round trip to planting events, while the remaining 45 % carpooled. This analysis assumed carpoolers had three persons per sedan. According to TreePeople records, staff and volunteers visited 5,719 trees over the 5-year period to inspect, prune, and perform other tree care activities as needed. Approximately 3,931 volunteers participated in 128 TreePeople-led stewardship events. It was assumed that these events did not involve the use of mechanized equipment. RPD staff drove a medium duty truck to each event. The same carpooling and vehicle assumptions used for tree planting were applied to stewardship activities. It was assumed that park trees received no new irrigation because most were planted in irrigated turf areas where supplemental watering was unnecessary.

Yard trees From 2006 to 2010, 22,861 trees (24.9 % of total planted, all #15) were planted in yard sites. NGOs transported trees and personnel to planting sites in light duty trucks. Trees were planted by residents without mechanized equipment or imported soil. It was assumed that all yard trees received supplemental irrigation and the WUCOLS approach was applied.

2.4.5 Tree irrigation

The WUCOLS (Costello and Jones 1994) approach was used to model irrigation water applied (IWA) annually to live street and yard trees after the 2-year establishment period (ESM Table S5, Eq. 4). Projected irrigation water demand depends on evaporation losses from the soil and plant and irrigation losses (ESM Table S5, Eq. 5). Species coefficients (K_s) reflect reference evapotranspiration (ET_0) 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). Irrigation efficiency was assumed to be 80 % in all locations. Reference evapotranspiration was measured as 112.3 and 131.6 cm at weather stations in Santa Monica (coastal) and Glendale (inland). Crown projection area, or area under the tree's dripline, was calculated for each species based on crown diameter modeled as a function of dbh. LADWP reported a CO_2 emission rate of 0.28 t CO_2 per 1,000 L for pumping and treating irrigation water (ESM Table S1).

2.4.6 Pruning

Pruning emissions were modeled as a function of total annual RT for pruning each species in inland or coastal climate zones at street, park, or yard locations (PHR, ESM Table S5, Eq. 6).

At 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 an eligible tree is pruned any given year. The total amount of aboveground biomass pruned annually was calculated for each species (PDW, ESM Table S5, Eq. 7). It depended on the total aboveground biomass, which was calculated with species-specific growth equations that provided tree dbh and height for each year after planting and allometric equations for biomass. Based on common practice, 15 % of the woody aboveground biomass was removed during each prune.

The Los Angeles Bureau of Street Services (LABSS) pruned street trees to eliminate conflicts with signage, lighting, utilities, vehicles, buildings, and other trees or to remove branches prone to failure. Budget cuts have lengthened BSS's inspection and pruning cycle such that each street tree is routinely inspected and pruned only once every 40 years. Two light duty trucks transported crew and equipment to the site and hauled pruned biomass to the green waste disposal site. A chain saw and chipper were used in street tree pruning operations.

Modeling emissions associated with yard tree care was hampered by a lack of data on historic and future residential tree care practices. Lacking data specific to the study area, information on the extent to which residents themselves perform tree care practices or hire an arborist was obtained from a residential survey in Sacramento, CA. That study found that 15 % of the respondents never pruned their trees (Summit and McPherson 1998). It was assumed that 85 % of the eligible yard trees were pruned and 100 % of street and park trees were pruned. For this study, it was conservatively assumed that eligible yard trees were pruned once every 10 years by contractors. Crews, equipment (chain saw and chipper), and pruned biomass were transported with two light duty trucks.

Once established, park trees were not inspected or pruned except to correct problems such as broken or low hanging limbs. On average, RPD staff pruned each park tree once every 20 years, drove two medium duty trucks, and used a chain saw and chipper.

2.4.7 Sidewalk repair

The roots of street trees, especially those planted in tree wells surrounded by concrete sidewalks, can heave the pavement causing a trip and fall hazard (Randrup et al. 2001; Costello and Jones 2003). Emissions associated with repairing and replacing damaged sidewalks were included in our assessment for the street trees planted in tree wells. Once heaved sidewalk joints are detected, they are ground down. Eventually, the concrete becomes too thin to grind and it is excavated. Before a sidewalk square is removed and replaced, the offending tree crown is pruned to reduce the crown to root ratio, making it more resilient to stress. Roots are pruned back, and a new concrete sidewalk is poured. Old concrete is hauled to a recycling center where it is crushed and used as an aggregate base material for roads. To incorporate emissions associated with this process, the city forester judged the relative potential of each tree species to heave sidewalks as low, moderate, or high (ESM Table S1). Species with low potential were assumed to cause no sidewalk damage. Species rated as moderate and high were assigned a repair schedule that required sidewalk grinding at approximately 10, 25, and 40 years after planting as well as sidewalk removal and replacement at 15 and 30 years after planting.

Sidewalk grinding was limited to one sidewalk joint (1.2 m) per tree and required a grinder and gas generator as well as two light duty trucks for transport of personnel and equipment. Tree crowns were pruned with the same vehicles and equipment used for regular pruning. Tree roots were pruned with a diesel-powered stump cutter prior to removing and replacing sidewalk squares (three 1.2 m×1.2 m squares per tree). A diesel loader was used to excavate the concrete, which was hauled to the recycling center in a heavy duty truck. At the recycling center, about 4,536 t of concrete was processed annually by a diesel-powered wheel loader, crusher, and screener.

2.4.8 Tree removal and stump grinding

To calculate CO_2 for tree and stump removal, annual RTs were calculated for each type of equipment used in these activities (RHR, ESM Table S5, Eqs. 8 and 9). Factors included the average tree size, which influenced RT, and the number of dead trees. The percentages of trees and stumps removed were 100 % for street and park trees, but 85 % for yard trees because some residents never remove dead yard trees (Summit and McPherson 1998). The percentages of trees and stumps eligible for removal that are actually removed varied by location because trees and stumps may not be removed when located in unmanaged areas or for budgetary reasons. It was assumed that 100 % of each tree's aboveground woody biomass (ADW) was removed during each removal (RDW, ESM Table S5, Eq. 10). Stump biomass was aggregated with root biomass because grinding involved a relatively small amount of total tree biomass.

Because of the hazard dead street trees posed, BSS removed all dead trees in the same year they died, and all stumps were ground into chips. Removal and chipping of trees was accomplished with a light duty truck, chain saw, and chipper. A stump grinder and two light duty trucks were used for stump grinding. Disposal of stump grinding debris required a separate haul to the green waste processing site with a light duty truck.

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

Eighty-five percent of all dead yard 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, chain saw, and chipper. Stump grinding required a stump grinder and light duty truck.

2.4.9 Biomass and concrete disposal

Emissions associated with processing woody biomass and sidewalk concrete were calculated on a mass basis for each year. BSS hauled chipped street tree biomass to the Van Norman Green Waste site, where it was converted into mulch. The site converted 58,967 t of green biomass (GW) into 54,431 t of mulch over the course of a year, a conversion efficiency of 77 %. A light duty truck and a medium duty diesel truck handled the material on-site. The large diesel tub grinder operated 2,600 h per year. To calculate an annual biomass processing constant, a ratio of 0.56 was used to convert green weight of biomass to dry weight (DW). This value is the average moisture content for hardwoods, which account for 95 % of all MTLA trees planted (Nowak 1994). The biomass processing constant was the sum of 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, removed biomass was redistributed in landscaped areas maintained by the city using their light duty trucks.

Once removed, park tree biomass was hauled to the Griffith Park green waste site for processing. Lacking specific information on the processing characteristics of this facility, it was assumed that the biomass was chipped with the same efficiency and emission rates as the Van Norman green waste site. After processing, it was redistributed in landscaped areas maintained by RPD using their light duty trucks.

Wood chips from pruned and removed yard trees were loaded into heavy duty trucks that hauled the material an average of 436 km to a biopower plant in Dinuba, CA. This round trip distance assumed 10 % of return trips involved a backhaul. Approximately 600 round trip hauls were completed annually. The Dinuba plant operated 70 % of time and consumed 80,626 t DW of biomass to produce 73,584 MW h^{-1} annually. The plant has a 7,211 MW h^{-1} parasitic load and consumed 140.1 m^3 of diesel fuel in biomass handling equipment (ESM Table S1). Electricity was sold to Pacific Gas & Electric, whose utility emission factor was 395 kg CO_2 MW h^{-1}. After subtracting on-site emissions, displaced emissions were 28,690 t CO_2 in 2010 and total biomass transport emissions were 4,922 t CO_2. Total net displaced emissions were 23,768 t or 0.295 t CO_2 t^{-1} DW of processed biomass.

2.4.10 Decomposition

CO_2 is released through decomposition of mulch derived from aboveground biomass and roots from removed trees. There is little research that quantifies the rate and extent of mulch and root decomposition. Decomposition rates vary with characteristics of the wood itself, the fate of the wood (i.e., left underground, chipped), and local soil and climatic conditions. 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 total tree biomass and 80 % of the CO_2 stored in belowground root biomass was released from dead trees to the atmosphere. Calculations conservatively assumed that 100 % of the CO_2 stored in mulch was released to the atmosphere. Release of CO_2 from root biomass and mulch was assumed to occur in the same year that the tree was removed or pruned.

3 Results

3.1 Tree planting, growth, and survival

Information from the MTLA databases indicated that 91,786 trees were planted from 2006 to 2010 and 87.5 % were planted in the inland climate zone. The number of trees planted each year ranged from 13,557 (14.8 %) in 2006 to 24,608 (26.8 %) in 2009. The MTLA 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 %).

Because equipment RTs as well as the magnitude of ecosystem services' trees produced are directly related to their mature size, the percentages of small (<10 m tall), medium (10–20 m tall), and large (>20 m tall) stature trees were calculated for street, park, and yard locations. Street tree species were quite evenly distributed among the three mature size classes. However, 65.5 and 14.0 % of the park trees were large and medium stature, respectively. The opposite was found for yard trees, 45.7 % were small and only 14.2 % were large.

The modeled street tree population reached 50,038 in 2010 and then gradually dropped to 17,231 by 2045 or 31 % of the number planted (Fig. 2). The modeled park tree population had the highest survival rate, peaking at 11,349 and finishing at 6,687, or 54 % of the 12,472 planted. Modeled yard trees exhibited the lowest survival, their population reaching 20,023 and closing at 6,895 (30 %). Across all locations, 33.6 % or 30,813 trees of the 91,786 planted were projected to survive until 2045.

3.2 Fuel inputs

Fuel inputs to all life stages except tree production are shown in ESM Table S6. These inputs are reported in total volume (kL) for the 40-year period and per tree planted (L). Diesel and gasoline accounted for 54.0 and 45.8 % of total fuel use, respectively. Trees planted in street, park, and yard locations used 50.1, 45.1, and 4.8 % of total estimated fuel use, respectively. On a per-tree planted basis, trees in parks required four times more fuel inputs (283.2 L) than trees in streets (69.6 L). Trees in yards required only 16.5 L of fuel per tree planted over the 40-year period. Fuel consumption across all locations averaged 85.4 L per tree planted.

Fuel used by vehicles accounted for 80.1 % (6,227 kL, 68.4 L per tree planted) of total fuel use, with the remaining amount used by equipment (1,560 kL, 17.0 L per tree planted). Vehicle fuel use in park and street locations accounted for 53.6 and 44.5 % of total fuel use, respectively.

Over 50 % of all fuels were used for tree removal and disposal (4,110 kL). The single largest fuel-consuming activity was hauling, handling, and grinding of biomass from dead street and park trees (2,570 kL, 28.0 L/tree planted). Stump grinding (812 kL) and tree removal (719 kL) were important fuel-consuming activities within the tree removal and disposal category.

Fuel used for tree planting activities accounted for 28.9 % of total consumption (2,268 kL), with most of that used for actual planting (2,221 kL, 24.2 L/tree planted). Pruning trees accounted for 18.2 % of total fuel use (1,423 kL, 15.5 L per tree planted). The sidewalk repair category accounted for less than 1 % of total fuel consumption (35.7 kL).

3.3 Fossil CO_2

Fossil CO_2 emission totals for the 40-year period are presented by activities and locations for vehicles, equipment, and materials in Table 1. Total CO_2 emissions of 17,048 t resulted in an average emission rate of 185.7 kg per tree planted for the 40-year period. Street tree emissions (11,222 t, 198.8 kg per tree) comprised 65.8 % of total emissions, while park (2,270 t, 182.0 kg per tree) and yard trees (3,556 t, 155.56 kg per tree) accounted for 13.3 and 20.9 %, respectively. Materials contributed 51.3 % (8,743 t) of total fossil CO_2 emissions, while equipment and vehicle emissions accounted for 27.6 % (4,704 t) and 21.1 % (3,602 t) of total fossil emissions for the 40-year period. Material emissions associated with treatment and delivery of water to irrigate trees (8,095 t) were the single greatest source of fossil CO_2 emissions (47.5 %). Vehicle emissions accounted for 73.0 % of the total for park trees because of the many volunteers who drove to planting and stewardship events.

Fossil CO_2 emissions at power plants were displaced by energy savings (−101,679 t) and biopower (−1,940 t), totaling −103,619 t (−1,128.9 kg per tree) for the 40-year period (Table 2). Street trees accounted for 71.7 % of the projected avoided emissions from energy savings because of their relatively large-stature and strategic locations compared to yard trees (McPherson, 2014).

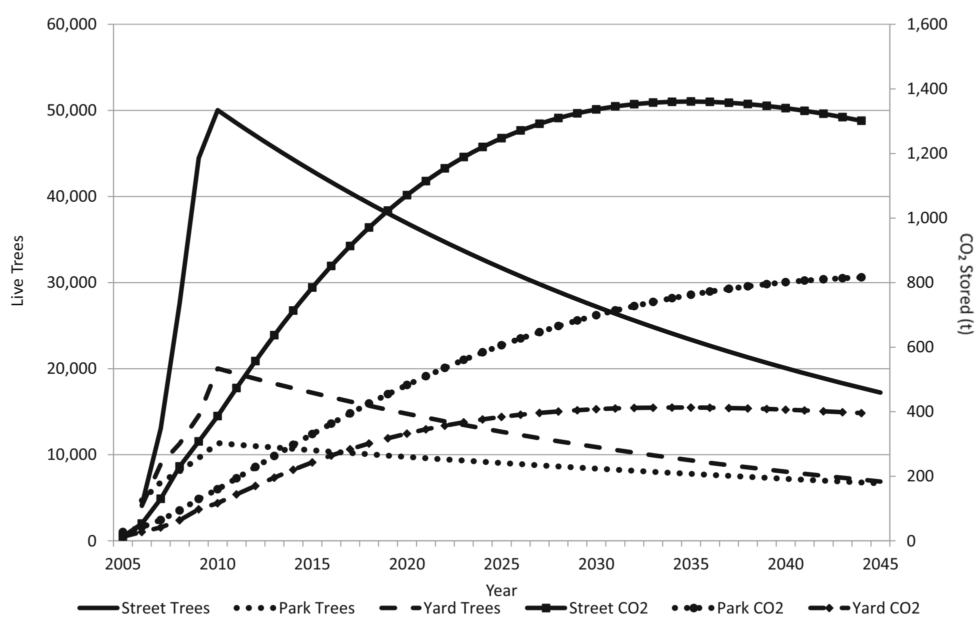


Fig. 2 Projected numbers of live trees and bCO_2 stored for trees planted in street, park, and yard locations (McPherson, 2014)

Table 1 Estimated fossil CO_2 emissions (t) for vehicles, equipment, and materials in street, yard, and park locations for the 40-year period

Categories/ activities	Street				Total/ tree planted (kg)	Park				Total/ tree planted (kg)	Yard				Total/ tree planted (kg)	Grand total	Total/ tree planted (kg)
	V	*E*	*M*	Total		*V*	*E*	*M*	Total		*V*	*E*	*M*	Total			
Tree production	173	474	431	1,078	19.1	31	84	76	191	15.3	56	154	140	350	15.3	1,619	17.6
Plant																	
Plant and tree well	52	67		119	2.1	224			224	17.9	48			48	2.1	391	4.3
Establish and water	25			25	0.4	273			273	21.9						298	3.2
Subtotal	77	67		144	2.5	497			497	39.8	48			48	2.1	688	7.5
Prune																	
Prune and chip	126	150		276	4.9	779	147		926	74.2	155	199		353	15.5	1,555	16.9
Process biomass	3	13		16	0.3	12	15		26	2.1						43	0.5
Distribute mulch	1			1	0.009	1			1	0.1						2	0.02
Subtotal	130	163		293	5.2	792	161		953	76.4	155	199		353	15.5	1,599	17.4
Remove																	
Remove, grind stump, and chip	1,092	2,140		3,232	57.2	269	212		480	38.5	87	413		500	21.9	4,211	45.9
Process biomass	109	432		540	9.6	64	80		144	11.6		97		97	4.2	781	8.5
Distribute mulch	17			17	0.3	6			6	0.4						22	0.2
Subtotal	1,217	2,572		3,789	67.1	338	292		630	50.5	87	509		596	26.1	5,015	54.6
Sidewalk repair	2	30		32	0.6											32	0.3
Watering			5,887	5,887	104.3								2,208	2,208	96.6	8,095	88.2
Grand total	1,599	3,305	6,319	11,222	198.8	1,657	537	76	2,270	182.0	346	862	2,348	3,556	155.5	17,048	185.7

V vehicle, *E* equipment, *M* materials

Net fossil CO_2 totaled −86,570 t (−943.2 kg per tree). Park trees were projected to be net fossil CO_2 sources because they did not shade buildings and avoid power plant emissions, while street and yard trees were net fossil CO_2 sinks.

3.4 Biogenic CO_2

Biogenic CO_2 (bCO_2) emissions totaled 66,359 t (723.0 kg per tree) for the 40-year period (Table 2). Sources were 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) stored in the roots and soil of dead trees after 40 years (Fig. 2). Net bCO_2 totaled −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 yard trees were estimated to store slightly less bCO_2 than the fossil CO_2 they emit.

3.5 Net total CO_2 emissions

Assuming that 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 is projected to be a net reducer of CO_2 after 40 years (−98,053 t, −1,068.3 kg per tree). Yard trees were estimated to produce the greatest reduction per tree planted (−1,161.3 kg), while street trees produced the largest total net reduction (−61,467 t).

3.6 Emissions by category and activity

The distribution of CO_2 emissions from both fossil and biogenic sources is shown in Fig. 3. Biogenic emissions associated with wood combustion and decomposition of mulch and dead root biomass were the largest category, 79.6 % for the 40-year period. Fossil CO_2 emissions associated with tree irrigation are the second largest emission source (9.7 %). After irrigation, tree removal was the next largest tree care activity

Table 2 Estimated total (t) and per tree (kg) fossil and biogenic CO_2 for street, park, and yard locations for the 40-year time period

	Street total	Per tree (kg)	Park total	Per tree (kg)	Yard total	Per tree (kg)	Grand total	Per tree (kg)
Fossil CO_2								
Total emissions	11,222	198.8	2,270	182.0	3,556	155.5	17,048	185.7
Avoided emissions	−72,853	−1,290.5		0.0	−30,766	−1,345.8	−103,619	−1,128.9
Net emissions	−61,631	−1,091.7	2,270	182.0	−27,210	−1,190.2	−86,570	−943.2
Biogenic CO_2								
Total emissions	43,200	765.2	9,294	745.2	13,866	606.5	66,359	723.0
Stored in live trees	−40,379	−715.3	−20,946	−1,679.4	−12,378	−541.4	−73,703	−803.0
Stored in root biomass (dead trees)	−2,657	−47.1	−657	−52.7	−825	−36.1	−4,139	−45.1
Net biogenic CO_2	164	2.9	−12,309	−986.9	663	29.0	−11,482	−125.1
Combined[a]								
Net total (fossil + biogenic)	−61,467	−1,088.8	−10,038	−804.9	−26,547	−1,161.3	−98,053	−1,068.3

[a] The implication of combining these two is that the stored carbon remains stored over long-time horizons, i.e., +100 years

(6 %). Tree production and pruning (both 1.9 %) were important secondary emission sources.

Equipment emissions accounted for 24 to 30 % of total fossil CO_2 emissions across the three types of locations. 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 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 yard 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. Most of these emissions (1,447 t) occurred when hauling crews, equipment and chips on tree removal, and stump grinding jobs. Pruning (1,077 t) activities were estimated to generate more vehicle emissions than planting (622 t).

4 Discussion

4.1 Comparison with literature

MTLA fossil plus biogenic CO_2 emissions were 46 % of CO_2 stored in tree biomass plus avoided emissions, a high proportion compared to the 1 to 4 % values previously reported for Montjuic Park, Leipzig, and Sacramento. Previous studies did not fully account for emissions from tree production, wood decomposition, and water, all important sources identified in this study. When decomposition and water emissions are omitted from this analysis, the remaining emissions are 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 tree production, planting, pruning, and removal categories are of the same order of magnitude as 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 as reported by Nowak et al. (2002).

4.2 Management implications

The relative magnitude of emissions across categories indicates potential for achieving reductions through management interventions. This potential is greatest for strategies that reduce decomposition, where values ranged from 78.7 (yard) to 770.4 kg per tree planted (street). Utilizing tree biomass as feedstock for biopower production proved to be the single most effective management practice simulated in this study. Avoided biopower plant emissions are associated with the conversion of wood chips from yard trees to biopower more than offset all removal emissions. Although there is growing

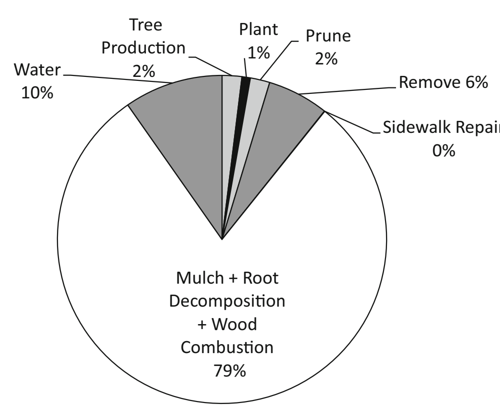


Fig. 3 Breakdown of fossil and biogenic CO_2 emission sources among categories

interest in this approach, economic, technical, and environmental barriers limit its widespread application in cities (Tinus and LaMana 2013; Nzokou et al. 2011). Delaying emissions by utilizing 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.

CO_2 emissions related to irrigation water ranged from 0 kg (park) to 104.3 kg per tree planted (Table 1). Planting trees in areas that already receive irrigation, such as turf, 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. Of the top 43 tree species planted by MTLA, nine were rated as low water use and the remaining were moderate (i.e., K_s=0.2 and 0.4). The program has avoided planting high-water-use species. It could increase the proportion of water thrifty species. 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). Further research is needed to better quantify drought tolerance and adaptation traits for different tree species. Other strategies to reduce tree water use include improved management of soil moisture for root growth, improved irrigation efficiency, and harvesting of rainfall (Gill et al. 2007).

Fossil CO_2 emissions for the street tree removal category averaged 67.1 kg per tree planted (street). 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 to the minimum required for the size of material to be removed as well as limiting equipment idling and RT by working more efficiently. Electric chain saws powered by batteries that are charged by the chipper can reduce fuel use. Vehicle emission 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 use of lower-carbon fuels such as CNG and biodiesel. These same strategies can be applied to tree pruning activities.

Although this study did not explicitly consider effects of tree survival and growth rates, it is apparent that promoting tree longevity will reduce removal and decomposition emissions. Other studies have found that simulated carbon storage rates are highly dependent on assumed tree mortality, growth, and mature size (Kovacs et al. 2013; Morani et al. 2011). More research is needed to document the range of GHG emissions associated with different management regimes, and how these regimes affect tree growth, survival, and carbon storage.

To maximize net CO_2 reductions, MTLA mangers can increase yard tree plantings, which produced the greatest average net CO_2 reduction per tree planted (−1,161.3 kg for 40 years). Potential reductions are greatest when trees are positioned to shade west-facing walls, especially in the hotter inland climates where air conditioning savings are greatest. Storage is increased by selecting trees that will grow as large as the space allows and long-lived species with dense wood.

5 Conclusions

MTLA, one of the nation's largest TPIs, planted 91,786 trees from 2006 to 2010, of which 30,813 (33.6 %) were estimated to survive by 2045. The program was estimated to release 17,048 and 66,359 t of fossil and bCO_2 over the 40-year period or 83,408 t total (908.7 kg per tree planted). This amount is slightly more than the amount MTLA trees were projected to store in aboveground biomass (−73,703 t) and roots (−4,139). Hence, the MTLA program would be a net source of CO_2 if not for avoided fossil CO_2 emissions from energy savings (−101,679 t) and biopower (−1,939 t). Our finding suggests that this TPI, and possibly others, can be net CO_2 sinks, especially if trees are strategically located to reduce energy consumed for air conditioning and space heating. Our results differ from most previous studies by projecting relatively higher levels of CO_2 emissions. This discrepancy is largely explained by inclusion of several important emission sources: bCO_2 emissions from decomposition and wood combustion as well as fossil CO_2 emissions from irrigation.

Decomposition of removed wood that was chipped and redistributed as mulch was the largest source of CO_2 emissions. Utilizing chips to generate electricity and displace power plant emissions was the single most effective management strategy found in this study. Delaying emissions by converting urban saw timber into wood products is an alternative approach that merits attention.

Although there are many regions where trees can grow without irrigation, this is seldom the case in Los Angeles. Emissions associated with energy used to pump, treat, and deliver water were estimated to account for 9.7 % of total CO_2 emissions. Sizable emission reductions are possible through soil and irrigation management, selection of drought-tolerant species, and water harvesting.

Projected equipment and vehicle emissions were of similar magnitude, but their proportions changed by location. In parks, where volunteers planted and maintained many trees, vehicle emissions were three times greater than equipment emissions. Strategies for reducing vehicle emissions include reducing travel distances, improving fleet fuel efficiency, and using low-emitting fuels. Equipment emissions exceeded vehicle emissions for trees in street and yard locations. Tree removal and stump grinding generated substantially more CO_2 emissions than other tree planting and care activities.

Equipment emission reductions can be gained from judicious selection of equipment size, use of more efficient practices that reduce run times, and increased use of low or non-emitting power sources.

Planting trees in cities can produce a host of co-benefits that improve quality of life. Trees reduce air pollution and stormwater runoff, provide wildlife habitat, increase property values, produce edible fruits and nuts, lower crime rates, and improve sense of well-being (Roy et al. 2012). At the same time, trees can damage infrastructure, exacerbate air pollution problems, and increase space heating costs and are expensive to maintain. CO_2 emission reductions are only one component of a sustainable TPI. TPIs should be planned and managed so that trees produce a diverse suite of services, while minimizing potential disservices such as CO_2 emissions.

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