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Does "Greening" of Neotropical Cities Considerably Mitigate Carbon Dioxide Emissions? The Case of Medellin, Colombia

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Abstract: Cities throughout the world are advocating highly promoted tree plantings as a climate change mitigation measure. Assessing the carbon offsets associated with urban trees relative to other climate change policies is vital for sustainable development, planning, and solving environmental and socio-economic problems, but is difficult in developing countries. We estimated and assessed carbon dioxide (CO_2) storage, sequestration, and emission offsets by public trees in the Medellin Metropolitan Area, Colombia, as a viable Nature-Based Solution for the Neotropics. While previous studies have discussed nature-based solutions and explored urban tree carbon dynamics in high income countries, few have been conducted in tropical cities in low-middle income countries, particularly within South America. We used a public tree inventory for the Metropolitan Area of the Aburrá Valley and an available urban forest functional model, i-Tree Streets, calibrated for Colombia's context. We found that CO_2 offsets from public trees were not as effective as cable cars or landfills. However, if available planting spaces are considered, carbon offsets become more competitive with cable cars and other air quality and socio-economic co-benefits are also provided. The use of carbon estimation models and the development of relevant carbon accounting protocols in Neotropical cities are also discussed. Our nature-based solution approach can be used to better guide management of urban forests to mitigate climate change and carbon offset accounting in tropical cities lacking available information.

Keywords: climate change mitigation; nature-based solutions; urban forest; carbon offsets; clean development mechanism; street trees; ecosystem services

1. Introduction

In 2015, the global population reached 7.3 billion with an increase of about 1 billion in the last twelve years alone [1]. According to the United Nations [2], the proportion of the population living in urban areas is expected to increase from 54% to 66% by 2050. This proportion of urban inhabitants is even greater in Latin America and the Caribbean, where approximately 80% of the population already resides in urban areas [2].

Policies and activities to address climate change in tropical Latin American countries generally focus on mitigating carbon emissions from the industrial and transportation sectors [3]. In Brazilian and Colombian cities, innovative transportation policies and programs have been reported as effective policies to mitigate local-scale anthropogenic carbon dioxide (CO_2) emissions [3]. In Medellin,

Colombia, the use of cable cars that reach less accessible, low income neighborhoods have been touted as measures that both promote social inclusion and provide other co-benefits such as offsets of carbon emissions [4,5]. Similarly, the role of deforestation and forest degradation in global-scale anthropogenic CO_2 emissions has been well established in the environmental literature, particularly for tropical forests [6]. However, less is known about the influence of existing urban forests, deforestation in peri-urban areas, and commonly touted urban tree planting programs and their role in local-level CO_2 regulation in cities such as those from Neotropical Latin America [7]. Indeed, urban areas worldwide play a major role, accounting for 71–76% of energy related CO_2 emissions [8].

While many different strategies at the national and local-level are needed to address increasing greenhouse gases emissions, local-level nature-based solutions can play an important role in mitigating local and regional urban environmental quality issues, not only in cities in high income countries, but also in low-middle income countries such as Colombia [9–11]. These nature-based solutions have recently been proposed in Europe as not only an approach for addressing climate change, but also for creating employment opportunities and a green economy [12,13]. Unfortunately, to our knowledge the concept has been little discussed outside the European Union and the United States [13]. However, such approaches are arguably more important in cities in regions such as Latin America, rather than in Europe, due to the marked socio-economic disparities and high proportion of vulnerable populations. The use of urban and peri-urban forests and agriculture, for example, are solutions that could also be used for improving urban air quality and food security, reducing temperatures, conserving biodiversity, maintaining water quality, and increasing employment through tree maintenance and green space management [12–15].

Urban trees directly remove CO_2 from the atmosphere through sequestration, and can reduce building cooling demands through shading and evapotranspiration, thus indirectly reducing CO_2 emissions from the use of fossil fuels to produce energy for building cooling [16]. Additionally, herbaceous vegetation and soils contribute to carbon sequestration and storage, and provide numerous other ecosystem services such as atmospheric pollution removal, biodiversity, and storm water regulation [17–19]. However, in addition to these benefits, urban trees can generate costs or ecosystem disservices, by incurring maintenance and management costs, production of allergenic pollen, and can lead to CO_2 emissions through decomposition, soil respiration, and maintenance-related fossil fuel burning activities [17,20]; as such, these types of costs and emissions must also be accounted for.

Understanding the CO_2 offset potential and effectiveness of urban tree plantings can help determine and promote their viability as a nature-based solution. A characterization and framework for nature-based solutions that includes an assessment of multiple co-benefits for the urban Neotropics is warranted. Such assessment would require the accurate estimates of benefits, one of which is carbon sequestration [21].

Improving carbon estimates would also improve the incorporation of urban tree plantings into carbon markets and climate policy. In December 2015, the United Nations Framework Conference on Climate Change (UNFCCC) produced the 2015 Paris Agreement. As a country party to the convention, Colombia submitted their new emissions target, committing to reductions of 20% below business as usual emissions by 2030, or 30% below business as usual with sufficient international support [22]. One mechanism for high income countries to provide this support to Colombia is through the Clean Development Mechanism (CDM) [23]. This mechanism allows developed countries to invest in offset projects in developing countries in exchange for certified emissions reduction credits [23]. The CDM accounting methodologies for receiving credits for a project must either be developed or adopted from a past project and approved.

From 2008 to 2012, a methodology for accounting for CO_2 sequestration from urban afforestation/reforestation, AR-AMS0002, was in effect, but is since inactive [23]. Currently, AR-AMS0002 does not account for avoided emissions from cooling or emissions from tree maintenance or plantings, only net sequestration [24]. However, a carbon offset registry with associated protocols has recently been developed for urban forest projects [25].

Previous studies in temperate high income regions of the world have looked at the potential of urban trees to offset CO_2 at multiple scales. In the US, national-level carbon storage and sequestration by urban trees was evaluated [26], as well as state level urban forest carbon sequestration [18]. Other authors have reported city-scale carbon sequestration by urban forests and public trees in several US and Chinese cities [16,19,27–29]. More recently, C storage and sequestration by urban trees in European cities such as Barcelona, Bolzano, Rome, and elsewhere are increasingly being studied [17,30–32]. A study much closer to Medellin estimated average carbon stocks per tree for Bogota, Colombia's public urban forests [9].

Some studies have also investigated management, maintenance, and socio-ecological dynamics and the interaction between urban tree carbon sequestration and emissions [20,27,33]. Another body of research is exploring if the use of trees is indeed an effective policy and activity to mitigate local CO_2 emissions [14,16,17,28,34,35]. In terms of policy effectiveness, studies in the United States have documented that local level reforestation of degraded peri-urban areas can cost effectively be used to improve air quality while providing other co-benefits, such as CO_2 sequestration and wildlife habitat [36].

Another study found that urban tree plantings "may be cost-effective" in certain locations in the US [15]. However, a different study found that urban forest management was "moderately" effective as a mitigation strategy in two cities in Florida, USA, relative to other reduction strategies [14]. Similarly, studies in Europe raise awareness to the fact that different urban tree and vegetation carbon calculation methods, such as the choice of allometric equations, carbon estimation models, resolution of geospatial data, and reporting of different carbon pools (i.e., above ground versus below ground carbon pools) will yield very different C sequestration results [17,32].

While the above studies have mostly analyzed cities in the US, Europe, and China, few have explored the use of trees as a nature-based solution for climate change mitigation in Neotropical cites and low-middle income countries. Assessments and studies have, however, looked at the use of innovative transportation strategies and policies to offset CO_2 emission in Latin American countries, such as in Colombia [4,5]. The need for other innovative measures (i.e., nature-based solutions) is necessary as a response to Colombia's projected rates of urbanization and population vulnerable to adverse climate change effects [5].

This study aims to develop an approach for assessing the potential use of public trees in Neotropical cities to offset CO_2 emissions where there is often a lack of data and information. Specifically, the objectives of this study are to: (1) estimate carbon storage and sequestration by public trees in the urban area of the MAAV (Metropolitan Area of the Aburrá Valley); (2) estimate the relative CO_2 emissions offset potential by the MAAV's public trees; and (3) discuss the effect that proposed large scale tree planting can have on #1 and #2.

2. Materials and Methods

2.1. Study Area and Inventory Data

The study area is Medellin and more specifically the Metropolitan Area of the Aburrá Valley (MAAV), Colombia. The MAAV is part of the Department of Antioquia and encompasses the municipalities of Medellin, Bello, Barbosa, Copacabana, La Estrella, Girardota, Itagüí, Envigado, Caldas, and Sabaneta. The urban zone of the MAAV resulted from the conurbation of the municipalities' town centers with Medellin at its center [37]. This area is the second most populated metropolitan area in Colombia, with a population over 3 million [37]. While the MAAV represents only 2% of the land area of the Department of Antioquia, it accounts for over 65% of the population [37]. The proportion of the Colombian population living in urban areas increased from 57% to 71% from 1970 to 2000 and is expected to reach 85% by 2050 [3].

The MAAV extends approximately 60 km along the Medellin River and covers 1152 km^2 [37]. The urban zone of the MAAV, however, covers 118 km^2 [37] (Figure 1). The MAAV is located at

about 1500 m above sea level, and it corresponds to Premontane moist forest (bh-PM) according to the Holdridge's Lifezones classification [38]. The precipitation is characterized by a bi-modal distribution, with an average annual value in the city of 1687 mm, while the average high and low annual temperatures are 28 °C and 17 °C, respectively [39].
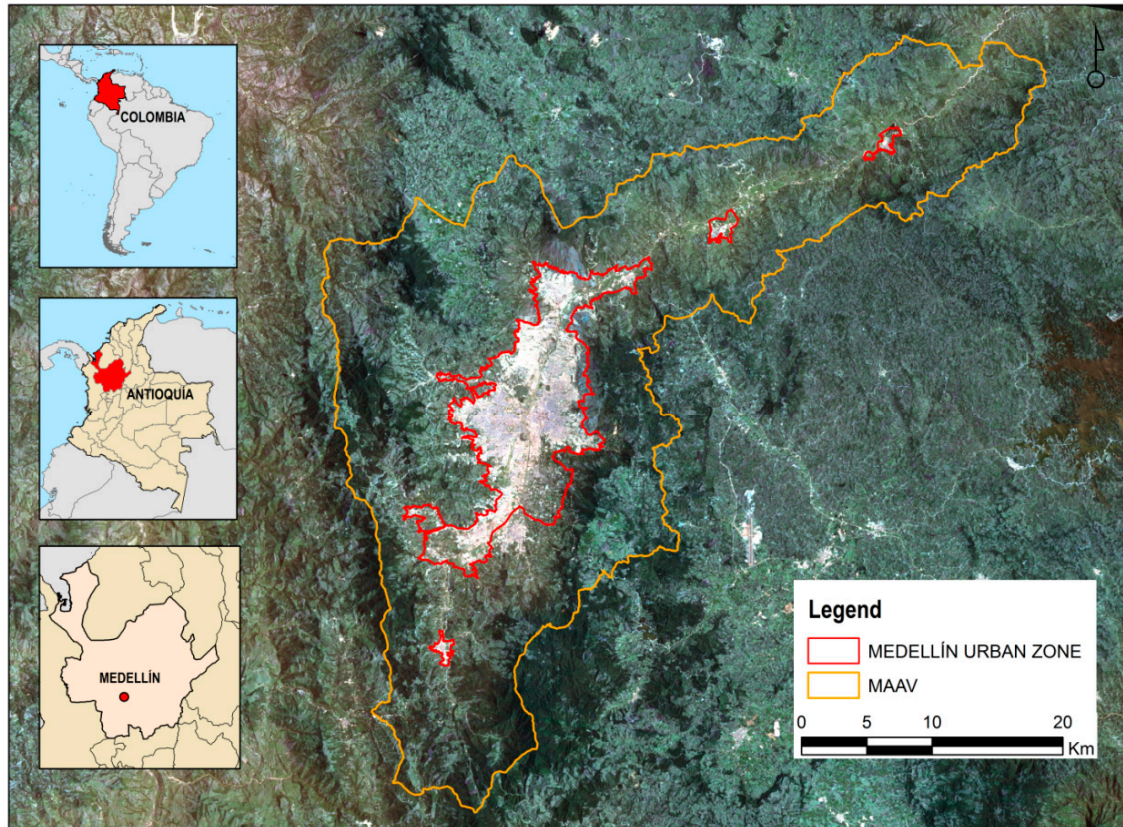
Figure 1. The Metropolitan Area of the Aburrá Valley (MAAV) and associated Medellín urban zone, Departamento de Antioquía, Colombia. Background image: Landsat 8 OLI.

In 2007, the Aburrá Valley Urban Environmental Authority implemented the Urban Green Spaces Master Plan for the MAAV as the main policy instrument to manage its vegetation [39]. This study used a complete inventory of all public trees compiled as part of the Master Plan. For this study, we define "public trees" as those trees located in all public areas, such as parks, front lawns, road corridors, sidewalks, road medians, as well as stream and river courses. The inventory originally consisted of 406,856 trees and shrubs, but was filtered to only include trees with (i) a Diameter at Breast Height (DBH) greater than 2.5 cm and (ii) a total height more than 2 m, resulting in 182,044 public trees, following [9]. Additionally, 352 trees were removed since they did not report any species data. The final inventory had 181,693 trees representing 358 different species. The inventory covered approximately 21.53 km^2 of public green spaces in the urban zone of the MAAV (118.22 km^2) [39].

2.2. Modeling Carbon Sequestration and Co-Benefits

Studies in Portugal and the United States have used i-Tree Streets, a model developed by the United States Department of Agriculture (USDA) Forest Service, to assess costs and benefits associated with urban trees [40,41]. The modeling approach behind the i-Tree-Streets model is based on 16 reference cities of the United States that represent 16 different climate zones (please see Figure 1 in [40]). For each reference city, 30–70 trees for each of the 19–22 of the most common tree species were sampled and measured [40]. Using these measurements, best-fit allometric equations were used to

model crown diameter, leaf surface area, and height as a function of a tree's size or a tree's diameter at breast height, or 1.3 m above the surface (DBH) [40,41].

Thus, the i-Tree-Streets model assumes that cities from the same reference zone will have comparable tree species with similar growth and mortality traits [40]. Accordingly, for each reference zone individuals from the most common species are measured for DBH and other metrics and then the tree planting dates are determined or cross dating of tree rings is used for each of these measured individuals and linear regressions are used to predict DBH as a function of age for each sampled species [40]. The i-Tree Streets model then applies a series of functions, using a tree's DBH and species or tree type, to estimate tree volume [42]. The aboveground dry-weight biomass is then derived from the estimated tree volume and wood density. Results are then adjusted to include below-ground biomass using a root-to-shoot ratio of 0.26 and are converted to CO_2 equivalent by multiplying by 3.67. This same data, allometric equations, and environmental characteristics from each selected reference city are also used to estimate other co-benefits such as air quality improvement, stormwater mitigation, and property value effects [40]. Other studies provide further background on the necessary modeling parameterization and calibration requirements [40,41]. Based on its use in other cities and its relevance to the stated objectives of our study, we applied this modelling approach to estimate annual CO_2 reductions from both sequestration by trees and CO_2 emissions avoided from energy use through microclimate regulation in Medellin [42].

To assign our modeling domain to a reference climate condition as required in the i-Tree Streets model, we used a systematic approach for selecting the best reference city [40]. This method assessed four different criteria from each reference city to determine the closest match to MAAV: heating degree days (HDD), cooling degree days (CDD), annual precipitation, and tree species match. The HDD value represents how much building heating is needed by calculating how much and for how long outside temperatures are below a chosen base temperature. Similarly, CDD represents how much building cooling is needed by calculating how much and for how long outside temperatures are above the baseline. The first three criteria (HDD, CDD, and annual precipitation) are listed for each reference city [40]. Tree species match, however, must be determined by comparing the species composition of the subject city to the species composition of each reference city.

Because of the importance of tree species for CO_2 estimates, two methods were used to find and compare a similar tree species composition match for Medellin. The first method was based on the previous study [40], and accordingly we compared the most common tree species in the MAAV inventory to the 19–22 species sampled and measured for each i-Tree Streets reference city. The number of each species that matched with the most common MAAV species on the genus or species level were summed. However, matching MAAV's most common species with only the 19–22 most common species for each US reference city can skew the selection process.

Accordingly, the second method for determining tree match accounts for all species in the study area and reference city's inventories, and their abundance. Overall, we found more tree species were matched with Honolulu (Tropical region), Orlando (Central Florida, Orlando, FL, USA), and Santa Monica (Southern California, CA, USA), rather than with Modesto (Inland Valley region). The total number of tree species in the MAAV inventory that had a similar species or genus to the Tropical and Inland Valley region were 121 and 29, respectively. To account for abundance, individuals for each matched species for each region were summed. Overall 128,635 (71% of the total inventory) individual trees in the MAAV inventory matched with Honolulu as the reference city, while only 21,093 (12%) matched using Modesto as the reference city. Tree match results for both methods for all four comparable reference cities are shown in Appendix A. Because this study's objective is focused on carbon storage and sequestration, we used this second method since tree carbon is a function of a tree's species, size, and other characteristics [13]. The criteria values (Appendix A) [40] were then normalized to allow for direct comparison among all listed criteria.

This normalization consists of first finding the range of values for each criterion listed across the reference cities. Each range was then divided into 10 equal intervals assigned a value 0–10. Next, the

difference value for each criterion for each reference city was found by subtracting the reference city value from MAAV's value. Since tree match is contingent upon the subject city's species composition, tree matching estimates were not normalized [40]. Normalized values were determined by comparing the difference values on a 0–10 scale. Next, each normalized value was weighted for importance, based on the study objectives and subject city climate.

To weight the criteria by importance, the normalized values were multiplied by a factor less than 1. All four factors should add up to 1 [40]. Tree species match was considered to be most significant because analyzing carbon storage and sequestration is the main objective, therefore it was given a factor of 0.4. HDD and CDD reflect building energy heating and cooling loads. While these do affect carbon emissions, Medellin has a fairly mild, consistent climate because of its altitude and proximity to the equator [37]. Because of this, HDD and CDD will have less impact on the results so they were both assigned a factor of 0.2. Annual Precipitation mostly accounts for rainfall interception and was thus assigned a factor of 0.2 [40]. Finally, the root mean square error (RMSE) for each reference city was determined by multiplying the normalized values by their weighted factor and summing the results. The city with the lowest RMSE should be selected as the reference city for the analysis [40]; as such, Honolulu, Hawaii, USA was selected (RMSE = 3.6).

Next, trees in the MAAV inventory are coded by species using i-Tree Streets codes available for the Honolulu reference city. When matches were not available on the species level, the genus level were used. When matches were not available on the genus level, the tree type were used. The inventory of Medellin trees consisted of 358 tree species, of which 121 were modeled using species or genus level parameters. The remaining 237 species were modeled based on tree type characteristics. The study from Morales et al. (2006) [43] was referenced to determine tree types and city characteristics as needed (i.e., city population and study area). These codes along with DBH and tree height were then entered into i-Tree Streets.

After the reference city was selected and the data were coded and entered, i-Tree Streets produced reports of tree costs and benefits, including CO_2 storage and sequestration, CO_2 equivalent energy savings from shading and cooling, and emissions from maintenance and decomposition. To facilitate the comparison of CO_2 sequestration estimates from this study with others, gross and net tree CO_2 sequestration per ha was calculated using land area specific to the land use analyzed in the study, or public green space area or street/transportation as reported by the Aburrá Valley Urban Environmental Authority [37]. Since the results from all relevant studies were reported in above and below ground CO_2, when necessary, a root-to-shoot-ratio of 0.26 was used to estimate below ground CO_2 and a conversion ratio of 3.67 was used to convert carbon to CO_2 [14,33]. All reported values for other cities are exclusively for street trees.

2.3. Estimating Tree Cover, Available Planting Space, and Carbon Offsets

As an additional metric to assess existing and potential CO_2 offsets, tree cover, i.e., the proportion of area covered by tree crowns, was also estimated using two different methods. The first method is based on the field measured individual tree crown diameter measurements [27], and the second method uses the i-Tree Canopy tool [44]; an online aerial image interpretation user interface to estimate tree cover as well as public versus private trees and available planting space.

For the first method, individual tree crown diameters recorded in the final analyzed inventory were used to calculate the crown area for each tree. These were summed and converted to hectares, giving the area of public tree cover, specific for the inventory. In the second method, i-Tree Canopy v6.1 was used to photo interpret tree cover from aerial imagery, and to create four reference land cover classes: (1) Non-Tree (NT; Any area not covered by a tree and not suitable for planting); (2) Public Tree (PubT; Tree crown associated with trees located in all public areas); (3) Private Tree (PT; Tree crown associated with residential, commercial, or private recreation areas); and (4) Available Planting Space (APS; Any area where a tree can be planted and expected to grow to maturity). Private trees were any tree inside residential, commercial, or recreational land uses. A set of 300 random points within the

study area was generated and displayed and a land cover class was assigned to each point. The area of each cover class was also determined by multiplying the cover class proportion by the total city area.

Using the area of public tree cover given by both methods, net and total CO_2 sequestration per m^2 of tree cover was determined by dividing net sequestration (CO_2 g) and total sequestration (Gross sequestration + emissions avoided from shading minus decomposition minus maintenance emissions) by estimated public tree area (m^2). This metric allows us to estimate potential CO_2 benefits from potentially planting trees in available space and total CO_2 benefits from all city trees (public and private) [27]. These were calculated by multiplying g CO_2 per m^2 of tree cover by the available planting space area and by the total tree cover area, respectively.

2.4. Selection and Description of Carbon Emissions Reduction Strategies

To better assess the results of this study relative to other technological-based solutions, carbon offsets from MAAV street trees were compared to two other reduction sources in the MAAV. Specifically, carbon offsets from the MAAV's new cable car transit system and from two landfill gas (LFG) management projects at landfills accepting waste from the MAAV were used.

In 2004, the first urban aerial cable car public transit system was implemented in the municipality of Medellin. The cable cars use ski-lift technology suited to the sloping streets of the Medellin and its hydroelectric power source [5]. The Metro Company that jointly financed the transit system with the city prepared a Project Design Document (PDD) under the Clean Development Mechanism (CDM) that proposed a methodology to report emissions reductions from the project. Reductions were based on baseline emissions defined as what would have been emitted if other forms of transportation were used [5].

In 2007, the University of Antioquia and *Empresas Varias de Medellin* (EEVVM) agreed to a landfill gas (LFG) management project at the *Curva de Rodas* and *La Pradera* Landfills [45]. The project uses landfill gas recovery systems and enclosed flare combustion stations to capture, flare, and destroy LFGs [4]. Construction at the landfills started in 2008 and in 2009 the UNFCCC registered the project under the CDM with approval from Colombia and the investment country, the United Kingdom [45]. The waste at both landfills comes from the MAAV [4].

These two technology-based solutions were selected because: (1) they both reduce emissions contributable to the MAAV; (2) they were both evaluated under methodologies approved by the UNFCCC under the CDM; and (3) they have publicly available PDDs reporting detailed estimates of offsets. This allows for comparisons within the same study area and emissions scope and provides insights for regional policy makers and investors regarding the viability of nature-based solutions and serves to give context and perspective to our results in terms of carbon offsets.

3. Results

3.1. Urban Tree Carbon Storage and Sequestration

The total CO_2 storage by public trees in the study area was estimated to be 103,820 Mg. Gross CO_2 sequestration was 2077 Mg/year and the avoided CO_2 emissions through energy savings were 5090 Mg/year. Decomposition and maintenance emissions were 332,222 and 122,130 kg CO_2/year, respectively. Taking all of these sinks and sources into account, public trees in the study area are responsible for 6712 Mg CO_2 reductions annually.

Using the first method to find tree cover (crown diameter), public trees covered 4.6% of the city area. Using the second method (i-Tree Canopy), public trees covered $8.33 \pm 1.60\%$ of the city area, private trees covered $5.67 \pm 1.33\%$, and $7.67 \pm 1.54\%$ was available for tree planting (Table 1). Net sequestration of CO_2 per area of tree cover was 320 gCO_2/m^2/year using the first tree crown diameter method and 177 gCO_2/m^2/year using the i-Tree canopy method (Table 2). Using these results, it was estimated that plantings in available space have the potential to increase net CO_2 sequestration by 1606 to 2913 Mg CO_2/year. If avoided emissions from shading and maintenance emissions are also

accounted for, estimates can increase to 6180 to 11,211 Mg CO_2/year. Net CO_2 sequestration for all trees, public and private, was estimated to be 2931 to 5318 Mg CO_2/year, respectively (Table 2).

Table 1. Public tree cover and green space characteristics in the urban zone of the Metropolitan Area of the Aburra Valley (MAAV) using two different tree cover estimation methods.

	Method 1 (Crown Diameter)	Method 2 (i-Tree Canopy)
Public Tree Cover	4.59%	8.33% **
Public Tree Cover Area	5.45 km^2	9.88 km^2
Public Green Space Area	21.53 km^2 *	21.53 km^2 *
Tree Cover in Public Green Spaces	25.31%	45.89% **

* Area reported by the Aburrá Valley Urban Environmental Authority [37]. ** Includes forested public areas.

Table 2. CO_2 benefits by public trees and potential CO_2 benefits in available space using actual tree crown diameters and i-Tree Canopy.

	Method 1 (Crown Diameter)	Method 2 (i-Tree Canopy)
Net Sequestration by public trees per tree cover area	320 g CO_2/m^2	177 g CO_2/m^2
Potential Net Sequestration in available space	2913 Mg CO_2/year	1606 Mg CO_2/year
Potential Total CO_2 sequestration by planting all available spaces	11,211 Mg CO_2/year	6180 Mg CO_2/year
Total CO_2 Net Sequestration (public and private trees)	5318 Mg CO_2/year	2931 Mg CO_2/year

3.2. Carbon Benefits by Species

As shown in Appendix B, the top three tree species that contributed to total public urban forest CO_2 sequestration were benjamin fig (*Ficus benjamina*), the mango tree (*Mangifera indica*), and the octopus tree (*Schefflera actinophylla*). Table 3 shows the above and below ground tree CO_2 sequestration per ha of public green area for this study and other different cities reported in the literature.

Table 3. Examples of above and below ground public tree CO_2 sequestration per ha of public green area in different cities.

Study Area	Kg CO_2/ha/Year *	Method	Reference
*Gross sequestration ** *			
Medellin, Colombia	965	i-Tree Streets	This study
Barcelona, Spain	1866	i-Tree ECO ***	[30]
Shenyang, China	9212	Allometric Equations from Lit	[34]
Bolzano, Italy	4366	Allometric Equations from Lit	[17]
Average of 35 cities in China	7927	Literature	[28]
Beijing	1835	Allometric Equations from Lit	[29]
*Net sequestration **** *			
Medellin, Colombia	869	i-Tree Streets	This study
Gainesville, US	2573	i-Tree ECO ***	[14]
Miami, US	855	i-Tree ECO ***	[14]
Sacramento US	1200	Allometric Equations from Lit	[16]

* Area of public green space or transportation land use; ** The amount of CO_2 taken up annually; *** Includes city-wide public and private urban trees; *** Sequestration minus CO_2 released through decomposition.

3.3. CO_2 Offset Potential and Co-Benefits

According to *Grupo de Investigaciones Ambientales* [46], a total of 2,864,090 Mg CO_2 were emitted in the urban zone of the MAAV in 2011, of which 2,587,957 Mg CO_2 were from transportation sources. Net sequestration by the MAAV's existing urban forests, through growth, offsets 0.06% of the current

total emissions and 0.07% of transportation emissions. Accounting for indirect energy effects, urban forests offset 0.23% and 0.26% of total and transportation CO_2 emissions, respectively. The potential offsets from planting all available planting spaces can however be up to 11,211 Mg CO_2/year (Table 4). The CO_2 offset of public trees in the urban zone of the MAAV was similar to that of other studies (Table 5).

　　The total economic value of the co-benefits provided by the MAAV's public urban trees were 3.5 million US$ per year or an average of 19 US$ per tree per year. Model estimates indicate that storm water regulation alone accounted for 35% of these benefits, while air quality and aesthetics accounted for 5 and 31%, respectively. Energy savings from tree shading and direct CO_2 sequestration through growth accounted for 28 and 1%, respectively; highlighting the important co-benefit of the cooling effect of trees. We note that these are based on values and benefit transfer values from US cites and the lack of city specific energy use, hydrological runoff, and cost data from the MAAV deem that these estimates be used as approximations.

Table 4. Emission Reductions of Tonnes of CO_2 (Mg CO_2) from different strategies in the Metropolitan Area of Medellin, Colombia.

		Emissions (Mg CO_2/Year)	
		City Total 2,864,090	Transportation Sector 2,587,957
Reduction Source	**Reductions (Mg CO_2/Year)**	**% Reductions of Total**	**% Reductions of Transport**
Net trees sequestration	1744	0.06%	0.07%
Avoided from cooling	509	0.18%	0.20%
Total public tree effects	6712	0.23%	0.26%
Planting in all available space (Min.–Max. **)	6180–11,211	0.22–0.39%	0.24–0.43%
Cable Cars	17,290 *	0.60%	0.67%
Landfill Methane Capture	167,321 *	5.84%	6.47%

* Tonnes of CO_2 equivalent (Mg CO_2e); ** (Min = Minimum and Max = Maximum).

Table 5. Reported CO_2 offsets of the transportation (Transp) sector and city level emission by public trees in different cities.

City	Gross or Net Sequestration *	Emissions Source	Reported Emissions * (Mg CO_2)	Offset (%)	Reference
MAAV, Colombia	Gross	Transp ***	2,587,957	0.08%	This Study
Bolzano, Italy	Gross	Transp	300	0.10%	[17]
MAAV, Colombia	Net	City ***	2,864,090	0.06%	This Study
Barcelona, Spain	Net	City	4,053,766 **	0.02%	[30]
Gainesville, US	Net	City	2,097,627 **	0.16%	[14]
Miami, US	Net	City	31,967,000 **	0.07%	[14]

* Above and below ground; ** Emissions in Mg CO_2e; *** [46].

4. Discussion

4.1. Comparison of Urban Forest Carbon Sequestration Across Cities

　　Although growth rates associated with a tropical climate are expected to be higher, sequestration by public trees in the urban zone of the MAAV had relatively lower CO_2 sequestration than what was reported for other cities (Table 5). The largest difference was with gross sequestration reported for "road forests" in Shenyang, China [34]. Road forests are defined as trees along railroads, highways, boulevards, roads, and streets. Gross sequestration for Shenyang was almost 10 times that found for the MAAV. One contributing factor could be the higher tree density in Shenyang road forests (27,900 trees/km^2) than in the MAAV (8400 trees/km^2), possibly due to a tree planting project five years before the city was surveyed in which 19 million trees were planted [34]. The authors also highlighted that fast-growing tree species contributed to high net sequestration rates. Conversely, they noted that road forests had slower growing species than other land types evaluated [34].

For net sequestration, the urban zone of the MAAV had a value very similar to trees associated with transportation land use in Miami, but much lower than in Gainesville in the US [14] (Table 3). This observation may be due to tree density and growth rates. Miami had a lower tree density (3800 trees/km^2) for transportation trees than Gainesville (15,100 trees/km^2) and the MAAV, but had high net sequestration rates per tree, most likely due to a more tropical climate than Gainesville [14]. Higher net sequestration by transportation trees in Gainesville than the MAAV is most likely due to higher tree density.

4.2. Carbon Offset in Medellin

To better understand how well public trees offset CO_2 emissions, offset estimates in the urban zone of the MAAV were compared to two other carbon offset strategies used for the MAAV: cable car public transportation and improved landfill gas management (Table 4). The PDD for the cable car strategy reported total reductions of 121,029 Mg CO_2e from 2010 to 2016, averaging 17,290 Mg CO_2e/year [47]. Based on this average annual reduction rate, 0.60% of the urban zone of the MAAV's total CO_2 emissions and 0.67% of its transportation CO_2 emissions were offset. The PDD for the landfill projects reported 1,171,245 Mg CO_2e reductions over the crediting period from 2008 to 2015, averaging 167,321 Mg CO_2e/year [4]. This offsets 5.84% of the urban zone of the MAAV's total CO_2 emissions and 6.47% of its transportation CO_2 emissions.

Comparing the offset potential of the different strategies, current public trees were not as effective as the cable cars or landfills. Avoided emissions from cooling must be considered for public tree offsets to be close to cable car offsets, and even then they are still lower. The two-landfill methane capture systems were significantly more effective than both the cable cars and the public trees, most likely due to the high global warming potential of methane compared to CO_2. However, if available planting space is considered, carbon offsets become more competitive with cable cars, although they are still far from methane capture (Table 4). Here we only analyzed CO_2 offset by urban public trees. Nevertheless, including other existing trees in public forests and private urban lands as well as carbon pools from urban soils in green spaces, the offsets would have been higher.

Another consideration when comparing such strategies to nature-based solutions are socio-economic and environmental co-benefits beyond climate change mitigation. Urban forests have been documented to provide a variety of important ecosystem services, ranging from environmental to economic to social (e.g., [48]). Some co-benefits from urban forests include atmospheric air pollution removal, property price premiums, recreation opportunities, temperature amelioration, and overall quality of life [9,48]. Both public trees and the cable cars have been studied under the lens of social equity. In Bogota, Colombia, for example, it was found that the distribution of ecosystem services from public trees was unequal across socio-economic rankings [9]. Management goals for public trees can address this inequity for added social benefits. Nevertheless, Medellin's cable cars also have co-benefits that can improve social equity such as cheap transportation options and even decreased crime [5,49]. However, methane capture in/by landfills serves a single purpose.

While this study focuses on the carbon offset potential for different strategies, economic efficiency largely influences what mitigation approach a government, business, or non-governmental organization may take. Costs and benefits of urban tree plantings as well as the current price of carbon credits in market schemes affect the economic attractiveness of urban forest initiatives. McPherson et al. (2005) [18] analyzed the costs and benefits of public trees in five of the reference US cities for i-Tree Streets (Fort Collins, Colorado; Cheyenne, Wyoming; Bismarck, North Dakota; Berkeley, California; and Glendale, Arizona). While this study only examined US cities, it shows that urban plantings may be economically favorable, especially when accounting for added co-benefits and as such are a viable nature-based solution. McHale et al. (2007) [15] found that the cost per Mg CO_2e (one credit), including avoided emissions from cooling, was $145.10 to $647.26, while the market price at the time ranged from $3 to $13 per credit, and that projects in climates with higher sequestration rates would be more cost effective [15].

Although recent studies and reviews on the use of nature-based solutions have discussed in great detail their potential and application in the European Union and its temperate climates, these discussions have all but excluded their application in Neotropical cities of the developing world [12,13]. Indeed, given the interdisciplinary focus and multiple functions of the nature-based solution approach in addressing not only climate change but other socio-economic problems, such an approach by definition is more warranted in tropical regions of Latin America and Asia where access to resources, employment, green spaces, and quality of life is often inequitable [7,9,17]. Such an approach is also in line with the recent United Nation's Sustainable Development Goals (Goal 11) of making, "cities inclusive, safe, resilient and sustainable" [50].

4.3. Limitations of the Modeling Approach

We note that most urban forest functional models such as i-Tree Streets will have sources of error. The possibility of CO_2 storage estimate errors of up to 40% for i-Tree Streets versus i-Tree Eco have been reported [33]. Another study found CO_2 sequestration estimates by i-Tree Streets are often 49% higher than that estimated using site and species specific growth rates and allometric equations [51].

A noteworthy shortcoming of i-Tree Streets is that all tree growth, mortality, and age-C relationships are derived from US cities. Thus, the model does not directly use site or species-specific tree growth or mortality rates [39,41]; therefore, the results presented in this study should be interpreted with care. Bare and Ashton [52] did determine a mean annual DBH increment of 1.0 cm for multiple, open-grown, species in a monitored restoration project in nearby Ebejico, Antioquia, Colombia. However, we know of no other comparable studies of tropical urban tree growth rates in Colombia or northern South America. Urban tree growth rates for larger trees in the North American subtropics have been found to range from an average of 1.1 cm per year in Gainesville, USA to 0.98 cm per year in San Juan, Puerto Rico [53,54]. While using a systematic process to choose the most appropriate reference city that accounts for different regional factors minimizes this error, applying US data to a different country still limits the accuracy of the results [40]. For this study, using the reference city with the highest tree match still left 29% of trees in the inventory without a species or genus specific code.

Another factor behind many of our reported limitations for i-Tree Streets is the lack of allometric equations specifically developed for urban trees in the neotropics, but also in other tropical and temperate cities. When urban tree derived equations are not available, i-Tree models use forest derived equations with adjustments to better reflect an urban environment [55]. Whenever an adjustment or substitute is used in modeling, results become less accurate. An average of 127–282 kg CO_2 per tree (Appendix B) were estimated for the MAAV, which is well below the 580–1260 kg CO_2 per tree found in Bogota, Colombia, [9] when adjusting for below ground carbon stocks and using allometric equations. Thus, the use of different models will affect the results [33]. That said, the i-Tree Streets model has been used internationally [41] and because of the minimum number of variables required, we propose that this makes its use appropriate for data poor, low income cities. In this work, the proposal of a characterization framework for nature-based solutions also acknowledges the need for improved carbon estimation for assessing the multiple co-benefits of these approaches [21].

An additional limitation of i-Tree Streets that was observed during our analysis is that it assumes that every street tree has some effect on building cooling. However, street trees are often located away from buildings. Future studies need to more accurately measure avoided emissions from cooling using additional factors such as the cardinal direction of a tree relative to a building, climate, deciduous or evergreen, and percent cover of buildings and trees in a plot [14].

The two methods used to estimate tree cover values, measured tree crown area and i-Tree Canopy, produced fairly different results. I-Tree Canopy reported almost twice as much tree cover than using the average crown area. Multiple factors could have caused this: (1) trees with a DBH <2.50 cm and a total height <2 m were filtered out and thus were not included in the average crown area method, whereas the i-Tree Canopy method could not discriminate among trees' structural characteristics; (2) The georeferenced boundaries of the study area imported into i-Tree Canopy included areas on the

outskirts of the urban area that consequently may have higher tree cover and more available planting space; (3) Trees inaccessible for measurement when the inventory was taken, as well as the 352 trees with no species data removed from the study were not accounted for with the crown area method. Because of these factors, the crown area method most likely underestimated tree cover while i-Tree Canopy most likely overestimated tree cover and available planting space. However, we posit that both values represent a range of reasonable minimum-maximum values for the CO_2 offset potential (Table 4).

In general, care is warranted when making comparisons between offset potentials, as many different factors influence it, such as the scope of the emissions. For example, Barcelona, Spain, had a gross CO_2 sequestration rate per ha almost twice that of the MAAV (Table 5). However, the MAAV has an offset proportion three times that of Barcelona. This does not necessarily mean the MAAV's public trees offset more than Barcelona's public trees. One reason for a lower offset potential in the Spanish city is that emissions were reported in Mg CO_2e, not only CO_2, i.e., additional greenhouse gases were accounted for in the calculations. For the urban zone of the MAAV, transportation emissions of 2,587,957 Mg CO_2 and total emissions of 2,864,090 Mg CO_2 for 2011 were used [46]. Nevertheless, the comparisons do show that MAAV's public trees offset a comparable amount of CO_2 to other cities in other studies, like Gainesville, US and Barcelona, Spain.

5. Conclusions

The use of a nature-based solutions approach for addressing climate change and other environmental and socio-economic problems has only recently been proposed in the scientific literature in the form of perspective pieces and in the European Union context. Noticeably missing from this discourse, are: (1) Evidence based examples of such strategies and solutions; (2) Data, information, tools, and models for documenting, monitoring, modeling, and assessing such solutions; and (3) examples from the developing world where such approaches can have a likely greater impact in providing more effective, sustainable, and equitable solutions. To these ends, although the urban ecosystem service and green infrastructure approach is used in Latin America, this study provides one of the first insights into the role of greening of neotropical cities, via tree planting programs, as a viable nature-based solution strategy.

Although urban forests, as a nature-based solution, provide many co-benefits; developing more accurate and region-specific methods and models for estimating carbon offsets by urban forests can help improve access to international funding for these types of nature based solution projects. Urban forests may also be incorporated into carbon markets on national or regional scales. The Climate Action Reserve, the carbon offset registry for the North American carbon market, has approved two protocols for urban forest projects: Urban Tree Plantings and Urban Tree Management. Both protocols only account for standing carbon; avoided emissions from cooling and maintenance emissions are not counted.

The consideration of nature-based air quality, socio-economics, biodiversity, and in particular CO_2 benefits from public trees can help guide management of these natural resources and the use of public space. As a potential carbon offset strategy, public tree plantings were competitive but less effective than other strategies in the region. Accounting for additional ecosystem services and social equity benefits may increase the favorability of tree plantings as a nature-based solution to the challenges of urbanization. Future studies could take a more holistic approach, assessing the economic feasibility and social acceptability of public tree plantings for the MAAV. More regional data and biomass equations based on urban trees as opposed to forest trees can improve the measurement of costs and benefits. Additionally, revising methods of selecting reference cities to better reflect the closest match could help to minimize the error associated with regional differences. Further studies on urban forests in low-middle income countries, especially in regions with rapid growth rates, are needed for improved urban planning and potential international investment in nature-based solutions.

Appendix A

Table A1. Criteria for Selecting a Reference City for Medellin, Colombia and the Values used to Calculate Root Mean Square Error (131).

Matching Criteria	Medellin	Honolulu	Modesto	Orlando	Santa Monica
Species Match % (Method 1)		13%	29%	0%	12%
Species Match % (Method 2)		71%	12%	43%	29%
Species Match % (Method 2, Normalized)		2.92	8.84	5.70	7.06
Heating Degree Days (Base 18 °C)	40	0	2746	644	265
Difference *		40	2706	604	225
Normalized		0.09	6.22	1.39	0.52
Cooling Degree Days (Base 18 °C)	1625	2526	597	310	1891
Difference		901	1028	1315	266
Normalized		3.63	4.14	5.30	1.07
Annual Precipitation (mm)	1687	392	315	1367	570
Difference		1295	1372	320	1117
Normalized		8.56	9.07	2.11	7.38
Root Mean Square Error		3.62	7.42	4.04	4.62

* Difference between the Medellin criteria value and the reference city criteria value (ex. HDD difference value for Honolulu is 40 − 0 = 40).

Appendix B

Table A2. Tree species in the Medellin Metropolitan Area, Colombia with the greatest CO_2 sequestration by total, density, and per tree.

Species	Total Kg CO_2/Year	Trees/km^2 Public Area
Ficus benjamina	1,094,837	430
Mangifera indica	758,928	510
Schefflera actinophylla	531,587	160
Spathodea campanulata	469,975	490
Persea americana	361,534	360
Terminalia catappa	226,665	680
Pithecellobium dulce	217,114	610
Araucaria heterophylla	156,275	110
Psidium guajava	128,067	200
Erythrina species	127,246	200
Tree Species or Type	**Average Kg CO_2/Tree/Year**	
Ficus carica	282	
Pimenta racemosa	239	
Manilkara zapota	220	
Broadleaf Evergreen Large	169	
Melia azedarach	159	
Schefflera actinophylla	159	
Erythrina variegata	156	
Persea americana	152	
Calophyllum inophyllum	132	
Podocarpus species	127	

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