Emissions Patterns In An Industrialized State: Overlapping Legacies of Time, Space, Climate, Geography, Poverty And Race

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November 30, 2022

Abstract

Understanding interactions among greenhouse gas (GHG) emissions, air pollution, race, and poverty is critical to developing strategies to slow climate warming, and is socially important as large GHG-emitting facilities often occur in poor and historically-marginalized communities. We examined such patterns in the American South, where a multi-centennial history of race and poverty coincides with a petroleum and petrochemical industry that is >100 yr old using open-access data to quantify emissions on a 0.1o x 0.1o scale annually from 1970 to the mid-2010s. 26-55% of Louisiana's emissions of several dominant GHGs and air pollutants are concentrated along the Mississippi River Industrial Corridor, which is $<$ 5% of the state's area. Despite some statewide emission reductions, fluxes in this corridor, and several parishes with large Black populations, have reduced more slowly or increased, raising environmental justice concerns. Methods herein provide a blueprint for future studies, particularly in marginalized communities, where limited scientific resources have hindered efforts to understand how climate change, air pollution and equity interact.

In Review At PLOS Climate

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ABSTRACT

Understanding interactions among greenhouse gas (GHG) emissions, air pollution, race, and poverty is critical to developing strategies to slow climate warming, and is socially important as large GHG-emitting facilities often occur in poor and historically-marginalized communities. We examined such patterns in the American South, where a multi-centennial history of race and poverty coincides with a petroleum and petrochemical industry that is >100 yr old using open-access data to quantify emissions on a 0.1° x 0.1° scale annually from 1970 to the mid-2010s. 26-55% of Louisiana's emissions of several dominant GHGs and air pollutants are concentrated along the Mississippi River Industrial Corridor, which is < 5% of the state's area. Despite some statewide emission reductions, fluxes in this corridor, and several parishes with large Black populations, have reduced more slowly or increased, raising environmental justice concerns. Methods herein provide a blueprint for future studies, particularly in marginalized communities, where limited scientific resources have hindered efforts to understand how climate change, air pollution and equity interact.

INTRODUCTION

The need to understand spatial and temporal interactions among greenhouse gas (GHG) emissions, air quality hazards, race, and poverty is one the most pressing research needs today [1–4]. This knowledge is critical to developing effective strategies reduce GHG emissions and slow the impacts of climate change.[5] Addressing this issue reflects a growing recognition that the overlap between greenhouse gasses, air pollution and demographics is a moral issue and a mitigation issue, as many large greenhouse emitting facilities occur in historically marginalized communities, including those with ethnic minorities, and impoverished individuals [6–8]. One place to understand these interactions is the American South, and particularly Louisiana, where a multi-centennial history of race and poverty coincides with an oil, gas, and petrochemical industry that is over a century old [9–12].

Here we examine spatial and temporal patterns in emissions of greenhouse gasses and common air pollutants, and demographic changes for Louisiana and Mississippi since 1970. These neighboring states have similar social histories, are relatively similar in geographic size, and have relatively similar demographics (Fig. 1, Table 1). However, Louisiana has a large energy and petrochemical sector, allowing one to quantitatively analyze contrasting emission patterns in an industrial and non-industrial state. Communities surrounding industrial facilities in Louisiana are often located near historic Black and poor communities, raising concerns about health impacts that have been highlighted by the Environmental Justice community [10,13,14], the United Nations' High Commissioner for Human Rights [15], and at the highest levels of the U.S. government [16].

Table 1. Basic Table 1: Basic Attributes of Louisiana and Mississippi

	Louisiana		Mississippi	
Total Area (km²)	135,382		125,443	
Land Area (km²)	112,927		121,607	
Water Area (km²)	21,455		3,940	
	1970	2019	1970	2019
Total Population	3,643,180	4,648,674	2,216,912	2,976,149
% White	70.1	62.2	63.0	58.4
% Black	29.6	32.2	37.6	37.7
Median Income (2019 US Dollars)	$46,552.46	$63,572	$37,532.54	$57,008
% Families In Poverty	21.5	14.5	28.9	15.5

Figure 1: Overview maps of Louisiana and Mississippi. A. Overview map of the region, with Louisiana outlined in green, Mississippi outlined in blue, and the Mississippi River Industrial Corridor outlined in red and the Mississippi River marked in white. 1. City of Shreveport, LA. 2. City of Jackson, MS. 3. City of Lake Charles, LA. 4. Location of specific communities in the Mississippi River Industrial Corridor mentioned; left to right- Romeville, Wallace and Reserve, LA. 5. City of Baton Rouge, LA. 6. City of New Orleans, LA. 7. City of Pascagoula, MS. B. Map of parishes in Louisiana and counties in Mississippi. Data Source: Google Earth and census.gov

This analysis used multiple open access federal and international data sources, including the Emissions Database for Global Atmospheric Research (EDGAR)[17]. This inventory provides global emissions for the major greenhouse gasses (CO_2, CH_4, and N_2O) and major air pollutants (PM_{10}, $PM_{2.5}$, NH_3, NO_x, Hg, SO_2, CO, and non-methane volatile organic carbon -NMVOCs, and Black Carbon- BC) on a 0.1º x 0.1º scale for each year from 1970 to the mid-2010s. (GHG data are available to 2018, most air pollutants are available 2015- except Hg and some NMVOCs, which are available to 2012). CO_2 is further broken down by EDGAR into short-cycle CO_2 (written as CO_2excel, which is largely fossil fuel combustion), and organic CO_2 from biomass burning (written here as CO_2org). These data are compared to other data of greenhouse gas emissions, including greenhouse gas fluxes from facilities, provided by the US Environmental Protection Agency, and metrics of poverty and race compiled by the US Census Bureau. This forensic approach, utilizing EDGAR's inventory, helps address one issue that has long hindered research into air quality in poor and marginalized communities like those in Louisiana: a dearth of financial resources has hindered data collection, which has hindered efforts to understand quantify emission fluxes and their societal impact. This multi-decadal analysis can aid future efforts to forensically determine environmental health exposures of underserved communities, particularly those who are understudied because they have been historically marginalized.

Overall, results indicate that 26-55% of Louisiana's emissions of two dominant greenhouse gasses (CO_2, N_2O) and several major air pollutants (NO_X, SO_2, HG, NMVOCs, $PM_{2.5}$, PM_{10}, BC, CO) are concentrated within a corridor along the lower Mississippi River that amounts to less than 5% of the state's area (Table 2). This contrasts with Mississippi, which has a more diffuse pattern of emissions of greenhouse gasses and most air pollutants. One notable exception is NH_3- which is more abundant in Mississippi, likely due to agricultural emissions. Statewide temporal trends in emissions appear to be impacted by local and national factors, including trends in energy utilization, domestic fossil fuel production, and environmental regulations. Yet trends at smaller spatial scales (e.g. parish/county level, and along Mississippi River corridor) sometimes contrasted with statewide patterns, highlighting areas of concern for community health and well being. The magnitude of Louisiana's emissions are potentially of global concern, accounting for ~ 0.5% of total anthropogenic CO_2 emissions, and while also representing some of the most concentrated emissions in the country that is one of the world's largest GHG and air pollutant emitters [18–20] . These methods provide a strategic blueprint to identify the intersection between among air quality concerns, carbon emissions, and social inequities, reflecting a growing global recognition that reducing carbon emissions and can provide other benefits to at risk communities [21,22].

Table 2: Emissions ranges and percentages for key greenhouse gases and air pollutants in Louisiana, Mississippi, and the Mississippi River Industrial Corridor

	Louisiana Emissions Range (metric tons)	Industrial Corridor Range (metric tons)	Percent Of Louisiana's Emissions In Industrial Corridor	Mississippi Emissions Range (metric tons)	Ratio of Louisiana Emissions to Mississippi Emissions
CO_2 tot	1.2×10^8 - 1.9×10^8	5.5×10^7 - 1.0×10^8	45 - 55%	6.3×10^7- 9.3×10^7	1.69 - 2.37
CH_4	3.5×10^5 - 4.4×10^5	8.0×10^4 - 4.6×10^4	13 - 18%	2.9×10^5- 4.5×10^5	0.98 - 1.36
Hg	6.9 - 1.3	0.50 - 2.6	35 - 41%	1.1 - 1.5	1.11- 4.92
N_20	1.9×10^4- 3.9×10^4	5.8×10^3 - 1.3×10^4	29 - 37%	1.5×10^4 -2.1×10^4	1.22-2.10
NH_3	2.7×10^4 - 4.2×10^4	1.7×10^3 - 4.0×10^3	5 - 12%	3.6×10^4 - 8.6×10^4	0.48 - 0.60
NMVOC	3.9×10^5 - 2.8×10^5	7.9×10^4 - 1.0×10^5	26 - 33%	1.7×10^5 - 2.9×10^5	1.33 - 1.48
NO_x	$4.8\ 10^5$ - 3.1×10^5	8.3×10^4 - 9.5×10^4	33 -45%	2.0×10^5 -3.5×10^5	.1.33 - 1.74
SO_2	7.9×10^5 - 1.3×10^5	7.0×10^4 - 4.2×10^5	44 - 55%	8.8×10^4 - 6.2×10^5	1.22- 1.96
pm2.5	5.4×10^4 - 4.1×10^4	1.1×10^4- 2.4×10^4	26 - 45%	2.7×10^4 - 3.73×10^4	1.25 - 1.76

Data and methods

Emissions data sources

Emissions data for this project were obtained from the Emissions Database for Global Atmospheric Research (EDGAR; https://edgar.jrc.ec.europa.eu/emissions_data_and_maps), which is an independent database is designed to track global emissions [20,23] [24]. EDGAR emissions of greenhouse gasses and air pollutants are calculated using a method that employs activity data and emissions factors; activity data are the magnitude of a process or activity, and the emissions factors are the quantity of gas emitted per unit of activity. For example, greenhouse gas emissions from fuel consumption are based on the liters of fuel consumed and stoichiometric relationships for the amount of CO_2 emitted per each liter of fuel. Emissions from pipelines are estimated from leakage size and leakage rates per unit length of pipelines. The data inputs come from major international sources, such as the International Energy Agency, and the Food and Agriculture Organization (FAO). In the United States, the US Geological Survey and the National Oceanic and Atmospheric Administration provided inputs, while globally private sources like BP PLC and the Global Gas Flaring Reduction Partnership also contributed data [17,20].

EDGAR emission's data are distributed spatially based on a wide array geographic and demographic data, such as population size, locations of electricity generation, fuel consumption, agricultural usage, and oil and gas infrastructure. The result is a series of maps with key atmospheric constituents with a spatial resolution of

0.1 x 0.1 degree. A full description of data generation methods are available at multiple sources [17,20].

The EDGAR database provides a globally comprehensive measure of emissions for the major greenhouse gasses (CO_2 N_2O, CH_4). CO_2 is broken down in two components, short cycle CO_2 (abbreviated here as CO_2-excel) which is mostly fossil fuel emissions and CO_2-org, which is short-term biomass burning [17]. These two are also added to yield total CO_2 emissions- CO_2-tot. The dataset does not include other parts of the carbon cycle, such as photosynthesis or natural respiration. EDGAR also contains data on the fluxes of major air pollutants, including CO, NH_3, NO_X, SO_2, non methane volatile organic compounds (NMVOC), organic carbon (OC), black carbon (BC), mercury (Hg), coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$). NMVOC data are further broken down into individual volatile organics compounds, of which benzene and formaldehyde are reported here. Mercury (Hg) fluxes presented here include data for the three major categories prevalent along the Gulf of Mexico; Hg from combined industry and power, Hg from other industrial sources (including oil refineries) and residential sources, and Hg from cement production. All datasets begin in 1970 and carry into the 21st century. Greenhouse gasses are calculated up to 2018, most major air pollutants are calculated up to 2015, while Hg, benzene and formaldehyde are calculated up to 2012.

Maps of greenhouse gasses and air pollutants based on the raw EDGAR data, are presented in Figure 2. Figure 3 presents changes in greenhouse gas emissions and air pollutant fluxes relative to the year 1970.

Figure 2. Maps of annual fluxes the major greenhouse gasses and air pollutants discussed in this paper, as determined from EDGAR.

Figure 3. Maps of the difference in the annual fluxes of greenhouse gasses and air pollutants from their value in 1970, as determined from EDGAR data.

To further understand industrial sources of emissions, we developed maps of greenhouse gas emissions from facilities, using self reported data provided to the US EPA as mandated by US Greenhouse Gas Reporting Program (https://ghgdata.epa.gov/ghgp/main.do). The data source is referred to as the Facility Level GHG Emissions Data Tool, or FLIGHT [25]. FLIGHT contains self-reported data for all facilities that emit over 25,000 metric tons per year of carbon dioxide equivalent (CO_2e), while many facilities that emit less than this threshold also report. Data is available for the period 2011-2020. Presented in Figure 4 are data for the year 2015, the most recent year for which all greenhouse gas and air pollutant data is available (except for Hg, formaldehyde and benzene.)

Figure 4. Data on emissions from large facilities, as obtained from the US Environmental Protection Agency Facility Level Information on Greenhouse gasses Tool (FLIGHT) for the year 2015. This year was chosen as it is the most recent year for which all EDGAR data, except Hg, benzene and formaldehyde are available.

Emissions calculations

Total annual fluxes of emissions of EDGAR data were calculated for each parameter for each year for several spatial regions. These regions include the states of Louisiana and Mississippi, and each parish or county in those states. (Parish and county are the equivalent level of governance, and the nomenclature difference reflects differing Francophone and Anglophone histories of Louisiana and Mississippi).

Additionally, we calculated emissions in a corridor in the State of Louisiana along the Mississippi River that extends from the start of the Mississippi River's largest distributary at the Old River Control Structure to the town of Phoenix, and extended 10 km in each direction (Fig 1). This corridor is an area of longstanding interest; it has many of Louisiana's industrial facilities, the state's largest two metropolitan areas (New Orleans and Baton Rouge), as is also a long-standing area of concern for the health and environmental justice communities [14,26,27]. While definitions of this area, in this paper termed the, "Mississippi River Industrial Corridor," have varied from source to source, the region chosen here reflects well known geographic patterns, and is also consistent with spatial scale of the EDGAR data (10 km is approximately the width of one EDGAR grid square).

For each region, we calculated the annual flux from EDGAR grid squares within the region, converting data available as kg m^{-2} s^{-1} to metric tons $region^{-1}$ yr^{-1} using standard mathematics. In cases where EDGAR grid squares spanned more than one polygon, values were prorated by the percentage of grid square within each polygon. We used these annual fluxes to develop time series for each emissions category for the two states and the Mississippi River industrial corridor, and these data are presented in

Figure 5. Data for each county/parish are available in the supplemental data section. These calculations were performed using code that is provided and documented in the supplemental material (S1, S2, S3). Lists of annual emissions for Louisiana, Mississippi and the Mississippi River Industrial Corridor are also presented in the supplemental material (S4, S5, and S6 respectively), as is the original data from the EPA FLIGHT database (S7).

Figure 5. Time series showing the change in the annual flux of each greenhouse gas and air pollutant for Louisiana, Mississippi, and Louisiana's Mississippi River Industrial Corridor, as determined from the EDGAR data.

Demographic data sources

To understand how patterns of emissions are related to demographics, we obtained public domain demographic data for the states of Louisiana and Mississippi from the US Census Bureau, the primary US-federal source for such information. Used in this paper primarily is data from the Decennial Census, which is supplemented with the information from the American community survey for the year 2015, and for poverty data for the year 2010, (in 5-year averages) as per census bureau data collection protocols. To assist in obtaining these data, we used the service Social Explorer, a third-party website that compiles US census data for ease of downloading [28].

Data used comprise the percent Black alone, and the percentage White alone. In the American deep south, the vast majority (88-99%) of people are typically classified as either White or Black alone. Poverty data is expressed as the percentage of families living beneath the US-federally defined poverty line, which in 2015 was $20,090 for a family of four. Data are presented as maps of race and poverty at the parish/county level for the years 1970, 1980, 1990, 2000, 2010, and 2015 (Fig. 6). These data are also presented as showing the changes in race and poverty for the periods 1970-1990 and 1990 - 2015 (Fig. 7).

Figure 6. Maps showing the percentage of Black residents for each parish/county as determined from the US Census. Left, time series for years 1970-2015. Center top, change map, 2015 vs 1970. Right. Annotated map for the year 2015.

Figure 7. Maps showing the percentage of families living below the poverty level for each parish/county as determined from the US Census. Left, time series for years 1970-2015. Center top, change map, 2015 vs 1970. Right. Annotated map for the year 2015.

Results

Spatial patterns of emissions

Data from EDGAR provide a granular view of emissions in Louisiana, Mississippi and across the region, allowing one to observe the impacts of industrialization, urbanization, agriculture, and in some cases roadways and shipping corridors as sources (Fig. 2). Easily visible in these data are cities and industrial areas (large concentrated areas of emissions), major roadways (linear areas of emissions connecting cities) and some agricultural areas (large areas of moderately concentrated emissions).

In Louisiana, one key region of emissions is the Mississippi River industrial corridor, objectively defined in this paper as a 400 km reach (including meanders) extending from the Old River Control Structure to Phoenix, LA, and extending 10 km in each direction from the river (Fig. 1, See Methods). Here, emissions of CO_2, CH_4, SO_2, CO, NO_X, BC, PM_{10}, $PM_{2.5}$, and Hg are at or near their highest levels in the state of Louisiana. Southwest Louisiana, including Calcasieu Parish and the Sabine River corridor along the Texas Border (Figure 2), also stands out as a region with high emissions of CO_2, NMVOCs, BC, PM_{10}, $PM_{2.5}$, SO_2, and Hg. There are hotspots of some constituents, including CO_2 (both short-cycle and organic), CH_4, and NMVOCs in northwest Louisiana, while CH_4 also shows a broad diffuse pattern in southwest Louisiana. In the neighboring state of Mississippi, there were fewer total emissions and fewer areas of highly concentrated emissions. Two notable exceptions to this pattern were NH_3, which is concentrated in central Mississippi, and N_2O, which is present along the upper Mississippi River, Louisiana's coastal zone, and to a lesser extent along the Red River.

Maps of temporal changes in emissions (Fig. 3) show some large spatial-scale reductions around cities, and broad spatial-scale increases in NH_3 across central Mississippi, as well as meso-scale changes (increases and decreases) along the Mississippi River, Sabine River, and near Lake Charles Louisiana. Some small spatial scale changes (single pixel - 0.1^o x 0.1^o) are also apparent in these data- for example, NO_x increased along the Mississippi River between New Orleans and Baton Rouge, and CO_2excel increased at the southern end of Bayou Lafourche.

An additional metric of greenhouse gas emissions is the US EPA's Facility Level Information On Greenhouse gasses Tool (FLIGHT; Fig. 4), which provides self-reported emissions of greenhouse gasses from all facilities that emit more than 25,000 metric tons of carbon dioxide equivalent (CO_2e) per year. These data show similar spatial patterns of emissions- particularly in Louisiana, where the lower Mississippi River corridor and the Lake Charles/Calcasieu Parish region stand out as areas of concentrated emissions. Other areas of large facilities include northwest Louisiana, and to a lesser extent around smaller cities including Pascagoula, MS and Jackson, MS.

Temporal trends in emissions: Louisiana

Figure 5 presents statewide temporal trends from 1970 to 2018 for greenhouse gasses and air pollutants of health concern in Louisiana, Mississippi and the Mississippi River Industrial Corridor. Annual total CO_2 (CO_2tot; CO_2excel + CO_2org) emissions for Louisiana ranged between 119 million and 187 million metric tons, and followed a quasi-sinusoidal trend, with a low in 1983, a high in 1998, and a 2018 value that was over 10 million metric tons greater than the 1970 value. The overwhelming majority of CO_2 emissions were CO_2excel, which is mostly fossil fuel consumption.[17] Methane emissions in Louisiana ranged between 352,000 and 463,000 metric tons per year, and also followed a quasi-sinusoidal pattern, with the high reached in 1981, the low reached in 2009 and the 2018 value near the higher end of this range. Louisiana’s N_2O emissions exhibited a quasi-asymptotic trend, decreasing from 38,000 metric tons per year in 1979, and reaching a lower plateau near 20,000 metric tons per year in the 2010s.

Louisiana's statewide SO_2 emissions exhibited a slight increase in the early 1970s, reaching a high of 768,000 metric tons in 1978, followed by a quasi-asymptotic decrease that reached a low of 132,000 metric tons in 2015. NO_x emissions ranged between 311,000 and 475,000 metric tons, with higher values in the 1970s, between 1985 and 2000, and after 2010. Statewide NH_3 increased from 21,000 metric tons in 1970 to nearly 42,000 metric tons in 2006, and stabilized near that level thereafter. Broadly speaking, NMVOCs exhibited a quasi-asymptotic statewide decrease in Louisiana, from > 386,000 metric tons in 1970 to 247,000 metric tons in 2009, followed by a slight increase afterwards. Also presented in Figure 5 are statewide trends in benzene (which generally decreased statewide) and formaldehyde, which experienced a quasi-asymptotic pattern. Statewide, PM_{10}, $PM_{2.5}$, and BC generally fluctuated around a mean, though PM_{10} and $PM_{2.5}$ decreased in later years while BC increased slightly. Statewide Hg emissions generally trend downward from over 6 metric tons per year in the early 1970s, to between 1.2 and 1.8 metric tons per year in 2010s.

Temporal trends in emissions: Louisiana's Mississippi River Industrial Corridor

The Mississippi River industrial corridor accounted for a considerable portion of Louisiana's total emissions. Over the periods for which data are available for each constituent, this region accounted for 46.2 to 55.1% of CO_2tot, 13.7 to 17.1% of CH_4, and 28.8 to 37.1% of N_2O emissions. The region also accounted for 32.6 to 44.8% of NO_x, 5.4 to 11.8% of NH_3, 45.2 to 55% of SO_2, and 25.6 to 32.8% of NMVOC emissions. In terms of specific NMVOCs, this corridor was responsible for 23 to 33% of statewide benzene emissions and 20 to 29% of formaldehyde emissions. The region was responsible for > 30% of BC emissions, > 24% of PM_{10} emissions, > 26% of $PM_{2.5}$ emissions, 35 to 41% of Hg emissions in Louisiana. Doubling the width of the area (20 km on each side of the river), resulted in only a modest increase (5 to 20% for most constituents), further demonstrating the concentrated nature of emissions in this corridor (S6). Also calculated are emissions totals for each parish/county. These data are presented in the supplemental online material, and in some cases differ from statewide trends.

Temporal trends in emissions: Mississippi

Mississippi's greenhouse gas fluxes exhibited similar statewide temporal patterns in emissions as Louisiana, though often with different magnitudes and rates of change. For example, statewide CO_2tot emissions in Mississippi also fluctuated in a quasi-sinusoidal pattern, though Mississippi's emissions were lower than Louisiana’s (85 million vs 146 million metric tons in 2018). N_2O statewide emissions also experienced a quasi-asymptotic decreasing trend, though Louisiana's starting magnitude, and percentage of decrease is greater. One area of difference; Mississippi's CH_4 statewide emissions gradually increased from 1970 to 2010, whereas Louisiana's CH_4 emissions were quasi-sinusoidal, and higher in magnitude.

For many air pollutants there were similar trends in the two states, though fluxes were generally higher in Louisiana than Mississippi. For example, SO_2 trends were generally negative in the two states, though total fluxes were greater in Louisiana. NMVOCs exhibited statewide declines in both Louisiana and Mississippi, though

Louisiana's fluxes are typically about 1.4 times more extreme than Mississippi's. Furthermore, while statewide $PM_{2.5}$ fluxes in Louisiana declined slightly, Mississippi's statewide fluxes increased slightly. Mercury fluxes in Mississippi were largely consistent over time, (~25% variation between 1970 and 2012), which contrasts with Louisiana's decline from 6.8 to 1.2 metric tons per year between 1978 and 2012. An additional contrast; NH_3 fluxes were generally greater in Mississippi than Louisiana. Also noteworthy, certain parishes in Louisiana and counties in Mississippi had trends that contrasted with the corresponding statewide pattern, the significance of which is elaborated on in the discussion section.

Spatial and temporal patterns in race

Overall, the largest geographic area with a predominantly Black population is the "Mississippi Delta (Fig. 6)." This is the region on both the Louisiana and Mississippi sides of the Mississippi River (though larger on the Mississippi side of the river) that extends from about 50 km north of Baton Rouge to the northern edge of Mississippi. (The Mississippi Delta also extends into neighboring Arkansas- not shown here. It is also different from the geologically defined Mississippi River Delta that contains the wetlands of south Louisiana.) In Louisiana, there are also a concentrations of Black residents along the Mississippi River Industrial Corridor, the Red River corridor (which follows a NW-SE line that runs approximately from Caddo and Bossier Parishes to Pointe Coupee Parish), and in the major cities. In Mississippi, in addition to the Mississippi Delta, there are also large Black populations near Jackson, MS, and near the state's eastern border. Mississippi and Louisiana respectively had the highest and second-highest percentages of Black residents of any state in the United States (37.7 and 32.2% in 2017).

In general, the percentage of White and Black residents stayed relatively constant in both Louisiana and Mississippi during the period 1970-2015, with a few notable exceptions. In Louisiana, there were increases in the percentage of Black residents in Orleans Parish and its suburbs of Jefferson and St Bernard Parish, as well as in East Baton Rouge Parish and along the Mississippi Delta. In Mississippi there was also an increase in the percentage of Black residents in the Mississippi Delta. In Mississippi, there was an increase in the Black population of Hinds County, where the state capital is located, and an increase in White residents in neighboring Madison and Rankin counties Overall, these patterns are consistent with a picture of states with relatively large endemic populations, little inward migration, and some changes in the White/Black ratios in cities and their surrounding suburbs. Also notable, Mississippi and Louisiana had the two highest percentage Black residents in the United States, (37.6% for Mississippi 32.2.% for Louisiana in the 5-year period centered on 2015).

Geographic and temporal patterns in poverty

Spatial and temporal patterns in poverty follow somewhat similar patterns as the patterns in race (Fig.7). In general, the highest poverty rates were found in the Mississippi Delta in both Louisiana and Mississippi. Additional high levels of poverty were found in northwestern Louisiana, south-central Louisiana, and eastern Mississippi. The biggest overall temporal trend is the reduction in poverty in the Mississippi Delta, though with poverty rates in the 20-40% range in 2015, poverty rates here are still several times the national average. In 1970, Louisinaa's poverty rate was nearly double the national average (21.5% vs 10.7), while Mississippi' was almost triple the national average (28.9% vs 10.7%). By 2015, statewide poverty values had decreased, but were still higher than national averages (14.3 % in Louisiana, 21.5 % in Mississippi vs 8.6% nationally.)

Discussion

Geographic concentration of Louisiana's greenhouse gas and air pollutant fluxes

Results from this study indicate that greenhouse gas and air pollutant fluxes in Louisiana are concentrated in a few relatively small areas; and particularly the Mississippi River Industrial Corridor. While this corridor comprises less than 5% of Louisiana's total area, it accounted for 26 to 55% of the emissions of two major greenhouse gasses (CO_2 and N_2O) and several major air pollutants (SO_2, NO_x, NMVOCs, BC, $PM_{2.5}$; Table 2). Definitions of geographic boundaries of the industrial corridor have varied in the scientific literature [26,30,31]. For example some authors used a 7-parish region [32], while others used an 11-parish region [33]. These disagreements point to the need for high quality, high resolution emissions data in regions where there are ample environmental health concerns l[4,14,26,34].

Results presented here indicate that high-spatial resolution data, like EDGAR [17] can provide an objectively defined region where changes in emissions can be tracked across both space and time [17]. The Industrial Corridor as defined here follows well established geographic patterns in the Mississippi River [29,35], and extends from the Mississippi River's major distributary (i.e. the Old River Control Structure) to the southernmost refinery along the river (Myrtle Grove, LA). This definition includes large population centers and rural areas, has a width (10 km) that is comparable to an EDGAR grid square[17] (0.1^{o}), and a total length of 425 km (including meanders). This corridor also has large communities of Black residents, contains areas with high poverty rates, providing opportunities to examine patterns of environmental justice quantitatively and qualitatively [4,26,36,37].

Industrial drivers of greenhouse gas emissions and air quality hazards: Louisiana

Comparing EDGAR-derived maps of greenhouse gas and air pollutant fluxes to maps of greenhouse gasses fluxes from large facilities (i.e. EPA's FLIGHT database) indicates a strong overlap, particularly along the Mississippi River Industrial Corridor (Fig. 8). This corridor included seven of Louisiana's top 10 GHG emitters in 2015, with individual facility emissions ranging from 2.8 million to 8.0 million metric tons of CO_2e annually. Facilities along this reach of the Mississippi River included, but were not limited to, oil refineries, fertilizer plants, iron smelters, power plants, and chemical manufacturing plants [25]. Additional overlap between datasets is also noteworthy in Calcasieu Parish, where there are numerous refineries and petrochemical facilities near Lake Charles, LA (Figs 4, 8). These maps also allow one to identify other areas of emissions hot spots, such as one associated with gas extraction in northwest Louisiana, or individual large facilities such as the Brame Energy Center in Rapides Parish, LA (Figs. 1,4, & 8).

Figure 8. Map showing the overlay between major greenhouse gas emissions and air pollutants, as determined from EDGAR, and greenhouse gasses fluxes from large facilities as determined from EPA's FLIGHT database.

Louisiana's industrial emissions: Infrastructure and economic factors

The spatial pattern of Louisiana's emissions is partially linked to the region's water-based economy. The lower Mississippi River is the largest pathway for waterborne commerce in the United States on a tonnage basis (S8). In 2018, the reach of the river between New Orleans and Baton Rouge, (comparable to, but somewhat smaller than, the industrial corridor defined in this paper) carried 381 million metric tons of commerce, of which nearly 41% (157 million metric) was oil, petroleum, refined products, chemical, petrochemical, and an additional 9% (38 million metric) was coal or coal coke [38]. The Lake Charles waterborne pathway in Calcasieu Parish carried 52 million metric tons of commerce in 2018, of which over 90% were directly linked to petroleum, petroleum products or petrochemicals [38]. In contrast, Mississippi's largest port, Pascagoula, carried 25 million metric tons of commerce in 2018, of which over 95% were petroleum related [38]. In addition to waterborne commerce, Louisiana has extensive rail and pipeline networks that connect industrial facilities to oil and gas supplies and end users across the United States. In our interpretation, this infrastructure network contributes to Louisiana's distinctive emissions pattern, whereas neighboring Mississippi, which otherwise is similar in land area and demographics, does not have a similar network, leading to fewer facilities, fewer emissions and less concentrated emissions.

To some extent, Louisiana's spatial pattern in emissions is the result of specific infrastructure siting decisions, reflecting how datasets like EDGAR and FLIGHT can reveal importance of historical events on modern activities. Most large facilities on the

Mississippi River are south of Huey P. Long Bridge on highway US-190 between Port Allen and Baton Rouge, LA. This bridge, completed in 1940, marks the northern end of the deep-draft section of the Mississippi River, and has a low air draft, both of which prevent large vessels from steaming northwards to ports in Mississippi [39]. This navigation restriction helps concentrate industrial facilities and their associated emissions along Louisiana's lower Mississippi River Industrial Corridor, and shows how decisions made decades ago impact climate and potentially health today.

Emissions in Louisiana: Demographic and historic factors

This spatial pattern is significant because the Mississippi River has a long-standing environmental justice concerns [10,15,16,40]. Almost all parishes/counties along the Mississippi River in these two states -including both the Mississippi River Industrial Corridor and the Mississippi Delta have a proportion of Black residents that is higher than national averages, and many have a proportion of Black residents that is higher than corresponding state averages (Fig. 6). Results from this study show that the Mississippi River Industrial Corridor, which accounts for about ¼ to ½ of Louisiana’s emission of two greenhouse gasses and several air pollutants, is an area with numerous Black communities. Many of the parishes in this region have a greater percentage of Black residents than the state average. In contrast Calcasieu Parish, which is Louisiana's single highest emitting parish of most greenhouse gasses and air pollutants, has a smaller percentage Black population than the statewide average. While the spatial resolution of the EDGAR dataset is too coarse to examine neighborhood or census-tract level emissions, where linkages between race and exposure are often greatest [10,17,25], these maps provide a critical step forward to focus further studies, in Louisiana, the United States, and internationally.

Temporal patterns in emissions: Potential drivers

Temporal trends in emissions appear to be linked to regulatory and economic patterns that can have either synergist or antagonist impacts on statewide and/or parish-level emissions. These drivers include increased energy demand for fossil fuels (which increases GHG emissions), changing air quality regulations, a shift in power sources from coal and oil to gas (which can decrease emissions of certain pollutants), increased extraction of gas and the development of new gas-related activities along the Gulf Coast (which cause an increase in some emissions)[52–54].

Louisiana's CO_2tot emissions illustrate some of these drivers (Fig. 5). Total CO_2 (and CO_2-excel) emissions fluctuated in the early 1970s, as domestic energy consumption fluctuated with demand and international oil embargos [55]. These emissions decreased between 1978 and 1983, reflecting, in part, a recession in the Gulf of Mexico's oil and gas industry. (This recession's impacts are also visible in the increase in poverty rates that occurred in both Louisiana and Mississippi between 1980 and 1990 [Fig. 7]). CO_2tot emissions increased between 1983 and 2000, reflecting growing oil production in the Gulf of Mexico and associated refining in Louisiana. These emissions declined between 2000 and 2011, reflecting increases in energy efficiency and a shift from coal and oil to gas [56], and then increased after 2011 as efficiency improvements were outweighed by an increase in total production. These findings are generally consistent with a recently released inventory of greenhouse gasses for the State of Louisiana [56].

Some of these trends are reflected in sector data in the FLIGHT database[25]. According to this source, between 2011 and 2018, Louisiana's greenhouse gas emissions from the power sector declined from 53.4 to 42.6 million metric tons of CO_2e, reflecting the fuel shift from coal to natural gas [56]. At the same time, emissions from the natural gas and petroleum systems sector (which is the production and transportation of these materials), increased from 16.2 to 20.8 million metric tons of CO_2e, and emissions from the chemical sector increased 36.3 to 39.8 million metric tons of CO_2e.

Emissions of several air pollutants decreased in Louisiana and Mississippi over the time period of this analysis. Most significantly is SO_2, which decreased by nearly 80% in Louisiana, Mississippi, and within the Mississippi River corridor. This decrease likely reflects the Clean Air Act, (passed in 1970, and modified in 1990), which regulates SO_2, a period of increased regulation in Louisiana during the late 1980s and early 1990s, and a fuel shift away from coal (which is often high in sulfur) to less sulfur-rich fuels like gas [54,56,57]. However, the scale of decrease is smaller in the ozone precursors NO_x, NMVOC and CH_4. In Louisiana, NO_x decreased by 20%, NMVOCs by 33%, while CH_4 increased by 13% over the time of this analysis. In the Industrial Corridor there was a 19% decrease in NO_x, NMVOCs and a 31% increase in CH_4.

Closer parish-wide analysis shows individual counties/parishes with trends that stand in contrast to statewide trends. For example, in Louisiana's Ascension parish (located within the Mississippi River industrial corridor) CO_2-tot emissions doubled between 1970 and 2018, while N_2O emissions trended upwards, and NO_x values increased by 50% between 1970 and 2015. This pattern is likely driven largely by the CF Industries Nitrogen Plant in Ascension Parish, which increased CO_2e emissions from 6.4 x 10^6 metric tons in 2010 to 8.7 x 10^6 metric tons in 2018, becoming Louisiana's largest single greenhouse gas emitter. Another relevant contrast, in Calcasieu Parish, where several large gas utilizing facilities were constructed in the 21st century, CH_4 emissions increased by 51% between 1970 and 2018, and NH_3 emissions increased by 59% between 1970 and 2015.

Patterns of NMVOCs are particularly noteworthy, as this category includes toxics, carcinogens, and ozone precursors. While Louisiana's overall NMVOC emissions decreased by about 32% between 1970 and 2015, in the Mississippi River corridor that decrease was less than 20% (Fig. 5). In some parishes, the decrease was even less- including St John the Baptist Parish, (3% decrease), St. James Parish (5%) and St. Charles Parish (10%; See Supplemental Data). Furthermore, in the Mississippi River industrial corridor, emissions of CH_4- both a greenhouse gas and an ozone precursor, increased by 31% between 1970 and 2015, and by 36% between 1970 and 2018 in the industrial corridor (Fig. 5). When viewed at the pixel level (Fig 2, 3), higher resolution patterns emerge, including long-term increases in NMVOCs, formaldehyde, and NOx at individual locations along the Mississippi River corridor, likely reflecting the build-out and development of particular facilities. Calcasieu Parish, another industrial center, had the highest NMVOC emissions of any parish, which ranged between 22,500 and 27,400 metric tons per year, decreasing by only 8% between 1970 and 2015. These patterns are consistent with industrialization in Louisiana; there were 143 industrial facilities that reported emissions to the Louisiana Department of Environmental Quality (LDEQ) in 1991; by 2019, there were 747 (LDEQ, 2021).

National and global significance of Louisiana's hotspots

Results presented here are consistent with other data indicating that Louisiana has among the highest total emissions of greenhouse gas and air pollutants of any state in the US, a country that is one of the world's emitters. Louisiana typically ranked in the top 3 to 7 states for greenhouse gas emissions over the past 3 decades- though results varied slightly with agency, methods, and whether emissions were energy-related CO_2 emissions or multiple greenhouse gasses [56,58,59]. It also ranked high in emissions of air quality hazards. The EPA's Toxic Release Inventory, which tracks emissions from industrial facilities that meet certain reporting requirements, indicates that Louisiana ranked between 11th and 1st in emissions of air toxics by mass for the period 2007-2018[18]. Louisiana's rank declined over this time frame, which took place as other states reduced their emissions, while Louisiana's emissions stayed approximately the same[18]. Louisiana's high emissions of greenhouse gasses and air pollutants, and high poverty, stand in contrast to its geographic area, and population size, and gross domestic product which are in the middle of US states [60,61].

For comparison, Louisiana’s total greenhouse gas emissions, which in 2018 were about 242 million metric tons of CO_2e,[56] were comparable to Iraq (166 million metric tons of fossil fuel CO_2/352 million metric tons CO_2e), and The Netherlands (164/222 million metric tons of fossil CO_2/CO_2e), of the same order of magnitude, but slightly smaller than Canada (591/762 million metric tons of fossil CO_2/CO_2e), and Italy

($342/418$ million metric tons of fossil CO2/CO_2e)[63]. These comparisons shows how relatively small areas, in this case the Mississippi River Industrial Corridor and Calcasieu Parish, can have emissions that are of national, if not global, significance.

Linkages to environmental justice concerns

Members of the scientific community, environmental advocates, and senior government executives have expressed a concern for adverse health impacts, and particularly cancer, in Black and impoverished communities in the Mississippi River corridor [13–16,64]. Our analysis indicates that the region that extends from Baton Rouge, LA to Phoenix, LA accounts for 26 to 55% of Louisiana's emissions of several greenhouse gasses and pollutants of health concern over the past 5 decades, despite consisting of less than 5% of the state's area. While elucidating the public health impacts of the industrial corridor is beyond the scope of this study, our findings provide geographic evidence that health-related investigations are clearly warranted. Furthermore, the time varying maps and time series we generate (Figs 2,3, and 5) provide a tool to forensically develop exposure records, a critical need given both many years of exposure that are often needed to develop cancer, and the historical inequalities many communities in Louisiana have experienced.

More broadly, two other patterns emerge. First, the different trends between those that occur at the statewide level and those that occur at the parish, corridor, or pixel level but instead mark areas of environmental justice concern. In the industrial corridor, emissions can occur near historically Black and poor communities, such as Romeville, Welcome, and Reserve where scholars have noted long standing environmental communities (Figs 1,2,3 8) [10,34]. Second, the multiple trends and fluctuations in statewide greenhouse gas fluxes potentially leads to series of, "shifting baselines." When viewed in the context of the spatial variability described above, this could confound, or confuse, regulatory decisions about whether a community's air quality was improving or deteriorating. Regulators may view air quality as improving when it is not improving for those most vulnerable- a concern in the American South and across the world.

While there is evidence, in this study and in other research to support environmental justice concerns [10,26,30], we note that we did not find simple statistical relationships between space, time, race and emissions- for two likely reasons. One is the issue of scale. EDGAR pixels, at 0.1º x 0.1º or ~10 km x 10km, are often too coarse to resolve racial and economic differences in Louisiana, which often vary at spatial scales of 0.5 ~ 5 km [11,65,66]. Also, to note, is the history of the petrochemical industry in Louisiana. It is over a century old and some of Louisiana's largest currently-operating refineries were initially constructed before 1920[67,68]. Growth in facilities occurred during multiple time periods, including post-World War II era (~1945- 1980) and since ~2014, after domestic oil and gas production increased through hydraulic fracturing [12,64,69]. During this century, there have been multiple large-scale trends that have influenced the movement of both White and Black communities across the south [65,66,70], complicating efforts to understand these interactions. While our results alone cannot address every statistical relationship, when viewed contextually [10,11,26], present a strategic map to study the intersectionality between atmospheric science, sociological, and oncology - particularly in communities with reduced access to science and monitoring.

Conclusion: Portrait of an energy state and broader implications

The data presented herein present an increasingly complete picture of the overlap between emissions of greenhouse gasses, air pollutants, race and poverty. Results from this region provide several potentially globally generalizable findings. 1) In Louisiana, a disproportionately large quantity of emissions occurred in a few relatively small regions. The most significant of these areas, the Mississippi River Industrial Corridor, a region with historic Black communities, indicates how minority groups can receive a disproportionately large degree of air quality hazards associated with greenhouse gas emissions. 2) Trends at the state, country or province-scale may differ substantially from those at the local level, which when viewed in the context of (1), results suggest that metrics of air quality improvements could overlook trends at the spatial scale of most concern for historically marginalized communities. 3) Historical emissions reconstructions like EDGAR are particularly useful in poor, minority, and historically marginalized communities, where a lack of resources -or will at the agency level, has monitoring efforts needed to understand air quality hazards, and their health and climate impacts. Given global, national, and local efforts to reduce emissions, as well as emerging and longstanding justice concerns, findings presented herein and their source data, provide a guide to reducing environmental risks as climate goals are addressed.

Acknowledgements

The authors thank Marilena Muntean and Diego Guizzardi from the European Commission's Joint Research Centre, Directorate for Energy, Transport and Climate for very helpful conversations regarding the EDGAR dataset and its scientific implications. Margo Moss, Kim Terrell, Gianna St. Julien and Jane Patton provided comments on earlier drafts of this manuscript.

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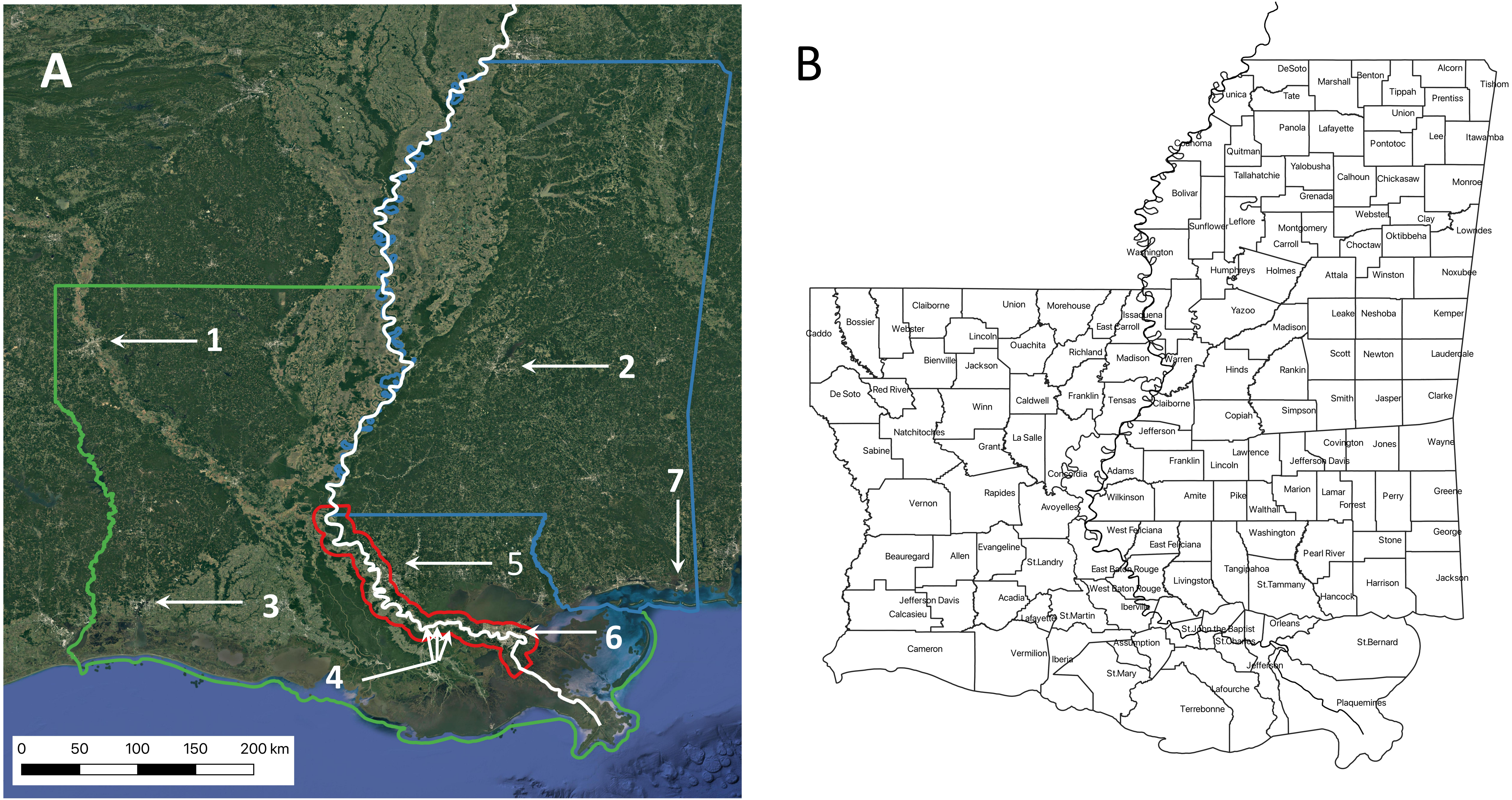
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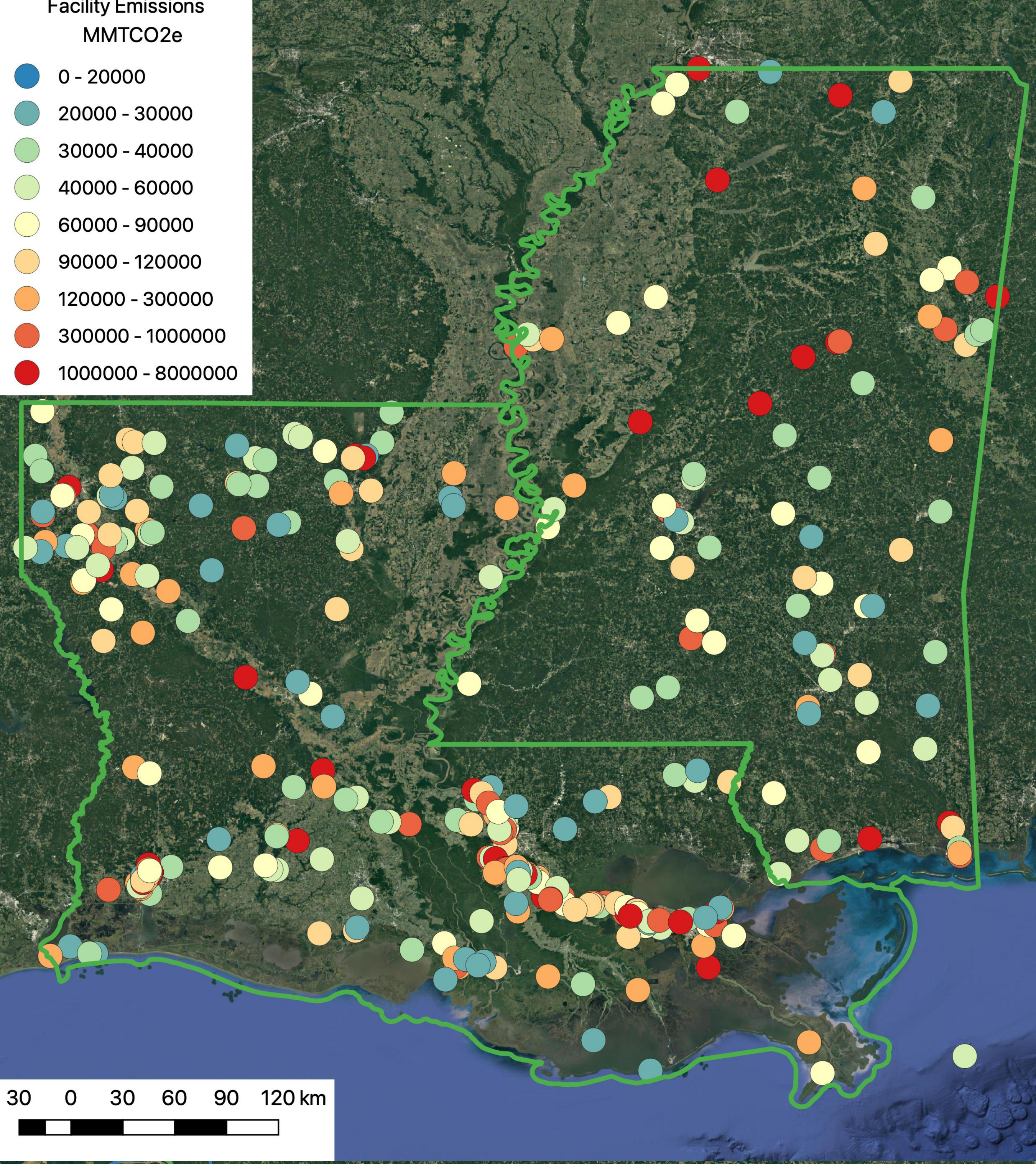
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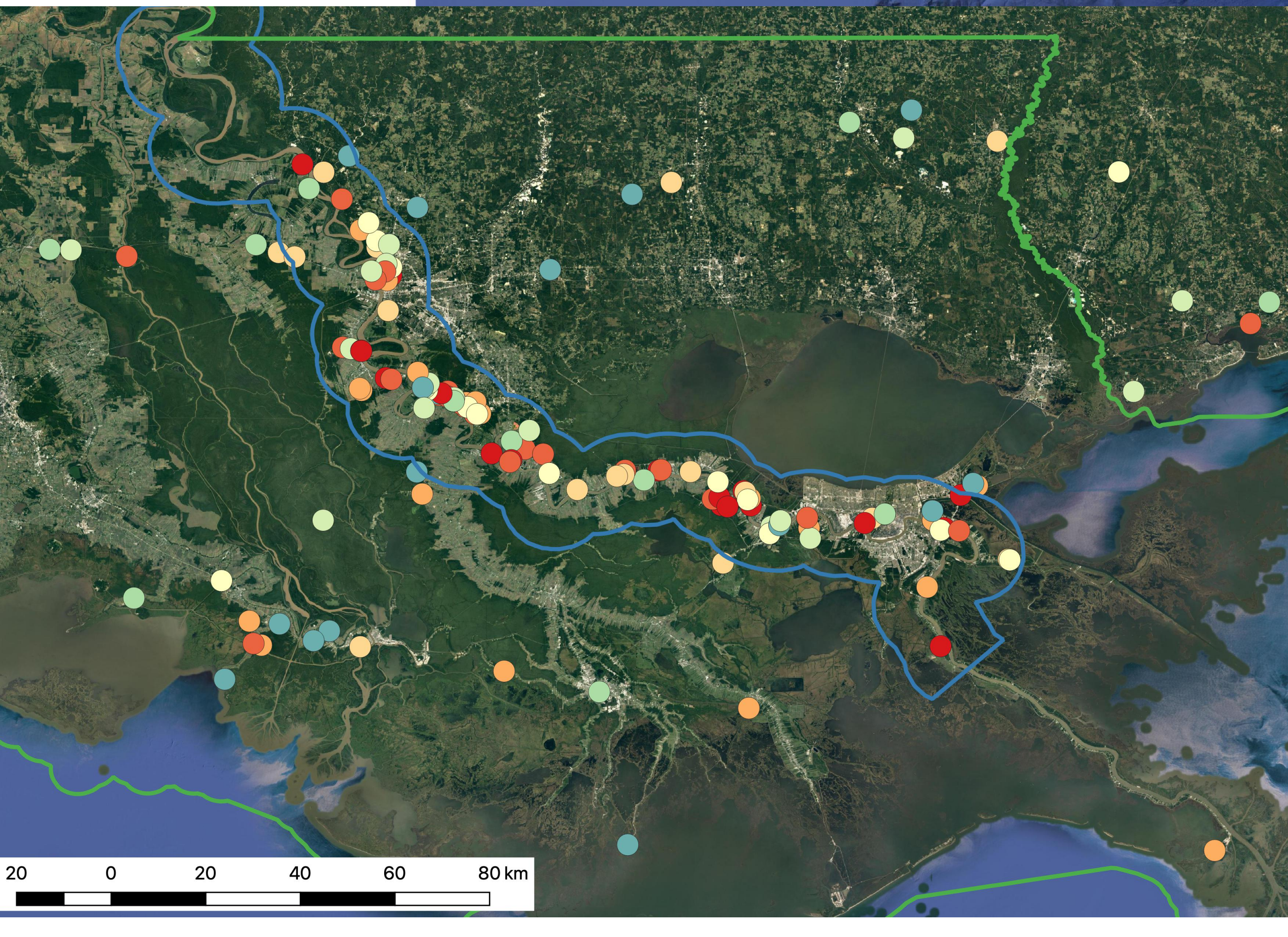
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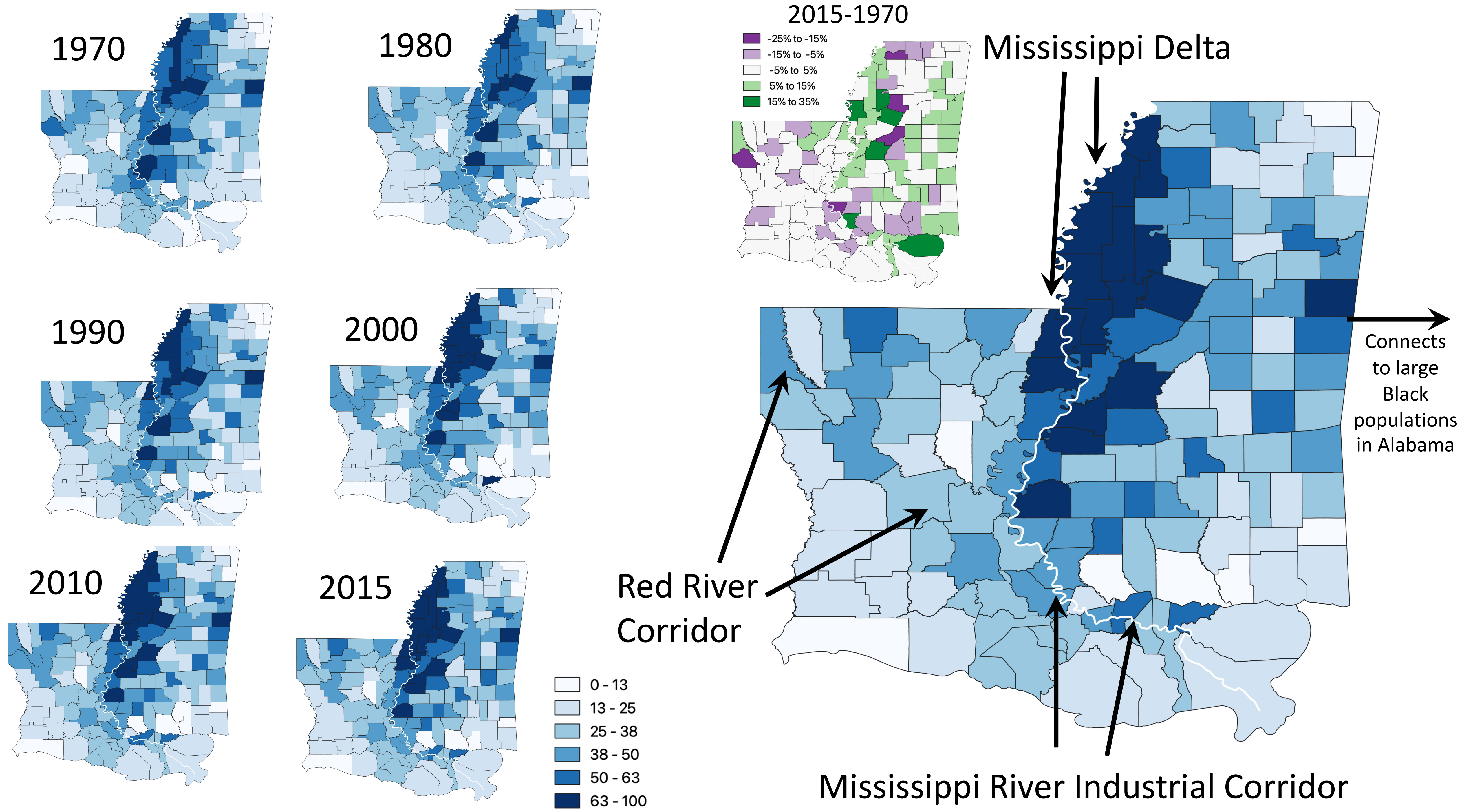
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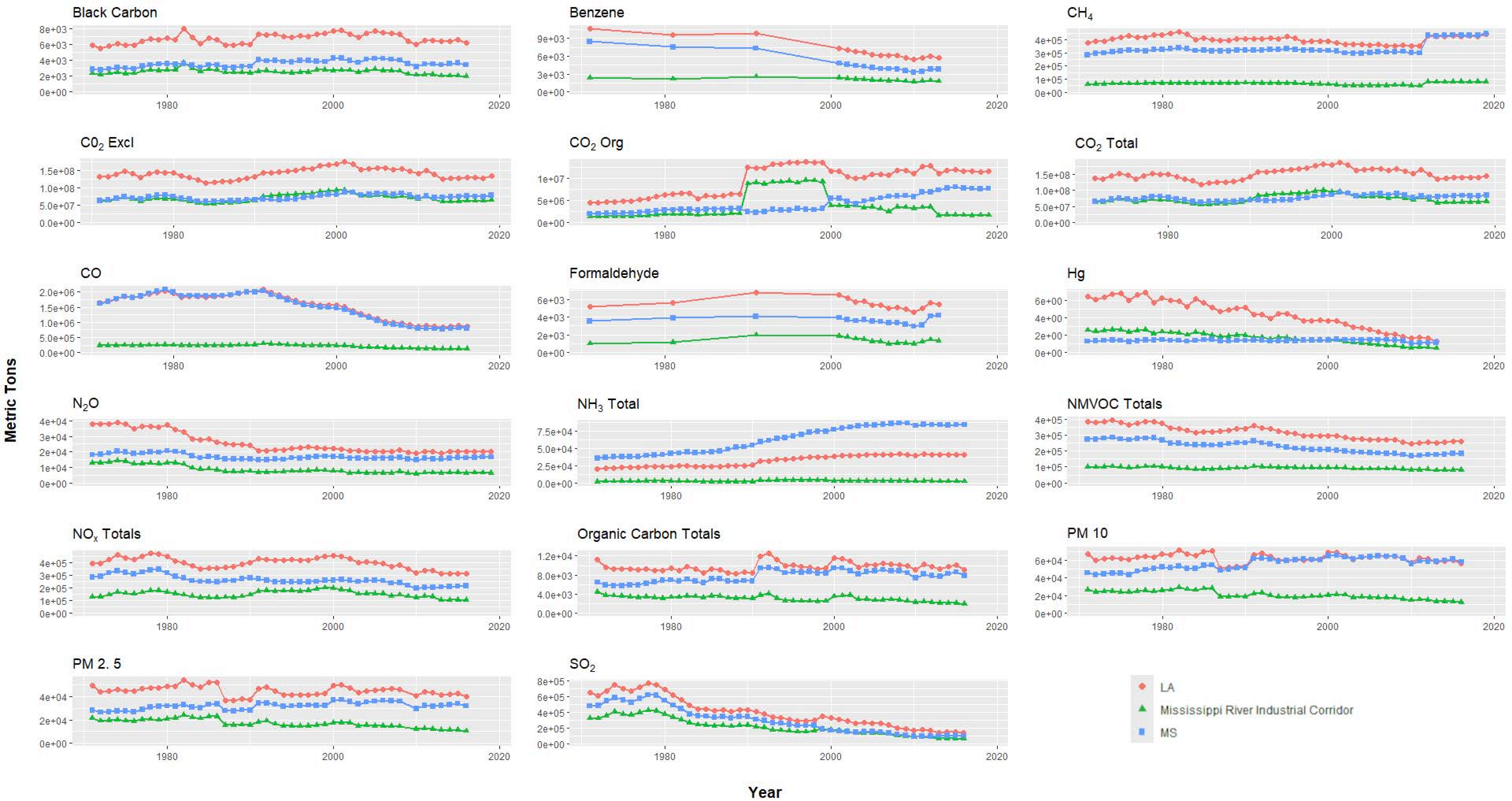
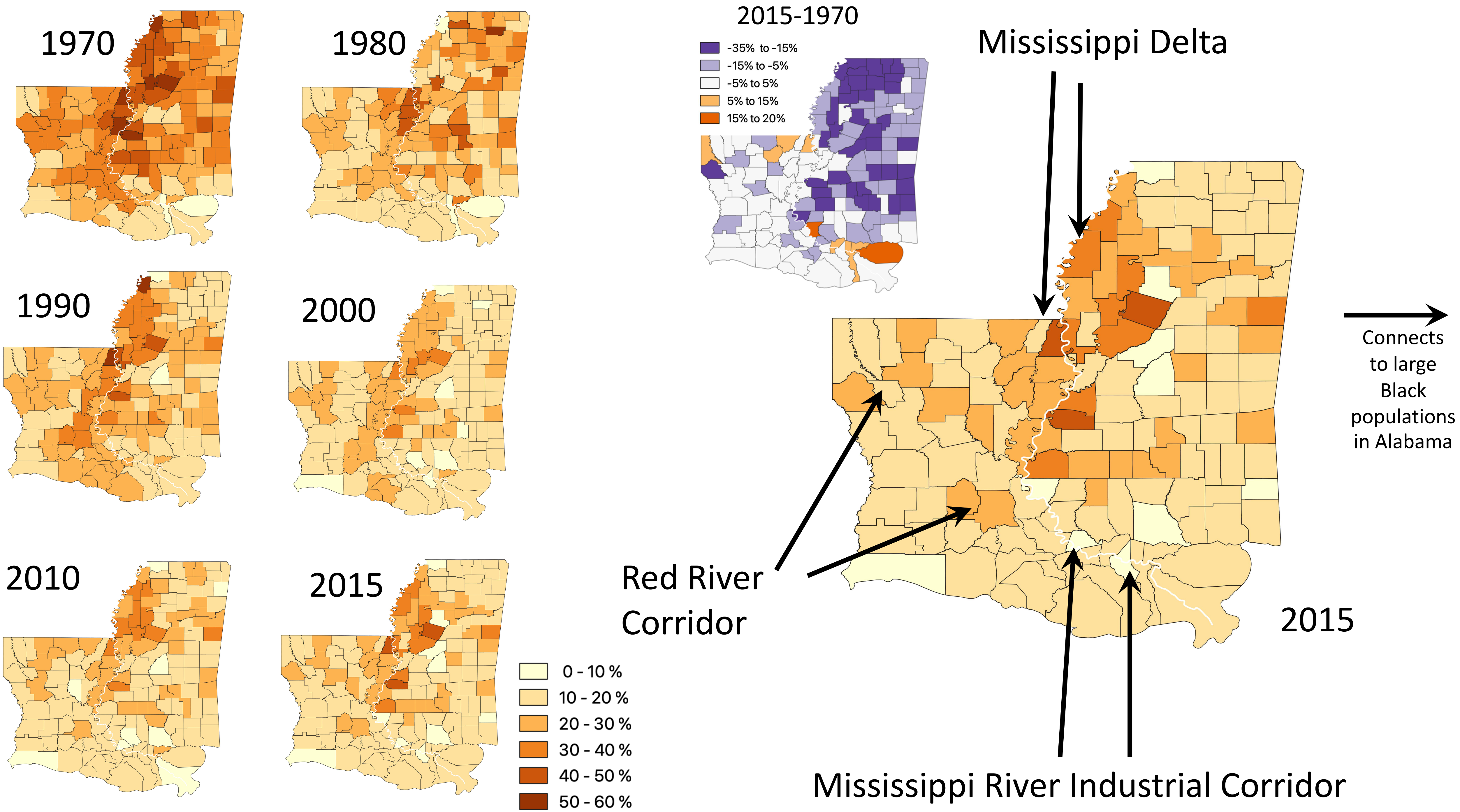
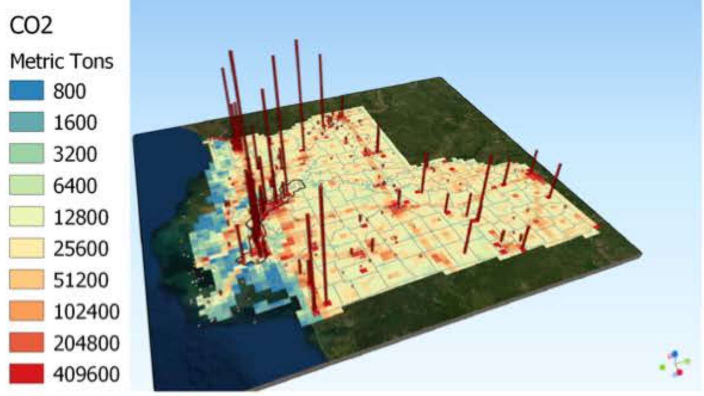
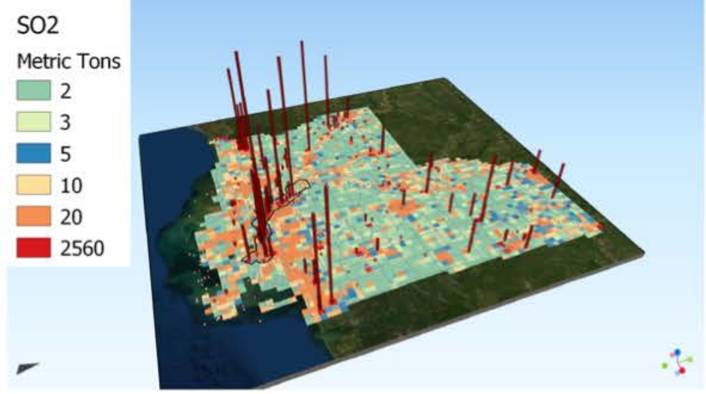
15% to 35%
Mississippi Delta
Connects to large Black populations in Alabama
Red River Corridor
Mississippi River Industrial Corridor
0 - 13
13 - 25
25 - 38
38 - 50
50 - 63
63 - 100

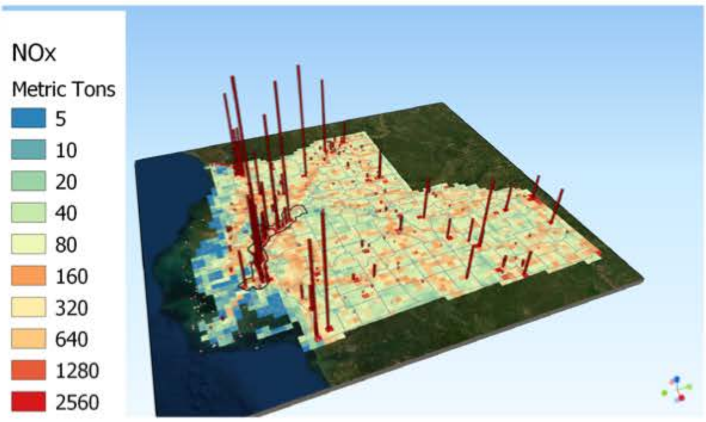

Black Carbon
Benzene
CH_4
$C0_2$ Excl
CO_2 Org
CO_2 Total
CO
Formaldehyde
Hg
N_2O
NH_3 Total
NMVOC Totals
NO_x Totals
Organic Carbon Totals
PM 10
PM 2. 5
SO_2
Metric Tons
Year
LA
Mississippi River Industrial Corridor
MS


1970
1980
1990
2000
2010
2015
0 - 10 %
10 - 20 %
20 - 30 %
30 - 40 %
40 - 50 %
50 - 60 %
2015-1970
-35% to -15%
-15% to -5%
-5% to 5%
5% to 15%
15% to 20%
Mississippi Delta
Connects to large Black populations in Alabama
Red River Corridor
2015
Mississippi River Industrial Corridor

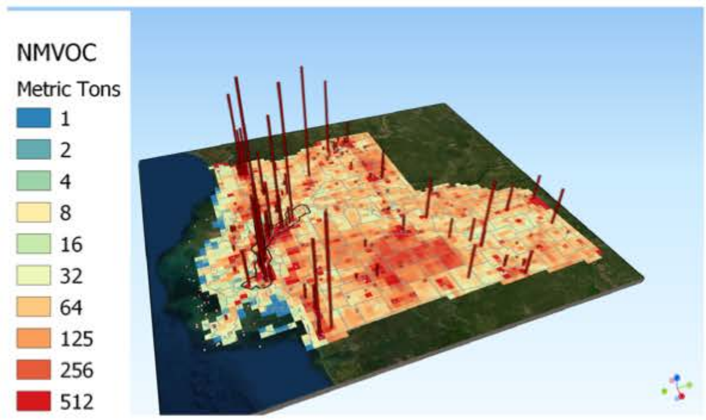




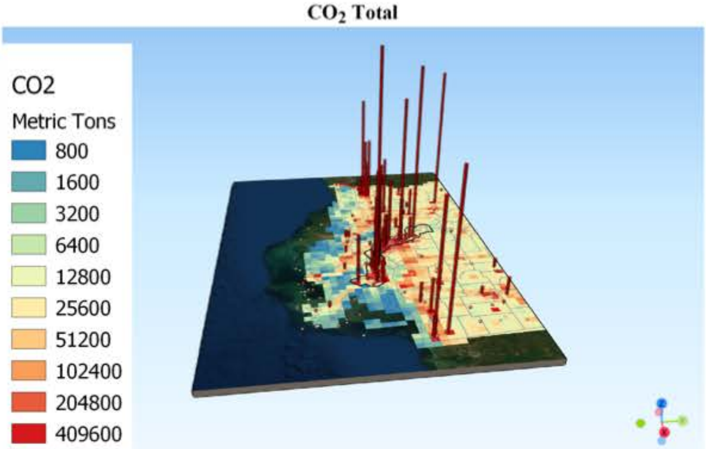
NO_x



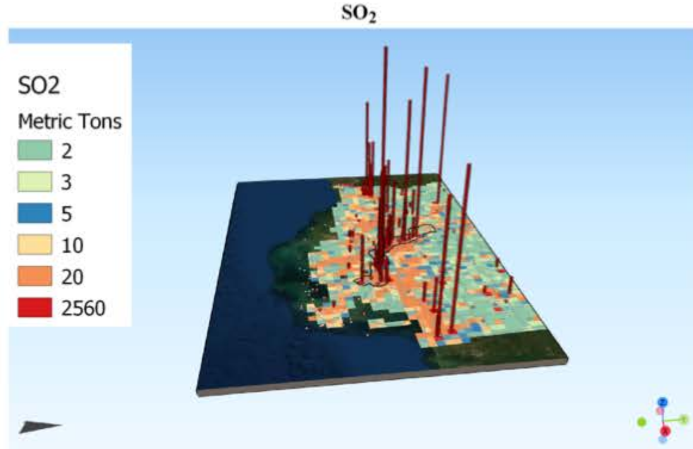
NMVOC



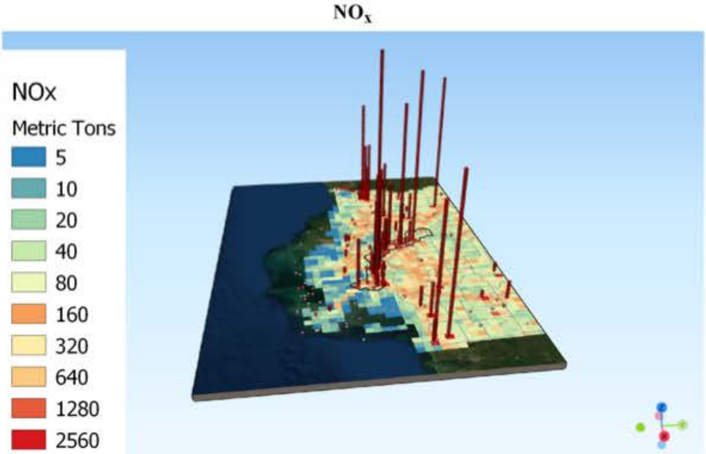
CO_2 Total



SO_2



NO_x



NMVOC