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Calculation of carbon sequestered through remote sensing in a metropolitan park in the city of Quito, Ecuador

Cálculo do carbono sequestrado por meio de sensoriamento remoto em um parque metropolitano na cidade de Quito, Equador

Cálculo del carbono secuestrado mediante teledetección en un parque metropolitano de la ciudad de Quito, Ecuador

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The study demonstrates the utility of satellite imagery and allometric equations for estimating carbon sequestration in urban forests, aiding in carbon footprint reduction strategies.
Originality/value:
This research provides original empirical evidence into the carbon sequestration potential of urban forests, facilitating urban planning for climate change mitigation and enhancing ecosystem services in cities.

ABSTRACT

This article investigates how much CO_2 is stored in the eucalyptus trees of the Guangüiltagua Metropolitan Park (PMG), as a contribution to inventories aimed at developing initiatives to mitigate the carbon footprint of the city of Quito, Ecuador. In the project's first stage, the Normalized Differential Vegetation Index was calculated from 1982 to 2030 using a Lansat 8 satellite image and QGIS software. A second phase was developed by obtaining a satellite image of SENTINELA-2 and using SNAP software to calculate the NDVI. Using a mathematical model, it was established how much CO_2 visually represents each pixel. In the third phase, information was collected in situ using allometric equations in a disaggregation of 50 quadrants, each of 100 m2. The DBH and total height of the existing trees were measured in each quadrant. From this data, we established the amount of CO_2 fixed per quadrant, which resulted in an average of 1.5 tons. Using linear regressions, the calculation was projected for the total area of trees in the park, resulting in 42,150 tons of CO_2 fixed.

Keywords: urban forest, biomass, carbon sequestration, allometric equations

RESUMO

Este artigo investiga quanto CO_2 está armazenado nas árvores de eucalipto do Parque Metropolitano de Guangüiltagua (PMG), como contribuição para inventários destinados a desenvolver iniciativas para mitigar a pegada de carbono da cidade de Quito, Equador. Na primeira etapa do projeto, o Índice de Vegetação Diferencial Normalizado foi calculado de 1982 a 2030 usando uma imagem de satélite Lansat 8 e o software QGIS. Uma segunda fase foi desenvolvida obtendo uma imagem de satélite do SENTINELA-2 e usando o software SNAP para calcular o NDVI. Usando um modelo matemático, estabeleceu-se quanto CO_2 representa visualmente cada pixel. Na terceira fase, usando equações alométricas, foram coletadas informações in situ em uma desagregação de 50 quadrantes, cada um de 100 m^2. Em cada quadrante, o DAP e a altura total das árvores existentes foram medidos. A partir desses dados, estabelecemos a quantidade de CO_2 fixada por quadrante, resultando em uma média de 1,5 toneladas. Usando regressões lineares, o cálculo foi projetado para a área total de árvores no parque, resultando em 42.150 toneladas de CO_2 fixado.

Palavras-chave: floresta urbana, biomassa, sequestro de carbono, equações alométricas.

RESUMEN

En el presente artículo se investiga cuánto CO_2 se almacena en los eucaliptos del Parque Metropolitano Guangüiltagua (PMG), como aporte a inventarios dirigidos a desarrollar iniciativas que mitiguen la huella de carbono de la ciudad de Quito. En una primera etapa del proyecto se calculó el Índice de Vegetación Diferencial Normalizado desde el año 1982 hasta el año 2030 usando una imagen del satélite Lansat 8 y el software QGIS. Una segunda fase se desarrolló con la obtención de una imagen satelital del SENTINELA-2 con ayuda del software SNAP se calculó el NDVI, Mediante el uso de un modelo matemático, se estableció cuánto CO_2 representa visualmente cada píxel. En la tercera fase con ecuaciones alométricas se recolectó información in situ en una desagregación de 50 cuadrantes, cada uno de ellos de 100 m^2. En cada cuadrante se midió el DAP y la altura total de los árboles existentes. A partir de este dato se estableció la cantidad de CO_2 fijado por cada cuadrante, que nos dio como resultado un promedio de 1,5 toneladas. Utilizando regresiones lineales se proyectó el cálculo para el total de la zona de arbolado del parque obteniendo como resultado 42.150 toneladas de CO_2 fijadas.

Palabras clave: bosque urbano, biomasa, secuestro de carbono, ecuaciones alométricas.

INTRODUCTION

Between 20% and 40% of terrestrial ecosystems experience a temperature increase of more than 1.5°C in at least one season of the year. Since the last century, climate change-related catastrophes such as floods, hurricanes, windstorms and sea storms have increased by 350%, as well as the melting of the poles and glaciers. There has been an 87% decrease in glaciers over the last 60 years. The Ministry of Environment (2016) contemplates the calculation of anthropogenic greenhouse gas (GHG) emissions. Emissions were estimated at 80,504 tons equivalent (te) of carbon dioxide, coming from the areas defined by the IPCC. (1) In the Energy area, the country generates 35,812 te of CO_2 , which represents 44.49% of emissions. (2) Industrial Processes is an area that emits 2,659 t of CO_2 , which represents 3.30% of total emissions. (3) The agricultural area emits 14,515 t of CO_2 , which represents 18.03% of total emissions. In addition to CO emissions$_2$, agriculture also emits methane (CH4) and nitrous oxide (N2O), which represent 52.48% and 47.52%, respectively. (4) Land Use Change and Forestry (USCUSS) generate 24,171 t of CO2, which represents 30.02%. (5) The Waste area generates 3,345 t of CO_2 , which represents 4.16%. Ecuador emits 1.9 metric tons (Mt) of carbon dioxide (CO_2) per inhabitant. This value represents 0.1% of total global emissions (MAE, 2016).

Quito has an annual emission of 5.1 million tons of GHG, which are generated by anthropogenic activities such as (1) industry, especially metallurgy that emits carbon monoxide (2) the waste area emits 661.689 tons of CO_2 , which corresponds to 13 %, (3) commercial, domestic and institutional activities with an emission of 1,016,305 tons of CO_2 , which constitutes 20% of the total emissions of the city (4) public transport with a negative emission of 2.8 million tons of carbon dioxide per year (Ministry of Environment, 2016).

The presence of vegetation in urban areas brings multiple benefits to populations. Among the benefits we can highlight 1) the increase in soil permeability through its roots as it reduces the flow of water generated by storms on the soil surface; therefore, it reduces erosion and sedimentation in streams (Lucero and Marco, 2019).

2) The development of urban microclimates that are generated through the relative humidity produced by tree transpiration (Murillo, 2021).

3) Mitigation of the effects caused by the phenomenon known as urban heat island, these islands are produced by the accumulation of energy in concrete, steel and asphalt, where the temperature is 3 to 10 degrees higher than the surrounding environment (Martinez et.al, 2010).

4) Trees capture carbon from CO_2 and store it in their structures through photosynthesis, a process known as carbon sequestration (González and González, 2019).

The thermal contrast between a street without green spaces and one with street trees ranges from 2ºC to 4ºC. The shade cast by trees and shrubs on the urban pavement prevents it from absorbing the radiation that it will later project in the form of heat. At the same time, the foliage absorbs shortwave emissions that when they touch the ground are converted into infrared rays (Murillo, 2021).

It is necessary to have information that allows knowing the potential of urban trees as carbon sinks through a forest inventory and diagnosis of the city's tree mass (Saavedra et al., 2019).

The Guangüiltagua Metropolitan Park is located north of the city of Quito, bordered by Eloy Alfaro, De Los Granados and Simón Bolívar avenues, and has an area of 557 hectares and an altitude ranging between 2,700 and 3,000 m. It is the largest forest reserve managed as an urban park in the country because it is planted almost entirely with eucalyptus. It is the largest forest reserve managed as an urban park in the country because it is planted almost entirely with eucalyptus. It also presents high endemism in flora and fauna with many native species such as linden, tocte, myrtle and quishuar; all present in the six gorges inside the park (Mariño, 2015). More than 10 species of hummingbirds and another 60 species of birds have been found.

The park's grasslands represent 14.02% of the area with 78.14 ha. Forest represents 50.44% of the area with an area of 281.21 ha. It is mainly composed of eucalyptus with shrubs and bushes that appear as undergrowth, representing 25.11% with 142.93 ha. The trails cover an area of 28.25 m distributed throughout the park. Spaces without vegetation correspond to 9.81% of the total area, with 3.37 ha (Mariño, 2015).

Remote Sensing

There are passive remote detectors that capture the natural radiation reflected by a specific object. Active remote detectors, on the other hand, do so by emitting energy and scanning objects and areas by measuring the reflected radiation (Nieto and Cardenas, 2018).

Satellite images can be used to obtain information in dangerous and inaccessible areas (Mirra, 2017). These images have been used since the launch of LANDSAT in 1972, this type of satellite delivers images used to assess and monitor the state of vegetation, at different levels (Nieto and Cardenas, 2018).

The Normalized Difference Vegetation Index (NDVI) is the most widely used due to its ease of calculation. It has a fixed range of variation (between -1 and +1), which allows us to compare images with a low-cost option for forest biomass studies (Perea et al., 2021); that is, the proportion of living matter present in forests. Quantifying biomass in trees is very important as it is directly related to carbon sequestration. The eucalyptus trunk is erect and has an ash-gray cover and a very resistant white wood. The greenish-gray leaves when the tree is young are round, but when the tree is adult they are oval (Mirra et al., 2017). Eucalyptus is one of the species that captures the most CO_2 , according to studies it captures 29.9 tons per hectare per year (Seppänen, 2002).

MATERIALS AND METHODS

Obtaining NDVI values of the Metropolitan Park using the LANSAT 8 satellite image on a time scale.

The use of the Google Earth Engine platform together with the LANSAT 8 satellite made it possible to obtain images of the park area. It was delimited by drawing a polygon. This image, the QGIS software and the trends tool. earth were used to obtain the NDVI history from 1982 to 2015 which are the data that the satellite has. With this data, a linear regression was performed in R software (González, 2021), where an equation was obtained to project the NDVI until 2030. For the formulation of the mathematical model, a statistical analysis consisting of linear regression tests was performed to define the best relationship (r2) (Mendoza, 2018).

Estimation of carbon sequestered and CO_2 fixed with SENTINELA 2 satellite imagery.

The basic procedure to estimate carbon in the Guangüiltagua Metropolitan Park with satellite images includes 1) obtaining an image of the study area, 2) standardizing the pixel size between the different spectral bands, 3) obtaining the NDVI through equation 2, and finally, 4) calculating Carbon and CO_2 .

An image of the study area was obtained from the Copernicus platform and the SENTINELA 2 satellite containing the 13 spectral bands. Since the SENTINELA 2 bands have different pixel sizes ranging from 10 m, 20 m and 30 m; we proceeded to standardize the size of all pixels in all bands to the minimum possible, i.e. 10m. It should be noted that it was not necessary to standardize the pixel size in band 2 because this band already has 10m pixels. To standardize the pixel size in the different bands, the Raster program (Geometric and Resampling functions) was used (Madroñero et al., 2021).

The images were taken to the SNAP software where different band combinations were performed; mainly the infrared band (band 8), the red band (band 4) and the bands of the nature spectra (3, and 2) (Augusto et al., 2017).

Comparing bands 8 and 4, the abundance of existing vegetation, we calculated the NDVI for the entire forested area of the park. For this we used the applications incorporated in the SNAP Raster and Band mathematics as well as the NDVI formula (Perea et al., 2021).

NDVI = (B8 - B4) / (B8 + B4) (Eq. 1)

The application of the formula gave us the NDVI value for each pixel and for the area that makes up the park. By means of multiple linear regression, the linear equation was obtained, from which it was determined that spectral bands 4, 8 and NDVI turn out to be the ones that best explain the behavior of carbon and its concentration (Augusto et al., 2017).

With these variables a multilinear regression was performed. Here we obtained the intersection, the constant and each of the coefficients by which each band was multiplied; leading to a multilinear equation (Mendoza, 2018).

Estimation of carbon sequestered and CO_2 fixed by means of allometric equations.

The most accessible method to calculate the biomass of a tree is the use of allometric equations (Parsa et al., 2019). For the use of this analysis, three assumptions must be made. 1. The sample must be obtained at random. 2. It must present a normal distribution. 3. Homogeneity in its variance (Madroñero et al., 2021).

Based on the park's area of 557 hectares, fifty 10 x 10 quadrats (one hundred square meters each) were established where a sample of 0.09% of the total area was obtained. The quadrats were chosen randomly to ensure that all the different physiographic positions were represented in our sampling. Measurements were taken of all *eucalyptus globulus* samples in each quadrat. The coordinate in the center of each quadrat was taken and assigned a code of C1-C50. Allometric equations were used for this research, which were based on the relationship of two parameters with which the aerial biomass of the trees was calculated. One of these parameters was the diameter (DBH) at breast height, which was established at 130 cm from the ground; the other parameter used was the total height of the tree (Pacheco, 2020).

To measure DBH, a tape measure was used to obtain the length of the circumference (CAP), dividing it in such a way that the diameter of the tree (DBH) was obtained (de Oca et al., 2020). For the cases that presented branches in the trunk, all the DBH were added.

WTP = CAP / π (Eq. 2)

The height of the tree was measured at a perpendicular distance from one end. Using a hypsometer, the height to the point of the highest crown of the tree was obtained (Cancino, 2012). The equations that had the lowest mean square error value were selected, being the equation that best estimates the biomass of this species:

Aerial biomass = 39.8643 - 3.51885dap + 0.02138dap 2h (Eq. 3)

For which:

dap is the diameter at breast height

h is the total height of the tree

Br = Ba * 0.5 (Eq.4)

The total biomass in kg was obtained, through the sum of aerial and root biomass, the carbon (C) and CO_2 fixed were deducted (McPherson et al., 2008). The observed biomass was considered aerial biomass (trunk, branches, leaves, among others), and the subway biomass (roots) was added to this value using the conversion factor of 0.50 (Pacheco, 2020).

Bt = Ba + (Ba * 0.50) (Eq. 5)

To perform the calculations of aerial, root and total carbon, three equations were used with the methodology proposed by (Muñoz, 2013), where the constant of 0.5 estimates the value of the carbon fraction at 50% for all species, 0.50 and 0.24 are the result of linear regressions (Fonseca, 2017).

CA = Bt * 0. 5 (Eq. 6)

CR = CA * 0.24 (Eq. 7)

CT = CA + CR (Eq. 8)

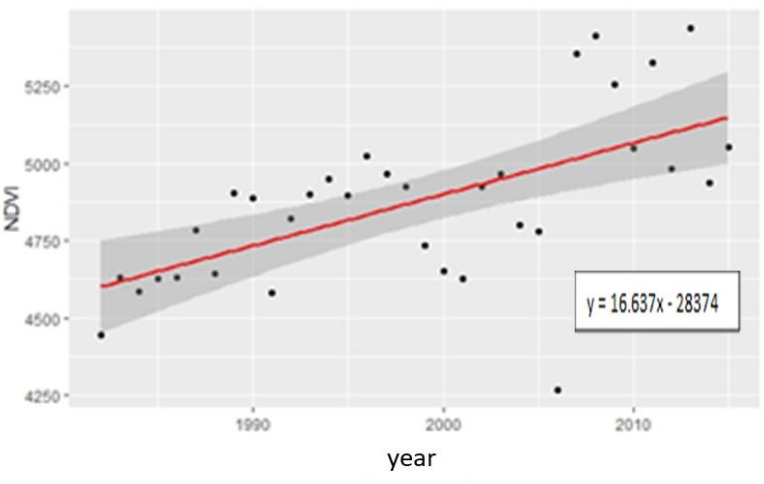
The calculation of CO fixation$_2$ was estimated by multiplying the value obtained from the total carbon and the coefficient 3.67, which is the result of the ratio of the weight of the CO molecule$_2$ (44) between the weight of the C atom (12) (de Oca et al., 2020).

RESULTS AND DISCUSSION

Obtaining NDVI values of the Guangüiltagua Metropolitan Park using a time-scale LANSAT 8 satellite image. Using a LANSAT 8 satellite image transported to QGIS, and the use of the Earth Trends tool, the NDVI history was obtained from 1982 to 2015. A projection of NDVI from 2015 to 2030 was obtained by linear regression.

By the equation: y = 16.637x - 28374 (Eq.10)

Figure 1. NDVI from 1982 to 2015, image generated in Argis software.



Source: own elaboration (2023)

As can be seen in Figure 1, NDVI maintains a constant increasing trend, starting in 2015 with a value of 5050 nm and is projected until 2030 at 5400 nm.

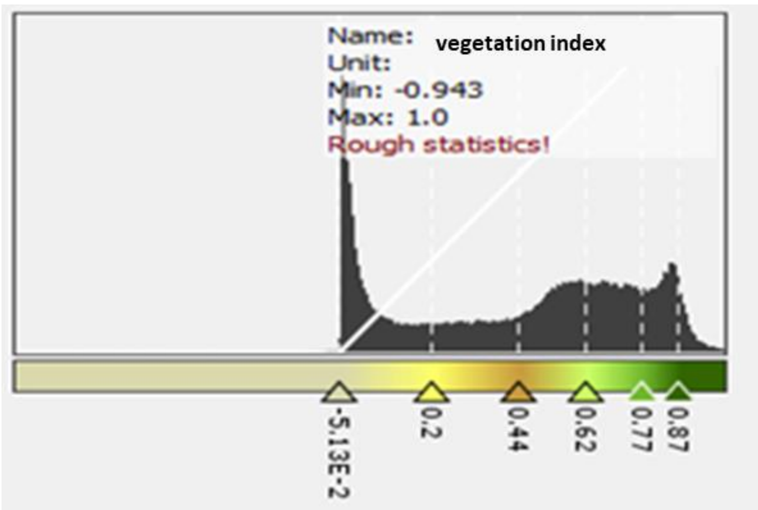
When applying the NDVI formula (B8 - B4) / (B8 + B4), in SNAP with the SENTINELA 2 satellite image, we notice that the area of the image changes colors to white. This denotes the existing vegetation index, according to the calculated value, as shown in Figure 2. Bright areas with light colors have vegetation, black areas denote absence or scarce vegetation.

Figure 2. NDVI image generated in SNAP software, with SENTINELA 2 image

Source: own elaboration with the research data (2023)

Next, the histogram is shown in Figure 3, with NDVI values between -1 and 1, observing that the greatest amount of vegetation is found between values of 0.3 and 1.

Figure 3. NDVI Histogram generated in SNAP software with SENTINEL 2 image.



Source: own elaboration with the research data (2023)

If a comparison is made between the forest and the city, based on the colors, it can be observed that the NDVI of the forest is between 0.3 and 1, and that of the city is between -1 and 0.3. With the help of the SENTINELA 2 image and the SNAP software, the values for band 4 and band 8 were obtained, and using the equation (B8 - B4) / (B8 + B4) for the calculation of NDVI, the values for the fifty quadrats were obtained.

The data obtained from band 4 through the SENTINELA 2 image show that there is a bias of the data to the left, where the minimum value is 0.022 nm and the largest is 0.11 nm; most of the quadrants range from 0.022 to 0.44 nm.

The data obtained from band 8 through SENTINELA 2 imaging show that there is a bias of the data to the left, where the minimum value is 0.09 nm and the largest 0.48 nm; most quadrants range from 0.15 to 0.22 nm.

The NDVI data obtained from the SENTINELA 2 image show that there is a bias of the data to the right, where the minimum value is 0.38 nm and the highest value is 0.93 nm; most of the quadrats range between 0.60 and 0.71 nm.

The total carbon values reflected for the fifty quadrants were obtained by applying the equation obtained from a multi-linear regression.

$$CT\ kg = -82{,}88 + 3271{,}41 * B4 - 506{,}37 * B8 + 658{,}51 * NDVI \quad \text{(Eq. 11)}$$

The data obtained for total carbon reflected through satellite images show that there is a bias of the data to the right, where the minimum value is 331.28 kg and the highest is 457.28 kg; most of the quadrants range between 385.28 kg and 403.28 kg.

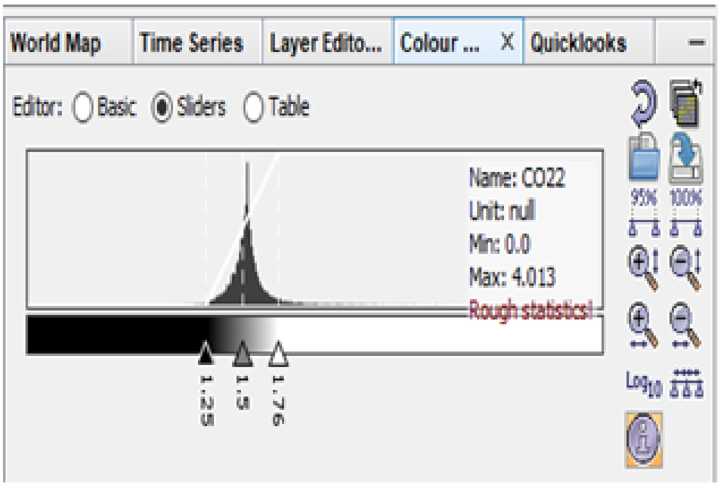
The values of CO_2 reflected per pixel for the fifty quadrants were obtained by applying the equation:

$$CO_2\ ton = -0.3039 + 13.6438 * B4 - 1.8565 * B8 + 2.4143 * NDVI \quad \text{(Eq. 12)}$$

The data obtained from the CO_2 fixed through the visual representation of the CO_2 concentrations given by the SENTINELA 2 satellite image show that there is a bias of the data to the left, where the minimum value is 1.33 t and the highest is 1.69 t; most of the quadrants oscillate between 1.45 and 1.57 t. The equation was entered and developed for the CO reflected in the SNAP program, where it was possible to verify that the CO values are related to those obtained in the field. The equation was entered and developed for the CO_2 reflected in the SNAP program, where it was possible to verify that the CO values$_2$ are related to those obtained in the field.

The reflected CO_2 fluctuated between values of 1.76 tons as a maximum value, and 1.25 tons as a minimum value, with an average of 1.5 tons reflected per pixel, for sites with NDVI values greater than 0.3. As shown in Figure 4.

Figure 4. Histogram generated in SNAP software



Source: own elaboration with the research data (2023)

Estimation of carbon sequestered and CO_2 fixed by means of allometric equations

In the sampling carried out in the Guangüiltagua Metropolitan Park, measurements of DBH (diameter at breast height) and total height were taken for 575 individuals of the *eucalyptus globulus species*, distributed in fifty 10mx10m quadrants. A coordinate was taken in the center of each quadrat. The average DBH of the individuals analyzed in the fifty quadrats was 49 cm, with values ranging from 26 cm as the lowest value to 92 cm as the highest; the data from the fifty quadrats have a leftward bias, with the largest number of quadrats having a DBH between 37 cm and 48 cm. The average height of all measured individuals is 28.92 m, their values are within 14.79 m height as the lowest value and 37.29 m as the highest value; the data of the fifty quadrats have a bias to the right, with the largest number of quadrats presenting a height between 28.29 and 32.79 m total height. The total biomass value calculated from the fifty quadrats is 33,017.08 kg; the values fluctuate between 511.82 kg as the minimum value and 856.82 kg as the maximum value; the data present a bias to the left and the majority of the quadrats are between 580.82 kg and 718.82 kg. Based on the use of the allometric equation chosen for this study, and with the total biomass data, total carbon was obtained from DBH and tree height.

The total carbon value of the fifty quadrats is 20,470.43 kg, the values fluctuate between 317.32 kg as the minimum value and 532.32 kg as the maximum value; the data are skewed to the left and most quadrats are between 360.32 kg and 446.32 kg. Based on the use of the allometric equation 11, and with the total carbon data, the fixed CO_2 was obtained from the calculated total carbon.

The total value of fixed CO_2 from the fifty quadrats is 75.05 tons, the values fluctuate between 1 t as the minimum value and 2.08 t as the maximum value; the data are right-skewed and most quadrats are between 1.54 t and 1.72 t of fixed CO . $_2$

Projection of CO_2 fixed in the forested areas of the Guangüiltagua Metropolitan Park

The CO fixation projection$_2$ was made for the 281.21 hectares corresponding to the forested area, resulting in 42,150 tons of CO_2 fixed for the entire forested area of the Guangüiltagua Metropolitan Park.

Results discussion

The NDVI values obtained in this research by the LANSAT 8 image and projected to 2030, show a growth. This trend is similar to that reported in the study of vascular plants in the city of Tuluma-Mexico. The author indicates the increasing values of NDVI in a period of time from 2000 to 2020. Obtaining NDVI values on a time scale is important to evaluate and monitor the state of vegetation (Muñoz 2013).

Although we found increasing values of NDVI in the PMG in the period from 1982 to 2030, these values can sometimes be reduced by external effects such as forest fires and droughts.

Baquero (2019) in his study on fire danger zones, based on the calculation of NDVI vegetation indices, identified areas of metropolitan parks as sensitive to suffer forest fires, whether natural or provoked. It also indicates that July, August and September are the most dangerous months for forest fires, due to the absence of rainfall.

The SENTINELA 2 satellite images allow the calculation of the CO_2 fixed by means of equations, which are the result of linear regressions, generating numerical values of CO_2 for each pixel. The values obtained in the present investigation using a SENTINELA 2 image range between 1 and 2 tons of CO_2 on average per pixel. This is how Mendoza (2018), in his study on *pinus patula* plantations, managed to determine that the 30 units studied in the district of Luya using SENTINELA 2 images, fixed 1.49 tons of CO_2 . The research developed by Mamani (2019) shows similar results in his study in the city of Lima-Peru, using SENTINELA 2 images. The eucalyptus trees of 249.78 ha absorbed 7,468.64 tons of CO_2 per hectare; that is, 29.9 tons per year approximately. However, solar radiation interacts predominantly with tree leaves; therefore, optical images present information from the upper level of the forest canopy (Mirra et al., 2017). According to the spectral analysis of the SENTINEL 2 satellite image, it is observed that each quadrant of *eucalyptus globulus* has different spectral information for each pixel, considering that each pixel corresponds to 100 square meters of the PMG area.

Analyzing the biomass data obtained from DBH and height, it was verified that there is a direct relationship between these variables; this is because plants acquire carbon from atmospheric CO_2 for their development and growth, to convert it into carbohydrates through photosynthesis and thus increase their plant tissue (Mendoza, 2018). This pattern is maintained in the fifty quadrats observed in the PMG, where there was a specimen with a DBH of 0.92 cm, 45 meters in height and a biomass of 58.79 kg, which became the highest value observed. Here they observed a direct relationship between DBH, height and biomass, where their tallest specimen had a biomass of 58.04 kg. In his research, McPherson (2008) described forest structure in urban areas throughout California. He used allometric equations with variables such as DBH and height to estimate biomass in *eucalyptus globulus* specimens. However, Pacheco (2020) mentions that carbon sequestration capacity decreases with increasing tree age; at early or intermediate ages carbon sequestration is higher.

Comparing the values of carbon and CO_2 , in the fifty quadrats, between the data obtained in the field and provided by the satellite, it was observed that the data obtained for carbon in the field are overestimated in relation to the satellite, while the data for CO_2 fixation is overestimated by the satellite in relation to the field. In the present study, we found that there is no direct relationship between NDVI and CO_2 fixation, i.e., higher fixation was not found at higher NDVI value. Echeverría (2018) in his study in the Yanacocha reserve with satellite images, analyzes what (NDVI) allows us to determine the vigor of the vegetation. It is higher when found in areas where the vegetation has abundant leaf area, as well as in the coastal and eastern areas of Ecuador. However, it is not as effective in the mountains and moorlands because their vegetation has a lower leaf area due to the existence of grasses and pastures; therefore, these areas presented low and medium NDVI values. This occurs because the red band, which is band 4, is related to the amount of chlorophyll, and the near infrared band 8 is related to the leaf area index, that is, the density of green vegetation (Mendoza, 2018); taking into account that *eucalyptus* *globulus* is a species that as its trunk matures thickens and its foliage decreases. It explains that it does not have high NDVI values in areas where it fixes more CO_2 (Mirra et al., 2017). The overestimation presented when comparing carbon and CO_2 results may be due to the fact that NDVI values are not related to biomass as the field results are.

Additionally, the use of allometric equations to estimate aerial biomass based on tree diameter at breast height (DBH) is consistent with established methods for quantifying carbon stocks in forest ecosystems (Chave et al., 2014). The finding that aerial biomass constitutes approximately 50% of forest biomass is supported by previous studies assessing carbon allocation in trees (Rodríguez-Veiga et al., 2017).

Furthermore, the estimation of carbon sequestered by urban forests underscores their significance in offsetting anthropogenic greenhouse gas emissions and contributing to urban climate resilience (Escobedo et al., 2019). The projected CO2 fixation of 42,150 tons for the entire forested area of the Guangüiltagua Metropolitan Park emphasizes the substantial carbon sequestration potential of urban forests, aligning with the findings of similar studies on urban forest carbon dynamics (Escobedo et al., 2019; Nowak & Dwyer, 2007). However, discrepancies between field-measured and satellite-estimated carbon values highlight the limitations of remote sensing techniques in accurately quantifying carbon stocks, emphasizing the need for ground-based validation and calibration (Avitabile et al., 2016).

Urban parks influence the reduction of carbon footprint in cities by reducing greenhouse gas emissions (Cuenca et al., 2017). In the PMG, the forested area was estimated to have fixed 42,150 tons of CO_2 . Farinango (2020), in his study estimating the carbon sequestration of the urban forest in the city of Otavalo, indicates that the CO_2 captured in the eighth avenue of the city was 2,640.22 t, which contributes to reducing the emissions generated by this city.

Main limitations of this study implications for urban sustainability and policy

While this study provides valuable insights into the carbon sequestration potential of urban forests using remote sensing and allometric equations, several limitations should be acknowledged. Firstly, the reliance on satellite imagery and allometric equations introduces inherent uncertainties and potential inaccuracies, particularly when applied to specific tree species or environmental conditions. Additionally, the sampling method focusing solely on eucalyptus globulus specimens may not fully represent the diversity of tree species within the forested area, leading to potential sampling bias. Furthermore, the study does not consider external factors such as forest fires, droughts, or human disturbances, which can significantly impact vegetation dynamics and carbon sequestration rates. The temporal and spatial resolution of the satellite imagery may also limit the ability to capture fine-scale changes in vegetation over time or accurately represent variations within the forested area. Lastly, the lack of validation against ground-truth data or independent measurements undermines the robustness and reliability of the results. Therefore, while the findings offer valuable insights, caution should be exercised in interpreting and generalizing them, and future research should aim to address these limitations to enhance the accuracy and reliability of carbon sequestration estimates in urban forests.

The findings of this study hold significant implications for urban sustainability and policy formulation. Urban forests play a crucial role in mitigating climate change, improving air quality, and enhancing the overall quality of life in urban areas. The positive correlation between NDVI values and carbon sequestration highlighted in this research underscores the importance of preserving and expanding urban forest cover. By incorporating these findings into urban planning frameworks, policymakers can develop more effective strategies for sustainable urban development.

Furthermore, the estimation of carbon sequestered by urban forests provides valuable insights for policymakers seeking to implement nature-based solutions to combat climate change. Integrating urban forest management strategies informed by carbon sequestration data can help cities meet their climate mitigation goals and enhance resilience to environmental challenges. Moreover, promoting the conservation and restoration of urban forests can contribute to achieving broader sustainability objectives, such as biodiversity conservation and ecosystem restoration.

CONCLUSIONS AND FUTURE RESEARCH

From the results obtained we can conclude that the NDVI calculated based on LANSAT 8 and SENTINEL 2 satellite images, present positive values for NDVI in the PMG. Satellite images provide valuable information that together with field data allow estimating variables such as biomass and carbon. This information is important to evaluate the role of forests in carbon sequestration and emissions. The use of DBH in the allometric model made it possible to establish the aerial biomass in the forest as 50%.

Moving forward, future research endeavors should address the limitations of this study and explore additional factors influencing carbon sequestration in urban forests. By refining remote sensing methodologies and incorporating more extensive and diverse datasets, researchers can improve the accuracy and robustness of carbon estimation models.

Furthermore, interdisciplinary collaborations between ecologists, climatologists, and urban planners are vital for developing holistic strategies to maximize the climate change mitigation potential of urban forests. Combining advanced technologies and interdisciplinary approaches, policymakers and urban planners can make informed decisions to enhance the resilience and sustainability of urban ecosystems, ultimately contributing to global efforts to combat climate change.

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	A1	A2	A3	A4
A. theoretical and conceptual foundations and problematization:	25%	25%	25%	25%
B. data research and statistical analysis:	25%	25%	25%	25%
C. elaboration of figures and tables:	25%	25%	25%	25%
D. drafting, reviewing and writing of the text:	25%	25%	25%	25%
E. selection of bibliographical references	25%	25%	25%	25%
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