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Urban form, land use, and land cover change and their impact on carbon emissions in the Metropolitan Area of Monterrey.

A thesis presented by

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Dedicatoria

Con mucho amor y cariño para mi familia por su apoyo incondicional, en especial a mis papás por siempre estar al pendiente de mí. A Any, mi compañera de vida, por todo tu apoyo para poder terminar este ciclo tan importante y a Elena por tu sonrisa que me regalas todos los días y por darme la dicha de ser tu papá.

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Urban form, land use, and cover change and their impact on carbon emissions in the Metropolitan Area of Monterrey.

Alejandro de Jesús Carpio Núñez

The process of rapid and uncontrolled urbanization related from intense economic growth periods have a strong relation with growing carbon emissions. Previous literature of urban form and CO_2 emissions have focused on developed cities but mainly in Europe, USA, and China. This thesis analyses the urban expansion of the Metropolitan Area of Monterrey (MAM) from 1990 to 2019 in intervals of 5 years using satellite imagery and GIS to determine its relation to carbon emissions. The study considers population data, urban expansion, gross domestic product, motor vehicle inventory, vegetation displacement, and energy usage from residential and commercial sector as key variables to relate CO_2 sink loss and CO_2 emissions per period. Results shows that MAM increased 2.6 times its size from 30,761 hectares in 1990 to 80,962 hectares in 2019. The percentage of urban land use including MAM and peri urban areas of the 12 municipalities in 1990 was 5.09%, and in 2019 increased to 13.99%. It is estimated that a total of 28,393 hectares of vegetation was removed including: scrubs, pasture, forest, and agriculture meaning a loss of CO_2 sink with a potential of absorption of 373,900 T CO_2 a year. In terms of CO_2 emissions, the average MAM CO_2 emission per urban block in 2015 was 258 TCO_2, also the average of TCO_2 per hectare for residential and commercial use is 376 and 347, respectively. This study establish an historical baseline of carbon emissions due to urban land change and rapid urbanization since the North American Free Trade Agreement was signed and also gives the different lines of research that will serve to complement the investigation in order to achieve a metropolitan urban carbon budget for Mexican cities that guide future environmental policy.

Contents

List of Figures

List of Tables

Disclaimer

For the present study, some assumptions and processes were made due to the lack of data, studies, or official information applied specifically for the Metropolitan Area of Monterrey. All the processes are described in the materials and methods section, but this are some of the information gaps identified:

- Urban land use was estimated with the aid of google information such as imagery from Google Earth and Google Maps labels that are displayed of the different business, retail, schools, among others; from November 2019. The process of mapping this data was done manually and at a block scale, the main vocation of each block was identified if the density of the labels occupied more than the 50% of the total block area. (the main goal to obtain an estimation of urban land use was to allocate commercial energy CO_2 emissions and to give and approximation of the evolution of urban land change)

- Emissions factors were obtained from official sources but all of them are from 2014 to 2018, due to the lack of older factors all the periods where estimated with this data.

- Due to the lack of in situ studies of aboveground biomass estimation, absorption factors for the different type of vegetation were obtained from a doctoral thesis which study area is Nuevo León and Tamaulipas but not the Metropolitan Area of Monterrey. This information is used because the natural context doesn´t differ significantly.

Chapter 1

Introduction

In the last 100 years, an extraordinary change happened in the face of earth due to cities have become our primary habitat (Girardert, 2004), the World Bank estimates that approximately 180,000 people are added to the urban population every day, likewise Population Reference Bureau forecast that cities will house 66% of the global population by 2050. On the other hand, growth projections indicates that in the next 30 years, urban space will need to double in developed countries and 326 percent in developing countries, which is equivalent to build a city with the size of London each month for the next 40 years (Habitat, 2013).

Nowadays, in terms of surface, urban areas occupy only 2% to 3% of Earth surface (Lombardi, Laiola, Tricase, & Rana, 2017). Despite of its low percentage of territorial occupation, cities represent a high level of resource consumption consuming approximately 75% of the world´s energy and producing 80% of global greenhouse gas emissions (Chuanglin, Shaojian, & Guangdong, 2015). Also, the process of rapid and uncontrolled urbanization related from intense economic growth periods have a strong relation with growing carbon emissions; therefore, it is essential to understand how urban morphology and land-use changes relate to CO_2 emissions through time.

According to Chuanglin and colleagues, previous literature of urban form and CO_2 emissions have focus on developed cities (mainly Europe and USA) and some Chinese cities. This thesis aim to analyze in a pragmatical way the urban expansion or urban sprawl of the Metropolitan Area of Monterrey (MAM) from 1990 to 2019 using satellite imagery and Geographic Information Systems in order to understand the relationship between cover change, urban morphology and energy consumption as relate to carbon emissions. This research intents to establish a baseline for further studies for metropolitan Mexican cities to have evidence to support political leaders for future environmental public policies to achieve a less harmful urban environment.

1.1 Motivation

The primary motivation of this research is to know the relationship between the lack of urban planning derived from intense economic growth periods and establish a precedent on a metropolitan scale in terms of environmental impact. This personal motivation comes from my professional background as an architect and my interests in sustainable urban development.

1.2 Thesis Statement

Rapid and uncontrolled urbanization processes have a strong relation with growing carbon emissions ; therefore, it is essential to understand how urban expansion and land-use changes relate to CO_2 emissions.

1.3 Purpose

1.3.1 Main Purpose

The purpose of this study is to understand the relationship between land-use and land-cover change and urban expansion with energy consumption as relate to carbon emissions in the Metropolitan Area of Monterrey (MAM).

1.4 Research Goals

The goals of this research are:

1.4.1 Main

Analyze the urban expansion of the Metropolitan Area of Monterrey from 1990 to 2019 using satellite imagery and GIS to determine its relation to carbon emission.

1.4.2 Specific

Analyze MAM in terms of:

- Urban Expansion: Land use change and morphology.
- Carbon Emissions: Carbon emission per type land-use types based upon energy consumption.

Establish an historical baseline of carbon emissions due to urban land change and rapid urbanization in the MAM since the North American Free Trade Agreement was signed.

1.5 Research Questions

These are some questions aimed to be a guideline for the research to accomplish the proposed goals:

- What is the evolution of land use and cover change (LUCC) in the Metropolitan Area of Monterrey from 1990 to 2019?
- Which areas are more affected?
- What is the displacement of natural vegetation in the urban area because of these phenomena?

- What is the relation between LUCC, urban morphology and carbon emissions?

- How does urban density affect carbon emissions in the city?

- How does each type of urban land use and building type impact in carbon emissions?

- What is the actual carbon emission hectare built in the NAM, specifically the commercial and residential sector?

- What are some possible actions or strategies to reduce carbon emissions and aid future urban planning?

1.6 Exclusions

For this research, the traffic patterns and the quantification of carbon emission per type of source are excluded due to its individual and extended need for separate evaluation. Also, there is a lack of Industrial energy consumption open data, and it is essential to address a different evaluation because of the diversity of industry types in the MAM, also gas calculation for commercial use is excluded due to the unclear information of consumption of the sector at MAM scale.

Chapter 2

Literature Review

2.1 Urban Growth and Land Use and Cover Change

Urban areas occupy only 2% to 3% of the Earth´s surface, while more than half of the world´s population (3.9 billion in 2014) live with the cities limits. Also, cities represent a high level of resource consumption (Lombardi, Laiola, Tricase, & Rana, 2017) . In addition, Population Reference Bureau forecasted that the urban population will increase by 66% by the year 2050 (Chou-Tsang, Chih-Hsuan, & Tzu-Ping, 2019).

Cities consume approximately 75% of the world´s energy and produces about 80% of global greenhouse gas emissions (Chuanglin, Shaojian, & Guangdong, 2015). Many strategies for reducing CO_2 emissions mainly focus on factors like fossil fuels, industrial processes, and transportation. Nevertheless, the spatial distribution of land use is another critical influencing factor, as it can define the spatial organization and arrangement of human activities and the related infrastructures (Wang, Han, & de vries, 2019). Therefore, the fact of Land Use and Cover Change (LUCC) and its spatial distribution can be a relevant issue to identify problems from a territorial perspective and guide strategies for environmental policy to achieve sustainable urban development. LUCC causes carbon emissions by displacing terrestrial ecosystems directly, and indirectly affects anthropogenic carbon emissions (Chuyu, et al., 2019). Also, previous research has demonstrated that the spatial distribution of the built environment plays a vital role in the mitigation of carbon emissions. The built environment refers to urban form characteristics such as density, land use diversity, and landscape composition (Wang, Han, & de vries, 2019).

2.2 Carbon Emissions in Urban Areas

Many factors affect CO_2 emissions in the city among them are: industrial production, transportation, local climate and burning fossil fuels (Chuanglin, Shaojian, & Guangdong, 2015). Urban density and spatial organization are crucial elements that influence energy consumption, especially in the transportation industry and building systems (The World Bank, 2010).

The first attempt to assess the level of environmental impact of cities was the application of the Urban Metabolism (UM) concept, elaborated in the 1960s, allowing the analysis of the energy and material flows associated with the production and consumption of human activities (Lombardi, Laiola, Tricase, & Rana, 2017). Following this first attempt, greenhouse gas (GHG) and carbon footprints in cities have received recent attention, because several studies demonstrated that better urban design could reduce carbon emissions more than alternative fuels, vehicles, and electricity generation (C.H., C.-L., C.-Y., & P.-T., 2013). however, studies on urban form related to urban energy use and CO_2 emission at city scale, are limited since most studies employ population density as a measure of urban form. According with Makido (2012) (Makido, Dhakal, & Yamagata, 2012), there are more comprehensive ways to represent urban form, especially its spatial configuration and its relation with energy use and CO_2 emissions.

Other relevant aspect, is the carbon emissions associated with the built environment that represent the dominant fraction of the total carbon footprint of society, mostly because it represents the intersection of the three main emitters: energy, transportation, and buildings. In the US, 40% of total electricity-related GHG emissions come from commercial and residential buildings (Fenner, et al., 2018). Other findings by (Tzu-Ping, et al., 2017) suggest that over-urbanized areas , where population density is higher than 5,000 people/km^2 concentrate CO_2 emissions. Also in this study found that buildings account for a high percentage of CO_2 emissions (54%) and produced 11% more carbon dioxide in summer. In under-urbanized areas, road traffic is the main source of CO_2 emissions (87%).

2.3 Urban Remote Sensing and Urban Analysis with Geographic Information Systems

Scientific contributions from remote sensing over the last fifty years have significantly advanced our understanding of urban areas. The first urban land cover maps were derived from color infrared film on hand-held camera from the Gemini and Apollo missions in 1965. (Zhu, et al., 2019). Since 1972, Landsat satellites have continuously acquired space-based images of the Earth's land surface, providing uninterrupted data that serve as valuable resources to visualize and analyze land use and land cover change (USGS, Landsat Mission, 2019). The imagery provided is not only from Landsat satellites but also from others like SPOT, IKONOS, among others, and are being useful to several applications, including forestry, agriculture, geology, regional planning, and education.

One of the principal contributions of remote sensing to urban knowledge today has been to characterize, measure, and map urban areas in a consistent way. Urban land cover change maps continues to be a dominant component of urban remote sensing research and has been essential to understand the drivers of urban development patterns. (Zhu, et al., 2019), also remote sensing can provide a useful and direct indication of the physical form and morphology of urban land cover in cities, furthermore this information can complement other data sources such as traditional population census and socioeconomic surveys (Elena Besussi, 2010).

Urban environment is difficult to understand due to the spatiotemporal complexity, this is why numerous researchers (Tzu-Ping, et al., 2017) use Geographic Information Systems (GIS) as a complementary tool for processing remote sensing data. With this technology, many studies have used landscape metrics to quantify the spatial characteristics and the change of urban land-use patterns. Landscape metrics are also considered very useful in assisting urban planning (Yimin, Xia, Yong, Yanyan, & Xiaoping, 2011). These indicators provide different metrics such as: patch density, mean shape index, mean patch fractal dimension, edge density, road density, built-up, density, green land, among others (C.H., C.-L., C.-Y., & P.-T., 2013).

2.4 Estimation of Carbon Emission in Urban Areas

It is recognized that urban form (the spatial pattern and structural features of urban land use), is related to urban CO_2 emissions, despite of this fact, only a limited number of studies have empirically evaluated the direct impacts of different urban form patterns and the relation in CO_2 (Chuanglin, Shaojian, & Guangdong, 2015).

In recent years, many methodologies have emerged to estimate the carbon emissions in urban areas. According to (Lombardi, Laiola, Tricase, & Rana, 2017) and (Fenner, et al., 2018) there are two main categories for estimating Urban Carbon Footprint (UCF); the first category is an accounting system related with the spatial and territorial characteristics, this inventory method is framed by the Intergovernmental Panel on Climate Change (IPCC), the second one, is based on economic characteristics and in terms of Life Cycle Based the way to account the carbon accounting system taking into consideration production and consumption, the leading inventory methods are Life Cycle Assessment (LCA) which has a bottom up approach, the Economic Input Output Assessment (EIOA) with a top down approach and Hybrid Methods.

To calculate a city´s carbon footprint it is necessary to carry out a GHG emissions inventory. This task can be complicated because the disparities of available data at the city-scale; the connection among population and economic activities, that complicate the GHG emissions allocation. Lombardi and colleagues (Lombardi, Laiola, Tricase, & Rana, 2017) suggest that it is required to complete and standardize, in the short term, the accounting and reporting frameworks to compare different UCFs to adopt shared climate actions.

According to (Chuanglin, Shaojian, & Guangdong, 2015) it is remarkable that there is a limited number of studies that have engaged in the task of quantitatively estimating supratemporal changes in urban form, or have quantified the impact of urban growth and sprawl on CO_2 emissions.

Yimin, et al (2011) found that: Urban size and fragmentation of land use patterns are positively correlated with energy consumption, , while the dominance of the largest urban patch is negatively correlated with energy consumption. Zhang and colleagues (2018) recognized that in the future, urban carbon studies could be extended to a broader scale such as metropolitan area, to analyze the relation of the process among cities. Also, they propose the use of spatial analysis tools planning and designing low-carbon cities with a scientific basis for urban sustainable development, because traditional urban carbon metabolism accounting has been focused more on carbon emissions caused by social and economic activities, while investigations of carbon emissions based LUCC focus more on carbon flows caused by change in the carbon stock of natural components. Therefore, forming a combined anthropogenic-natural process to complete the urban carbon metabolism is necessary.

2.5 Similar Studies

2.5.1 Quantifying the spatial patterns of urban carbon metabolism: A case study of Hangzhou, China.

Chuyu and colleagues (2018) analyzed in their study of Hangzhou City, the changes in carbon emission and sequestration in order to understand spatial patterns of cities carbon transition in urban metabolism processes and explore ways to achieve low carbon-emitting cities based on land use types using data with five years intervals from 1995 to 2015. Also, they quantified harmful and beneficial carbon transition with empirical coefficients and GIS techniques (Figure 1). Finally, a panel data regression analysis was employed to investigate how urban forms and road structures influence urban carbon emission at the district level. Panel data analysis demonstrated that urban expansion modes with high connectedness and a better coupling relationship between urban form and road structure could help to emission reduction. (Chuyu, et al., 2018)

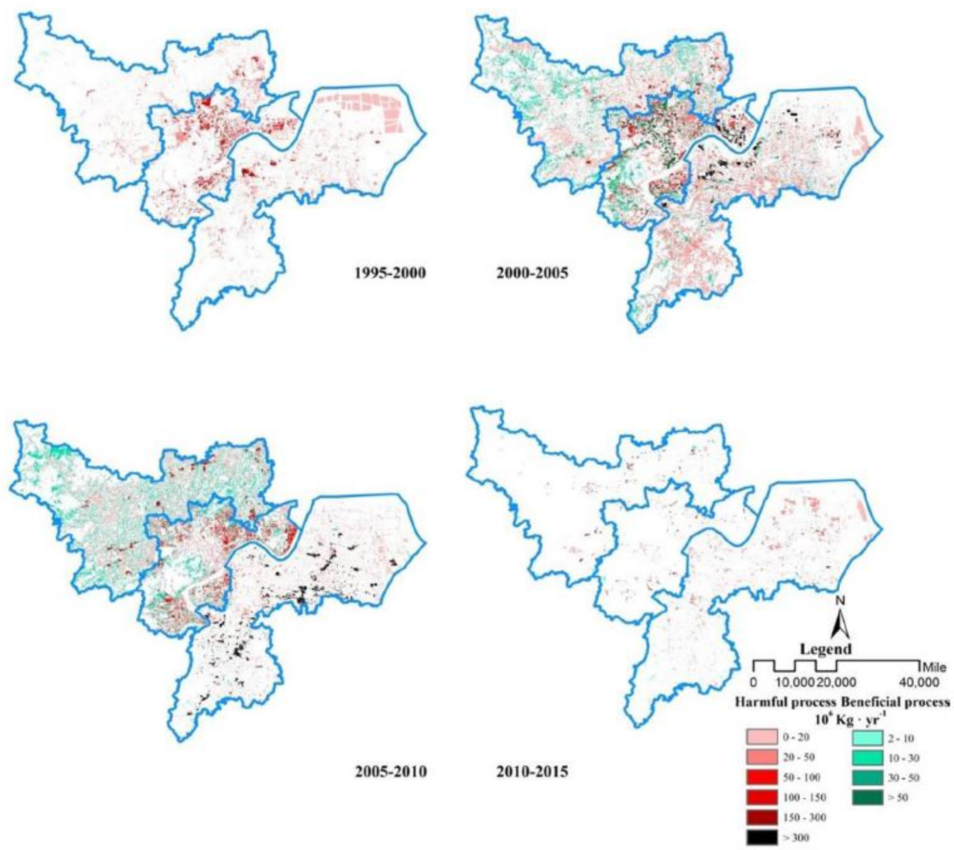

Figure 1. Spatial patterns of beneficial and harmful carbon processes from 1995 to 2015 in Hangzhou. Source: (Chuyu, et al.,2018)

2.5.2 Carbon dioxide emissions evaluations and mitigations in the building and traffic sectors in Taichung metropolitan area, Taiwan.

Taichung metropolitan was the research target and assessed carbon emissions concerning buildings, traffic, and carbon sinks. The overall carbon budget of the metropolitan area was mapped following a statistical analysis of the numerical data and urban space information. The method for calculating the carbon footprint of a building was given in Life Cycle Assessment Model that includes materials, construction, use, maintenance, renewal, and demolition. Traffic carbon was calculated based on the CO_2 emissions attributable to the fuel consumption, and the absorption capability of a carbon sink was calculated based on the total amount of CO_2 sequestration per unit area. The results indicated that adjusting the floor area ratio of buildings is the optimal carbon reduction approach. A high-resolution grid was used to present the multi-scale carbon budget results (Figure 2). They establish three simulation scenarios of various implementation stages. (Chou-Tsang, Chih-Hsuan, & Tzu-Ping, 2019)

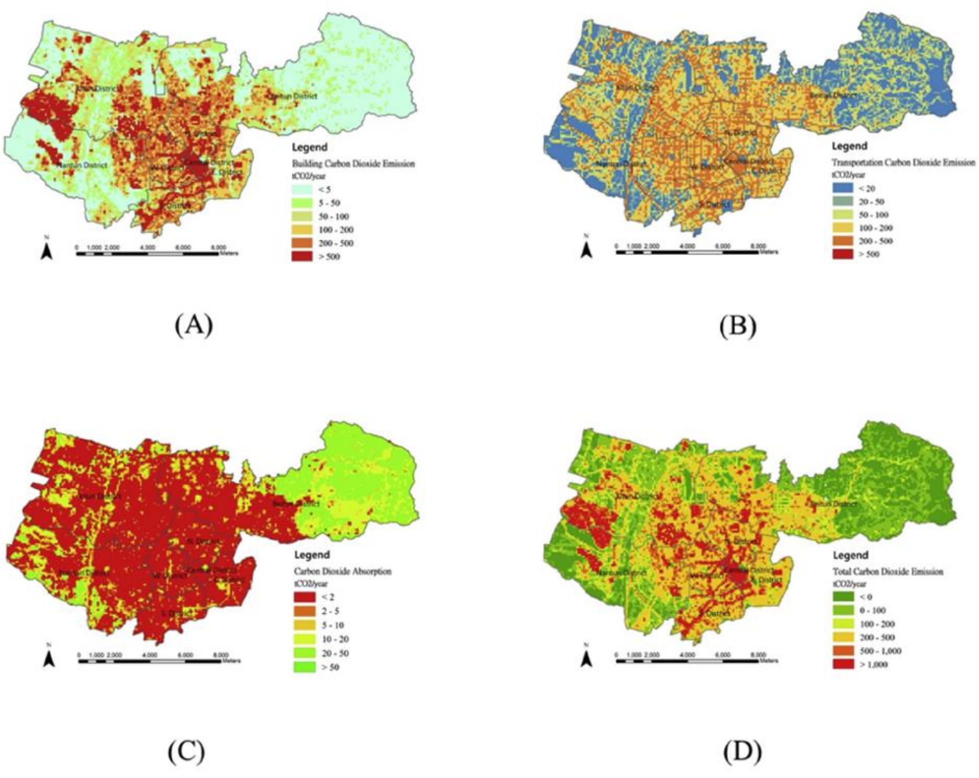

Figure 2.Carbon budgets for the Taichung metropolitan area: (A) building carbon emissions, (B) traffic carbon emissions, (C) amount of carbon absorbed by parks, green spaces, and other carbon sinks, and (D) the overall carbon budget of the metropolitan area. Source: *(Chou-Tsang, Chih-Hsuan, & Tzu-Ping, 2019)*

2.5.3 Multiscale analysis and reduction measures of urban carbon dioxide budget based on building energy consumption.

In the study urban spatial and statistical data for metropolitan Tainan area are used to explore the CO_2 system of the city and estimate the amount of CO_2 emissions from road traffic, the use of electricity and gas in buildings and the amount of CO_2 absorbed by green spaces and water bodies (Figure 3). Also, it is quantified the potential reduction of carbon dioxide using rooftops with solar panels. A carbon budget of 200x200 m grids are developed for the city with GIS. GIS data on buildings and land use and traffic flow data from the city are used to yield urban spatial data. An estimation of the carbon budget was done with variables like CO_2 emission of buildings (18 types of uses). Emissions from road traffic and the amount of CO_2 absorbed by vegetation, soil, and water bodies. Then a comparison by adopting solar energy is made to estimate de CO_2 emission mitigation. Findings suggest that CO_2 emissions are concentrated in over-urbanized areas, where population density is higher than 5000 people/km2. Buildings account for most carbon dioxide emissions (54%) and produced 11% more carbon dioxide in summer. Road traffic is the primary source of CO_2 emissions for under-urbanized areas (87%). (Tzu-Ping, et al., 2017).

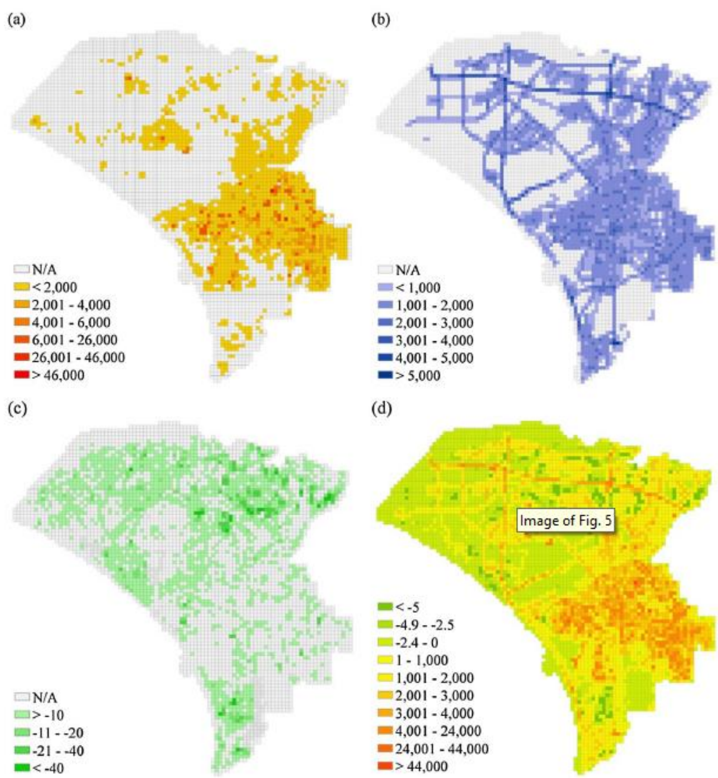

Figure 3.Annual carbon budget map for Tainan: (a) amount of CO2emissions from buildings, (b) amount of CO2 emissions from traffic, (c) amount of CO2 absorbed by greenspaces, and (d) overall carbon budget. (in tCO2yr−1/grid). *Source:* (Tzu-Ping, et al., 2017).

Chapter 3

Materials and Methods

3.1 Study Area

3.1.1 Geographical and economical background

The study area (Metropolitan Area of Monterrey), is located at the state of Nuevo León situated at the northeast part of the country with its territorial limits at north with the Bravo River and the U.S., at west with Coahuila and Zacatecas, at south with San Luís Potosí and east with Tamaulipas, Figure 4 . The main vegetation cover found at MAM are forest, scrubs, and grasslands. Also, the natural barriers that distinguish the area are the Sierra Madre Oriental, Cerro de la Silla, Cerro de las Mitras and Cerro del Topo Chico. (INEGI, Anuario estadístico y geográfico de Nuevo León , 2017)

The geographical area of MAM is composed by several municipalities: Apodaca, Cadereyta Jiménez, García, San Pedro Garza García, General Escobedo, Guadalupe, Juárez, Monterrey, Salinas Victoria, San Nicolás de los Garza, Santa Catarina and Santiago. It covers an urban area of 92,700 hectares or 927 square kilometers. It has a population of almost 4.8 million people according to the last Census from 2015 (INEGI, 2015 and Secretaría de Economía y Trabajo, 2019).

The very steep mountains around the MAM have a significant impact on the distribution of the urbanized areas, the mixing of emissions into the atmosphere, and the direction of the main roads and highways that communicates the MAM with the important surrounding cities like Nuevo Laredo, Saltillo, Matamoros, Ciudad Victoria and Tampico (Garza, 1999).

MAM has a very important industrial history contributing significantly to the national economy, the process of globalization and the changes in the economic models from the import substitution model (1930) to the neoliberalism (1983) have contribute to the level of industrial production and the expansion of urban areas in the city (Sousa, 2008).

The State policies represented in the import substitution model where quickly adopted by the businessmen from Monterrey, this model facilitated economic growth of the city, also another momentous historical event during this period was the production alliance between the businessmen and the president José López Portillo (1976-1982). By 1983, with the adoption of the neoliberalism the situation changes radically, obligating the Monterrey industrial sector to redefine its policies. The different commercial sectors in the MAM with the foreign investment policies derived from General Agreement on Tariffs and Trade (GATT) and with the signature of the North American Free Trade Agreement (NAFTA) leading in the industrial sector and having a geographical advantage among other States from México because of the proximity to the United States. This economic boom boosted the employment generation that attracted immigrants from different regions of the country (Sousa, 2008).

3.1.2 Urbanization Process of MAM from 1950 to 1990

As a reaction to the different development policies derived by the federal government in the XX century and more pronounce with the signature of NAFTA, the MAM has experienced a population and urban growth phenomenon.

The first phase was the beginning of the industrial base of Monterrey municipality in the early years of the past century, represented by some key industries: steel, glass, and beer, among others. In the decade of 1940-1950 Monterrey started to experience a metropolitan transformation adding to adjacent municipalities: Guadalupe and San Nicolás de los Garza (Sousa, 2008). Between 1950 and 1970 the growth dynamic of MAM accelerated, tripling the population and enlarging the urban area with more than 6% annual rate. In 1990 NAM was considered the 87th most populated city in the world and conform by the following municipalities : Apodaca, San Pedro Garza García, General Escobedo, Guadalupe, Juárez, Monterrey, San Nicolás de los Garza and Santa Catarina.

(Garza, 1999). Table 1 describes urban growth process between 1950 and 1990.

Table 1.Urbanization Process of MAM from 1950 to 1990. Source:(Sousa,2008).

Period	Population	Density (Pop/Ha)	Surface (Ha)
1950	375,000	93	4,032
1970	1,300,000	98	13,193
1990	2,666,809	87	30,761

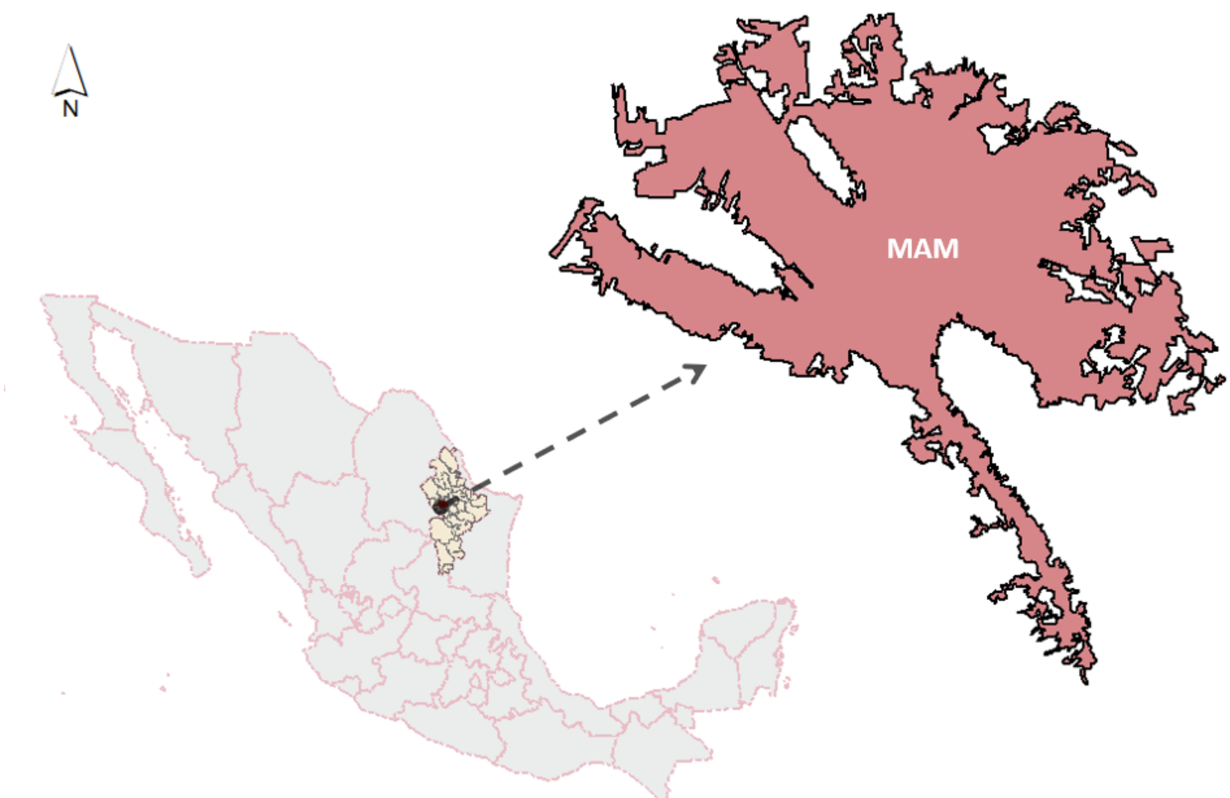

Figure 4. Study Area Map - Metropolitan Area of Monterrey Location

3.2 Methodology Process

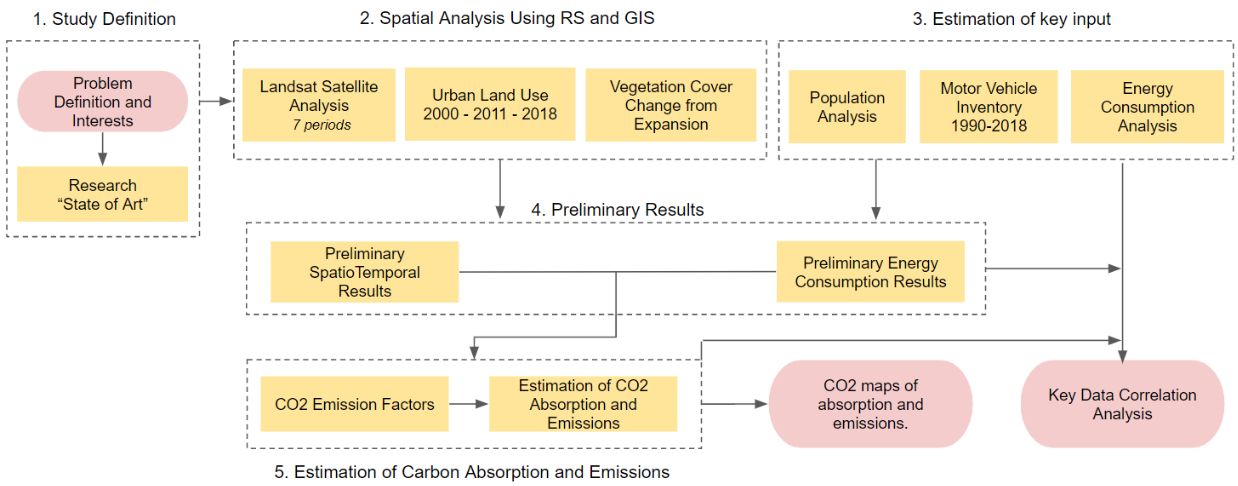

Figure 5.Methodology Process Diagram

3.2.1 General Description of the Process (*Figure 5*)

1. An exhaustive research of the "State of the Art" to define the problem and interests of the study was done by reviewing more than 15 articles from indexed journals from recent years.
2. A spatial analysis was carried out using Landsat imagery, urban cartography from INEGI, and Google Maps and Google Earth information. The information was processed mainly with ARCGIS, but multispectral images were produced with ERDAS IMAGINE^{TM} software.
3. Different variables were analyzed to estimate energy consumption and growth patterns.
4. Thematic maps were obtained to measure the evolution of MAM in terms of urban growth, urban land use, and vegetation cover change. Also, energy consumption and growth estimations were analyzed to provide further information for the estimation of Carbon Budget, based on established coefficients.
5. A definition of CO_2 sink and CO_2 Emissions was done with energy consumption and land cover change to obtain spatiotemporal CO_2 Maps for different periods.

3.3 Landsat Satellite Analysis

3.3.1 Generalities

MAM urban growth was analyzed with several Landsat Thematic Mapper images in intervals of 5 years from 1990 to 2019 (last period 4 years). Each period is supported with two images in case of clouds or other elements that can lead to an incorrect interpretation. All the satellite images were downloaded from the USGS Earth Explorer website (USGS, Earth Explorer - Home, 2019). There were three Landsat satellites imagery used, Landsat 5, Landsat 7 and Landsat 8 (Table 2).

Table 2. Landsat images used in this study.

Satellite	Periods	Date of Images
Landsat 5	1990 / 1995 / 2000	• 1990 = March 16, 1990 and June 23, 1991 • 1995 = October 08, 1995 and November 25, 1995 • 2000 = July 01, 2000 and August 10, 2000
Landsat 7	2005 / 2010	• 2005 = May 09, 2005 and March 20, 2006 • 2010 = January 10, 2010 and June 03, 2010
Landsat 8	2015 / 2019	• 2015 = July 27, 2015 and August 12, 2015 • 2019 = July 06. 2019 and August 07, 2019

3.3.2 Imagery Processing and Photo Interpretation

The main goal of this step of the process was to acquire a consistent set of layers depicting the limits of the urban expansion for the period 1990 to 2019. The imagery obtained from the USGS server was processed with ERDAS IMAGINA^{TM}. The various bands in each image were integrated into a single data set with the "Layer Stack" tool. A total of 14 multispectral images were generated as shown in Table 2. The multispectral images were photo interpreted in ArcGIS by combining the bands in the Red, Green, and Blue channels. The band combination varied depending on the sensor used for each date, due to their specific characteristics and band composition (Table 3 and Table 4).

Table 3. Landsat 5 and Landsat 7 band combination.

Channel	**Red**	**Green**	**Blue**
Band combination #1	4	3	2
Band combination #2	4	5	3

Table 4. Landsat 8 band combination.

Channel	**Red**	**Green**	**Blue**
Band combination #1	5	4	3
Band combination #2	5	6	4

The criteria of the delineating of the urban area was based upon the ideas proposed by Galster et. Al. (2001), specifically continuity and proximity. Not only the main urban sprawl was mapped, but also the peri-urban areas were identified to monitor the evolution through time because some of them merged into the main MAM area (Figure 6).

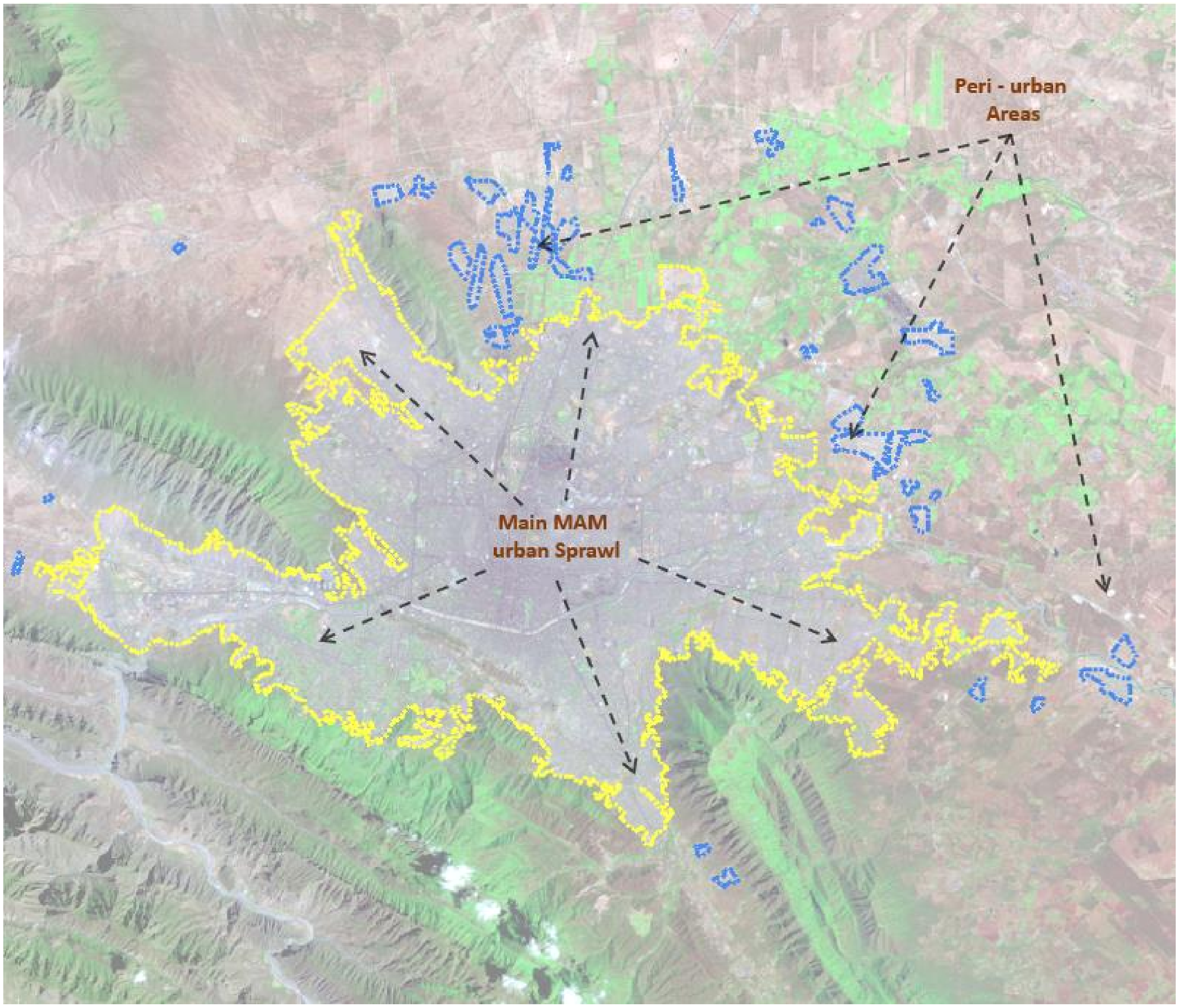

Figure 6. Multispectral image with territory delimitation example (period 1990).

As shown in Figure 6, the main urban sprawl appears in yellow and the most relevant peri-urban areas are shown in blue color. As expected, In the following periods some of the peri-urban merge with the main urban polygon, therefore forming a bigger urban area (yellow area). This delimitation process was done in the same way in all the periods to determine the urban growth; also, the polygons are used to determine the vegetation displacement in each period with the aid of the geostatistical framework from INEGI.

3.4 Urban Land Use analysis

Using the official 2018 Geostatistical Framework from INEGI and with the aid of Google Maps and Google Earth historical imagery (from 2005 to 2018), the different urban land use were identified at block scale. The labels that displays Google Maps(data from November 2019) from commercial establishments, schools, among others; were used to know the main vocation of each urban block to obtain and approximation of the metropolitan urban land use, the process was done manually and the criteria for selecting a specific urban land use was mainly about the density or percentage of area of labels of each type at each block in order to map the general its main vocation, if the labels that where displayed occupied more than 50% the vocation of commercial use was applied. The urban land use was divided mainly in eight categories described in Table 5. Also, density was mapped parametrically in order to have an evolution of vertical behavior of the territory, the process was dividing the vertical area using 3D imagery from Google Earth and counting the floors of the different buildings and divided into the total block area to obtain a parametric block density. From previous periods from 2018, only undeveloped land was mapped because Google displays only the most recent labels.

Table 5. Land use types analyzed.

Land Use	Description
Residential	Residential Areas
Commercial	Retail, malls, pharmacies, among others.
Mixed Use	Areas with commercial and residential use
Industrial	Industrial areas
Services	Schools, churches, universities, government offices, among others.
Parks	Parks and plazas
Natural Parks	Natural areas like urban basins and some areas near the mountains.
Undeveloped Land	Brownfields, and areas with very low development (rural houses / “quintas”)

3.5 Vegetation Cover Change and Displacement from Urban Expansion

Vegetation cover change and displacement was based upon INEGIs cartography at 1:250,000 scale. ((INEGI, Use of soil and vegetation, 2019). These data sets are available for the periods 1992, 1997, 2003, 2010,2013 and 2016. Each period was geo-processed using ARCGIS software and using the polygons of MAM and Peri-urban areas mapped with Landsat imagery and clipping the area of each period to see the loss of de vegetation. The result of the process is having vegetation displacement maps from 1990-1995, 1995-2000, 2000-2005,2005-2010, 2010-2015, and 2015-2019. Figure 7 shows an example of the process for period 1990-19905.

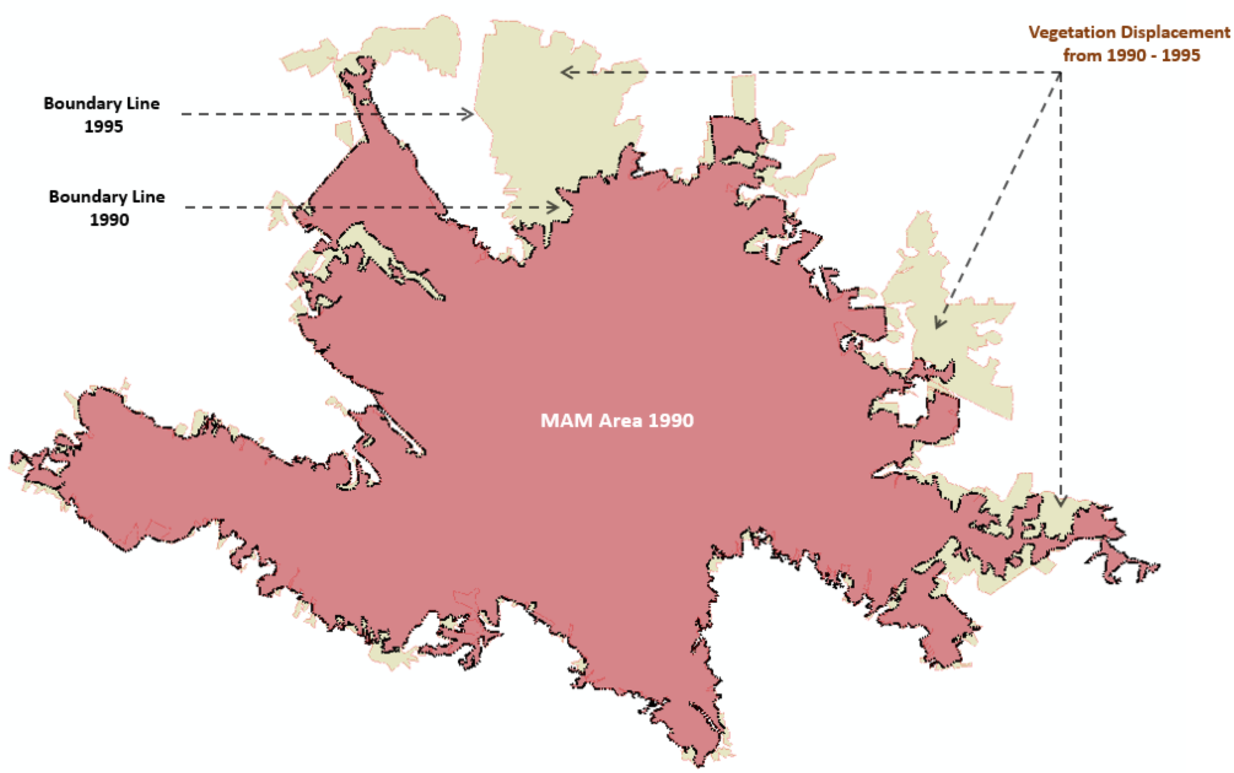

Figure 7. Vegetation Displacement from 1990-1995 example image.

3.6 MAM Population Analysis

Population was analyzed per Municipality that conforms MAM from 1990 to 2015 (12 Municipalities). The main data source come from INEGI and from intercensal surveys (INEGI, 2015 and Secretaría de Economía y Trabajo, 2019), in order to have the specific information from the different periods 1990, 1995, 2000, 2005, 2010, 2015.

3.7 Motor Vehicle Inventory Evolution

For the present study a motor vehicle inventory was done per municipality of MAM from 1990 to 2018 using information on registered motor vehicles in circulation (VMRC) acquired by Motor Vehicle Bureau from INEGI (INEGI, Registros Administrativos - Estadísticas, 2019).The inventory provides four main categories: Passenger car, buses, freight transport and motorbikes. This inventory tracks the evolution of the increase of motor vehicles in the MAM. This evidence will serve to track people transportation behavior in the metropolitan area for each period.

3.8 Energy Consumption Data

To estimate carbon emissions based on energy consumption, data was collected from different official sources such as the Federal open data web page and was complemented with the research of Morales et. Al (Morales Ramírez, Luyando Cuevas, & Flores Curiel, 2012) that describes consumption behavior of the Metropolitan Area of Monterrey. Also, for gas consumption, the data was obtained from prospective reports and internet databases.

3.8.1 Electricity consumption data

Electricity consumption was obtained from the official website of open data from the Federal Government and the Comisión Federal de Electricidad (CFE, 2019). Data was analyzed from 2010 to 2017 per Municipality and per type of fare. The different fares were divided into five main categories according to the type of use. The type of use and the fare code is described in Table 6. Commercial fare from CFE, represents electrical consumption from the following urban land uses: commercial, mixed use, and services (Table 5).

Table 6. Electricity Fare Code per Type of Use according to CFE.

Type of Use	**Fare Code**
Residential	1, 1A, 1B, 1C, 1D, 1E, 1F, DAC, DB1, DB2
Commercial	3, OM, 2, PDBT, GDBT, HM, HMC, GDMTH, GMTO
Public Services	APBT, 5, 5A, APMT, 6
Industrial	HS, HSL, DIST, HT, HTL, DIT
Agriculture	RABT, RAMT, 9, 9CU, 9N, 9M

For previous years the estimation of electrical energy was obtained using per capita consumption from 2010 and 2015 according to the residential fare and for the commercial consumption, the area from commercial, services and mixed use described in Table 5 were added and divided by the known consumption to obtain a factor for older periods.

3.8.2 Natural gas and LPG consumption data for residential use

Index Mundi database contains detailed country statistics, charts and maps compiled from multiple sources and from different sectors such as energy usage; per capita natural gas consumption according to the database is equivalent to 648 m^3 / year (Mundi, 2019)

According to the national GAS L.P. Prospective Report (2017-2031) from the National Energy Department (SENER, 2017) the residential consumption per capita of LPG gas was 74 kg / year meaning the 57.7% of the national demand. For this research, this data will be used as a parametric number to estimate the MAM LPG Gas consumption.

3.9 CO_2 Emission and Absorption Factors

3.9.1 CO_2 Emission Factors

The Emission Factor of the National Electric System reported by CFE is used to calculate the CO_2 emissions derived from electrical consumption for residential and commercial use. For practical purposes, the average from six years is used (Table 7).

Table 7. Emission Factors reported by CFE.

T CO_2 e / MWh	**Year**
0.527	2018
0.582	2017
0.458	2016
0.458	2015
0.454	2014
0.4958	**Average**

Table 8 and Table 9 show the factors considered for emissions for LPG Gas and Natural Gas for residential energy usage according to the National Institute of Ecology and Climate Change (INECC).

Table 8.Emission factor for MAM for LPG Gas.

kg CO_2 / kg LPG	Source	Year
3.01	INECC	2014

Table 9. Emission factor for MAM Natural Gas.

kg CO_2 / m^3 GN	Source	Year
1.89	INECC	2014

3.9.2 Absorption Factors

Table 10 shows four absorption factors that were obtained from the doctoral thesis “Dynamics of carbon capture derived from anthropogenic impacts on ecosystems of northeast México” by (Yerena, 2013). The main objective of the thesis was to estimate the carbon content in aboveground biomass in different land use systems in Nuevo León and Tamaulipas. This information is used because of the contextual relation with the Metropolitan Area of Monterrey.

Table 10. Absorption factors used in the study according to Yerena,2013.

Vegetation Cover	Mg CO_2 Ha Year
Scrub	14.25
Pasture	8.03
Forest	82.91
Agriculture	2.98

3.10 Equations Used for Estimating Carbon Sink and Emissions

3.10.1 Estimating Carbon Sinks

To estimate the carbon sink the following equation is used according to (Tzu-Ping, et al., 2017):

$$\boldsymbol{CO2\ sink} = \sum_{i=1}^{n} CS * \ Ai$$

- Where CSi (-kg CO_2 m^{-2}) is the CO_2 absorption coefficient of each type of vegetation cover according to previous research and A_i is the area of each land type determined by vegetation cover maps and land use maps using GIS.

3.10.2 Estimating CO_2 derived from Energy Use

The calculate the CO_2 derived from energy usage per sector the following equations are used:

$$\boldsymbol{CO2\ gas} = (Gas\ Energy\ residential) * \ COi$$

$$\boldsymbol{CO2\ elec} = (Electric\ Energy\ residential + Electric\ Energy\ commercial) * \ COi$$

- Where CO_2 gas or electric is equal to the sum of gas or electric energy and COi is the emission factor of each type of energy.

3.10.2.1 Residential Energy Usage

To get the energy usage from residential sector the following equations are used:

$$\boldsymbol{Electric\ Energy\ Residential} = \sum_{i=1}^{n} Pb * \ per\ capita\ electric$$

- Where electric energy residential is the summation of Pb equals people living in the block according to the census times the per capita energy electric energy usage.

$$\boldsymbol{L.P. Gas\ Energy\ residential} = \sum_{i=1}^{n} Pb * \ per\ capita\ L.P.$$

- Where L.P. gas energy residential is the summation of Pb equals people living in the block according to the census times the per capita energy L.P. gas usage.

$$\boldsymbol{Natural\ \ Gas\ Energy\ residential} = \sum_{i=1}^{n} Pb * \ per\ capita\ natural\ gas$$

- Where natural gas energy residential is the summation of Pb equal people living in the block according to the census times the per capita energy natural gas usage.

3.10.2.2 Commercial Energy Usage

$$\boldsymbol{Electric\ Enery\ commercial}\ = CAE\ * \frac{2015\ Commercial\ Electric\ Energy}{2015\ Commercial\ area}$$

- Where CAE is the commercial area is the area of the period to estimate multiplied by the consumption per hectare of a known period, in this case 2015.

Chapter 4

Results

4.1 Urban Surface Evolution of MAM

Table 11 shows the municipalities that conforms MAM and their total surface. Table 12 describes the evolution of MAM area and peri urban areas and the percentage of the urban surface respect to the total area of the municipalities.

Table 11. MAM municipalities total surface.

Municipality	**Surface** (Ha)
Apodaca	22,261
Cadereyta Jiménez	112,981
García	102,239
San Pedro Garza García	7,011
General Escobedo	14,797
Guadalupe	11,661
Juárez	24,493
Monterrey	32,131
Salinas Victoria	165,269
San Nicolás de los Garza	5,957
Santa Catarina	90,698
Santiago	73,195
Total	662,693

Table 12. Urban surface evolution of MAM and peri urban areas from 1990 to 2019.

	1990	1995	2000	2005	2010	2015	2019
MAM (Ha)	30,761	36,729	39,744	52,932	58,973	75,424	80,962
MAM (%)	*4.64*	*5.54*	*6*	*7.99*	*8.9*	*11.38*	*12.22*
Peri-Urban (Ha)	2,994	3,466	4,761	4,589	9,158	8,431	11,736
Peri-Urban (%)	*0.45*	*0.52*	*0.72*	*0.69*	*1.38*	*1.27*	*1.77*
Total (Ha)	33,755	40,195	44,505	57,521	68,131	83,855	92,698
Total (%)	*5.09*	*6.06*	*6.72*	*8.68*	*10.28*	*12.65*	*13.99*

Figure 8 shows the spatiotemporal evolution of MAM urban growth from 1990 to 2019, in this figure can be appreciate the changes of each municipality and the peri urban area in 2019. Figure 9 shows a spatiotemporal comparison between the initial period (year 1990) and the last period (2019) in terms of MAM and Peri Urban Growth.

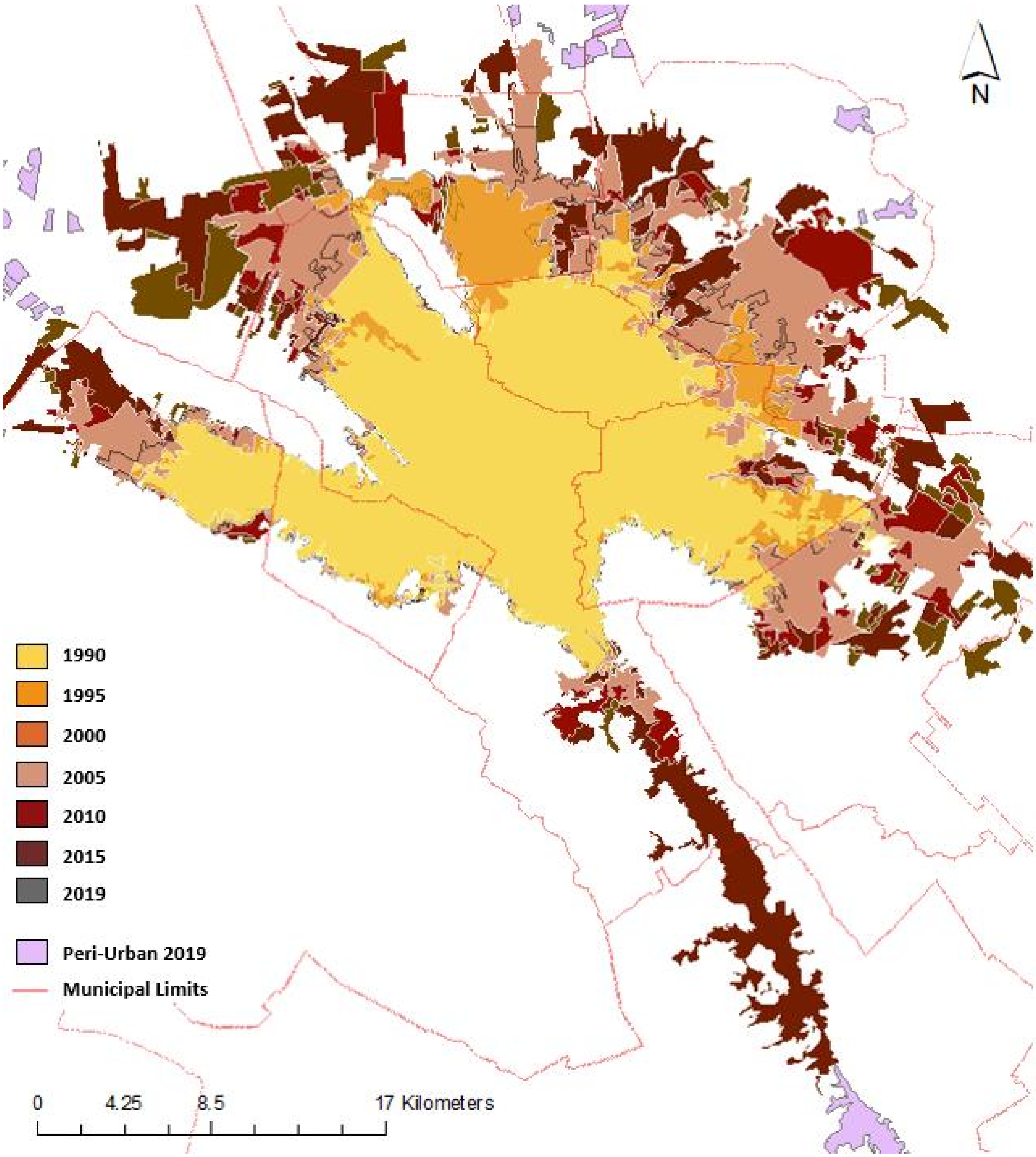

Figure 8.MAM urban growth from 1990 to 2019.

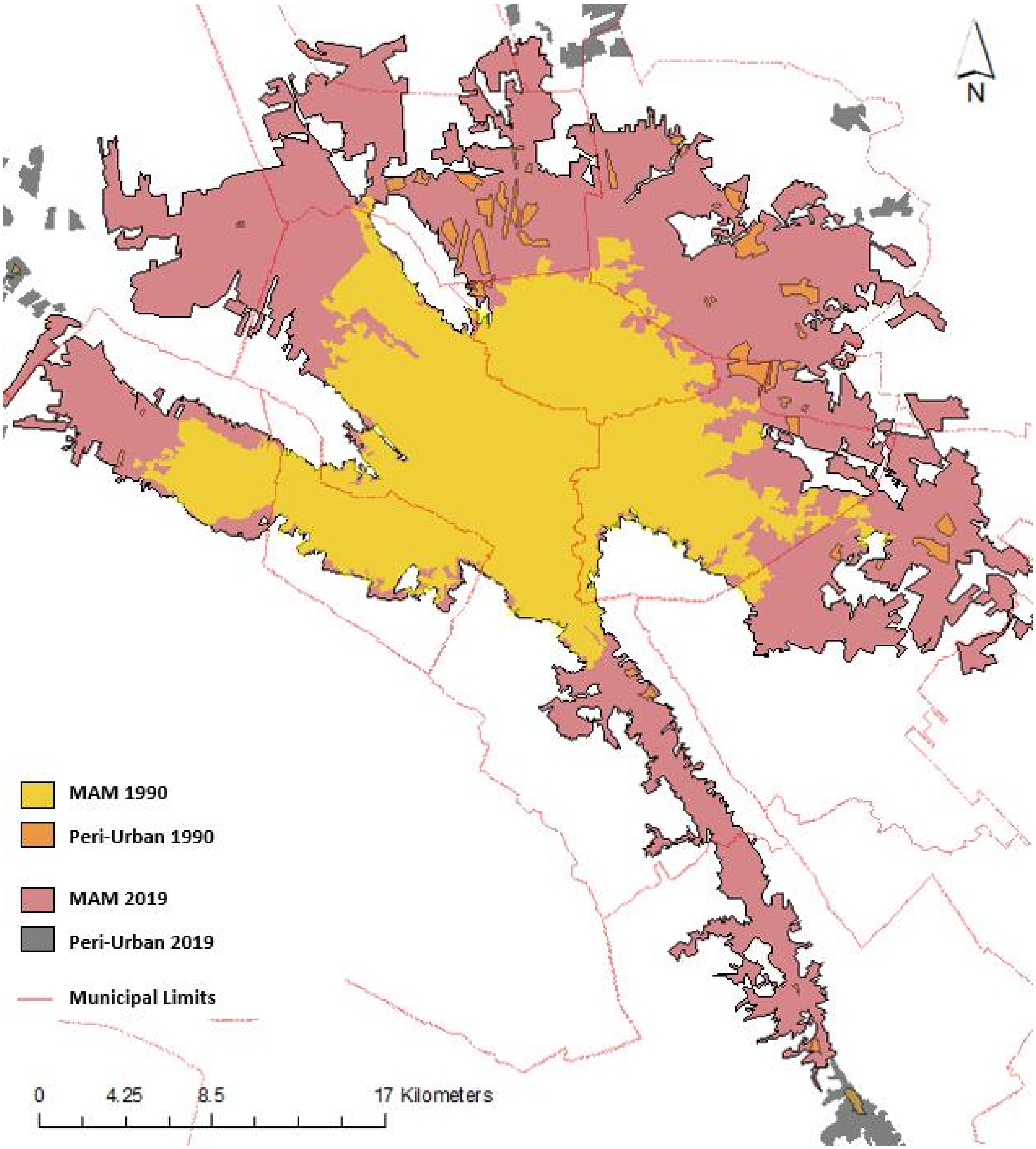

Figure 9.MAM and peri urban area comparison periods 1990 and 2019

4.2 Urban Land Use Evolution

To estimate urban land use the geostatistical framework from 2018 from INEGI and Google Maps labels at a block scale, in order to identify the main use of the urban block. Figure 10 shows per period, the hectares and the proportion of each urban land use, as described in Table 5 with the specific description per urban land use. Figures 11 to 17 describe the spatiotemporal distribution of each urban land use per period.

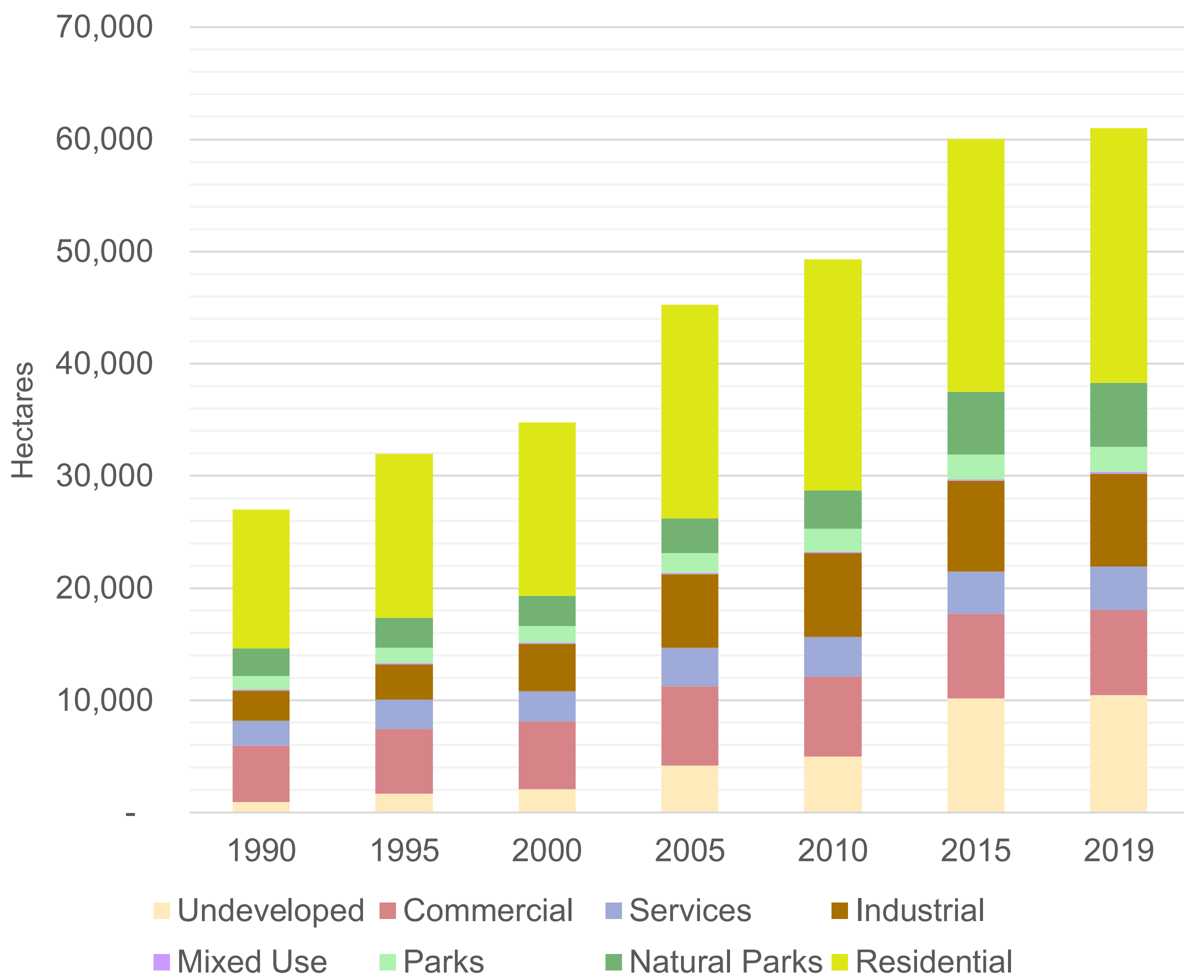

Figure 10.MAM land use evolution from 1990 to 2019.

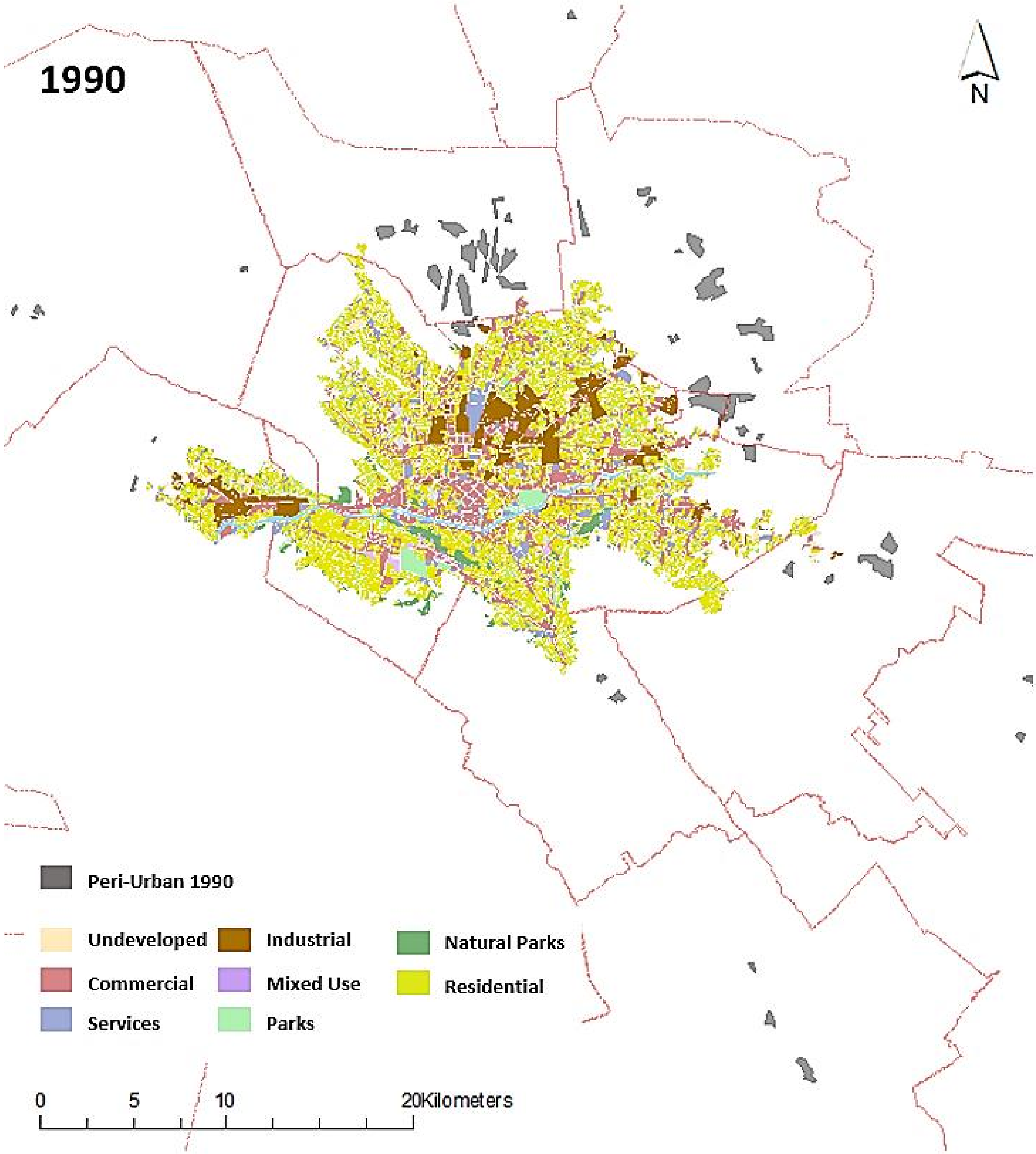

Figure 11. MAM urban land use map 1990.

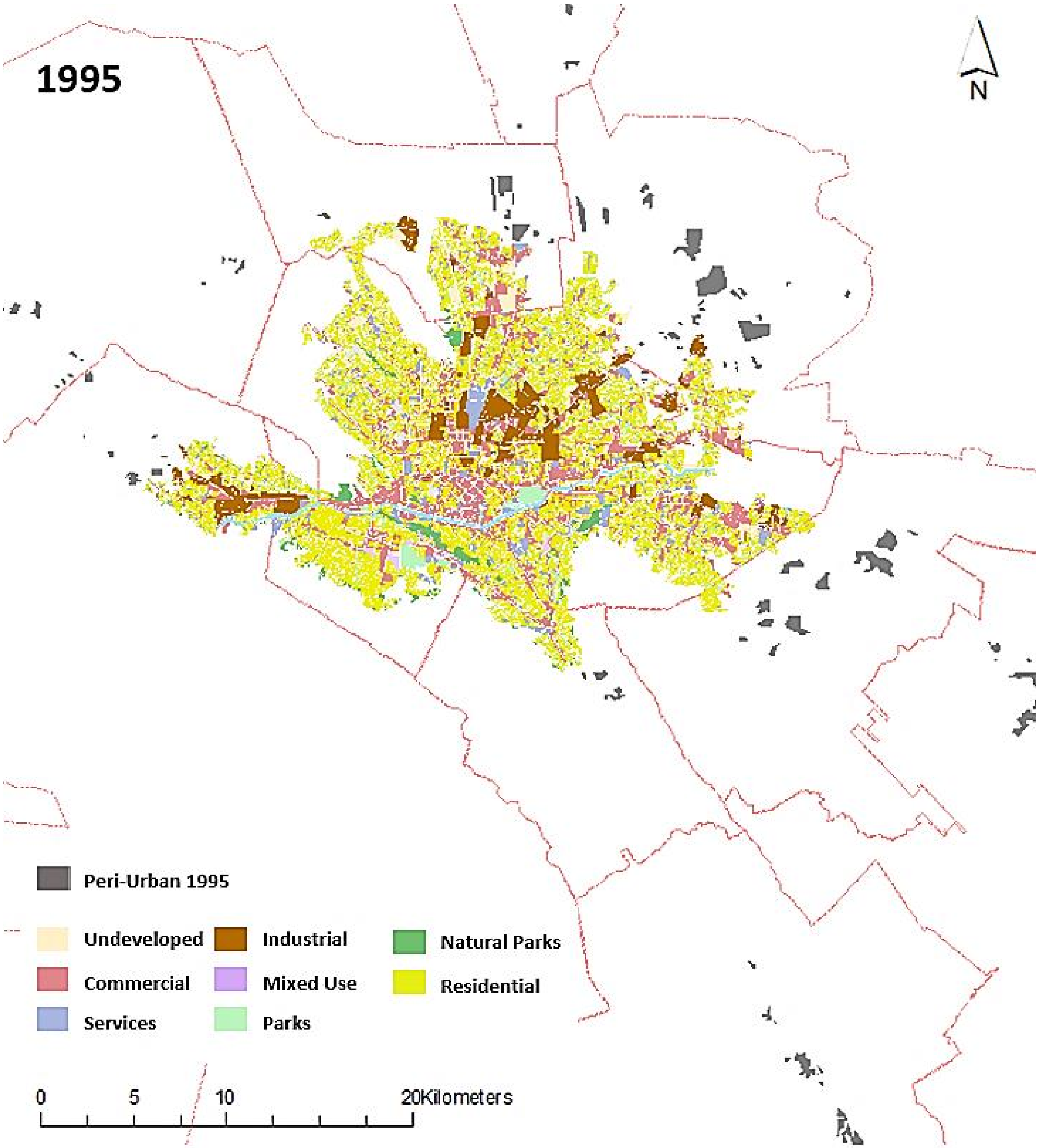

Figure 12. MAM urban land use map 1995.

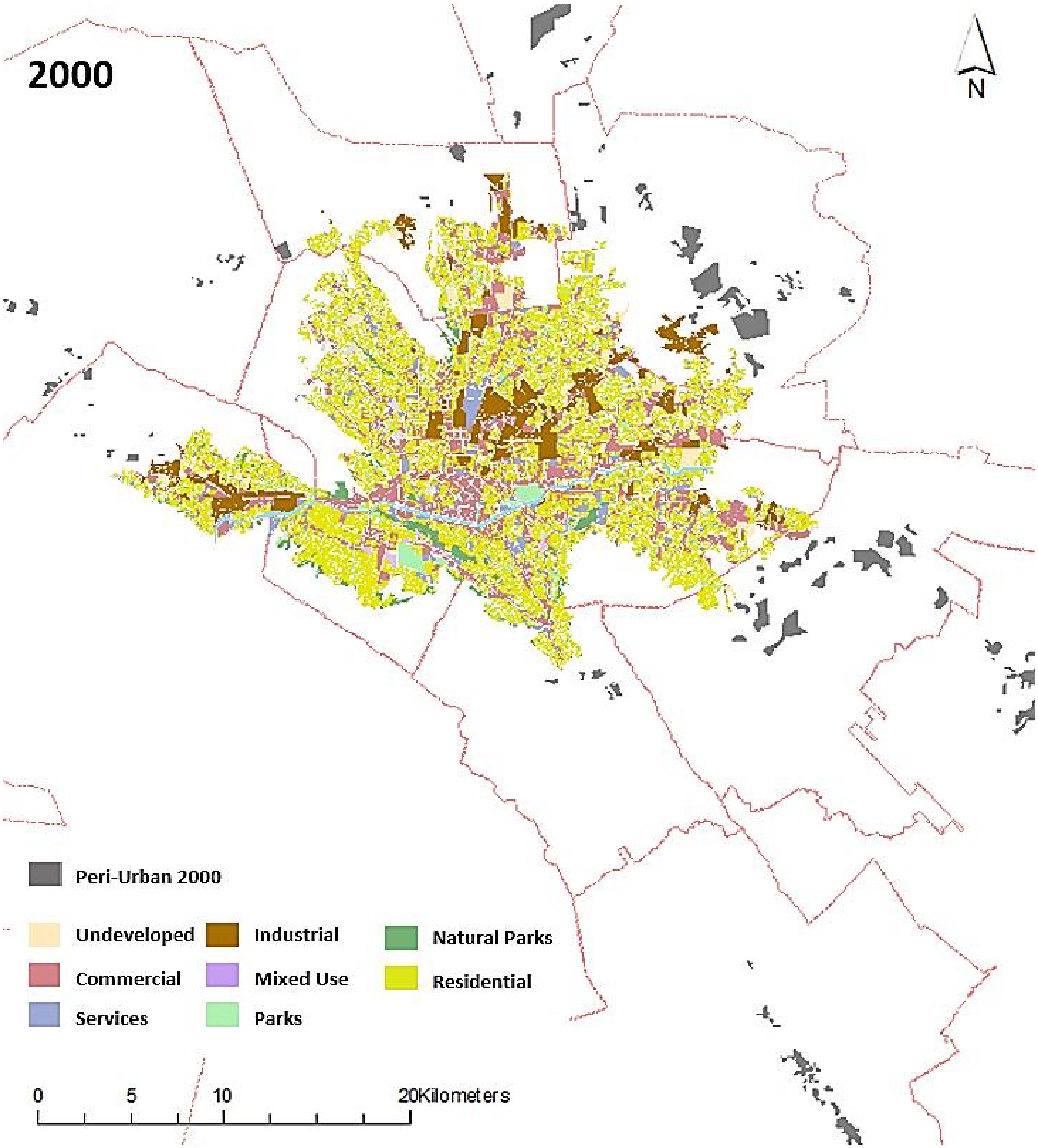

Figure 13. MAM urban land use map 2000.

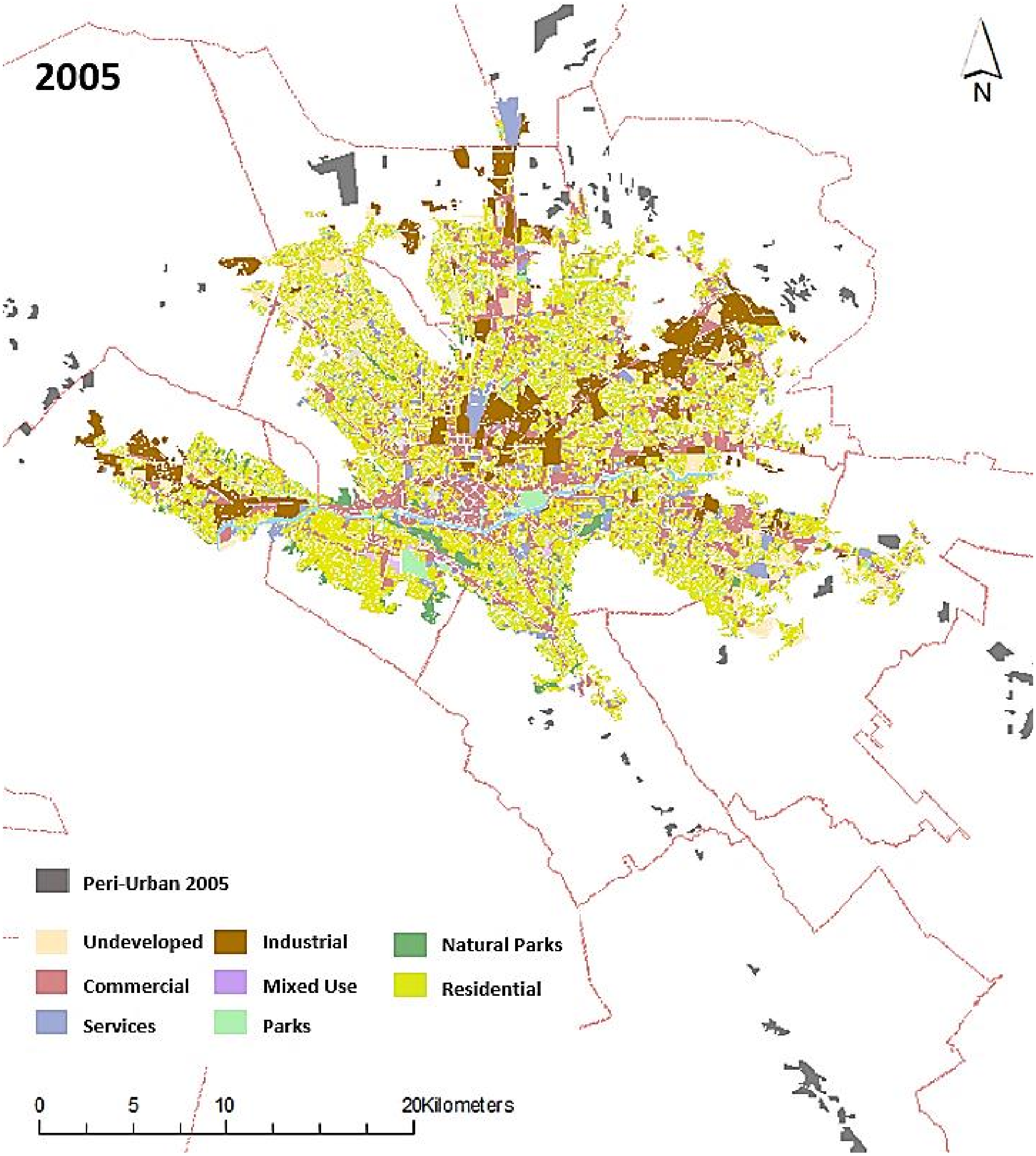

Figure 14. MAM urban land use map 2005.

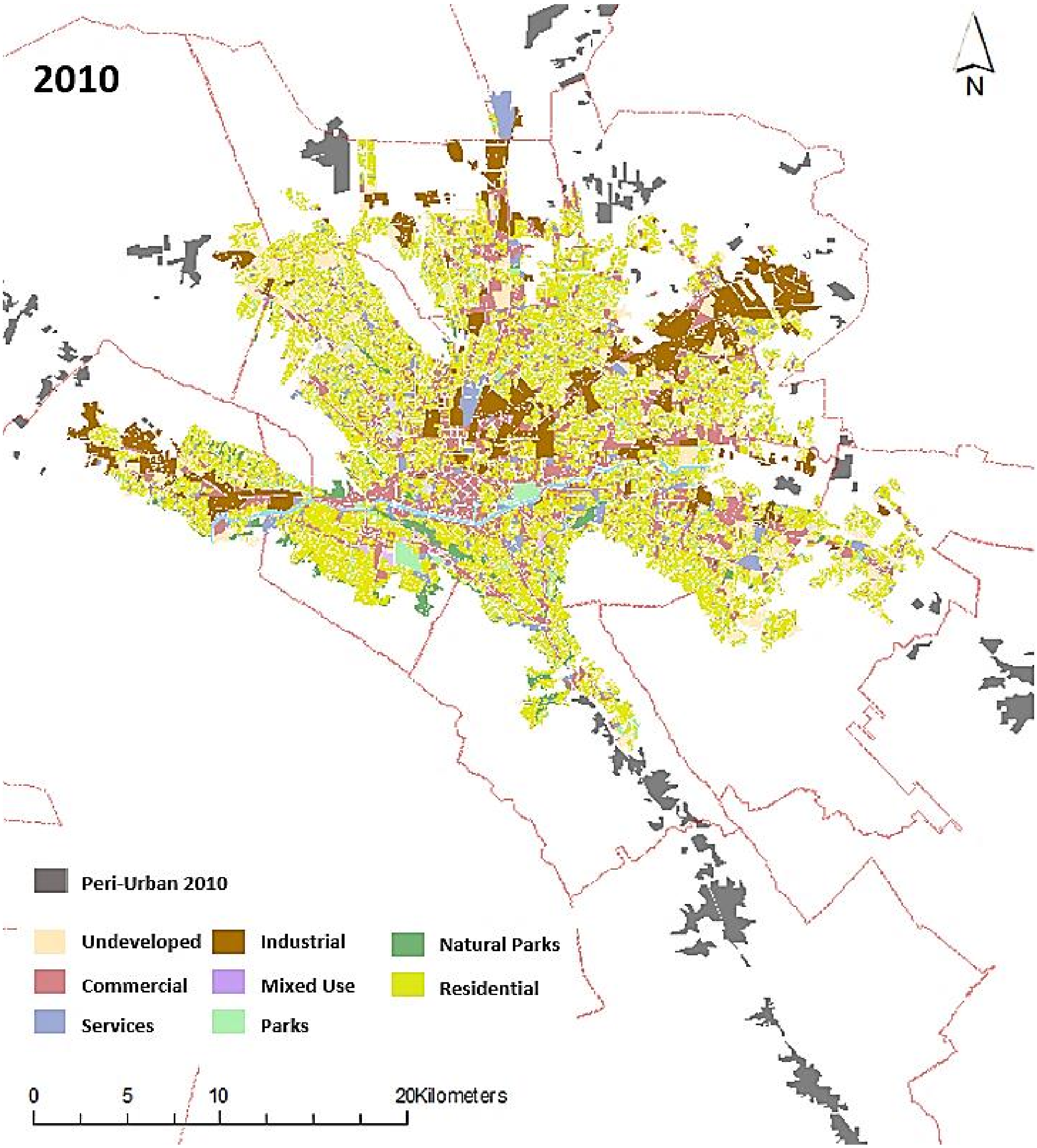

Figure 15.MAM urban land use map 2010.

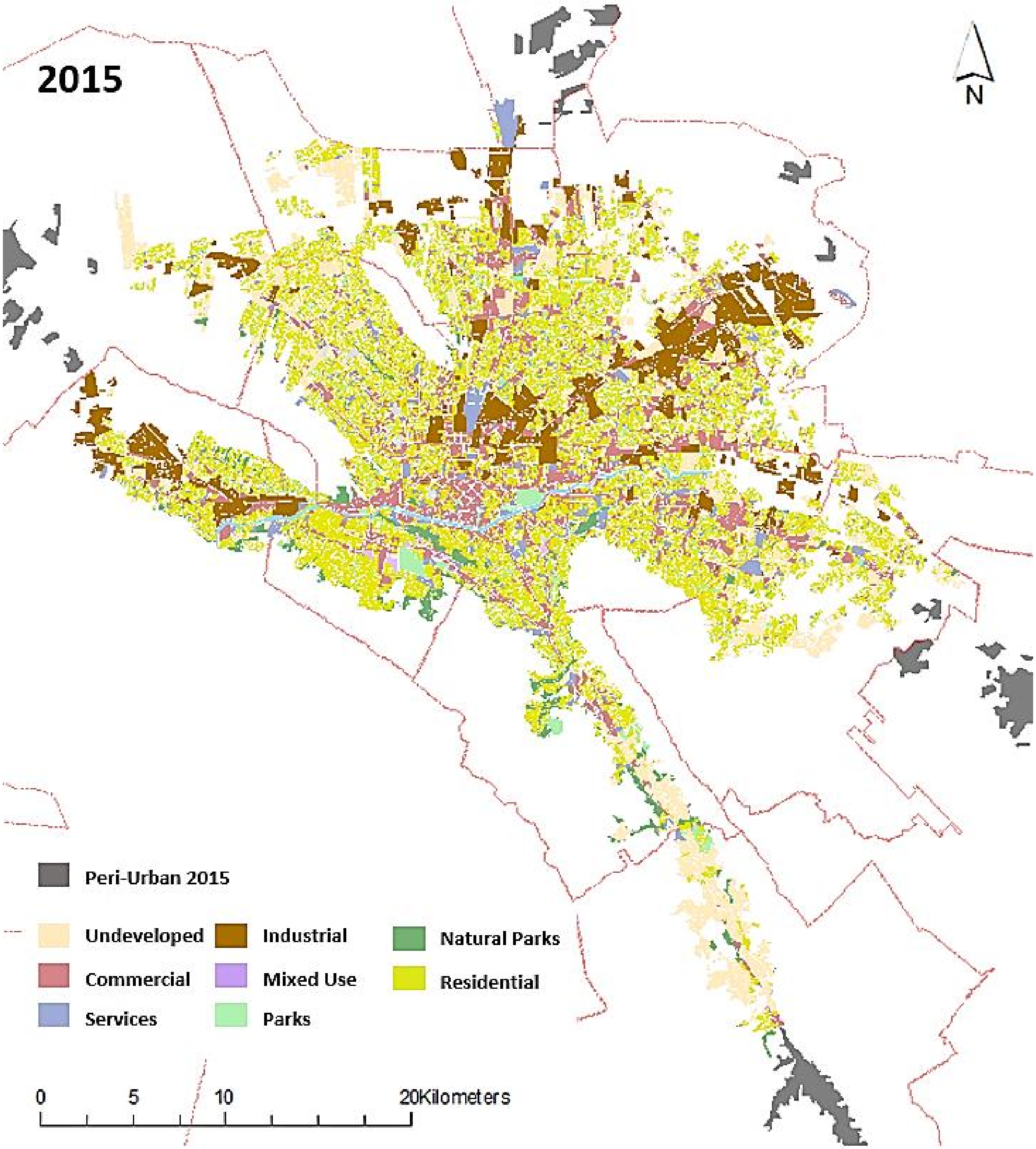

Figure 16. MAM urban land use map 2015.

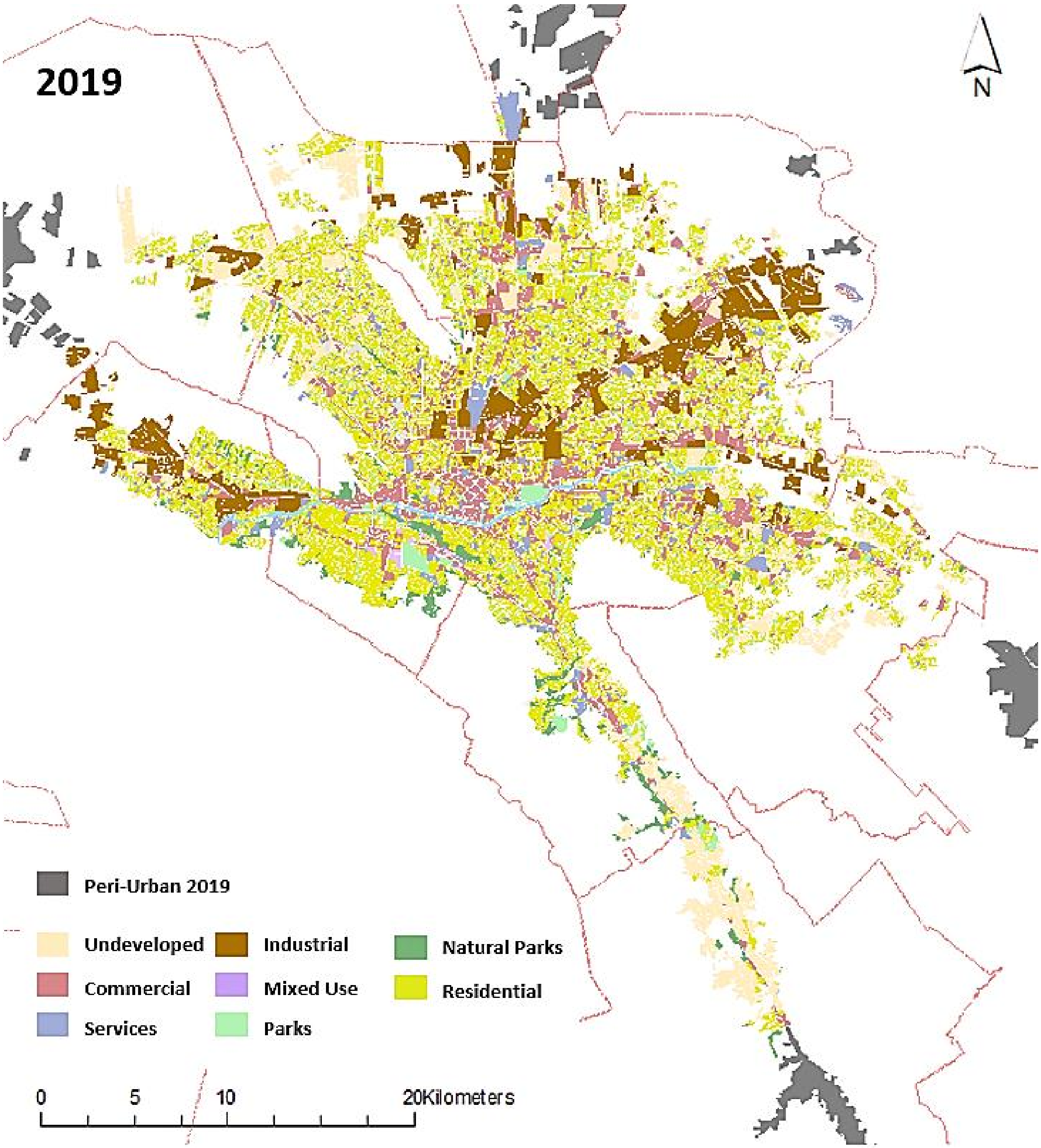

Figure 17. MAM urban land use map 2019.

4.3 Land Use and Vegetation Cover Evolution

Figure 18 describes the total vegetation displacement due to urbanization of the four entities of vegetation identified from INEGI data. In Table 13 is represented the percentage of each entity per type of vegetation displaced. The spatial distribution of vegetation displacement from 1990 to 2019 is shown in Figure 19.

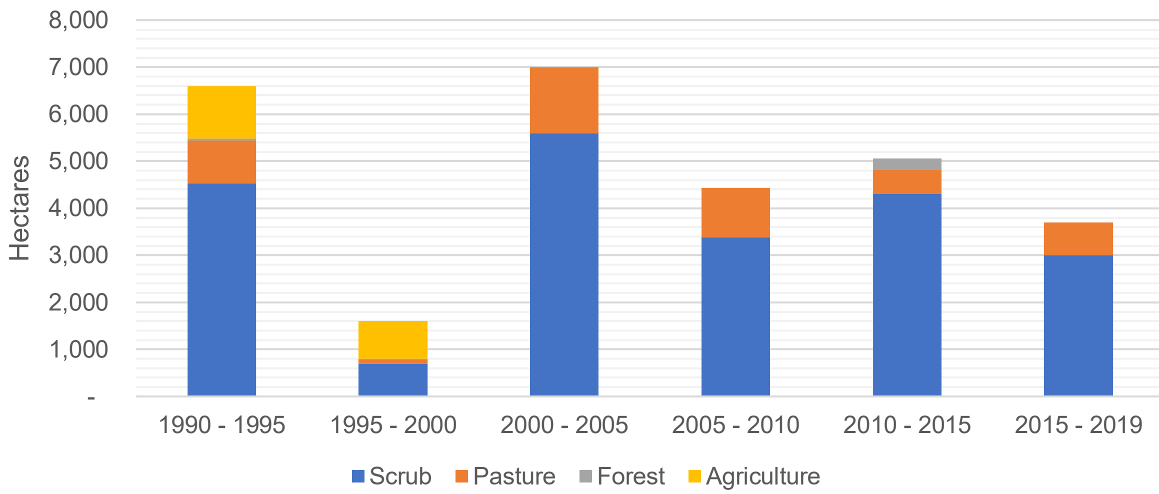

Figure 18. MAM Vegetation Displacement from 1990 to 2019.

Table 13. Percentage of type of vegetation per entity.

Entity		**1990-1995**	**1995-2000**	**2000-2005**	**2010-2015**	**2015-2019**
Scrub	Espinoso Tamaulipeco	3.89	0	5.32	7.67	5.35
	Submontane	96.11	99.75	94.65	91.39	94.46
	Rosetfile Desert	0	0.25	0.03	0.05	0
	Microfile Desert	0	0	0	0.89	0.19
Pasture	Cultivated	1.57	0.06	0	0	0
	Induced	98.43	99.94	100	100	100
Forest	Oak	100	100	3.16	100	0
	Oak-Pine	0	0	96.84	0	0
Agriculture	Irrigation	90.73	67.45	0	0	0
	Rain Based	9.27	32.55	0	0	0

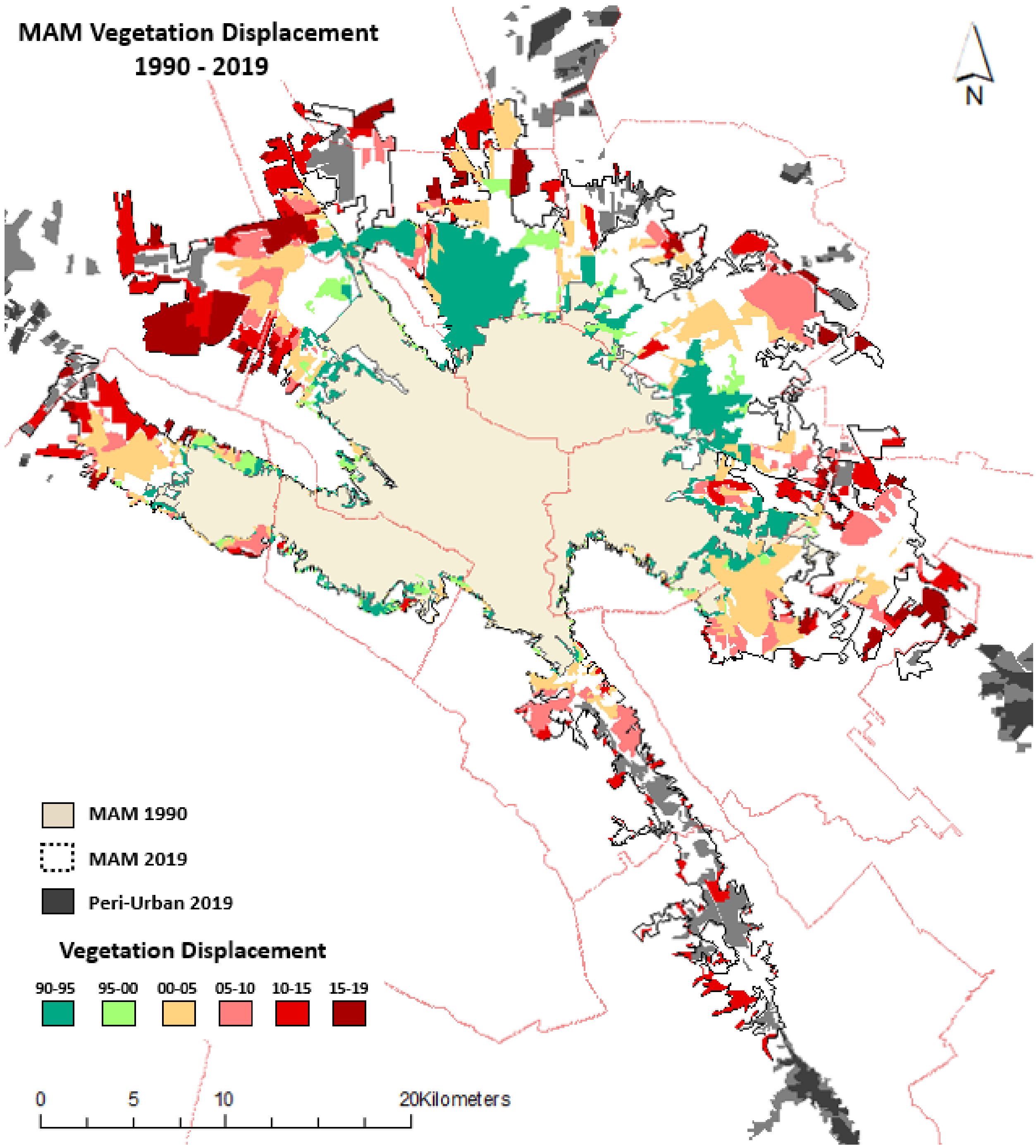

Figure 19. MAM spatial distribution of vegetation displacement from 1990 to 2019.

4.4 Estimation of CO_2 sink loss from 1990 - 2019

CO_2 sink loss of aboveground biomass was estimated using the vegetation displacement areas per entity and then multiplied by the absorption factors of Table 10. Table 14 shows the area of each vegetation entity and the equivalent in tons of CO_2 per period. Figure 20 shows the vegetation loss per period and per Municipality from 1990 to 2019. Figure 21 shows the territorial distribution of CO_2 sink loss.

Table 14. Loss of vegetation per entity and CO_2 emissions from 1990-2019.

	1990 -1995		**1995 - 2000**		**2000 - 2005**		**2005 - 2010**		**2010 - 2015**		**2015 - 2019**	
	Ha	T CO_2	Ha	T CO_2	Ha	T CO_2	Ha	T CO_2	Ha	T CO_2	Ha	T CO_2
Scrub	4,523	64,453	692	9,864	5,583	79,554	3,390	48,307	4,314	61,470	2,998	42,720
Pasture	914	7,336	101	810	1,407	11,300	1,040	8,350	513	4,120	702	5,636
Forest	44	3,656	3	222	17	1,380	-	-	229	18,986	-	-
Agriculture	1,122	3,342	803	2,392	-	-	-	-	-	-	-	-
Total	**6,602**	**78,787**	**1,599**	**13,288**	**7,007**	**92,234**	**4,430**	**56,657**	**5,056**	**84,576**	**3,700**	**48,356**

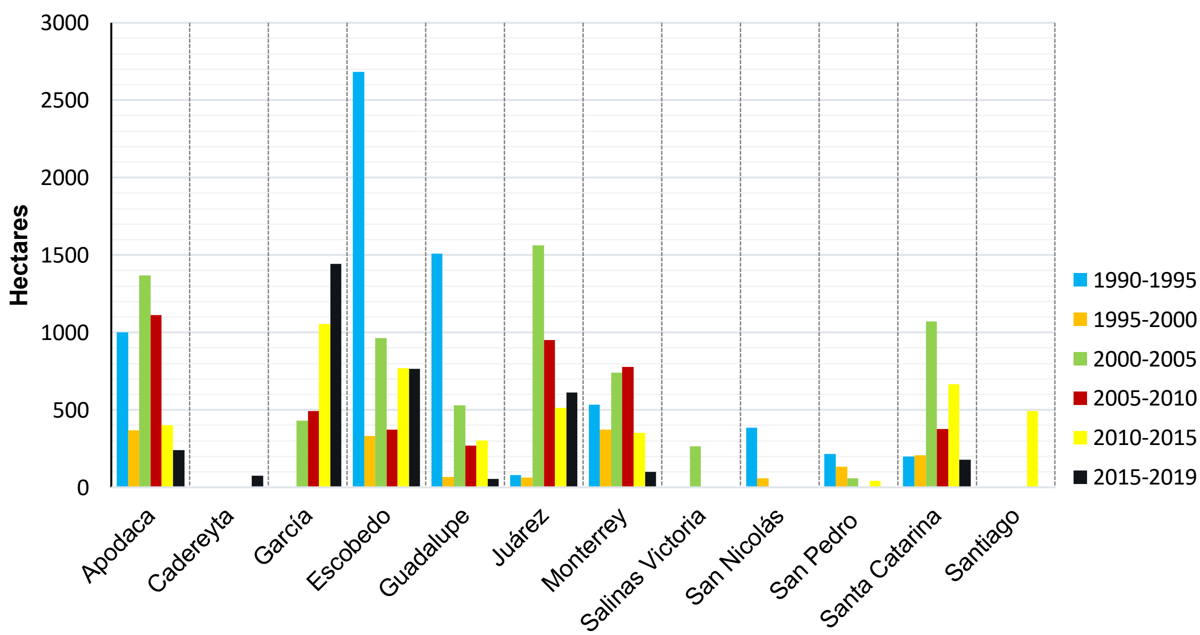

Figure 20. Vegetation loss per Municipality from 1990 to 2019.

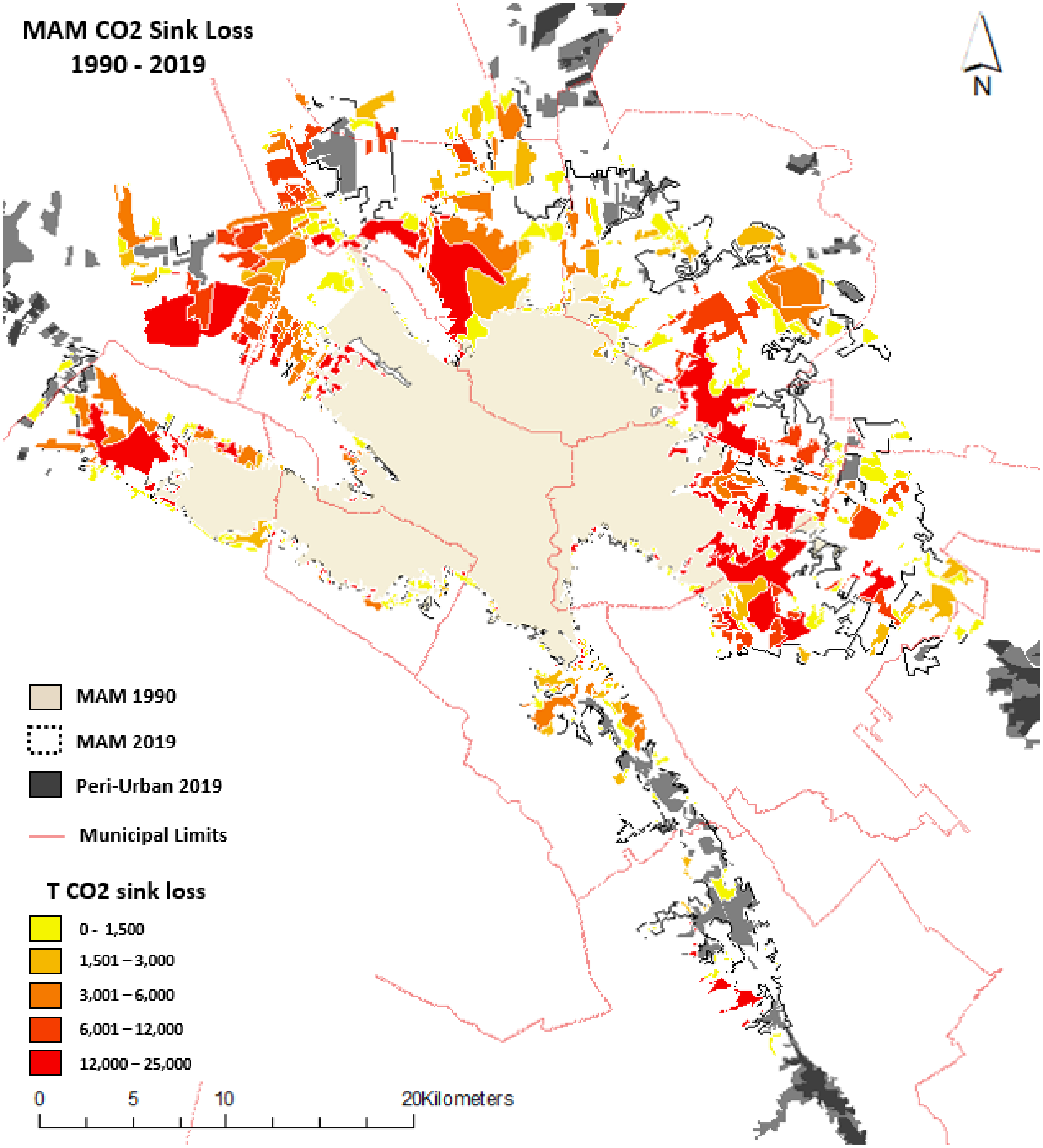

Figure 21.MAM CO2 sink loss from 1990 to 2019.

4.5 Estimation of CO_2 Emissions residential and commercial use from 1990 – 2019

A parametric estimation of CO_2 emissions is given in Table 15, the calculation includes the consumption of LPG gas, natural gas and electric energy for residential sector and for commercial sector exclusively electric energy and also CO_2 sink loss is given. Each type of energy was multiplied by the emission factors described in Tables 7, 8 and 9. Figure 22 shows the average of CO_2 emissions per urban block from each municipality from 2015 and Figure 23 shows the spatial distribution of MAM CO_2 emissions from residential and commercial sector, and MAM possible carbon sinks from 2015.

Table 15. CO_2 Emissions from 1990 to 2019 and CO_2 sink loss.

	1990	**1995**	**2000**	**2005**	**2010**	**2015**	**2019**
Residential	4,881,000	5,675,000	6,176,000	6,842,000	7,486,000	8,122,000	8,770,000
Commercial	2,761,000	3,151,000	3,281,000	3,875,000	3,950,000	4,160,000	4,247,000
CO_2Sink Loss	-	78,787	13,288	92,234	56,657	84,576	48,356
Total T CO_2	7,642,000	8,904,787	9,470,288	10,809,234	11,492,657	12,366,576	13,065,356

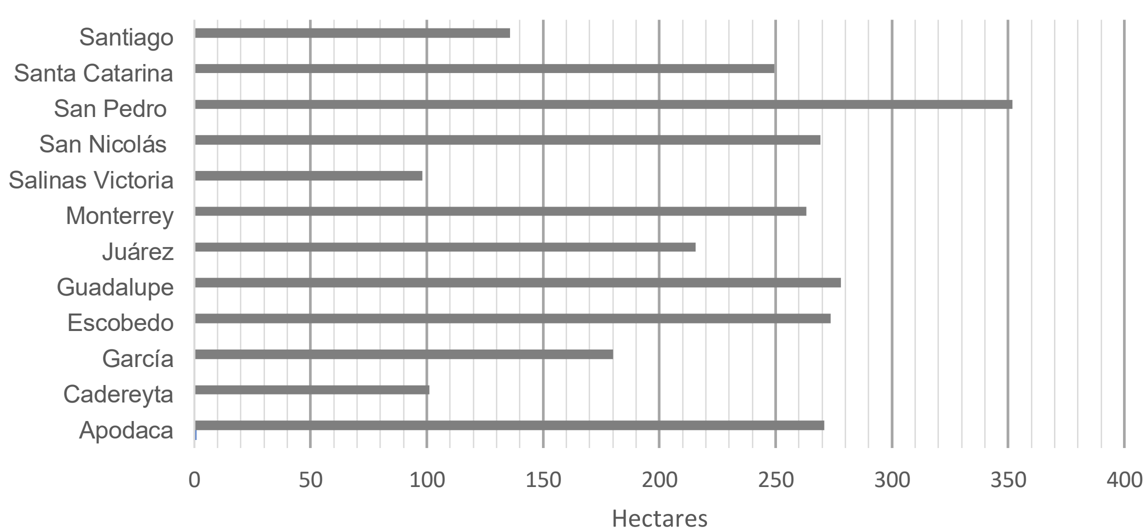

Figure 22.Municipality average CO_2 emission per urban block from 2015.

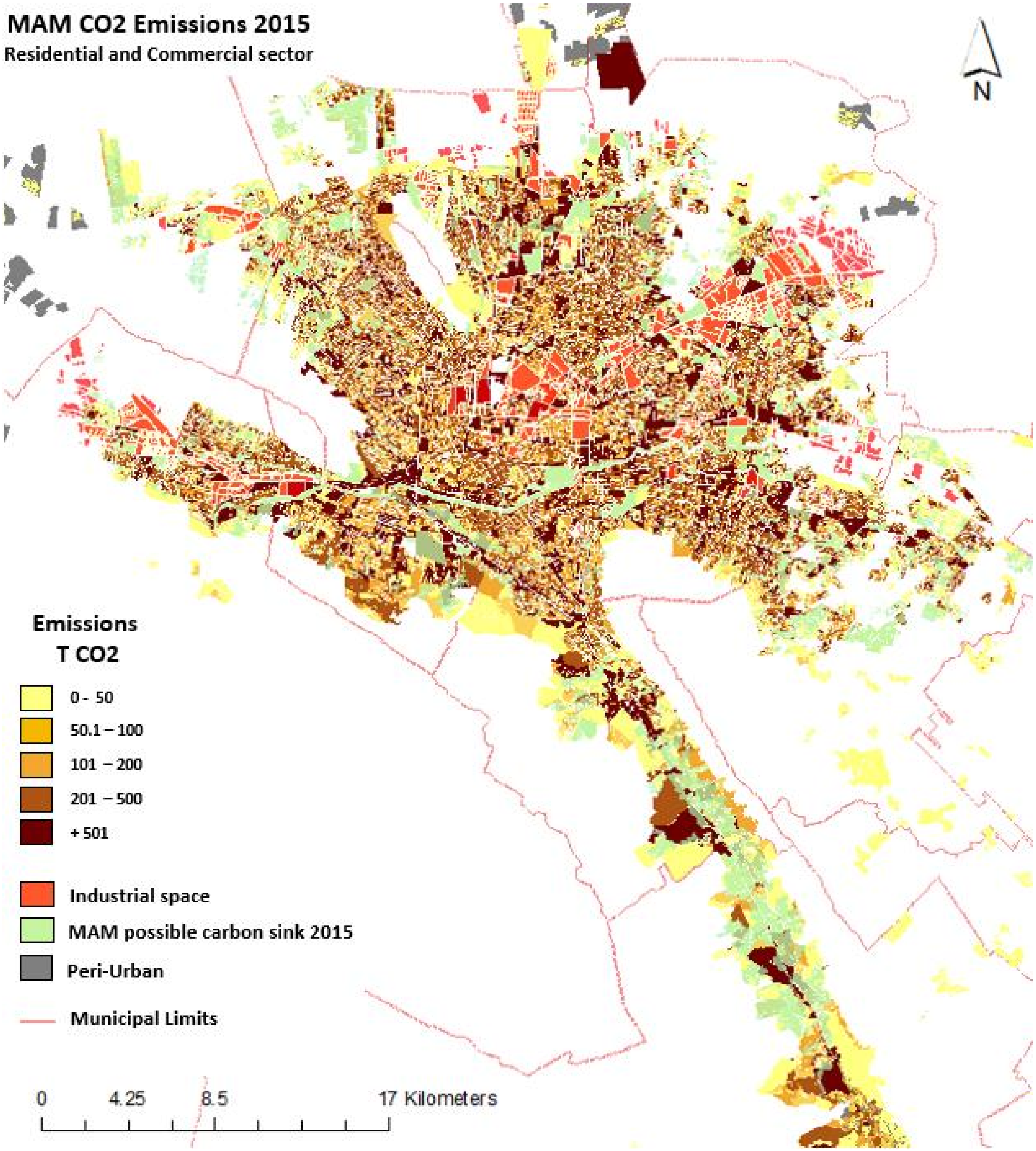

Figure 23.Spatial distribution of CO2 emissions from 2015

(Residential and Commercial only)

4.4 Population Analysis

Table 16 shows MAM population from 1990 to 2015 and the total population from Nuevo León and percentage of total state population living in the Metropolitan Area. Figure 24 shows the evolution of population per municipality according to data from (INEGI, 2015 and Secretaría de Economía y Trabajo, 2019).

Table 16.MAM Population Analysis and relationship with state population.

	1990	1995	2000	2005	2010	2015
MAM	2,666,809	3,100,633	3,374,361	3,738,077	4,089,962	4,437,643
Total NL	3,098,736	3,550,114	3,834,141	4,199,292	4,653,458	5,119,504
% MAM Population	86%	87%	88%	89%	88%	87%

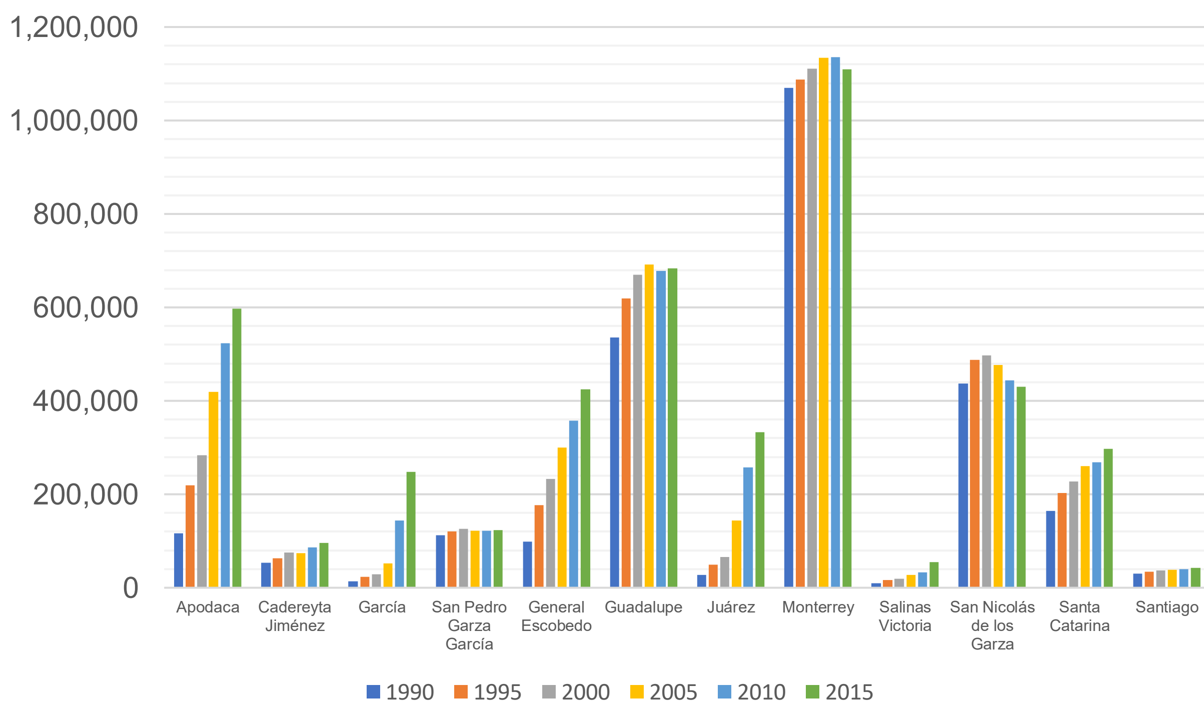

Figure 24.Population per Municipality according to INEGI

4.5 Motor Vehicle Inventory 1990 – 2018

Figure 25 shows the number and the proportion per type of motor vehicle for each period exclusively from the municipalities that conform the Metropolitan Area of Monterrey.

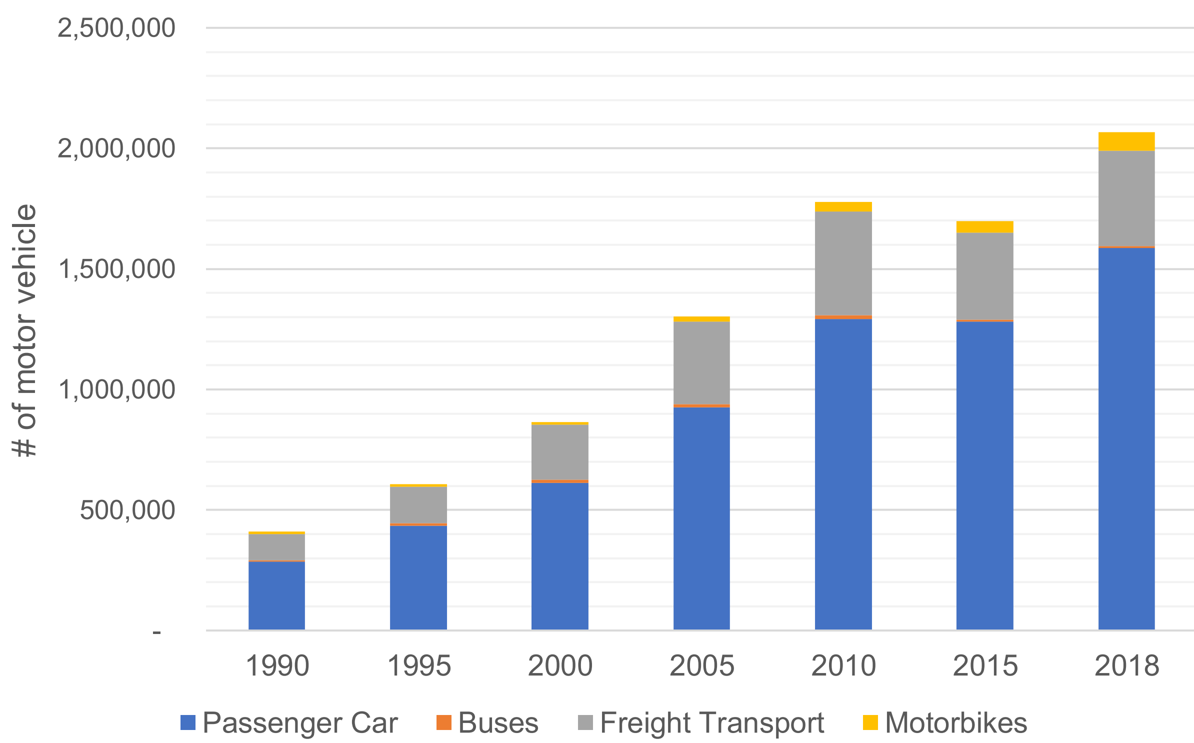

Figure 25.MAM motor vehicle inventory from 1990 to 2018 according to INEGI.

4.6 Electric Energy Consumption from 2010 to 2017

Figure 26 shows the electrical consumption in megawatts – hour from 5 sector from 2010 to 2017 according with the different fares from CFE (Table 6) and data from SENER.

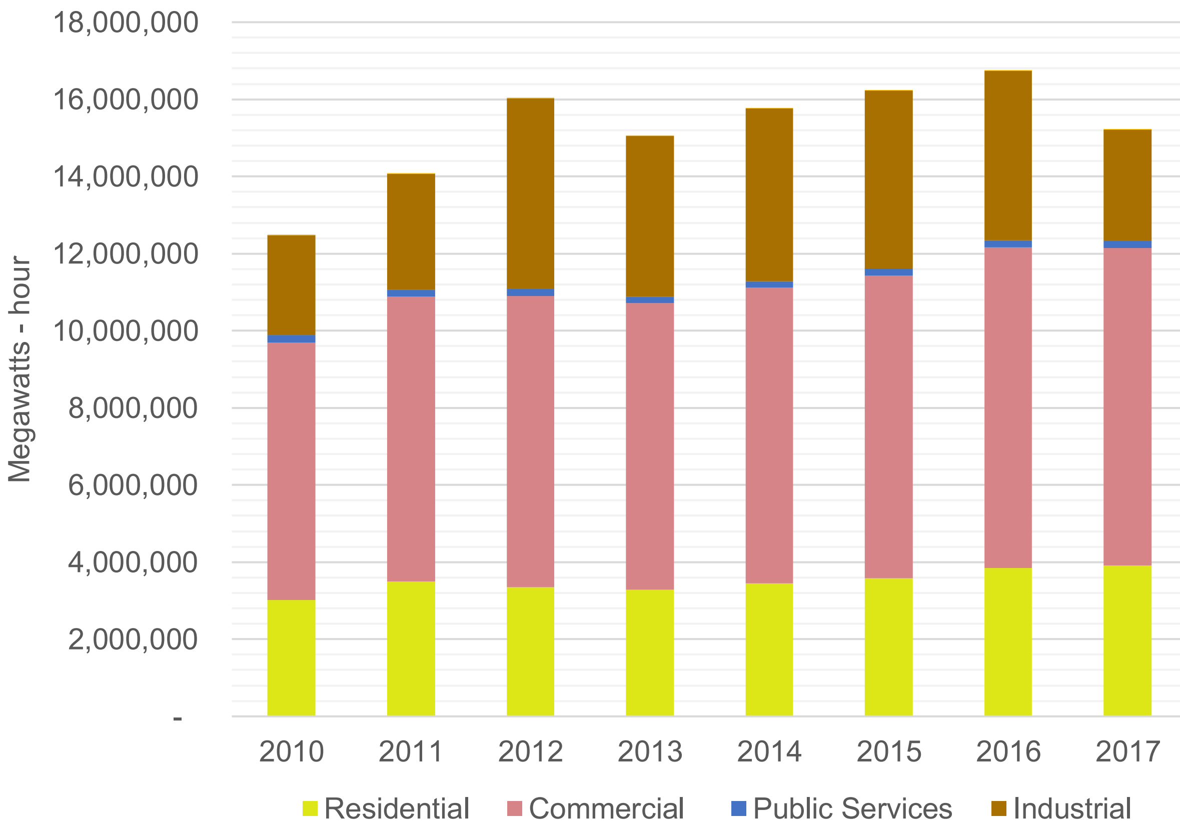

Figure 26.Electrical Energy consumption.

4.7 Key Data Correlation Analysis

Key data was correlated using the Statistical program Minitab 18. The variables are shown in Table 17 and is related to the synthesis of key results from 1990 to 2019 in Table 19.

Table 17.Key data correlation analysis variables.

Variable	Description
MP	MAM Population
M GDP	MAM Gross Domestic Product
M G	MAM Urban Growth
P U	Per Urban Areas Growth
MD	MAM Density
V U	Vehicle Units
V D	Vegetation Displacement
CO_2 S	CO2 from carbon sink loss
E	Emissions from Residential and Commercial

Figure 27 shows the variables from Table 17 being compared with each other and graphed in a matrix plot fitted with regression fit line to better appreciate the data dispersion and to see if there is a positive or a negative correlation. A positive slope is given when indicates that two variables are positive related, when a variable increase, so does the other or when the variable decreases there also the other variable decreases. A negative slope is given when two variables are negatively related, when one variable increases the other decreases. Tables 18 shows the Pearson correlation coefficients with a 95% confidence interval. Coefficients range from -1 to 1 being -1 a perfect negative correlation, 0 a non-correlation value and 1 as a perfect positive correlation. The main goal is to measure in a quantitative way to complement graphical information from Figure 27, also it measures in a quantitively the degree of correlation.

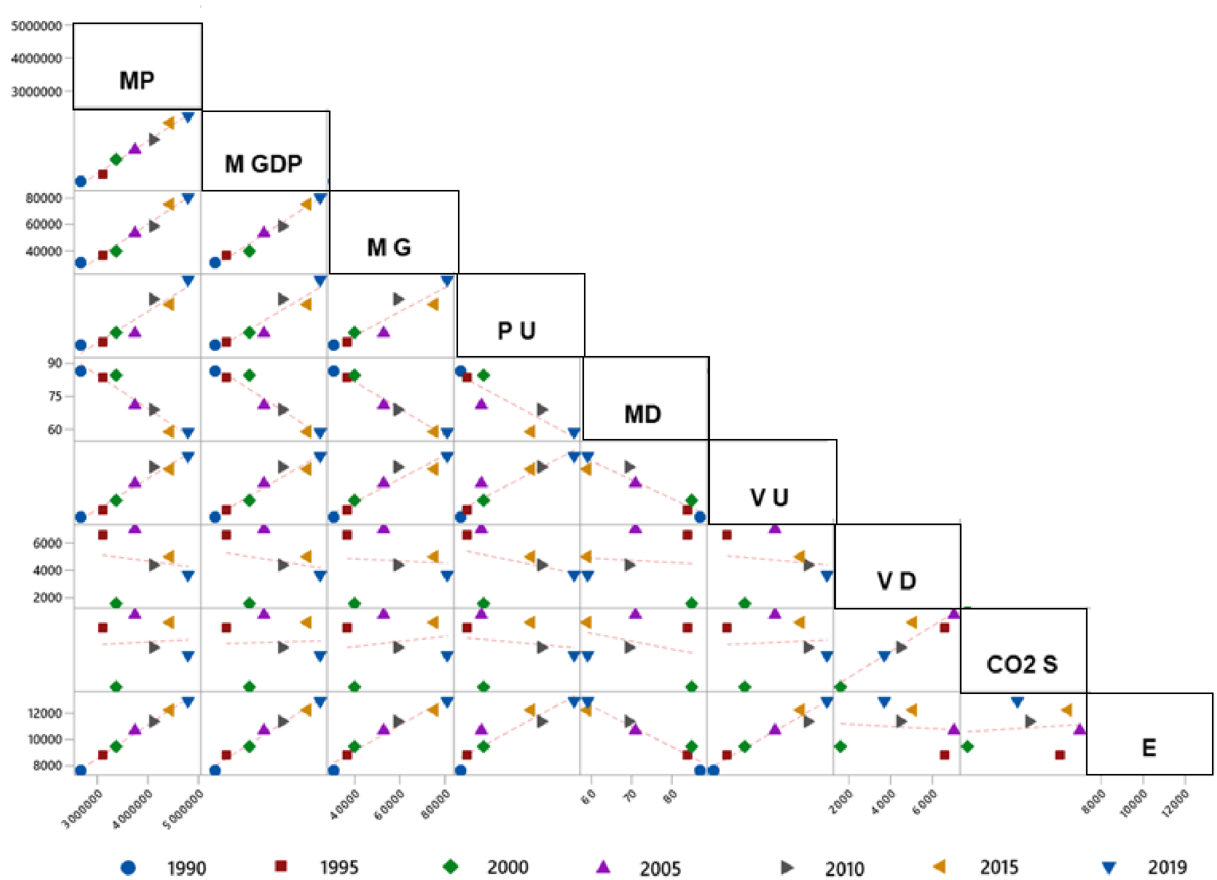

Figure 27.Matrix Plot of key variables.

Table 18.Pearson correlation, 95% confidence interval.

	MP	M GDP	M G	P U	MD	V U	V D	CO_2 S
M GDP	0.994							
M G	0.984	0.989						
P U	0.939	0.934	0.922					
MD	-0.960	-0.963	-0.985	-0.874				
V U	0.979	0.969	0.953	0.948	-0.945			
V D	-0.160	-0.208	-0.069	-0.316	-0.092	-0.130		
CO_2 S	0.066	0.037	0.171	-0.141	-0.334	0.067	0.947	
E	0.998	0.990	0.980	0.922	-0.966	0.982	-0.104	0.124

Table 19.Synthesis of key results from 1990 to 2019.

	Units	1990	1995	2000	2005	2010	2015	2019
MAM Population	Population	2,666,809	3,100,633	3,374,361	3,738,077	4,089,962	4,437,643	4,791,810
MAM GDP	Millions of Mexican Pesos	430,035	482,649	681,050	796,895	922,666	1,097,358	NA
MAM Area Growth	Ha	30,761	36,729	39,744	52,932	58,973	75,424	80,962
MAM Density	Pop / Ha	87	84	85	71	69	59	59
Peri-Urban Area Growth	Ha	2,994	3,466	4,761	4,589	9,158	8,431	11,736
Total Urban Growth (MAM Municipalities)	Ha	33,755	40,195	44,505	57,521	68,131	83,855	92,698
% Urban Area (Relation of Total Municipality Area)	%	5.09	6.07	6.72	8.68	10.28	12.65	13.99
Principal Urban Land Use	%	Residential 45% Commercial 18% Industrial 10%	Residential 45% Commercial 18% Industrial 10%	Residential 44% Commercial 17% Industrial 12%	Residential 42% Commercial 15% Industrial 14%	Residential 41% Commercial 15% Industrial 15%	Residential 37% Undeveloped 17% Industrial 13%	Residential 37% Undeveloped 17% Industrial 13%
MAM Motor Vehicle Inventory	Units	410,914	606,556	863,472	1,302,767	1,777,086	1,698,197	2,066,754
Vegetation Displacement	Ha		6,602	1,599	7,007	4,430	5,056	3,700
CO_2 sink removed	T CO_2		78,787	13,288	92,234	56,657	84,576	48,356
Estimation of CO_2 Emissions (Residential and Commercial)	T CO_2	7,642,000	8,826,000	9,457,000	10,716,000	11,435,000	12,282,000	13,017,000

Chapter 5

Discussion

The economic development that MAM has experienced since its beginning as a metropolitan area and more noticeable in the 90´s when international agreements such as NAFTA were signed detonated rapid and intense urban development; this growth and development of the area followed a pattern that is representative on agglomeration economies, defined by those economic production systems that benefit from colocation (Elena Beussi, 2010). In fact, MAM´s industrial dynamism makes it the second city with the greatest industrial potential, concentrating the main heavy industries in the country (Centro Mario Molina,2018), indeed the percentage of industrial land increased considerably from 1995 to 2010 (from 10% to 15%). The national economical attractiveness that the metropolitan area represented promoted a very pronounced development of the region, bringing employment and many other opportunities for people, this translated into greater population and territorial growth.

Results shows that MAM area increased its size 2.6 times from 1990 to 2019, but population only did 1.8 times considering around 4.8 million of people in 2019, meaning that density decrease more than 30% people per hectare. The percentage of urban land use including MAM and peri urban areas of the 12 municipalities in 1990 was 5.09%, and in 2019 increased to 13.99%. The most intense MAM growth occurred during the period 2010-2015 growing by 2.48%. In 2019, San Nicolás de los Garza is the municipality with the least amount of free space to urbanize; in the case of Monterrey and San Pedro Garza García, also this is happening, and urban limits adjoin with Natural Protected Areas such as Chipinque, Sierra las Mitras, Cerro Topo Chico, and Cerro de la Silla.

The distribution of the population in the MAM is mainly under a low-density urban model where the people is located principally in the periphery, and with a clear abandonment of the central area (Centro Mario Molina,2018) , this model is traduced as urban sprawl where low density residential development, unconstrained and noncontiguous development, homogenous single-family residential development with scattered units, land uses which are spatially segregated from one another (Elena Beussi, 2010)

Moreover, according to the information presented, municipalities that are located in the central area of MAM such as Monterrey, San Pedro Garza García, San Nicolás de los Garza and Guadalupe have been experiencing stagnation and in some cases a decrease of population rather than those located outward from the central area like: Apodaca, García, General Escobedo and Juárez. In general terms, it is estimated that the periphery increased its density by 40% and the urban core depopulated around 15% (Centro Mario Molina,2018). Also, the expansion to the periphery was given by the high cost of urban land in the central area and because there is a lack of urban affordable housing projects (IMPLANc,2013).

In general terms, the MAM expansion follows a Linear Strip Development physical pattern according to (Galster et. Al 2001) where the allocation of the different commercial and industrial areas are related with the main axes of the metropolitan transport infrastructure and connected to Downtown Monterrey which is the metropolitan urban core where it houses important medical, educational and other commercial uses (IMPLANc,2019), actually 38% of the total economic units from the MAM are located in the municipality of Monterrey (Centro Mario Molina,2018).

In contrast, residential areas seem to be the most prominent urban land use in the peripheral areas lacking with a mixture of some other uses like commercial and services, meaning that people living in those areas need to take a way of transportation to work, do groceries, among other daily activities. Nowadays, the average trip in the MAM has a duration of 1.3 hours but people living in the periphery can spend up to two hours (Centro Mario Molina, 2018). Also this reliance on the automobile for transport is reflected in the vehicle inventory in Figure 25 that indicates that the principal type of vehicle is the passenger car which category change drastically from 1990 to 2018 increasing 5.5 times going from 286,000 to 1,585,000 units. Other relevant aspect is that also motorbikes increased its number 7.5 times, showing another interesting private individual transportation preference rather than public transportation. Besides, freight transport increases almost 3.6 times going from 110,00 to 395,000 units.

Some of the externalities of the MAM urban expansion that were identified and quantified in the present study were vegetation displacement, CO_2 sink loss and CO_2 emissions from residential and commercial sector.

It is identified that there are two striking periods of vegetation displacement, the first one is from 1990 to 1995 and the second one from 2000 to 2005, together they make up almost the half of the total vegetation displaced from all periods that were evaluated. The most affected type of vegetation is the scrub but specifically the sub montane scrub. It is estimated that a total of 28,393 hectares of vegetation was removed meaning a loss of CO_2 sink with a potential of absorption of 373,900 T CO_2 a year, according to absorption factors from Table 10. Figure 20 describes that in the first two periods that were evaluated, the most affected municipalities due to vegetation loss and therefore CO_2 sink were Escobedo, Guadalupe and Apodaca, and in the las two periods the most affected municipalities are García, Escobedo and Juárez. The municipalities with the least impact in the last two periods are San Pedro and Salinas Victoria.

In terms of CO_2 emissions considering operation (gas and electric consumption) plus the loss of vegetation attributable to the area , the average MAM CO_2 emission per urban block in 2015 was 268 TCO_2/year, also the average of TCO_2 / year per hectare for residential and commercial use is 391 and 362, respectively. San Pedro, San Nicolás, Monterrey, Guadalupe, Escobedo, and Apodaca have higher values in relation with MAM average, represented in Figure 22. The municipality with the highest average of CO_2 emission per urban block is San Pedro Garza García with approximately 350 TCO_2/year and the Salinas Victoria is the municipality with the lowest value, almost 100 TCO_2/year. The spatial distribution of CO_2 emissions in Figure 23 shows that the highest values are concentrated in the center of the MAM and along the commercial and industrial corridors that connect the whole urban area. The maximum three values of CO_2 emissions per block are located at Monterrey and San Pedro Garza García with more than 24,000

TCO_2/year. Per capita of CO_2 emissions for residential sector in the MAM is around 1.83 TCO_2/year, as a comparison the Xinzhuang District in the study by (C.H.Liao and colleagues, 2012) per capita emission for residential in 2007 was 1.51 TCO2/year and in the study from 50 Japanese cities by (Makido, Y., Dhakal, S., & Yamagata, Y. , 2012) the average of this sector is 1.27 TCO_2/year from 2005.

The analysis of electric energy consumption according to SENER and CFE from 2010 to 2017 described in Figure 26, shows that the proportion of change didn't change dramatically during the seven years; commercial sector accounts more than a half of the total amount of megawatts consumed in the Metropolitan Area. Residential consumption per capita is 0.7616 Mwh a year, according to the average of consumption from 2010 and 2015 and divided by the known population. An interesting fact is that agriculture land use is identified only from 1990 to 2000 as described in Figure 18, and according with electric energy data, electrical consumption of this type of fare in the MAM is decreasing, meaning that this type of land use has experienced expulsion to other territories and the land that use to be for agricultural purposes are converted to other use with greater economic exploitation such as residential, commercial, or industrial use. Last, it is important to note that in the last two periods (2015 and 2019) undeveloped land represents 17% of the total urban area, meaning that in the upcoming periods this land will change its vocation. These changes in urban land vocation (Agricultural and undeveloped land) are relevant because the conversion from land cover to land being used progresses predominantly agricultural surfaces are transformed into settlement and traffic surface, resulting in decreased settlement density, increases traffic and costly infrastructure development (Netzband & Jürgens,2010).

Also, according to the "Proposal for the sustainable development of a Mexican city. The study of the Monterrey Metropolitan Area" by Mario Molina center from 2018, large vacant or undeveloped areas, road congestion problems and unsustainable mobility patterns with its industrial potential of the area; represents intense energy consumption that contributes the high generation of GHG emissions and as consequence deteriorated air quality for inhabitants of the area. These negative effects can be faced with a model of urbanization that integrates principles of urban sustainability since the actual policies and urban infrastructure condition the consumption patterns of users, and have an impact on energy demand and therefore CO_2 emissions.

On the other hand, the main goal of the correlation presented in section 4.7 is to relate the different variables between them and to see how much they depend on each other in the context of the Metropolitan Area of Monterrey. This analysis is needed to be expanded with more variables such as landscape metrics to have a better comparison with other studies and cities in the world. These are some findings that reinforce previous results:

1) Gross Domestic Product is positive correlated with increasing urban population motor vehicle acquisition, MAM and peri urban areas growth and emissions from residential and commercial sector, in contrast GDP shows a negative correlation with urban density.

2) MAM population growth has a positive correlation between almost all variables except vegetation displacement which shows a weak negative correlation, but it shows a clear negative correlation with density, this is attributable to the drop down with 30% on density from the initial period to the last one.

3) MAM urban growth shows that has a high positive correlation with peri urban growth and increase of number of motor vehicle units, plus is related with emissions of residential and commercial sectors.

4) In contrast, has a strong negative correlation with MAM density.

5) Peri Urban areas have a strong positive correlation with the incremental of vehicle motor units in the area and emissions from residential and commercial urban land use.

6) MAM density has a strong negative correlation with almost every variable evaluated except from vegetation displacement and CO_2 sink removal showing a weak negative correlation.

7) Vehicle unit’s data has a strong positive correlation with emissions from buildings from commercial and residential area, this may be given from the fact that the city grows in extension but not in density.

8) CO_2 sink removal is clearly positive correlated to vegetation displacement but demonstrates a weak correlation in almost all variables.

For the present research, it is important to consider a degree of uncertainty in some periods due to data availability, for example, electrical consumption and exact urban land use. Also cadastral scale information is required and will help to better allocate CO_2 emissions. Further research is needed to evaluate carbon footprint of the different kind of buildings in the geographical context of MAM from a Life Cycle Assessment Model perspective including materials, construction, use, maintenance, renewal, and demolition to consider de actual CO_2 emission factor per type of building. Also, its necessary to evaluate and characterize the potential areas for carbon sink to obtain specific factors of absorption for plazas, public parks, Santa Catarina River, among others. In addition, urban tree inventories will help to calculate CO_2 absorption. Traffic patterns and Industrial energy consumption analysis and its territorial distribution is highly needed to complement the research. Besides, an extensive analysis of landscape metrics will help to better understand the evolution of the metropolitan area and to have a better classification of urbaneness of each municipality and to have more measurements from satellite imagery and census data over space and time.

Chapter 6

Conclusion

Due to factors like economic growth from last decades, industrial potential from the area and the strategic territorial location with respect to the United States, the Metropolitan Area of Monterrey experienced a growth from 1990 to 2019 increasing 2.6 times its size from 30,761 to 80,962 hectares. The percentage of urban land use including MAM and peri urban areas of the 12 municipalities in 1990 was 5.09%, and in 2019 increased to 13.99%.Population grew 1.8 times considering around 4.8 million of people in 2019, meaning that density decrease more than 30% people per hectare. The distribution of the population in the MAM is mainly under a low-density urban model where the people is located principally in the periphery, and with a clear abandonment of the central area. Some externalities due to this type of development pattern were identified and analyzed, specifically vegetation displacement, loss of CO_2 sink and a carbon emission from commercial and residential sector.

In terms of vegetation displacement related it is estimated that a total of 28,393 hectares of vegetation was removed including: scrubs, pasture, forest, and agriculture land; meaning a loss of CO_2 sink with a potential of absorption of 373,900 TCO_2 a year. The most affected type of vegetation is the scrub which loss represents 21,500 hectares. The four municipalities with the greatest loss of vegetation and therefore CO_2 sink due to urban expansion are Apodaca, García, Escobedo and Juárez; the municipality with the least impact in the last period was San Pedro Garza García.

Natural cover was replaced mainly with residential areas in the following municipalities: Apodaca, García, General Escobedo and Juárez; with a lack of mixture of other urban uses like commercial and services this represents an important problem because people living in those areas need to take a way of transportation to work, do groceries, among other daily activities. Vehicle inventory analysis reinforces the fact that people need to move long distances in the area which average in time is 1.3 hours, but people located in the periphery may spend up to 2 hours. Also, inventory shows that there is a strong reliance in private individual transportation such as passenger car and motorbikes are the most common way of transportation.

In terms of CO_2 emissions considering operation (gas and electric consumption) plus the loss of vegetation attributable to the area , the average MAM CO_2 emission per urban block in 2015 was 268 TCO_2/year, also the average of TCO_2 / year per hectare for residential and commercial use is 391 and 362, respectively. San Pedro, San Nicolás, Monterrey, Guadalupe, Escobedo, and Apodaca have higher values in relation with MAM average. San Pedro is the municipality with the highest average of emission per urban block with approximately 350 TCO_2/year. Per capita emissions from the residential sector in the MAM is around 1.83 TCO_2/year whose value is higher than some Asian cities from other studies that were consulted.

Finally, some studies should be carried out in order to estimate more variables to determine a complete metropolitan carbon footprint in order to have comparable information to other context with the intention to establish future environmental policies to mitigate the negative effects of the current urban development model.

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Curriculum Vitae

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