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Analysis

The marginal cost of carbon abatement from planting street trees in New York City

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ABSTRACT

Urban trees can store carbon through the growth process and reduce fossil fuel use by lowering cooling and heating energy consumption of buildings through the process of transpiration, shading, and the blocking of wind. However, the planting and maintenance of urban trees come at a cost. We estimate the discounted cost of net carbon reductions associated with planting and caring for street trees in New York City (NYC) over 50- and 100-year horizons. Depending on the species planted, the cost of reducing carbon, averaged across planting locations, ranges from \$3133 to \$8888 per tonne carbon (tC), which is higher than current cost estimates of forest-based carbon sequestration. The London plane tree is the most cost-effective species because of its long life span and large canopy, and the marginal cost of carbon reduction for the species ranges from \$1553 to \$7396/tC across planting locations. The boroughs of Staten Island and Queens have planting locations with the lowest average costs of carbon reduction (\$2657/tC and \$2755/tC, respectively), resulting from greater reductions in energy consumption in nearby buildings, which have fewer stories and more residential use than buildings in the other boroughs.

1. Introduction

The concern about global climate change has led many U.S. cities to adopt local policies and programs to reduce greenhouse gases (GHGs) in the atmosphere. As of 2012, 1054 mayors across 50 states have signed the U.S. Conference of Mayors' Climate Protection Agreement (Mayors Climate Protection Center, 2012), and New York City has pledged to reduce GHG emission by 30% from 2005 levels by 2030 (City of New York, 2013). Under the agreement, cities vow to reduce carbon emissions below 1990 levels through programs that improve urban transit, reduce non-renewable energy consumption, restore urban forests, and many others. Restoring urban forests is a promising way to offset carbon emissions because the carbon storage attributed to U.S. cities is estimated at 10% of the total land carbon storage in the U.S., where more than half of this urban carbon storage is attributed to soils, 20% to vegetation, 11% to landfills, and 5% to buildings (Churkina et al., 2010). The carbon density of human settlements is high because carbon is stored not only in vegetation and soils, but also in buildings, furniture, printed materials, landfills, and people. Trees are more than 95% of the urban vegetation carbon pool (Davies et al., 2011).

Urban forests reduce GHGs in the atmosphere by capturing carbon as they grow (carbon sequestration). Total tree carbon storage in U.S. urban areas circa 2005 is estimated at 643 million tonnes of carbon (tC), about 3.2% of the estimated carbon stored in U.S. forestland and urban forest trees combined (Nowak et al., 2013). Annual carbon sequestration in U.S. urban forests is estimated at 25.6 million tC/year (Nowak et al., 2013). Urban forests also reduce energy use in nearby buildings (Donovan and Butry, 2009) and thereby indirectly reduce GHGs emitted from fossil-fuel-based combustion (energy conservation). As an example of trees reducing energy use, urban trees in California are estimated in 2008 to reduce annual air conditioning energy use by 2.5%, suggesting a reduction in 1.1 million tC/year (McPherson, 2008; McPherson and Simpson, 2003). In New York City, energy conservation from street trees reduces fossil-fuel emissions by an estimated 0.069 million tC/year (Peper et al., 2007). Trees on residential lots can reduce fossil-fuel emissions from the heating and cooling of homes, but the cost to plant and maintain private trees could be higher and is not explored in this study. Park trees are farther away from buildings and have less influence on a building's energy use, but park trees are less costly to plant and maintain than street trees. The reforestation of parks to reduce carbon is also not explored here.

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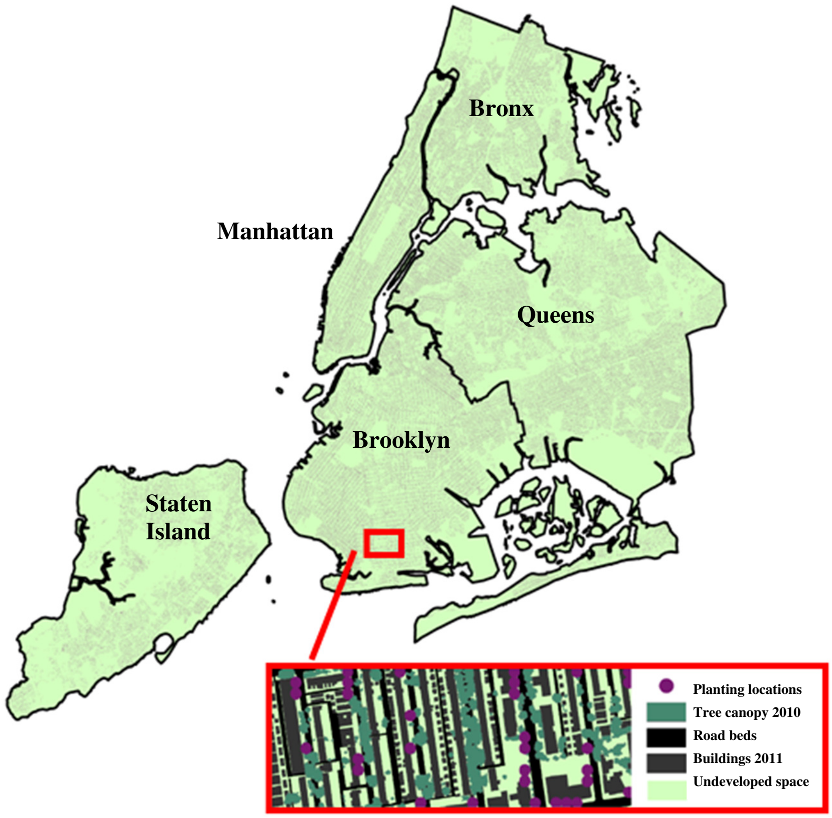

Fig. 1. Study area with street tree planting locations near buildings in 2011. Inset is a magnified section of the Homecrest neighborhood in Brooklyn with the planting locations, buildings, tree canopy, and road beds shown.

The carbon reductions from planting urban trees come at a cost in the form of expenditures for planting, pruning, and removal. We estimate the cost effectiveness of street tree planting for reducing carbon. The division of the discounted cost of tree care by the discounted tons of carbon abated from sequestration and energy reduction represents the cost effectiveness of a tree planting program. Only one study has been found that evaluates the cost effectiveness of urban tree planting to reduce atmospheric carbon (McHale et al., 2007). Street trees are more expensive to plant and maintain than park trees, but the proximity of street trees to buildings enables the trees to reduce building energy use.

Our measure of the cost-effectiveness of street tree planting focuses on carbon abatement and does not consider other services provided by street trees, such as reducing air and water pollution, increasing aesthetics, reducing crime, increasing property values, and mitigating heat-islands (Dwyer et al., 1992; Morani et al., 2011; Sander et al., 2010; Susca et al., 2011; Troy et al., 2012). Accounting for all of the tree services reveals the social gain of a forest (Feng and Kling, 2005; Plantinga and Wu, 2003), but the full suite of benefits may be secondary if the forestry program has the expressed purpose of reducing carbon (Lubowski et al., 2006). The aim of this paper is to estimate the carbon offset benefit of street trees, which may add to the attractiveness of urban forestry initiatives even if carbon abatement alone is not a cost effective strategy.

Our case study involves street tree planting in New York City (NYC). In recognition of the environmental, social, and economic benefits of urban trees, including the reduction of atmospheric carbon, NYC launched a program in April 2007 known as MillionTreesNYC, a city-wide, public–private initiative to plant and care for one million new trees across the city's five boroughs by 2017 (MillionTreesNYC, 2013). The Million TreeNYC initiative is in its fifth year, and more than 750,000 trees have already been planted (MillionTreesNYC, 2013). One of the most visible components of MillionTreesNYC is its commitment to street tree planting: 220,000 new street trees will be planted to bolster the 600,000 street trees that existed prior to the initiative.

In our study, we first identify public, street, planting locations near buildings in each of the five boroughs of NYC (Fig. 1). Next, we simulate the net carbon benefits and management costs over 50-year and 100-year planning horizons for four representative tree species in each location. Net carbon benefits include carbon sequestration and loss from tree growth and decay, avoided carbon emissions from energy savings, and carbon emissions from tree planting and maintenance (Nowak et al., 2002). Management costs include planting, pruning, and removal expenditures. Carbon benefits and management costs are discounted to the present to estimate the dollars per ton of carbon abated ($/tC). Finally, planting locations are ranked from lowest to highest $/tC to construct a marginal cost curve plotting cost ($/tC) versus cumulative carbon abated (tC/year) for additional tree planting.

2. Methods

2.1. Identifying Tree-planting Locations

The study area includes the five boroughs of NYC (Fig. 1). We identify potential tree-planting locations by dividing the study area into cells that are fifty feet square in size.[1] From this set, we restrict our analysis to cells on public land beside roads where the city can plant. Further, we restrict our analysis to cells that are within 100 ft of the nearest building, which is close enough to affect building energy use. We exclude planting locations on private land because the city cannot access these sites. We also exclude planting locations on public land that are further than 100 ft from buildings

[1] The borough boundaries are available in a geographic information system (GIS) at the NYC Data Mine http://www.nyc.gov/html/datamine/html/data/geographic.shtml.

because trees in these locations will have a limited influence on energy use. Overhead wires can also influence where trees are planted, but no digital information on the location of the wires is available to exclude those locations. Locations within 100 ft of a building do not necessarily reduce energy use because this depends on building characteristics such as the number of stories and the proportion of commercial space. Finally, locations are excluded that we estimate as already occupied by trees, and we assume no other impervious cover prevents plantings in the locations between the road and buildings.

Digital information on roadbeds and buildings is available in a geographic information system (GIS) from the NYC Department of Information and Telecommunications (DOITT).[2] The tree canopy data are based on 3.2 ft resolution LiDAR data of NYC in 2010 processed by the University of Vermont's Spatial Analysis Laboratory (MacFaden et al., 2012; O'Neil-Dunne, 2012). A location is estimated to be unoccupied by a tree if there is less than twenty-five percent tree canopy cover over the location. A location that has 24% tree cover could have a tree in it, or the canopy of surrounding trees might be the 24%. We do not have the data to distinguish, and 25% is used as a threshold. Using these data, we find 182,736 potential tree-planting locations that are fifty feet square in size, adjacent to streets, and close to buildings in NYC. For comparison, the initial tree canopy assessment for MillionTreesNYC suggested a total of 220,000 suitable locations for street tree planting (personal communication, NYC Parks and Recreation 2012). Our number of potential tree-planting locations (182,736) is 17% less than the MillionTreesNYC estimate of locations (220,000) because we restrict planting locations to within 100 ft of buildings, and some locations may already have been planted from the Million Trees initiative that began in 2007.

Site characteristics of the planting locations are collected in a GIS for measuring the influence of the trees on building energy use. The characteristics include the distance and direction to the nearest building and a set of associated building characteristics, including the years built and altered, the areas in residential, commercial, and office use, and the number of floors. We assume the tree planted at a location only affects the energy use of the nearest building although the tree could potentially affect other nearby buildings. The building characteristics are based on the tax lot features from the Department of Finance and provided in a GIS by the Department of City Planning.[3] We extract the building characteristics important for energy use such as the age, the type of the heating and cooling equipment, the number of floors, and the proportion of the building in residential, commercial, and office use.

2.2. Simulating Net Carbon Benefits and Management Costs for a Planting Location

We created a stochastic simulation model to compute discounted carbon benefits and management costs over a given time horizon for a newly planted tree in a given location (Fig. 2). The model consists of two embedded loops. The inner loop is the tree simulation, which loops over each year of a 50- or 100-year horizon. Because the tree simulation includes a random variable for annual tree survival, the outer loop is for 10,000 independent replications of the tree simulation loop.

At the beginning of each replication, a six-year-old tree with a size of 2.5 to 3 inch caliper is planted and counters for management costs and carbon sequestration, avoidance, and emissions are initialized. For each year in the simulation loop, tree survival is the outcome of a Bernoulli random variable with a given survival probability (i.e., 0.98). We also assume that the tree has a maximum lifespan (e.g., 90 years). If the tree survives and has not reached its maximum age, the counters are updated with the carbon sequestered from a year's growth, carbon emissions avoided from heating and cooling reductions in nearby buildings, carbon emissions from management activities (e.g., pruning), and management costs incurred, all discounted to a present value. The simulation moves to the next year with a tree that is one year older. If the tree does not survive or has reached its maximum age, it is removed and a new six-year-old tree is replanted. The counters are updated with discounted management costs and with discounted carbon emissions from wood decay, tree removal, and replanting. The simulation moves to the next year with a newly planted six-year-old tree. The simulation loop continues until the end of the horizon, whence the program exits the loop, saves the total discounted net carbon and management cost for the replication, and moves to the next replication. After all the replications are complete, the program exits the replication loop and computes expected discounted net carbon benefits and management costs for the planting location, where the expectations are the averages of the results over all of the 10,000 replications.

Carbon sequestration and loss from tree growth and decay, avoided carbon emissions from energy savings, carbon emissions from tree planting and maintenance, and management costs are all discounted to the present with a 2% real discount rate (Howarth, 2009). If the marginal damage of climate change is growing over time, Richards (1997) indicates the discount rate to use for carbon should be less than the rate for management costs. However, economic studies (Lubowski et al., 2006) frequently use the same discount rate for both carbon and cost, which assumes the marginal damages of climate change over time are constant. We also performed sensitivity analysis to determine the effects of increasing the discount rate.

2.3. Constructing the Marginal Cost Curve of Carbon Abatement from Tree Planting

For each planting location, the discounted management cost is divided by the discounted net carbon benefit to obtain the cost per ton of carbon abated ($/tC). Further, the discounted net carbon benefit is converted to an annualized carbon flow (tC/year). By ordering the planting locations from the lowest to the highest cost per ton of carbon abated and plotting $/tC versus cumulative tC/year abated for each additional planting location, a marginal cost curve of carbon abatement from planting street trees is obtained. The marginal cost curve suggests how, for a large-scale program of tree planting, carbon can be cost-effectively reduced by planting street trees near buildings.

2.4. Representative Street-trees

To account for differences in the mature size and growth rates of different tree species, we simulate the net carbon benefits and management costs for four representative street trees: London plane tree (*Platanus acerifolia*) (large deciduous), callery pear (*Pyrus calleryana*) (medium deciduous), kwanzan cherry (*Prunus serrulata*) (small deciduous), and eastern white pine (*Pinus strobus*) (large conifer). These species are the most abundant of their size categories in New York City or were selected as representative of their size categories for modeling (Peper et al., 2007). Although NYC does not currently plant eastern white pine as a street tree, over a thousand white pine street trees were counted in the 2005–2006 street tree census for NYC (Peper et al., 2007), and we are interested in examining the potential cost-effectiveness of planting conifer street trees to reduce carbon.

Our assumptions about tree mortality and growth are as follows. For each of the four planted tree species, we assumed an annual survival rate of 0.98 based on information from a survey of forestry personnel at the NYC Department of Parks and Recreation in 2011 and observations of tree mortality by Peper et al. (2007). We also estimated the maximum lifespan of trees of each species as the age of trees in the

[2] The DOITT website for the GIS data downloads is http://www.nyc.gov/html/doitt/html/eservices/eservices_gis_downloads.shtml.

[3] More detail on the tax lot data in MapPLUTO is available at http://www.nyc.gov/html/dcp/html/bytes/applbyte.shtml.

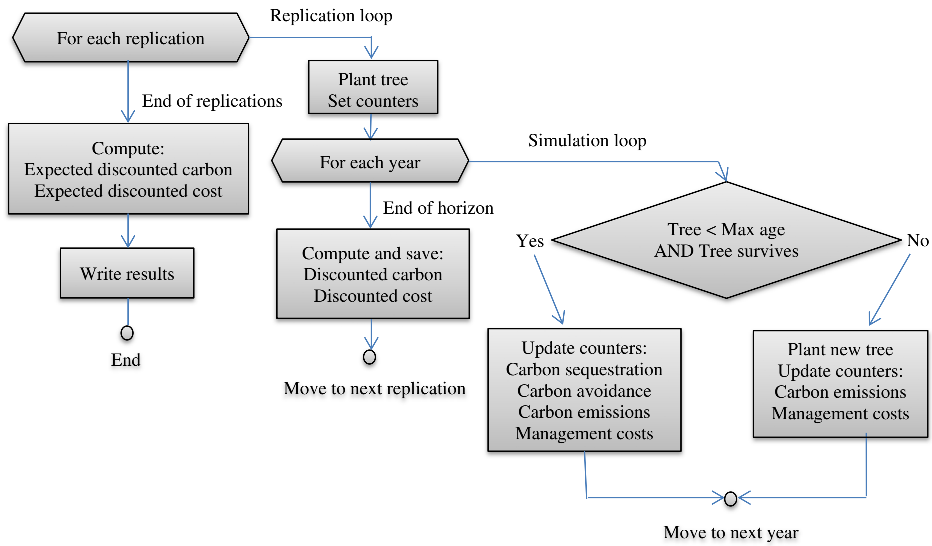

Fig. 2. Flow chart of a stochastic simulation model to project discounted carbon benefits and management costs over a given time horizon for a newly planted tree in a given location.

95th percentile of the diameter distribution of that species in NYC (Peper et al., 2007). The maximum lifespans of London plane tree, callery pear, kwanzan cherry, and eastern white pine are 90, 25, 54, and 80 years, respectively. We use relations among tree age, diameter, and height that were developed from street trees in NYC by Peper et al. (2007) as a basis for estimating carbon sequestration, carbon emissions avoided, and management costs, which depend on tree size.

2.5. Carbon Sequestration

We use the Tree Carbon Calculator (U.S. Forest Service, 2012) to calculate annual carbon sequestration for each of the four species (Fig. 3). Models used by the Tree Carbon Calculator are described in Peper et al., 2007 and summarized here. Annual sequestration includes carbon storage in above- and belowground biomass over the course of one growing season. It is calculated by first using estimates of tree height and diameter to estimate above-ground biomass (McHale et al., 2009; Pillsbury et al., 1998). Biomass is then converted to green and dry-weight estimates and divided by 78% to incorporate root biomass following the study on urban trees by Nowak and Crane (2002). Finally, dry-weight biomass is converted to carbon (50%). The amount of carbon sequestered each year is the annual increment of carbon stored as biomass.

2.6. Avoided Carbon Emissions from Energy Conservation

Urban trees may reduce energy use in buildings and consequently reduce GHG emissions from fossil-fuel combustion. Trees influence energy use by shading, providing evaporative cooling, and blocking winter winds. Potential reductions in energy use depend on the tree size and

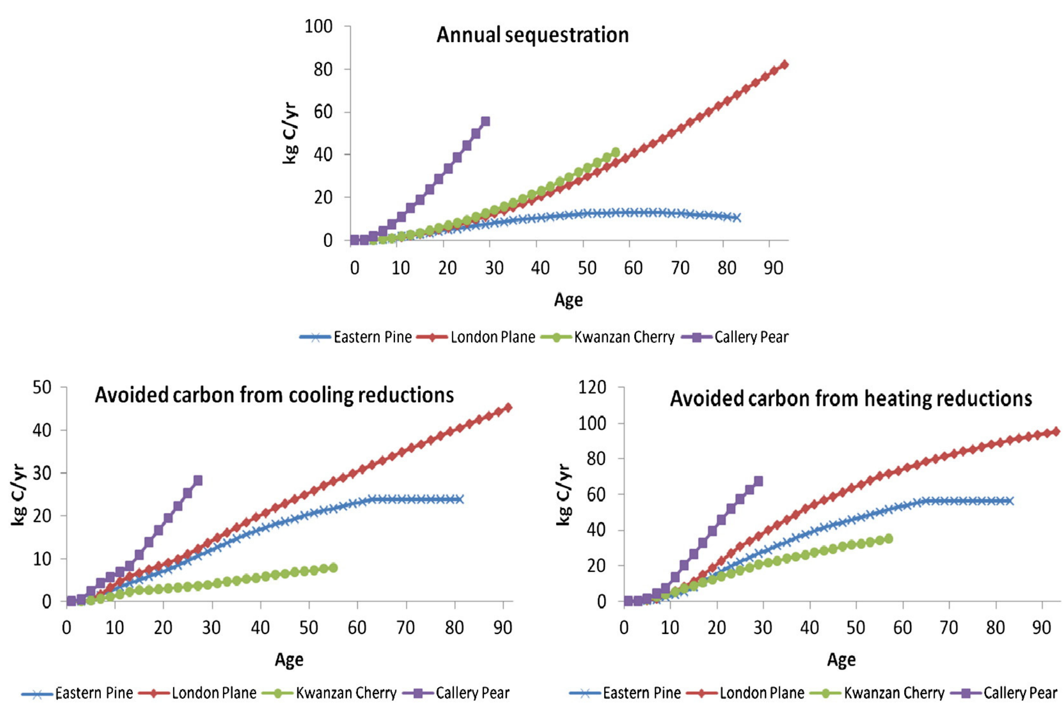

Fig. 3. Annual sequestration and avoided carbon from cooling and heating reductions by the age of the tree species. The curves for avoided carbon are for planting locations to the west of a building and within 21 to 40 ft of a pre-1950 vintage building with central air-conditioning and natural gas heating.

location relative to the building as well as the building's size, insulation, and heating/cooling equipment (McPherson and Simpson, 1999).

We use the Tree Carbon Calculator (U.S. Forest Service, 2012) to estimate annual avoided carbon equivalents (includes methane and nitrous oxide), hereafter simply called carbon, from cooling and heating reductions associated with each species in each planting location. The details of estimating annual avoided carbon are described in McPherson et al. (2007) and Peper et al. (2007). In short, the calculator includes estimates of annual electricity and natural gas use per residential or commercial unit based on computer simulations that incorporate building, climate, and shading effects, following methods outlined by McPherson and Simpson (1999).

Energy consumption depends on building characteristics such as cooling and heating equipment saturations, floor area, stories, insulation, window area, and building age. An average building type is used in the Tree Carbon Calculator with adjustments possible for building age, number of stories, and the heating and cooling equipment. Annual changes in energy consumption due to the effects of trees are calculated on a per-tree basis by comparing results before and after adding trees. These effects depend on the distance and direction of the tree in relation to the building. Annual changes in energy consumption are then converted to emission savings from fossil-fuel combustion. Space cooling comes from electricity assumed to come entirely from coal-fired power plants which emit twice the amount carbon per unit of energy than do fuels for space heating such as oil and natural gas.

The Tree Carbon Calculator needs the following information to calculate annual carbon emissions avoided: species of the tree planted, maximum dbh a tree can reach at that location, the tree's direction with respect to the closet building, distance of the tree from the closest building, the year the closest building was built, and the kind of equipment for air conditioning the building uses based on a state average (Energy Information Association, EIA, 2009). We calculated the annual avoided carbon (kg C/year) from cooling and heating reduction for various types of planting locations. Each location was classified by distance from the center of the cell (0 to 20 ft, 21 to 40 ft, 41 to 60 ft) to the closest building, direction with respect to the building (North (includes Northeast and Northwest), West, East, Southeast and Southwest, South), and the vintage of the building (pre-1950, 1950 to 1980, post-1980). For each type of planting location, we used the Tree Carbon Calculator to predict annual carbon emissions avoided as a function of tree age. Curves for avoided carbon by species are listed in Fig. 3 for planting locations to the west and within 21 to 40 ft of a pre-1950 vintage building.

The effect of the various types of planting locations on avoided carbon from the cooling and heating reductions by tree species is shown in Table 1. Examining direction, a planting location to the north or south is much less effective at reducing energy from cooling by the shading of the tree than locations to the west or east due to the position of the sun throughout the day. A planting location to the north is more effective at reducing energy from heating by the blocking of winter winds whereas a planting location to the south is less effective than locations to the east or west based on the direction of the winter winds. A tree planted to the South of a building can even increase energy use and the associated carbon. The distance of the tree from the building affects energy use because cooling is more effective the closer the tree is to the building from the shading and evaporative cooling. However, a tree closer to a building is a less effective wind break, and the reduction in energy from heating is more if the tree is farther from the building within 60 ft.

The building characteristics also influence how a nearby tree affects energy use. The vintage of a building influences energy consumption because of the construction material and the quality of craftsmanship of the building. Newer homes conserve energy for heating more effectively, and this makes a nearby tree less important for reducing energy use. However, a tree adjacent to a home built from 1950 to 1980 is particularly useful for reducing air conditioning. The carbon calculator accounts for the air conditioning equipment the building uses. A building with a wall/window unit uses less energy for cooling than central air measured in kWh, meaning less excess energy for the tree to reduce. A building heated using electrical resistance rather than natural gas or oil uses less energy measured in MBtu.

In addition, the number of stories and the presence of commercial space of a building affect how effectively trees reduce energy. A tree adjacent to a multi-story building does not reduce energy consumption as much as a tree next to a shorter building because multi-story buildings have more interior rooms unaffected by adjacent trees. A reduction factor of 0.74 is applied to avoided energy if the multi-story building is more than two floors, and a reduction factor of 0.51 is applied to a building more than five stories (Peper et al., 2007). A lower reduction factor for the especially tall buildings present in Manhattan may be appropriate, but the reduction factor for these building is not known. Peper et al. (2007) indicate that commercial buildings are less sensitive to outdoor temperatures than houses, and a reduction factor of 0.41 is applied to the commercial portion of the building. Simpson (2002) estimates that reductions in cooling and heating energy use fall for each tree added after the first by about 5%. A multiple tree reduction factor of

Table 1
Percent change in avoided carbon of heating and cooling energy reductions from trees by energy reduction factor. The percent change is from a baseline tree that is twenty years old at a western azimuth and 20–40 ft away from a pre-1950 vintage building with central air and that is heated by natural gas.

	London plane *Platanus acerifolia*		Callery pear *Pyrus calleryana*		Kwanzan cherry *Prunus serrulata*		Eastern white pine *Pinus strobus*	
	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating
Azimuth								
North	−70.64	7.79	−63.06	5.84	−46.14	3.26	−57.78	8.35
East	−12.66	−9.64	−11.75	−6.44	−15.82	−3.03	−13.15	−5.66
South	−66.02	−69.16	−57.96	−26.39	−44.73	−13.89	−51.70	−57.47
Distance								
Close (0 to 20 ft)	60.11	−21.57	41.25	−6.61	59.27	−3.22	39.74	−17.52
Far (41 to 60 ft)	−41.85	5.26	−33.80	2.82	−23.47	0.63	−33.69	6.48
Vintage								
1950–1980	48.77	−19.64	49.48	−14.65	44.29	−12.52	61.51	−18.96
post-1980	−16.53	−37.34	−14.09	−34.39	−18.30	−32.80	−2.84	−36.57
Air conditioning equipment								
Wall/Window Unit	−92.19	0.00	−91.18	0.00	−87.26	0.00	−90.57	0.00
Heating equipment								
Electrical	0.00	−88.72	0.00	−87.39	0.00	−83.21	0.00	−85.78
Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2
Planting, pruning, and removal costs ($/tree) for street trees in New York City.

Management activity	Tree age (years)				
	6–20	21–35	36–50	51–70	71–90
Planting	1550	–	–	–	–
Pruning	–	55	68	68	–
Removal	317	666	1284	1963	2944

0.85 is applied if more than 20% of a 100 foot buffer around a building is covered by tree canopy, equivalent to approximately three existing trees per building.

2.7. Carbon Emissions from Decomposition and Maintenance

When a street tree dies, its biomass decomposes and emits carbon. We divide a tree's biomass into aboveground and belowground components based on a root-to-shoot ratio of 0.25 (Cairns et al., 1997). We assume that the aboveground biomass is mulched and decomposes within three years following tree mortality, whereas the belowground biomass decomposes in 20 years (Nowak and Crane, 2002). Utilizing urban wood as fiber (i.e. furniture, cabinets) would extend the period of time the carbon remains in solid form out of the atmosphere, or burning wood to produce energy would offset the impacts of other more carbon-intensive fuel sources.

Tree management practices, including removal, planting, and pruning, release carbon from maintenance equipment (e.g. chain saws, trucks, chippers). We assume that planting takes place at the beginning of the horizon, and removal and planting take place whenever a tree dies or reaches its maximum age during the horizon. Based on information in the 2011 NYC Parks survey, we assume that pruning takes place when a tree reaches 27 years old and every 21 years thereafter. Further, we assume that emissions from planting, pruning, and removal activities are 0.498, 2.294, and 7.716 kg C, respectively, based on information about fuel consumption averaged across all the trees involved in those activities in 2011 from the NYC Parks survey and appropriate conversion factors from fuel use to carbon emissions (U.K. Department of Transport, UKDOT, 2008).

2.8. The Costs of Tree Care

Based information in the 2011 NYC Parks survey, we assume that the costs of management practices vary by broad age classes (Table 2). The cost of planting a six-year-old tree is $1550. Pruning takes place at ages 27, 48, and 69 with costs ranging from $55 to $68 per tree. Tree removal costs range from $317 to $2944 per tree.

3. Results

To begin, the characteristics of the locations available for tree planting near buildings are examined. Next, the benefits in terms of carbon sequestered and avoided from tree planting are weighed against the costs by tree species and planning horizon. The cost per ton of carbon abated for the planting locations can be ordered the lowest to the highest to create a marginal cost curve of carbon abatement. We conduct sensitivity analysis based on the time horizon that the planted trees can reduce atmospheric carbon. Finally, the best places across the study area to undertake tree planting activities for carbon abatement are presented.

3.1. Planting Locations

Across the city, there are 182,736 planting locations with the majority (65%) occurring in Queens and Brooklyn (Table 3). The planting locations are on average 28 ft from the nearest building, measured as the distance from the edge of the 50 ft cell planting location to the edge of the nearest building. The buildings average 3.3 stories and 63 years of age, and 71% of the building floor area is residential space. Most of the planting locations are to the West or North of the buildings, and this is the case for all the boroughs. Not surprisingly, buildings near planting locations in Manhattan have more floors and less residential area than buildings in other boroughs. The average canopy cover for a 150 ft buffer around the planting locations is 12%.

3.2. Average Discounted Carbon Abatement and Cost per Tree

The average discounted carbon abatement and cost per tree across all planting locations in NYC are reported in Table 4. The London plane tree has the highest average carbon abatement among the four species because it lives the longest and produces the largest canopy, even while the Callery pear has higher annual carbon abatement because of a faster growth rate. As a result, a London plane tree leads to more energy savings in neighboring buildings (Fig. 3) and has lower levels of carbon decomposition. Tree cost is highest for Callery pear because its relatively short lifespan (25 years) causes more frequent removal and replacement expenditures. Putting these figures together, we find that London plane trees have the lowest average cost per ton of carbon abated ($3615/tC) across the planting locations. Other species cost 1.7–2.3 times more on average.

Extending the horizon from 50 to 100 years reduces the cost per ton of carbon abated somewhat for each species. With the longer horizon, the trees grow larger, sequester more carbon, and reduce energy consumption in nearby buildings. Planting and maintenance costs go up, but not as fast as carbon abatement, so that costs per ton of carbon abated go down. Nevertheless, the ranking of tree species stays the same

Table 3
Attributes of planting locations and nearest buildings.

Attribute	Manhattan	Queens	Brooklyn	Bronx	Staten Island	City
Distance (feet) from building	24.6	28.8	26.3	27.9	31.6	27.9
Percentage of planting locations by direction						
N, NW	31.6%	30.2%	29.5%	28.7%	32.1%	30.2%
S, SE	11.8%	13.7%	13.3%	13.6%	17.5%	13.8%
E, NE	13.8%	12.9%	12.6%	12.3%	13.7%	12.9%
W, SW	42.8%	43.2%	44.6%	45.4%	36.7%	43.1%
Year building built	1955	1946	1940	1955	1965	1949
Percentage residential area of building[a]	48.9%	77.2%	65.9%	64.6%	84.9%	70.7%
Number of floors	10.7	2.3	2.9	3.3	1.9	3.3
Percentage tree canopy cover for a 150 foot buffer[b]	9.4%	13.5%	10.3%	9.8%	14.5%	11.9%
Number of planting locations	16,811	67,829	50,292	25,419	22,385	182,736

Note: Averages shown across planting locations for the five boroughs and the city.
[a] This is the percentage of the floor area of a building that is residential space.
[b] This is the percentage of tree canopy in the area comprised of a 150 ft buffer around the 50 ft square planting locations.

Table 4
Average discounted carbon abatement (tC/tree), cost ($/tree), and cost effectiveness ($/tC) for the 50 and 100 year horizon by tree species.

	London Plane *Platanus hybrida*	Callery Pear *Pyrus calleryana*	Kwanzan Cherry *Prunus serrulata*	Eastern White Pine *Pinus strobus*
50 year horizon				
Abatement (tC/tree)				
Biomass storage	0.29	0.71	0.32	0.18
Energy reductions				
Cooling	0.10	0.09	0.04	0.07
Heating	0.61	0.48	0.31	0.40
Maintenance	−0.01	−0.01	−0.01	−0.01
Decomposition	−0.07	−0.58	−0.19	−0.05
Net abatement	0.93	0.69	0.46	0.59
Planting and maintenance costs ($/tree)	2951	4791	3451	2951
Cost effectiveness ($/tC)	3615	8410	8399	5986
100 year horizon				
Abatement (tC/tree)				
Biomass storage	0.59	1.00	0.46	0.27
Energy reductions				
Cooling	0.17	0.13	0.05	0.11
Heating	0.99	0.66	0.44	0.63
Maintenance	−0.01	−0.02	−0.01	−0.01
Decomposition	−0.32	−0.88	−0.32	−0.15
Net abatement	1.41	0.89	0.62	0.86
Planting and maintenance costs ($/tree)	3830	6323	4378	3927
Cost effectiveness ($/tC)	3133	8888	8087	5711

Note: Carbon abatement and management costs are discounted to the presented using a real discount rate of two percent. Averages are computed across 182,736 street tree planting locations in New York City.

with London plane tree providing the lowest average cost per ton of carbon abated ($3133/tC).

Net abatement is 1.41 tC per tree, discounted over 100 years for London plane tree and averaged over 182,736 planting locations (Table 4). Dividing by the annual annuity factor for the 100 year period using a 2% discount rate, we obtain 0.033 tC abatement per tree per year. For comparison, the estimated average annual net carbon abatement for existing street trees in NYC is 0.19 tC per tree per year (Peper et al., 2007). Our average annual carbon abatement for a planted London plane tree is less than the average annual carbon abatement for existing street trees because we start with a six-year-old tree when its carbon abatement is low and discount subsequent carbon abatement from tree growth at a 2% rate over a 100 year horizon. In contrast, the average annual carbon abatement for a NYC street tree is based on existing tree inventory, which includes many large trees, and there is no discounting of carbon abatement.

3.3. Marginal Cost Curve of Carbon Abatement from Tree Planting

For each species, we ranked the planting locations from lowest to highest $/tC abated and plotted $/tC versus cumulative tC/year abated for each additional planting location (Fig. 4). Each curve shows the cost per ton of carbon abated for planting an additional location in NYC. The sets of curves for the 50- and 100-year planning horizons show that London plane tree has the lowest cost of carbon abatement relative to the other three species. For a 50-year horizon, the curve for London plane tree is relatively flat with costs <$4000/tC for most planting locations. The curves for kwanzan cherry and eastern white pine rise slowly with costs <$6000/tC for most locations. The curve for Callery pear rises fastest with the most expensive locations costing $15,000–18,000/tC. The results for the 100-year horizon are very similar, although the curves shift down slightly to account for higher levels of carbon sequestration and energy savings over the longer horizon. The marginal cost curves in Fig. 4 also show that the maximum carbon abatement attainable by planting London plane trees in all locations (27 tC/year for a 50-year horizon and 37 tC/year for a 100-year horizon) is twice the maximum abatement attainable by planting any of the other tree species. The cost-effectiveness of planting London plane tree to abate carbon is attributable to its longevity and mature tree size.

We ran simulations with discount rates of 4% and 6% and confirmed that higher discount rates lower the present value of both costs and carbon flows relative to the baseline estimates with a 2% discount rate. We found that higher discount rates increase unit costs of carbon abatement ($/tC), and decrease annualized carbon flows (tC/year). Thus, similar to the results of Lubowski et al. (2006), the marginal cost curves for carbon abatement shift up as we move from lower to higher discount rates.

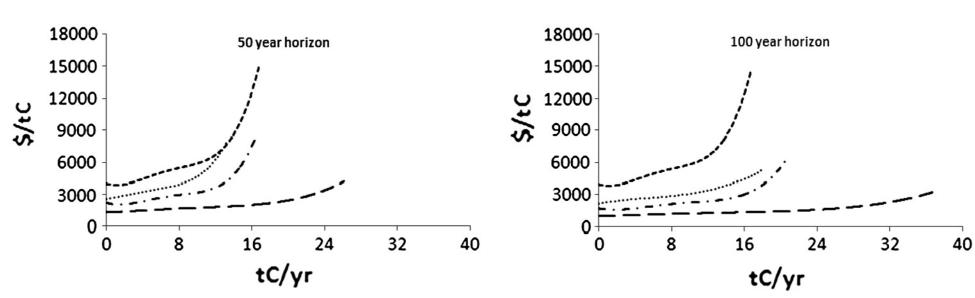

Fig. 4. Marginal costs of carbon abatement from planting street trees in New York City. Each curve is for a single tree species and management horizon and shows the range of marginal costs across planting locations by ordering locations from the lowest marginal cost to the highest marginal cost.

Table 5
Average discounted carbon abatement (tC/tree), cost ($/tree), and cost effectiveness ($/tC) by borough for the London plane over a 100-year horizon.

	Manhattan	Queens	Brooklyn	Bronx	Staten Island	New York City
Abatement (tC/tree)						
Energy reductions						
Cooling	0.09	0.19	0.15	0.15	0.21	0.17
Heating	0.50	1.12	0.97	0.88	1.11	0.99
Biomass net maintenance and decomposition	0.26	0.26	0.26	0.26	0.26	0.26
Net abatement	0.84	1.57	1.39	1.29	1.58	1.41
Planting and maintenance costs ($/tree)	3830	3830	3830	3830	3830	3830
Cost effectiveness ($/tC)	4938	2755	3116	3399	2657	3133
Number of planting spaces	16,811	67,829	50,292	25,419	22,385	182,736

Note: The carbon and the costs are discounted to the presented using a real discount rate of 2%.

3.4. Spatial Consideration in the Cost of Carbon Abatement from Tree Planting

Using London plane tree as an example, we find that Staten Island and Queens have street tree planting locations with the lowest average costs of carbon abatement ($2657/tC and $2755/tC, respectively), slightly lower than Brooklyn and Bronx ($3116/tC and $3399/tC, respectively) and much lower than Manhattan ($4938/tC) (Table 5). The lower costs in Staten Island and Queens result from higher levels of avoided energy consumption in nearby buildings, which tend to have fewer stories and more residential use than buildings in the other boroughs (Table 3). This is in spite of the fact that planting locations in Staten Island and Queens have higher levels of canopy cover in the surrounding area (Table 3), which leads to lower increases in energy savings when additional trees are planted. Planting locations in Manhattan have the highest cost of carbon abatement, mostly because they have lower levels of avoided energy in adjacent buildings, which are taller and used more for non-residential purposes. Neighborhoods with the lowest costs of carbon abatement are concentrated in Queens (Fig. 5).

4. Discussion and Conclusion

We find that the average discounted cost per ton of carbon abated from planting trees near buildings for a 100 year planning horizon ranges from $3133/tC for the London plane tree to $8888/tC for the Callery pear. The wide range arises from differences in life span, growth rate, and the size of tree canopy across species. Nowak et al. (2002) observe that the tree species that reduce carbon the most are large, have a long life span, and grow at a medium rate, and this is the consistent with our findings. The cost of carbon abatement for the London plane tree varies widely across planting locations, ranging from $1553 to $7396/tC, because of the variation in the energy savings obtained in nearby buildings.

Planting locations with the lowest cost of carbon abatement are 60 ft to the west of nearby buildings that are more than 60-years-old, less than a couple floors in height, entirely residential, and without nearby tree canopy. Trees in these locations provide a winter wind break and a little summer shade thereby reducing energy for heating and cooling. Conversely, planting locations with the highest cost of carbon abatement are closer than 20 ft to the south of nearby buildings that are

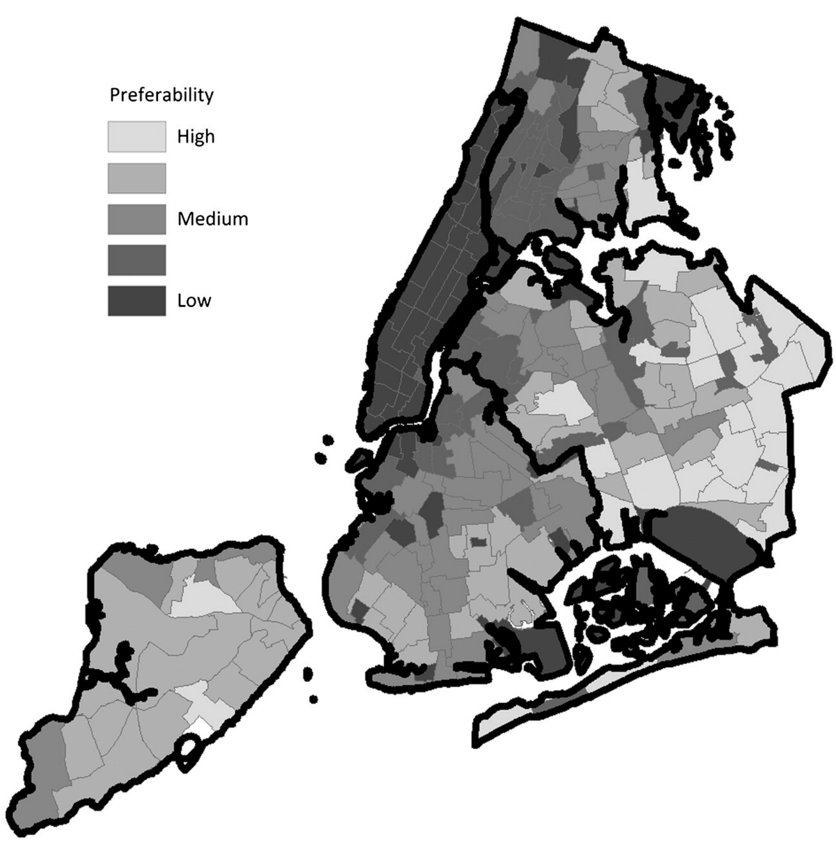

Fig. 5. Neighborhood shading based on the ranking of cost-effective carbon abatement from street tree planting of the London plane tree for the 100 year horizon.

less than 30-years-old, more than four floors high, entirely commercial, and with neighboring tree canopy. Although these locations are good for reducing summertime energy use, they are the least well suited for a winter windbreak.

A focus of this paper is the ranking of planting locations from the lowest to highest cost of carbon abatement to identify the marginal cost curve for each tree species. The curve can aid the comparison of different carbon reduction programs, for example between planting trees near buildings or growing green roofs, once a green roof study identifies the marginal cost of carbon. Spatial examination of where to plant trees in NYC indicates that the boroughs of Queens and Staten Island are preferred because the buildings are mostly residential and less than a few stories tall. While locations with low costs of carbon abatement are found in all the boroughs, Staten Island and Queens have more of these locations than other parts of the city. McHale et al. (2007) find lower marginal costs of carbon for neighborhood tree planting in Colorado from \$145 per tonne in Denver to \$647 per tonne in Fort Collins. The Colorado case studies were more cost effective because of lower planting and maintenance costs in Colorado where non-street trees were planted and volunteers used to reduce costs. Even lower costs of carbon have been estimated from afforestation on rural lands.

Investment in rural forest-based carbon sequestration can be a cost-effective complement to programs for fuel switching and reduced fossil fuel use for lowering atmospheric carbon (Richards and Stokes, 2004). A meta-analysis of fifty-five studies of the cost of creating carbon offsets using rural forestry programs find the average cost of sequestering carbon through forest conservation and planting, when appropriate account is taken of the opportunity cost of land, is between \$117 and \$1407/tC (Manley, 2002; Van Kooten et al., 2004). A more recent study investigates the cost of forest-based carbon sequestration by econometrically analyzing land use preferences and potential program adoption in a comprehensive analysis of private landowners in the contiguous United States. The marginal cost from the resulting estimated sequestration supply function is between \$50 and \$150/t C (Lubowski et al., 2006). We find that a street tree planting program is less cost-effective than estimates of the cost-efficiency of rural tree planting programs for carbon sequestration. While a street tree reduces more carbon than a plantation tree, the higher costs of planting and maintaining street trees make such programs less cost-effective.

We did not include the opportunity costs of the land used for tree pits, which could raise costs and potentially reduce the cost-effectiveness. We assume that the opportunity cost of the land for tree pits is low because these small areas could not be developed for valuable commercial or residential uses. Another assumption is that the avoided combustion of fossil fuels because of street trees means the fuel is never used. Since the demand for energy continues, the fossil fuels will eventually be used though the fuel combustion has been delayed. This therefore overestimates the carbon abatement from avoided energy use, and this makes the program less cost-effective than projected. The extent that trees reduce carbon emissions by reducing air temperatures and the consequent emissions associated with urban heat islands is left unexplored. Any extra reduction in emissions from the mitigation of heat islands makes street trees more cost-effective than estimated. Planting through volunteer effort could lower costs and thus increase cost-effectiveness. We do not consider urban forestry that includes residential lots, parks, and natural regeneration. An analysis of the carbon cost for MillionTreesNYC's substantial parks reforestation is an avenue for future research. Another direction for research is how cities use incentives (e.g. rebates) to increase planting on private land, especially close to buildings to enhance energy savings.

In addition to carbon abatement, the co-benefits of planting trees in urban areas are substantial. Trees reduce air pollution and stormwater runoff (Morani et al., 2011; Nowak et al., 2007; Raciti et al., 2006). Their aesthetic values have been linked to socio-psychological benefits (Dwyer et al., 1992; Hartig et al., 1991). Small patches of vegetation (Rudd et al., 2002) and individual street trees provide habitat in urban areas for avian species (Fernandez-Juricic, 2000). The reduction in energy use by buildings counts as a cost savings for private landowners. Tree canopy can lower rates of crime by increasing the "eyes on the street" or by acting as a territorial marker cue that residents actively care about their neighborhood (Troy et al., 2012). The local climate is influenced by tree canopy, and in the summer this mitigates the urban heat island effect (Susca et al., 2011). Tree canopy can also increase property values (Sander et al., 2010) and may draw residents back to the cities thereby reducing vehicular emissions. Therefore, planting programs may seek to balance a suite of management objectives (Locke et al., 2010), and enumerating the carbon benefits adds to the growing case for trees in urban areas as part of an overall strategy for reaching sustainability goals. A comprehensive assessment of all the benefits of urban trees, rather than a focus on carbon alone, is appropriate for deciding how much investment to make in an urban forest.

Cities such as NYC with the goal of a 30% reduction in GHGs by 2030 will be looking for projects to reduce carbon emissions to 1990 levels while simultaneously generating the most overall benefits for their residents. There is increasing evidence that human settlements can store carbon densely in soils, vegetation, landfills, and buildings (Churkina et al., 2010). The storage of carbon by urban turf is controversial because of large indirect emissions from fertilizer, fossil fuel combustion, and frequent surface restoration (Townsend-Small and Czimczik, 2010). More than 97% of the carbon stored in aboveground vegetation in the British city of Leicester is associated with trees rather than herbaceous vegetation (Davies et al., 2011). More rigorous studies are needed addressing carbon storage and the vulnerability of the storage in human settlements. Additional research should explore how volunteer programs or natural regeneration can lower the cost of tree planting below that of the city contractors. Also, more research is needed on how effectively trees and other plants reduce energy use of multi-story buildings as well as commercial and industrial buildings.

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