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Designing resilient bicycle paths in Puno, Peru: Combating urban CO_2 emissions with GIS analysis

Juan Nihol Bravo Inchuña, Luz Clara Calisaya Rojas *, Grover Marin Mamani

Academic Department of Architecture and Urbanism, Faculty of Civil Engineering and Architecture, Universidad Nacional del Altiplano de Puno, Puno, Peru

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ABSTRACT

This study watched over the amount of CO_2 gas that cars and other vehicles put into the air in Puno, Peru. The goal was to create a plan for bike paths that can last through tough conditions. These paths would lead to places where people can relax and have fun and also focus on the parts of the city with the most CO_2 pollution. This was done using a tool called Geographic Information Systems (GIS). The researchers figured out how much CO_2 was in the different areas of the city, pointing out places with a lot of CO_2. They also looked at how easy it is to get to places where people go for fun (called Affluence of Recreational Spaces or ARS) and used maps to show how CO_2 levels and ARS relate to each other. They measured CO_2 using a method called Kernel density in a program called QGIS. To find out about ARS, they asked 350 people questions in person and online using Google Forms, with answers based on a rating scale. This study was done after the COVID-19 pandemic in 2022. The researchers put all their information into a GIS system using map math and checking how everything connects. Their findings showed that places with more CO_2 and ARS were linked. The city had a lot of CO_2 - 615.76 parts per million (ppm), which is 76% more than what is considered natural. They found nine main spots in the city with the most CO_2, the highest being 713.49 ppm. They also identified six spots that were most popular for fun activities. By looking at both CO_2 and ARS spots, they made a plan for bike paths totaling 8,849 meters. These paths would link to the main fun places in Puno.

1. Introduction

Carbon dioxide (CO_2) is a greenhouse gas produced by various anthropogenic activities, with motorized transport serving as the primary source of pollution in cities as a consequence of urban modernization. The scientific community has acknowledged it as the main contributor to climate change since 1863. In 1896, researchers established that the burning of fossil fuels causes global warming (Weart, 2013), conclusively demonstrating that CO_2 is primarily responsible for the 60% to 63% increase in pollution radiating through the layers of the atmosphere since 1979 (Hofmann et al., 2006).

The 2007 WMO bulletin reported a temperature increase in January and April of 1.37°C and 1.89°C, respectively, with an average of 14.42°C between 1998 and 2007 (the average for the period 1961-1990 was 14.0°C). The latest IPCC 2007 report indicates that the highest level of global warming occurred in 1998, with a temperature of 14.54°C (Ballesteros and Aristizabal, 2007). According to the 2007 IPCC, "Warming of the climate system is unequivocal, as evidenced by observed increases in global mean air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level" (Pachauri and Reisinger, 2007). Furthermore, WHO states that 58% of premature deaths occurred in 2016 are related to CO_2 pollution (Venkatesan, 2016). The CO_2 emissions from motorized vehicles globally exhibit the highest percentage, with a more significant contribution observed in developed countries (Leroutier and Quirion, 2022; Abreu et al., 2020). Latin America, particularly Peru, ranks 21st in air quality according to the 2018 World Air Quality Report, highlighting a substantial contribution to anthropogenic air pollution. Metropolitan Lima faces heightened fossil fuel consumption, resulting in severe environmental and atmospheric pollution,

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* Corresponding Author.
Email Address: gmarin@unap.edu.pe (L. C. Calisaya Rojas)
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Corresponding author's ORCID profile:
https://orcid.org/0009-0009-1388-1058

notably impacting residents' physical and mental well-being. A survey found that 51.3% of Lima's population perceives a decline in their quality of life due to vehicular congestion (Cordova et al., 2021).

In the Puno region, the vehicular fleet, especially in the city of Puno, is diverse. In 2000, there were 13.33 vehicles per 1,000 inhabitants, and by 2001, this figure surged to 27.17 vehicles per 1,000 inhabitants, marking a notable increase of 2.04 vehicles. This underscores the urgency for targeted interventions in the region to address escalating challenges associated with vehicular emissions and their adverse impacts on air quality and public health.

Currently, motorized vehicles are the preferred choice due to the convenience they offer to individuals. Non-motorized alternatives, such as sustainable mobility, remain unexplored due to the lack of a comprehensive cycling infrastructure plan. Around 2000, bicycles were the most popular mode of transportation in Puno, with 62% of households having one, especially in urban areas. However, in subsequent years, bicycle usage declined due to a lack of infrastructure and the increasing number of motor vehicles.

Bicycles (Luna et al., 2021), dedicated cycling lanes, and scooters, among other options, are considered less environmentally impactful forms of sustainable mobility for mitigating climate change. They are also recognized as essential elements of urban spaces, helping reduce the consumption of carbon-intensive energy sources. The term "sustainable mobility," coined mainly in the 20th century in response to social and environmental concerns arising from motorized transport, advocates for a strategic model prioritizing public transportation, cycling, and walking to minimize energy consumption and air pollution, with a specific focus on addressing social connectivity needs (Pucher and Dijkstra, 2003).

Research has designed tourist-centric cycling routes, providing opportunities to contribute to the reduction of environmental and acoustic pollution, as well as enhancing the local economy. Project results demonstrated feasibility and gained significant social acceptance. The concept of linking sustainable mobility with cycling networks and public recreational spaces leverages mandatory commutes for both passive and active recreation, resulting in a resilient, self-sustaining network of cycling paths.

This research addresses the increasing CO_2 levels and the threat of climate change to Earth by monitoring CO_2. The goal is to design a network of bike lanes linked to recreational spaces, emphasizing critical CO_2 nodes. Monitoring took place at 47 points in the city of Puno to determine CO_2 levels and identify critical nodes. Additionally, a survey identified nodes with higher Relative Spatial Autocorrelation (ARS). Tabulating this data, we represented it through heat maps using variable interpolation and network analysis, revealing a resilient bike lane network with a CO_2 database. Furthermore, we analyzed an analogous study on emerging bike lanes in France and Colombia, focusing on lanes implemented during the 2020-2021 pandemic. Subsequently, provisional networks of emerging bike lanes were dismantled, with some retained. The study in France led to the creation of the National Database of Bike Infrastructure (Base Nationale des Aménagements Cyclables (BNAC) (Demoraes et al., 2024), underscoring the importance of planning, zoning, and infrastructure in bike lanes.

2. Methodology

The analysis involved observational, retrospective, analytical, and cross-sectional methods, allowing us to measure the CO_2 variable. This process resulted in various findings that described the extent of atmospheric pollution caused by CO_2. We established the connection between this variable and recreational spaces through the use of Geographic Information System (GIS) maps. GIS facilitated our input and management of diverse data, commonly referred to as maps. We applied the Kernel density method to generate simplified maps, identifying neighboring patterns for calculating point/data density within a specified bandwidth. The practical and effective application of map algebra analysis assisted in data interpolation through geoprocessing tools.

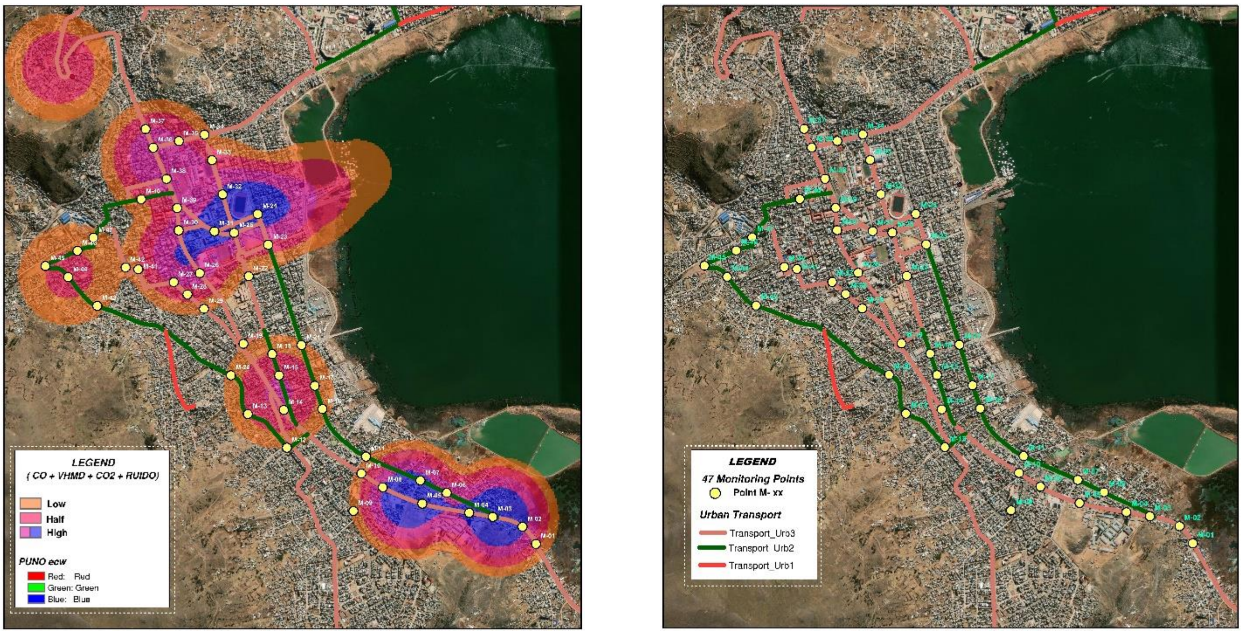
Additionally, we gathered data from previous years' CO_2 sampling, helping us pinpoint areas with elevated pollution for specific CO_2 monitoring. Consequently, we determined the degree of CO_2 pollution in the city of Puno and outlined critical CO_2 nodes. The monitoring period covered nine months, from August 2022 to May 2023, excluding months without monitoring (December 2022, January, and February 2023) due to social unrest impacting the country and the city.

Simultaneously, we surveyed over a 4-month period, from December 2022 to March 2023, using the Likert scale to identify nodes with higher Air Recirculation Systems (ARS), efficiently grading respondents' responses. Finally, we executed an interpolation of the two variables, CO_2 and ARS, to achieve an optimal outcome for zoning and the network of resilient and autopoietic cycle paths. The utilization of the Net Work Analysis method for the shortest distance facilitated our problem-solving concerning network navigability, flow, or connection capacity in resulting networks.

2.1. CO_2 level measurement

The process consisted of two phases: background data collection and new data collection, each comprising two stages: Data collection and data analysis. In the initial phase of background data collection, we utilized three bibliographic theses related to air pollution caused by the automobile fleet in the city of Puno. The background information included Investigation 1 on CO (carbon monoxide) and VHMD (hourly volume of maximum demand of vehicular influx), Investigation 2 on CO_2 (Yucra, 2017), and Investigation 3 on Noise. A geographic information system (GIS) was employed to tabulate this existing data. We approached each variable independently, following the same development process: Combining vectors and raster and applying the Kernel density method (Okabe et al., 2009). This approach resulted in obtaining four partial maps. Subsequently, we performed map algebra by interpolating these partial maps of CO, CO_2, VHMD, and Noise. The expression used was $CO+VMHD+CO_2+Noise=1$, assigning a percentage of influence to each variable in air pollution: CO (0.35%)+VMHD (0.35%)+CO_2 (0.15%)+Noise (0.15%)=100%. Consequently, we obtained the total air pollution background map of Puno. Afterward, we defined monitoring points using a 250-meter grid, locating them on the main and secondary roads of Puno following the road hierarchy. Fig. 1 illustrates the final map of the background analysis.

For the execution of the second phase, we utilized monitoring equipment. We employed the carbon dioxide sensor JD-3002, the anemometer UNI-T UT363 BT, and supporting instruments such as tripods and GPS Etrex Garmin 64s with the UTienv application (UNI-T). Each instrument was positioned at a height of 1.5 meters. Monitoring occurred only once a day during the peak hour period, including the morning peak hour (07:00-09:00), the midday peak hour (12:00-14:00), and the evening peak hour (18:00-20:00). We monitored the initial points for 2 hours with a standardized interval. CO_2 measurements were expressed in ppm. We monitored a total of 47 points, as illustrated in Fig. 1b. Each monitoring point produced 24 sets of reading data. To calculate the final data, we applied Eq. 1: $X=\sum(n_1+n_2+...+n_{24})/24$. Furthermore, we applied Eq. 2 to determine the average CO_2 level: $Y=\sum(n_1+n_2+...+n_{47})/47$. These data underwent tabulation utilizing the Kernel density method.



a

b

Fig. 1: Final air pollution background map, (a) results of $CO+VHHD+CO_2+Noise$, (b) new monitoring points

2.2. Identification of critical nodes of higher CO_2 contamination

Node identification utilized the CO_2 level results through the Kernel density method, applying more intense coloring in areas proximate to other vectors (Guler and Yomralioglu, 2021). A bandwidth of 500 meters was employed, and a color scale was categorized into five levels: low, medium, and high. The points identified belonged to the high-level color range (dark blue and blue). Additionally, values exceeding 600 ppm up to 900 ppm (dark blue) and from 700 ppm to 900 ppm (blue) were taken into consideration. We considered values above 600 ppm up to 900 ppm (dark blue) and from 700 ppm to 900 ppm (blue). The nine nodes identified with the highest contamination underwent monitoring using the specialized equipment mentioned earlier. This monitoring occurred in three stages during peak hours: morning, noon, and night. The morning (07:00-09:00), noon (12:00-14:00), and night (18:00-20:00) peak hours were encompassed within a 2-hour standardized interval. At each monitoring point, 24 reading data points were acquired, and the final data were calculated using Eq. 1. Additionally, Eq. 3 ($Z=\sum(\bar{X}_1+\bar{X}_2+\bar{X}_3)/3$) was employed to determine the average across the three periods (morning, noon, and night), with the data tabulated using the Kernel density method.

2.3. Determination of the ARS and interpolation for the design of a bicycle lane network

The execution involved two phases: Google Forms and in-person surveys, which surveyed 350 subjects. To validate and ensure survey reliability, we employed the R software with Cronbach's Alpha method (Pinto et al., 2014). This method evaluates internal survey consistency, with values ranging from 0 (low) to 1.0 (high).

We calculated feasibility using the equation: $\alpha=k/(k-1)*[1-(\sum vi)/vt]$, where α represents Cronbach's Alpha, k is the number of items, vi is the variance of each item, and vt is the total variance. A pilot survey with 21 subjects, encompassing general and 22 specific questions about recreational space attendance, was conducted. These questions included inquiries like "How frequently did you visit the park...?" for each of the 22 parks in Puno, rated on a Likert scale from 1 to 5 (1 being the lowest and 5 being the highest).

In the sample, 55% were women, and 45% were men, all over 18 years old. The instrument reliability analysis yielded a result of 0.90, indicating high reliability for both the instrument and the questions. After confirming the pilot survey's reliability, we administered the 350 surveys to the general public, both virtually and in person.

We tabulated data from the 22 parks, considering high and medium values on the Likert scale (3, 4, and 5), using the Kernel density method with a 500-meter bandwidth and a color scale categorized as low, medium, and high. We identified six ARS (Recreational Space Attendance) nodes situated in the high-color category (dark purple and purple), with parks having attendance equal to or greater than 150 people.

Finally, we generated a density map of nodes with higher ARS. To create the final interpolation map of two variables (CO_2 and ARS), we once again utilized the Kernel density method, along with map algebra, expressing CO_2+ARS=1. This determined the percentage of influence of each variable on air pollution: $CO_2(0.50)+ARS(0.50)=100\%$. The bandwidth used was 500 meters, and the color scale was divided into 10 ranges. For the design of the bike path network, we performed an analysis using Network Analysis with the shortest distance method (Semenzato et al., 2023).

3. Results

3.1. CO_2 level

The rise in the number of cars in Puno has caused more CO_2 pollution. Each car can release up to 1,000 parts per million (ppm) of CO_2, which is much higher than the natural level of around 350 ppm. Research shows that when CO_2 levels go beyond 800 ppm in workplaces, people may start to notice unpleasant odors. If the concentration exceeds 1,000 ppm, it's essential to ventilate the area until the CO_2 levels drop to a safe or healthy level (Subils and Domínguez, 2000). In the collected data on CO_2 levels in Puno, represented on heat maps with 47 datasets (M-1 to M-47) in ppm units, the color range shows the CO_2 pollution levels (dark blue and blue = high CO_2 concentration; light blue = medium CO_2 concentration; green = low CO_2 concentration). The data range from 486.29 to 755.42 ppm (dark blue, with 12 points), 439.25 to 884.17 ppm (blue, with 19 points), and 425.25 to 716.67 ppm (light blue, with 16 points). The green areas, indicating low CO_2 concentration, do not have monitoring points. The lowest and highest CO_2 levels recorded were 425.25 ppm at M-6 (Av. Simón Bolívar - Jr. Toribio Pacheco) and 884.17 ppm at M-13 (Av. Circunvalación Sur - Jr. Pacheco Vargas). Additionally, 24 data points were collected at each monitoring location, with some points significantly exceeding 1,000 ppm at M-03, M-05, M-08, M-11, M-13, M-16, M-18, M-19, M-21, M-25, M-26, M-27, M-34, M-36, M-42, and M-44. The highest recorded CO_2 pollution level was 1,797 ppm at M-16 (Av. Simón Bolívar - Jr. 9 de Octubre).

Finally, we obtained an average CO_2 contamination level of 615.76 ppm, which exceeds the natural limit of 350 ppm by 76%, corresponding to 100% as allowed by nature (Subils and Domínguez, 2000). These results are depicted in the map in Fig. 2.

3.2. Critical nodes of major CO_2 pollution

The pollution in the city of Puno surpasses the permitted natural levels by 76%, negatively impacting the surrounding ecosystem. We attribute this heightened pollution to both the vehicular fleet and critical nodes, which contribute to increased CO_2 emissions. The comprehensive map depicts the identified points, as mentioned earlier. There are a total of 9 points with the following averages: M-08=780.08 ppm, M-13=884.17 ppm, M-15=667.67 ppm, M-18=701.63 ppm, M-25=694.25 ppm, M-26=751.50 ppm, M-27=755.42 ppm, M-36=707.88 ppm, and M-38=670.38 ppm. The highest recorded CO_2 level is 884.17 ppm, and the lowest is 670.38 ppm. Fig. 3a illustrates the CO_2 concentration range of 600 to 900 ppm maintained by these 9 points. Naturally, CO_2 concentrations typically vary between 350 ppm and 550 ppm (Subils and Domínguez, 2000).

During the second monitoring phase, the collected data identified 9 critical nodes with higher pollution levels during three phases of the day. The results are reflected in the corresponding node maps for morning, afternoon, and night hours. Finally, we obtained the overall average for the three stages of the day for the 9 nodes (M-08=655.67 ppm, M-13=693.69 ppm, M-15=683.24 ppm, M-18=674.10 ppm, M-25=713.49 ppm, M-26=630.89 ppm, M-27=597.64 ppm, M-36=676.38 ppm, and M-38=601.46 ppm), represented on the average map of the 9 critical points, as shown in Fig. 3b.

The highest recorded CO_2 concentration among these 9 points was an average of 713.49 ppm at M-25 (Av. El Sol - Av. Del Puerto - Jr. Cahuide). It's important to note that the final data for the three monitoring stages do not vary significantly, remaining within the initial range of 600 to 900 ppm. However, there is an exception observed at point M-27 (Jr. Arequipa - Jr. Huancané), with an average of 597.64 ppm.

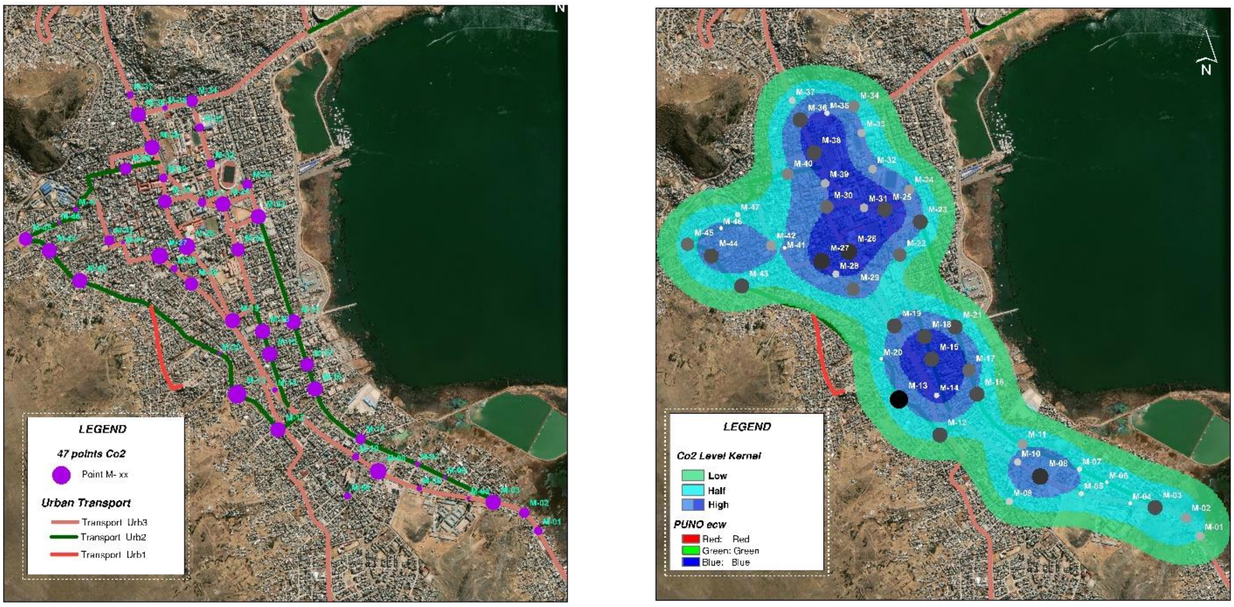


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Fig. 2: (a) Map of monitored points, (b) CO_2 level densification in the city of Puno

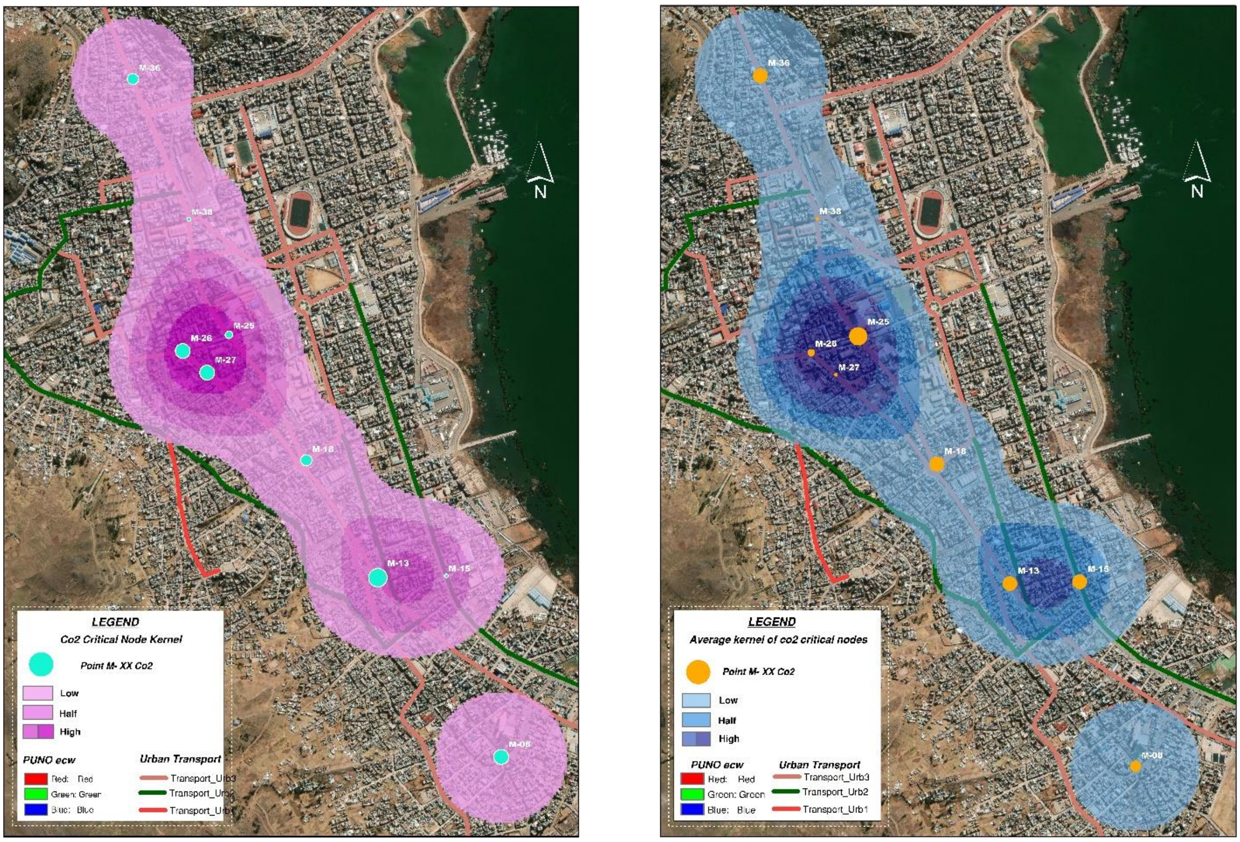

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Fig. 3: (a) Map of 9 critical nodes of highest CO_2 pollution in Puno, (b) Average map (morning, evening, night) of 9 critical nodes of highest CO_2 pollution in Puno

3.3. ARS and cycling network

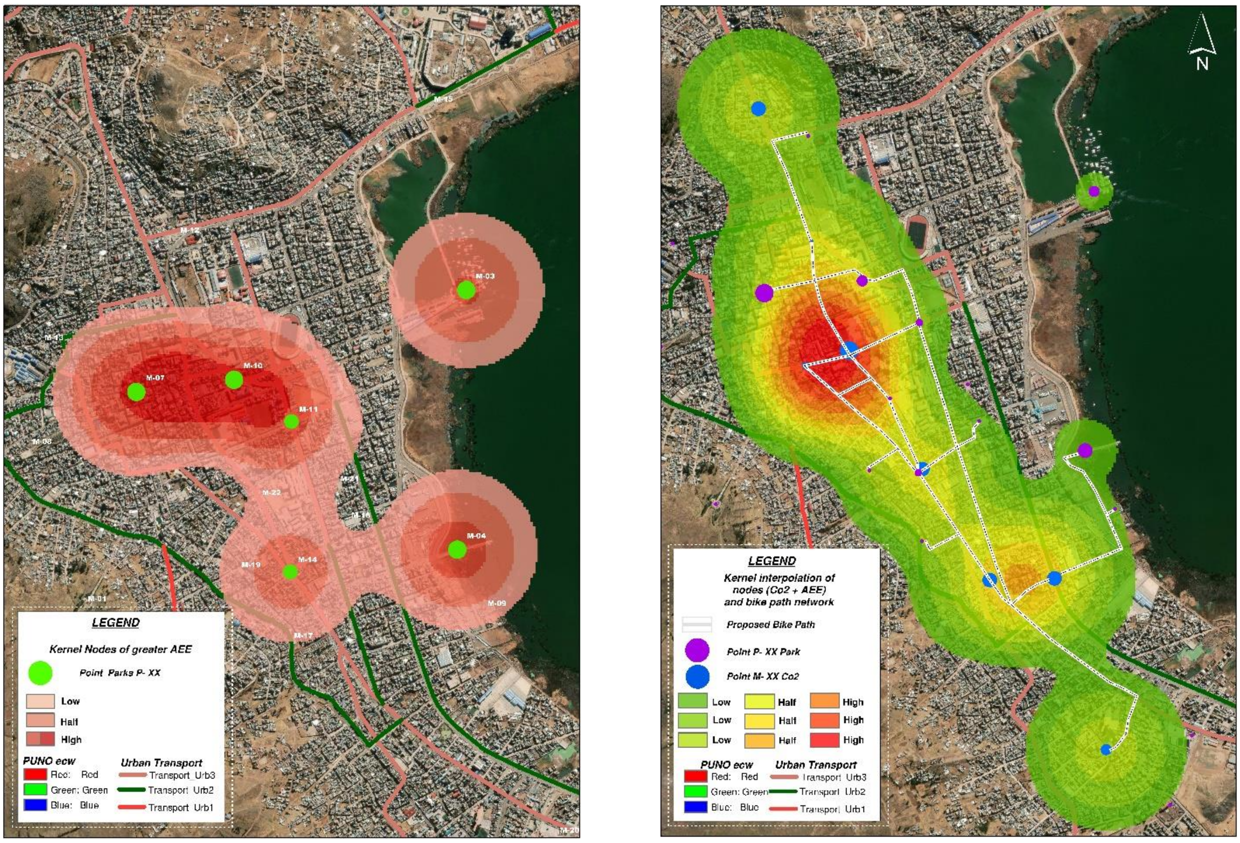
Recreational spaces, recognized for their ecological, cultural, heritage, and social values, have the capacity to offer positive experiences that contribute to the quality of life of individuals. It is also proposed that time, activity, and environmental surroundings constitute essential elements for the experience of both active and passive recreation, influencing urban configuration and transformation while also possessing significant potential for social flow.

The affluence in each recreational space affects the nodes of greater social concentration. The city of Puno boasts numerous recreational spaces, and to determine the Affluence of Recreational Spaces (ARS), we conducted a survey of 350 people in 22 parks (P-1 to P-22). Out of these surveys, 150 were conducted virtually and 200 in person, with 53.10%

of the respondents being women and 46.90% being men.

The results showed that there are parks with different levels of affluence. For example, César Vallejo Park was the area with the lowest affluence, registering 40 people, while the area with the highest affluence was the Casco Monumental, Armas Square, and Pino Square, with 267 people. Six nodes with the highest ARS were identified (P-11=Ramón Castilla oval, P-14=Dante Nava Park, P-10=the water park, P-3=Muelle Lacustre port, P-4=Banchero Rossi port and P-7=Casco Monumental the Armas square and Pino square), with affluence varying between 158 and 267 people, as shown in the heat map in Fig. 4a. The interpolation of the variables for the most relevant CO_2 and ARS nodes revealed areas with a higher incidence of CO_2 and ARS influx. These areas were depicted with red-orange and orange-green colors at 8 points (M-25=713.49 ppm, M-26=630.89 ppm, M-27=597.64 ppm, M-13=693.69 ppm, M-15=683.24 ppm, and P-7=Casco Monumental, Plaza de Armas, and Plaza del Pino, P-10=Parque del Agua, P-11=Óvalo Ramón Castilla) in Fig. 4b. Future investigations will be aided by these zones that have been identified with higher incidences.

Finally, an analysis was also performed on a network involving both variables: 9 critical CO_2 points and 6 ARS points with an 8849m extension of the bike lane network, as shown in Fig. 4b.



a b

Fig. 4: (a) Map of nodes with the highest ARS, (b) Map of interpolated variables and network of roads

4. Conclusion

The modernization of the city of Puno has prompted rapid growth in the automotive fleet, turning it into the primary source of CO_2 emissions, a gas that contributes to global warming and environmental pollution. To tackle this challenge, we conducted a thorough monitoring of CO_2 and planned a network of bike lanes using Geographic Information Systems (GIS). The results reveal that CO_2 levels in Puno exceed the permissible limits, with a recorded concentration of 615.76 parts per million (ppm). We identified 9 critical CO_2 nodes and 6 nodes of higher density through Kernel density analysis.

We evaluated the relationship between these nodes using Network Analysis, resulting in a network of bike lanes comprising 8,849 linear meters that connect critical CO_2 nodes with those of higher density. This node configuration generated resilient and autopoietic flows, supported by a robust CO_2 database.

Analyzing an article on emerging bike lanes in France and Colombia (Demoraes et al., 2024), it became evident that provisional bike lanes are disadvantageous for sustainable mobility, and they are commonly dismantled. Therefore, our research addresses deficiencies in the planning and zoning of the bike lane network through a detailed study of CO_2 and density, resulting in the creation of resilient bike lane networks. This study provides us with a solid foundation to continue exploring the optimization of the bike lane network and the application of CO_2 mitigation technologies, thus contributing to the advancement of knowledge in the field of sustainable mobility and environmental management in urban settings.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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