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Using environmental justice to inform disaster recovery: Vulnerability and electricity restoration in Puerto Rico

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ABSTRACT

This paper uses an environmental justice framework to explore whether existing vulnerabilities in Puerto Rico are associated with the rate of electricity restoration after Hurricane María. Based on the literature discussing the relationship between vulnerability and environmental justice, we expected that the areas identified as vulnerable to environmental injustice would recover more slowly than less vulnerable areas. We use regression analysis to analyze how well three vulnerability indices based on environmental justice variables predict electricity restoration. We also map the resulting data to spatially situate recovery patterns. This analysis produces mixed evidence of our predictions. In addition to environmental justice factors, other factors, such as terrain and proximity to electric transmission lines, also affected recovery rates, complicating the narrative of recovery. These findings suggest that policymakers seeking to mitigate vulnerability to electricity outages in the wake of natural disasters should incorporate environmental justice analysis in their recovery prioritization decisions, and that this analysis should be contextually specific to the recovery area. Our analysis also includes the construction of environmental justice indices, which have the potential to be a useful advocacy tool for communities seeking to uncover the priorities of stakeholders engaged in recovery.

1. Introduction

As the effects of climate change increase the devastation caused by natural disasters, the most vulnerable communities tend to suffer the strongest impacts. As a result, theories and frameworks used by researchers and policy-makers to study the intersection of disaster recovery and vulnerability have expanded. The environmental justice literature offers a useful approach to studying natural disaster recovery because it explicitly considers factors that may lead to differential rates of recovery. Though race and poverty have been incorporated into vulnerability and disaster recovery literature, environmental justice analyses in such contexts are sparse (Fothergill et al., 1999). An environmental justice analysis offers a useful way to understand the underlying vulnerabilities within a particular place, and is well suited to guide disaster recovery because it can help to identify communities that are socially, economically, and environmentally vulnerable before disaster. As a result, researchers, first-responders, disaster aid agencies, and policy-makers can identify communities where targeted recovery should be prioritized in the aftermath of a natural disaster. Puerto Rico, as an island territory subject to both energy and economic dependence on the United States, and the increasingly dangerous effects of climate change, is an ideally situated case study to explore the intersection of disaster recovery, environmental justice, and energy infrastructure (García-López, 2018).

Environmental justice analyses highlight the importance of specific historical and political contexts for understanding differential environmental impacts. The field sprang from activism concerning the siting of hazardous waste and municipal landfills near poor communities of color (Commission for Racial Justice, 1987; GAO, 1983). Therefore, much of the seminal research in the field concerns the question of how race and income correlate with, and are predictive of, where environmental hazards are located (Bullard, 1990; Mohai and Bryant, 1992a). Methodologically, environmental justice analyses tend to focus either on improving quantitative assessments of pollution effects from different point sources near a community, or qualitative case studies that illustrate the historic economic and political origins of environmental injustice. Demographic indicators used in environmental justice research generally include race and ethnicity, income, and education;

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environmental indicators are usually operationalized as distance from a pollution source, such as landfills, incinerators, hazardous dumping sites, or power plants. Some work has been done to study how social and environmental vulnerability affect natural disaster preparations, management, and recovery, recognizing that natural disasters exacerbate similar inequalities observed with other environmental issues, but more exploration is needed (Wailoo, 2010).

This paper adds to the literature on the intersection of disaster recovery and environmental justice by contextualizing environmental justice in Puerto Rico. Our research centers on two questions: (1) are traditional environmental justice indicators useful predictors of natural disaster recovery? And (2) when environmental justice indicators are combined into a cumulative vulnerability measure, do those cumulative indicators contribute usefully to recovery analysis? To answer these questions, we use demographic and environmental indicators to identify communities vulnerable to environmental injustice and compare these vulnerability measures to the electricity restoration time for communities across Puerto Rico.

2. Conceptual framing

2.1. Defining and contextualizing environmental justice

Three key concepts of justice have been incorporated into the environmental justice literature – distributive justice, procedural justice, and justice as recognition (Schlosberg, 2007). Quantitative environmental justice studies typically focus on distributive justice analysis by identifying predefined geographic units (such as a county or census tract) within which environmental hazards (such as a Superfund site, a waste incinerator, or a power plant) are located, and comparing the demographic makeup of those geographic units to units that do not have environmental hazards within their borders (Krieg, 1998; Krieg and Faber, 2004; Mohai and Bryant, 1992a; Mohai and Saha, 2006). This research has consistently found that poor and non-white communities in the United States are disproportionately located near environmental hazards, and accounting for income, race is a determining factor in hazard siting (Mohai and Bryant, 1992a).

Environmental justice research grew out of concerns regarding environmental racism in the context of the United States (Bullard, 2001; Commission for Racial Justice, 1987; GAO, 1983; Mohai and Bryant, 1992a). Therefore, the research (both quantitative and qualitative) on environmental justice has focused on the specific distribution of environmental hazards in relation to the location of poor and nonwhite communities. Of course, the field of environmental justice has expanded to incorporate a multiplicity of contexts in which environmental injustice is considered, with an expansion in the social and environmental dimensions considered (Walker, 2012). This paper contributes to the growing field of research that argues for a contextualized understanding of environmental injustice.

An environmental justice analysis should be constructed based on the community in question – for example, rural and urban communities have different environmental harms or vulnerability measures that should be taken into consideration (Brainard et al., 2002; Harner et al., 2002). Environmental justice scholarship has expanded to include analysis of international communities, studying the relationship of demographics and environmental hazards in the specific context of the country in question (Adebowale, 2008; Agyeman, 2014; Brainard et al., 2002). Environmental justice is reconceptualized for different populations within the United States as well, including Native Americans and Latinos (de la Hoz, 2016; Lynch, 1993; Vickery and Hunter, 2016). These analyses use different environmental concepts beyond the geographic distribution of pollution point-sources, focusing in addition on the relationship between a person and land, or a community and their food source.

2.2. Measuring and analyzing environmental justice

Quantitative environmental justice analyses examine the statistical relationships between demographic factors and environmental hazards. The methodology used to study environmental indicators has become increasingly sophisticated, incorporating a growing understanding of how pollution is released, travels, and is absorbed into the food chain and by humans. Advances include dispersion modelling of air pollution (Ash and Fetter, 2004; Brainard et al., 2002; Brooks and Sethi, 1997; Fairburn et al., 2009), weighting environmental variables by the toxicity of the pollution in question (Ash and Fetter, 2004; Brooks and Sethi, 1997), or incorporating cumulative health impacts due to multiple modes of exposure to toxicity (Krieg and Faber, 2004). Many studies, however, do not incorporate multiple environmental harms into their analysis and only focus on one measure of pollution, such as Toxic Release Inventory sites, Clean Air Act Violations, or air pollutants (Konisky and Reenock, 2013; McLeod et al., 2000; Wu and Heberling, 2013). Some research incorporates environmental benefits such as parks, woodlands and nature preserves, or vegetation, as opposed to environmental hazards (Boone et al., 2009; Fairburn et al., 2009; Schwarz et al., 2018).

While environmental indicators have expanded in scope as environmental justice is applied to increasingly diverse contexts, demographic indicators have remained more constant, and are generally the sole indicators used to identify communities at risk of environmental injustice. However, there is a lack of consensus regarding the definition of an environmental justice community or area, in part because the Environmental Protection Agency (EPA) has intentionally not published such a definition. The Clinton administration required federal agencies to incorporate environmental justice into their missions through executive order. This Executive Order defined environmental justice as “disproportionately high and adverse human health or environmental effects…on minority populations and low-income populations” (Executive Order No. 12898, 1994). The EPA’s approach in fulfilling the requirements of this executive order was to distribute environmental justice work to their regional offices to allow for local context and prioritization.

Many states have their own definitions of environmental justice communities (including New York, Massachusetts, Illinois, and Minnesota) but these definitions are generally based on demographic indicators such as household income and race/ethnicity. Using this approach recognizes the link between these demographic indicators and likelihood of proximity to environmental hazards that is perpetuated in the United States through institutional processes, such as a history of housing segregation and discrimination, strategic zoning designations, and economic depression in formerly-industrial areas (Kojola & Pellow, 2020). Environmental hazards also vary based on local context and geography. Environmental justice analyses of states based on their definitions of an environmental justice community incorporate the localized context of these definitions and what environmental hazard indicators affect these populations (Liang, 2016). The Bush administration expanded the idea of environmental justice to include health and environmental impacts that affect any population, effectively removing the focus on minority and low-income communities (Holifield, 2012) and de-contextualizing the federal government’s approach to environmental justice. The EPA began refocusing on low income and minority populations in Bush’s second term, but attempts to create national environmental justice screening tools faltered, and no definition of an environmental justice community has been produced (Holifield, 2012). Puerto Rico’s state agencies do not have their own definition of an environmental justice community, and using income and race/ethnicity as key indicators is not necessarily as useful in Puerto Rico, which has a history of colonial rule and complicated racial identification distinct from that of the United States. Puerto Rican’s racial self-identification has changed over the decades of the twentieth century as whiteness’s relationship to civil and economic rights evolved (Loveman, 2007).

Explorations of environmental justice in Puerto Rico have highlighted the entire island's vulnerability to environmental injustice (Brown et al., 2018); however, it is important to also recognize the inequality that exists among communities in Puerto Rico, based on income, economic opportunity, and geographic proximity to urban centers (García-López, 2018).

2.3. Environmental justice and disaster recovery

There is an established body of literature on how race and income affect and interact with disaster preparedness and recovery in the United States (Fothergill et al., 1999). The most comprehensive body of literature on the subject is research on Hurricane Katrina which disproportionately affected minority and poor communities in Louisiana and along the Gulf coast (Bullard and Wright, 2009). For example, Hurricane Katrina stranded hundreds of thousands of people in New Orleans who were unable to evacuate due to a combination of factors, including the lack of an evacuation plan for immobile people. The vast majority of people left behind during Hurricane Katrina were poor and/or Black, and had no savings to fall back on and no car with which to evacuate (Bay, 2010). However, most literature on disaster recovery that incorporates demographic and/or socioeconomic factors does not explicitly invoke environmental justice analysis techniques, in that environmental hazards are not included as vulnerability indicators (the aforementioned literature on Hurricane Katrina is a valuable exception). The literature uses the demographic indicators common in environmental justice studies (such as race and ethnicity, and income or poverty status), and analyzes the relationship between these demographic indicators and disaster recovery metrics. In this way, the disaster recovery literature parallels the environmental justice literature, which correlates demographic indicators with indicators relating to environmental hazards (such as distance from Superfund sites or landfills). This paper asks whether using both demographic and environmental indicators can improve our understanding of how disaster recovery occurs – in effect, bringing environmental justice squarely into the disaster recovery literature.

There have been some attempts at building a theoretical bridge between environmental justice and disaster recovery literature (Ryder, 2017). Few case studies have been produced, and of the existing literature, electricity restoration is a useful and unique indicator for studying vulnerability in the context of disaster recovery (Miles et al., 2016; Miller et al., 2011; Mitsova et al., 2018). Literature in the environmental justice field supports the use of these indicators, as proximity to transmission lines or power plants is generally considered an environmental hazard (Wartenberg et al., 2010). Using electricity restoration also allows for the location of power plants and transmission lines to be incorporated into the environmental justice analysis as environmental hazard indicator variables. The inequity of electricity restoration in Puerto Rico post-Hurricane María – both among Puerto Rican communities (García-López, 2018), and in comparison to mainland states (Willison et al., 2019) – highlights the need to explore the link between existing environmental justice inequities in Puerto Rico and the island's disaster recovery.

3. Hurricane María in Puerto Rico

In 2017, Hurricane María devastated the island of Puerto Rico, leaving the population with limited or no access to electricity, radio announcements, roads, potable water, food, sewage, judicial process or police protection, or help from the government (Lugo, 2019). Health services were interrupted, with hospitals struggling to provide adequate care using only back-up diesel generators (Alcorn, 2017). Medical care for the population suffered, with mortality estimates far exceeding the official count of 64 (Santos-Burgoa et al., 2018). Communication systems were nonfunctional, food, water, and gas remained scarce, and for many people, the power didn't come back on for months (Zorrilla, 2017). The southeastern coast of the archipelago's main island was impacted first, though the entire island was affected due to its small land mass and the intensity of the storm (Pasch et al., 2019).

Puerto Rico as a whole suffers from a long history of environmental injustice, leading some scholars to characterize its main island as an "environmental justice island" (Brown et al., 2018). However, different levels of vulnerability exist within Puerto Rico, making it important to draw comparisons within the local context instead of using the mainland United States as a benchmark when identifying communities at risk of environmental injustice. We identify communities at higher risk of environmental injustice in comparison to the rest of Puerto Rico using an environmental justice vulnerability index based on demographic and environmental factors. We then ask whether these communities experienced longer recovery times after Hurricane María.

The environmental justice research focusing on Puerto Rico consists predominately of qualitative case studies (Baver, 2012; Dietrich, 2011; Santana, 1993). Vieques is a common site for analysis, as is Casa Pueblo's activism in the central mountainous region of Puerto Rico (Baver, 2006; Massol-González et al., 2008; McCaffrey, 2008; McCaffrey & Baver, 2006; Santana, 2002). These case studies illustrate how Puerto Rico's colonial history informs its specific environmental justice issues. For example, the people of Vieques organized in response to the negative health effects resulting from military weapons training near their communities, and their displacement from their homes to accommodate these military priorities. Casa Pueblo originated as a grassroots opposition to the Puerto Rican government's plan to allow international corporations to purchase land at cheap prices and extract gold, silver, and copper from large-scale open-pit mines in the central region of the island, evicting impoverished residents in the process. Other communities are plagued by groundwater and soil contamination from pharmaceutical companies that moved production to the island due to federal tax incentives, leaving a legacy of economic depression and hazardous waste sites when these tax incentives expired.

Quantitative environmental justice studies of Puerto Rico exist, but like most quantitative environmental justice analyses, focus on specific pollution sources, and find that immigrant populations, lesser educated populations, and populations with high levels of unemployment are disproportionately subject to environmental hazards (Wu and Heberling, 2013).

4. Data and methodology

4.1. Environmental justice indices

As a first step in analyzing the relationship between environmental justice and recovery, we created an environmental justice index specific to the Puerto Rican context. As discussed above, the EPA has taken tentative, if insufficient, steps towards defining environmental justice communities and incorporating those definitions into a screening tool that can be used to identify communities at risk of environmental injustice. The Environmental Justice Screening and Mapping Tool (EJSCREEN) is the result of multiple attempts by the EPA to produce an environmental justice screening tool, but its uses are limited. The tool displays maps of environmental and demographic indicators common to environmental justice analyses (EPA, 2019). EJSCREEN provides information on environmental indicators (particulate matter, ozone, and diesel pollution; cancer and respiratory hazard risks from inhalation of air toxics; age of housing stock as a proxy for lead poisoning; toxicity of wastewater; and proximity to traffic, polluting facilities, Superfund sites, and hazardous waste disposal sites) and demographic indicators (race and ethnicity; income; linguistic isolation; education status; and vulnerability due to old or young age). EJSCREEN displays these indicators at the census block group level in two different contexts – as percentiles in comparison to the United States as a whole, and as percentiles in comparison to the state under consideration. The three main weaknesses of EJSCREEN are incomplete indicator data in the context of

Puerto Rico; reliance on ethnicity as a substitute for race; and difficulty combining or layering multiple indicators. Firstly, the indicator data for particulate matter and ozone measurements in Puerto Rico is unavailable through EJSCREEN, even though Puerto Rico is subject to the National Ambient Air Quality Standards and therefore has monitoring equipment to measure these pollutants. Secondly, EJSCREEN defines “minority” status as self-identification as a race other than white and/or self-identification as Hispanic/Latino; as nearly all Puerto Ricans identify as Hispanic/Latino according to U.S. Census reports, this indicator is not particularly useful for exploring inequality among communities on the island. Third, EJSCREEN provides useful maps for individual indicators, but does not offer the option of layering indicators to study intersections of these vulnerabilities The tool creates “environmental justice indices,” but these indices are demographically-weighted versions of single environmental indicators, such as pollution or Superfund-proximity measures. They are not cumulative indices that incorporate multiple environmental hazards, or demographic data beyond income, race, and ethnicity.

For a more advanced example of an environmental justice screening tool, see California’s CalEnviroScreen tool, which calculates an environmental justice score for communities within the state based on various environmental and demographic indicators (California Office of Environmental Health Hazard Assessment, 2020). This tool uses many of the same indicators as EJSCREEN, but includes specific environmental and demographic indicators that are relevant to California’s context, especially the state’s traffic problems, agricultural pesticide use, and housing cost. CalEnviroScreen allows more nuanced exploration of environmental justice across the state than EJSCREEN; it provides a demographic index and pollution index which each combine percentiles of, respectively, demographic and environmental indicators. More detail on CalEnviroScreen and EJSCREEN’s indicators and indices can be found in the Supplemental Materials section.

For our analysis, we draw on CalEnviroScreen’s approach to environmental justice indicators by constructing an environmental justice mapping tool that utilizes demographic and environmental indicators. We use EPA EJSCREEN indicators as a basis for our index construction, while taking preliminary steps towards incorporating the specific history and context of Puerto Rico into these indices. Two indices were created from indicator variables – an environmental index and a demographic index. These two indices were averaged to produce an environmental justice index. This environmental justice index allows for comparisons of census tracts across the island on a single scale. Further detail on the construction of the environmental and demographic indices is found below and in the Supplemental Materials section.

4.1.1. *Environmental index construction*

We compiled an environmental index using five environmental indicator variables. Table 1 shows the variables used to create the environmental index. These indicators cover common environmental hazard categories found in the literature on environmental justice (Walker, 2012). Each variable is scaled to a unit range using maximum-minimum scaling and weighted equally in the construction of the environmental index. Puerto Rico’s history of intensive pharmaceutical production has left the island with continuing environmental concerns regarding water pollution (Dietrich, 2011). The federal government used tax incentives as part of an economic development program known as “Operation Bootstrap” in order to encourage expedited industrialization and foreign investment; this economic development resulted in polluting industries (such as cement, glass, paper, and others) emerging as fundamental economic forces in Puerto Rico (Santana, 1998) with little enforcement of environmental regulations (Cabán, 2002).

The EPA provides Air Quality data at the level of a ward within a municipality. For our analysis, we constructed a maximum impact zone around the source of the pollution causing nonattainment status as of 2017 (Puerto Rico Environmental Quality Board, 2017). If the impact zone intersected the border of a census tract, we labeled that census tract as not in attainment. The Lead Risk data was taken from the 2017 American Community Survey (ACS) at the census tract level. The number of housing units per census tract was divided by the number of housing units built before 1960, creating a new percentage value. The data for the three remaining variables – RMP, NPL, and TRI sites – are from the EPA’s public records for the year 2017 (EPA, n.d.-a, n.d.-b; *RMP Facilities in Puerto Rico*, n.d.). Each site had a latitude and longitude associated with it, as well as the municipality it is located in. The site locations were displayed on ArcGIS, then spatially linked to a census tract whose borders contain the site. Each census tract therefore has a count of the number of RMP, NPL, and TRI sites within its borders.

4.1.2. *Demographic index construction*

We compiled a demographic index using six demographic indicator variables. Table 2 shows the indicator variables. These indicators cover common demographic categories found in the literature on environmental justice (Walker, 2012). Each variable is scaled to a unit range using maximum-minimum scaling and weighted equally in the construction of the demographic index. Race and ethnicity are commonly used in environmental justice analyses (Mohai and Bryant, 1992a). In the United States, nonwhite and/or Latino populations are considered at-risk for environmental injustice due to historically discriminatory housing, zoning, and siting policies (Mohai and Bryant, 1992a). As the purpose of this analysis is to study the specific context of environmental justice in Puerto Rico by identifying the most vulnerable communities on the island, identification as Latino/Hispanic was discounted from the demographic index, as the vast majority of Puerto Ricans self-identified as Latino/Hispanic regardless of racial identification. Other post-Hurricane María research has highlighted the importance of considering race and ethnicity when analyzing disaster recovery, as Afro-Caribbean communities tended to receive less aid after Hurricane María (Dieppa et al., 2020), and so we included race despite its problematic interpretation in Puerto Rico. Median income highly correlates with environmental injustice issues in the United States, and we utilized

Table 1
Environmental Indicator variable names and descriptions. Air Quality, RMP, NPL, and TRI sites data is from the EPA. Lead poisoning risk data is from the ACS.

Variable	Description
Air Quality	An area within the boundaries of the census tract is in nonattainment with the NAAQS as of 2010 (0 = in attainment or no data; 1 = not in attainment)
Lead Risk	Percent of housing units in the census tract built before 1960 (and therefore at risk of lead poisoning). Data is from 2010.
RMP Sites	Number of Risk Management Plan sites within the borders of the census tract. Sites registered as of December 31, 2010 are included.
NPL Sites	Number of National Priority List sites within the borders of the census tract. Sites on the list as of December 31, 2010 are included.
TRI Sites	Number of Toxic Release Inventory sites within the borders of the census tract. Data is from the 2010 annual reports.

Table 2
Demographic Indicator variable names and descriptions. The data is taken from the ACS.

Variable	Description
% Non-White	Percent of population in the municipality that is nonwhite
Income	Median household income value
Linguistic Isolation	Percent of population living in a household where all members age 14+ speak a non-English language and also speak English less than “very well”
Education	Percent of population age 25+ who did not receive a high school diploma or the equivalent
Youth in Poverty	Percent of population under the age of 5 living below the federal poverty level
Elderly in Poverty	Percent of population over the age of 64 living below the federal poverty level

the same indicator of economic vulnerability here (Mohai and Bryant, 1992b). Linguistic isolation is also used by the EPA to measure demographic vulnerability, and is commonly used as a social vulnerability measure (Casey et al., 2017; EPA, 2019). In Puerto Rico, Spanish and English are both official languages of the executive branch, after decades of political struggle over the use of Spanish and English in schools and government and the extinction of the native language before colonization, Taino. This context may lessen the vulnerability traditionally associated with linguistic isolation; however, the indicator is still included in order to test its relationship to recovery. Environmental injustice and its related health impacts affects children disproportionately; when combined with poverty, these chronic diseases compound the effects of environmental injustice (Landrigan et al., 2010). Similarly, elderly people are particularly at risk when power shutoffs occur, as they are more susceptible to extreme temperature effects and may have mobility or transportation issues (Ghanem et al., 2016; Liévanos and Horne, 2017).

The percent of the population in the municipality that is nonwhite is derived from U.S. Census data, and consists of self-identification as a race other than white (Black, American Indian or Alaskan Native, Asian, Native Hawaiian or other Pacific Islander, other or two races). Median household income value, linguistic isolation, and the youth and elderly in poverty data are provided by the Census. We measured the education attainment rate by analyzing the percentage of people age 25 and older who have completed a high school degree, or the equivalent (such as a GED), mirroring the education indicator used in EJSCREEN. The data for these six indicators is taken from the 2017 ACS.

4.2. Electricity generation

Existing research has used electricity restoration as a proxy for the more general phenomenon of recovery because extended periods without access to electricity affect people's access to healthcare and medication, clean water and food, banks and legal assistance, and communications (Miles et al., 2016; Román et al., 2019). In alignment with this existing research, this analysis uses electricity recovery time as a way of exploring disaster recovery more generally. Therefore, it is important to understand the context of the electric grid system in Puerto Rico. Fig. 1 shows the transmission grid and major power plants in Puerto Rico. The 230 V transmission lines form a coastal ring around the island, and connect the southern coast (where major electricity generation occurs) and the northern coast and San Juan area (where the population is more densely concentrated than in the south). Lower voltage transmission lines further connect communities around Puerto Rico, including the island of Vieques. The bulk of electricity generation is from petroleum, with natural gas and coal providing most of the remainder. Renewable energy is growing in Puerto Rico, but remains a small percent of total electricity generation (U.S. Energy Information Administration, 2018).

4.3. Electricity recovery data

The electricity recovery data used in this analysis was based on data compiled in a collaboration between the Rocky Mountain Institute (RMI) and Resilient Power Puerto Rico (RRPR) in developing their Puerto Rico Energy Toolkit (Resilient Power Puerto Rico & Rocky Mountain Institute, n.d.). This data was based on public announcements by PREPA of electricity restoration in various communities across Puerto Rico. It documents the number of days a community was without power after Hurricane María hit. Fig. 2 provides an overlay of the electricity recovery data against the transmission grid, in order to visualize the locations of communities that had long electricity restoration times and compare these locations with the energy infrastructure on the island, including transmission lines and power plants

The next step of the analysis was to run a regression analysis with the electricity recovery data as the dependent variable, and the demographic and environmental indices as independent variables, to test the relationship between environmental justice indicators and recovery. Each community with an electricity recovery time was located in a specific census tract, and each census tract had demographic index, environmental index, and environmental justice index scores. To further understand the impact each indicator had on electricity recover, a second regression was run with the electricity recovery data as the dependent variable, and the demographic and environmental indicator as independent variables.

Finally, in order to visualize the geographic distribution of electricity restoration reports, the electricity restoration wait time data was disaggregated into quintiles and mapped.

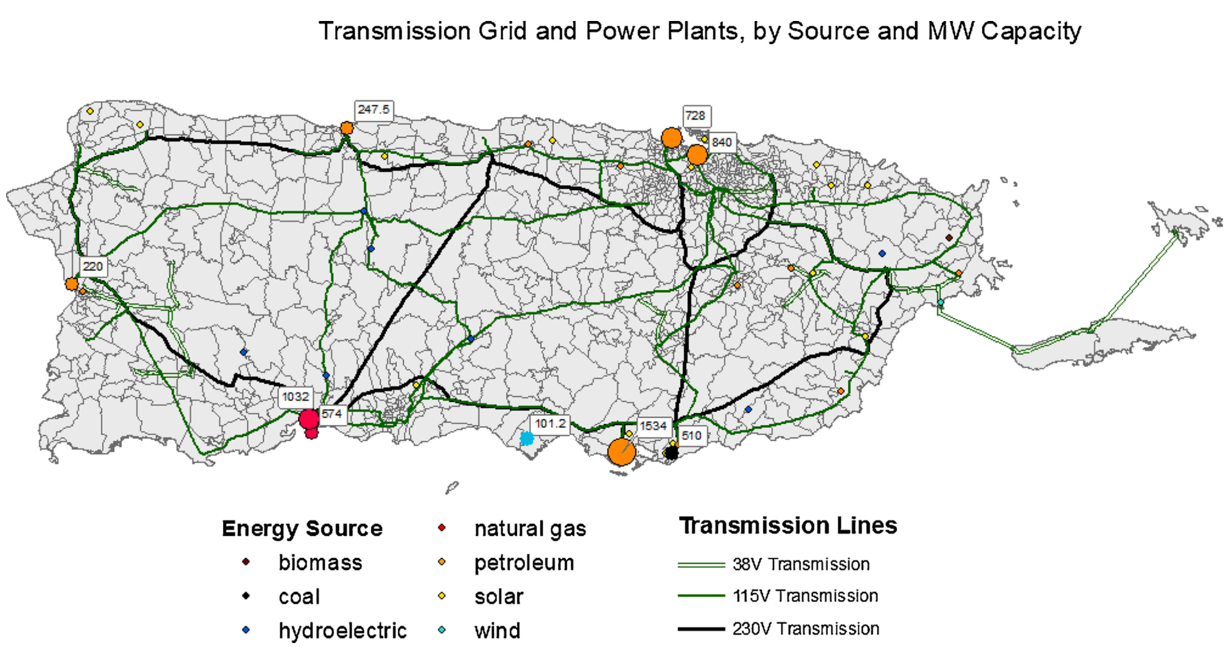

Fig. 1. Major transmission lines (38 V, 11 V, and 230 V) and power plants by source and generation capacity.
Source: IEEE.

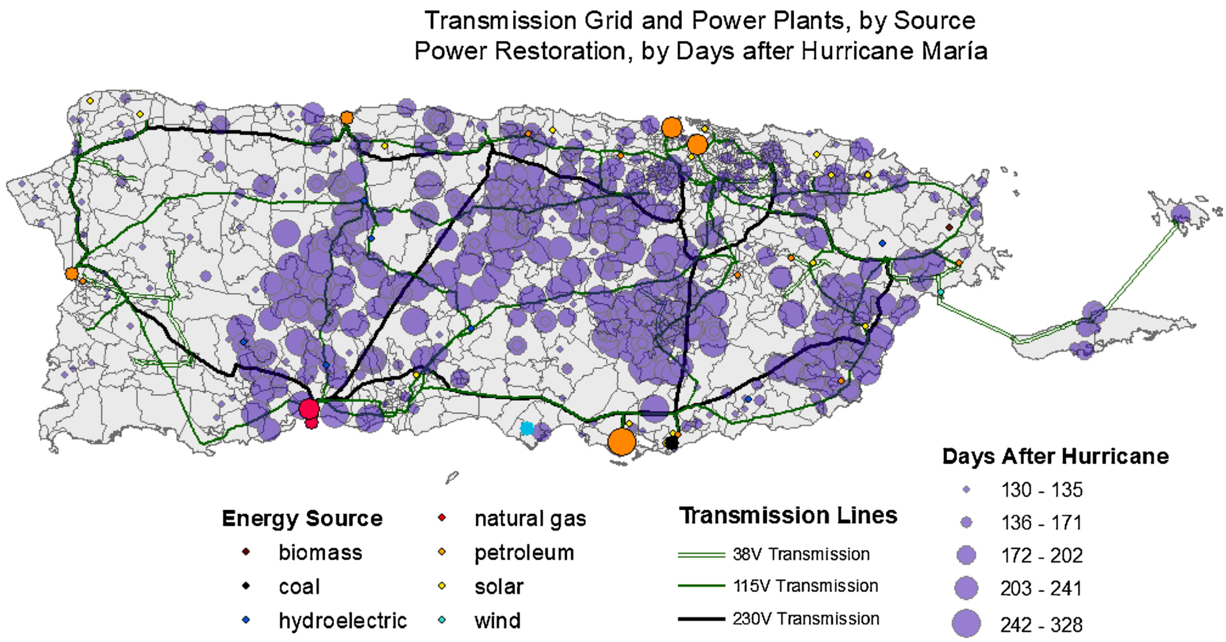

Fig. 2. A map of the transmission grid and power plants, as well as the time passed before communities had their electricity restored.
Source: IEEE and RPPR.

4.4. Methodological and data limitations

The data underlying this analysis is derived from the census, which systematically undercounts certain racial minority groups, rural communities, and renters (U.S. Census Bureau, 2012). In addition, racial categorization through census data is complex in Puerto Rico due to the contested definition of whiteness, and colonial relationship between the U.S. Census Bureau and Puerto Rico (Loveman, 2007). Environmental data is often self-reported by facilities required to collect and publish data on their annual emissions or hazard levels, introducing more uncertainty, and likely a bias towards conservative estimates of pollution, into the data. For example, the Toxic Release Inventory is made up of release data reported by each facility. Research has shown that these reported amounts can be significantly less than actual air emissions (Marchi and Hamilton, 2006), indicating that any correlational effects we find in this analysis may be underestimating the relationship between pollution data and recovery.

The electricity recovery data collected by RMI and RPPR represents the last 30 % of the population to have electricity restored; areas not represented in this data set were among the first 70 % to have electricity restored. To our knowledge, a more comprehensive electricity restoration data set has not been made available to the public. A more comprehensive data set would be useful in future research, as earlier restoration patterns would lead to a more informative analysis of electricity restoration across the island, and enable analysis of electricity restoration patterns between, and inside of, communities. However, analyzing data on the last 30 % of the population to have their electricity restored allows us to focus on those most affected by loss of power.

The environmental justice index constructed here is not a definitive formulation of an environmental justice community. It highlights areas that may be at risk of environmental injustice due to demographics, environmental factors, or both, and should be explored further in a qualitative, context-specific manner. This study is meant to expand the conversation around environmental justice in Puerto Rico, and add to the literature that utilizes an environmental justice lens when studying disaster recovery.

Independent and dependent variables were transformed using a Box-Cox transformation to approximate normal distributions. We used a multivariate linear regression analysis to highlight which of the given indicators are statistically significant predictors of electricity recovery time. As such, the model is not optimized to maximize the amount of variance that the indicators explain in electricity recovery time; low R^2 values are expected as a result. There are also potential issues with the data (nonlinear relationships between the independent and dependent variables and homoscedascity). Despite these shortcomings, we use the regression analysis as a way to investigate the relative importance of the indicators, and to highlight areas of further study using more qualitative methods (as conducted in this paper) or more sophisticated quantitative methods, should a more comprehensive electricity restoration data set become available.

5. Results

5.1. Environmental and demographic indices

Our analysis highlights communities at risk of environmental injustice based on demographic and environmental indicators. Fig. 3 shows the environmental index and Fig. 4 shows the demographic index we constructed.

Fig. 3 shows the resulting environmental index values by census tract. The environmentally vulnerable communities are found along the north coast, in San Juan, Mayagüez, Guayama, Ponce, and the northern coast. San Juan contained many of the census tracts with the highest environmental index scores (see Appendix A), due to NPL, TRI, and RMP sites located in the area, a high percentage of housing units at risk for lead poisoning, and nonattainment of air quality standards. The Mayagüez, Guayama, and Ponce regions also have numerous TRI and RMP sites; Mayagüez and Ponce also had high risk of lead poisoning, while Guayama was in nonattainment of air quality standards. The concentration of power plants along the southern coast, near Ponce and Guayama, contributed to these high environmental index scores. The high concentration of NPL sites across the northern coast increased the environmental index score for those regions. Vieques is also notable for the location of an NPL site on the island.

Fig. 4 shows the demographic index values by census tract. Demographically vulnerable communities are found in the central mountainous region, the southwest coast, the southeast coast near Guayama, and in certain neighborhoods in San Juan. Of note is the overlap in

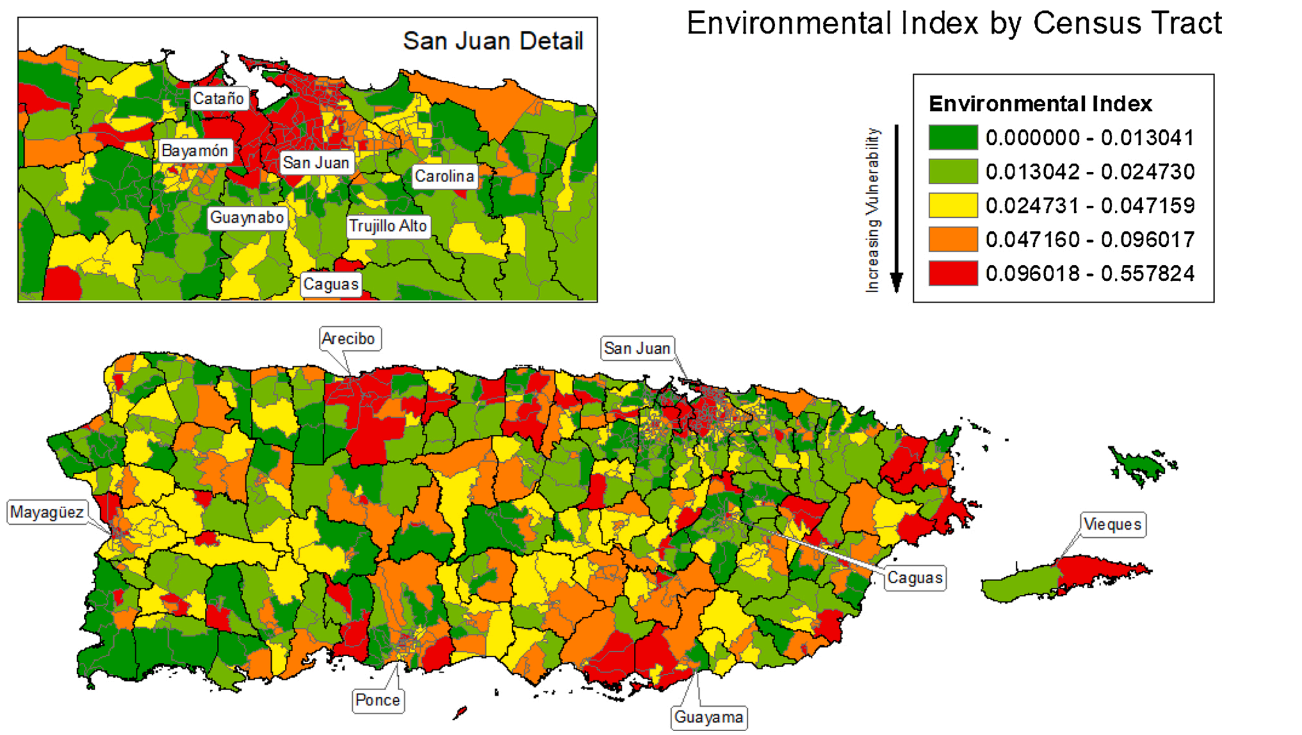

Fig. 3. The environmental index by census tract. Environmental index values are cumulative measures of environmental indicators measuring vulnerability.

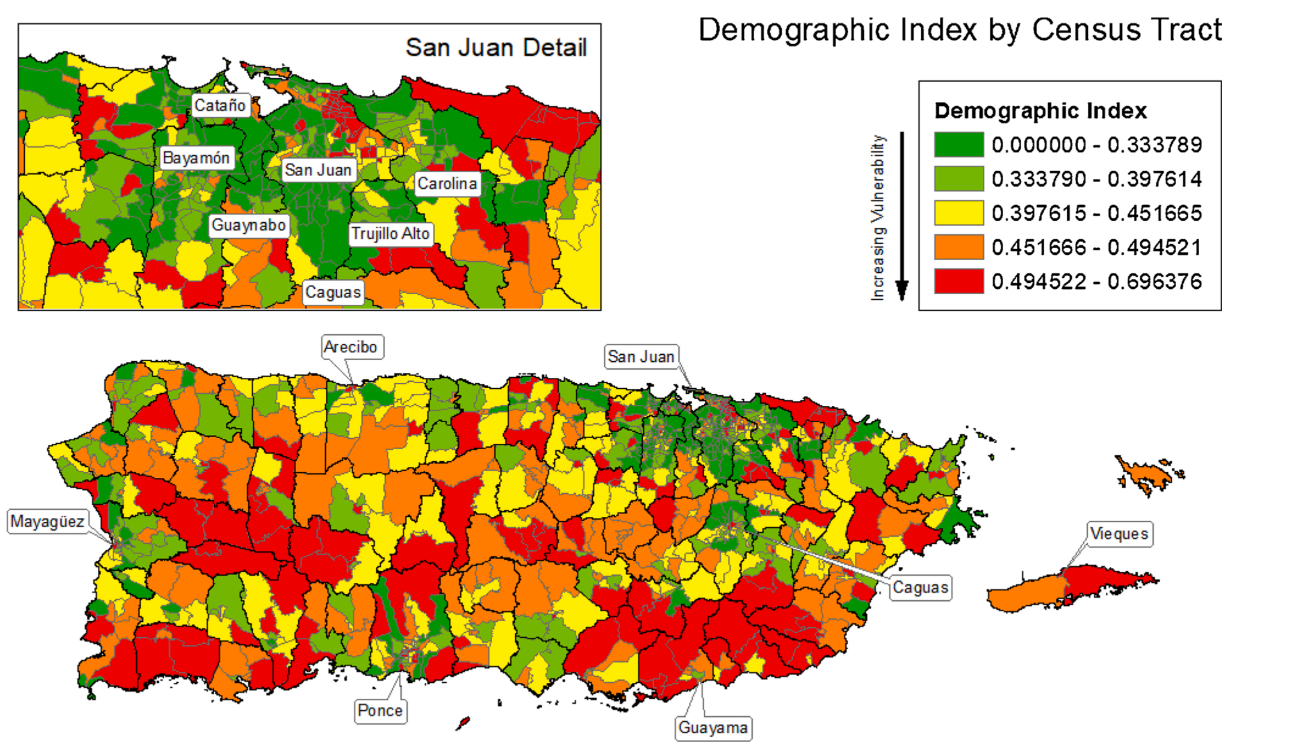

Fig. 4. The demographic index by census tract. Demographic index values are cumulative measures of demographic indicators measuring vulnerability.

demographically vulnerable communities in the southeast with the communities impacted first by Hurricane Maria. These communities, comprising the municipalities of Patillas, Maunabo, Yabucoa, Humacao, and Las Piedras, have a large Black population, a low median income, and should have been identified as communities at risk of slow recovery from the hurricane, given the combined EJ vulnerability and the path of the hurricane.

High demographic index scores are also found in San Juan, largely due to a high rate of identification as nonwhite and low household median incomes. San Juan also contains the communities with the lowest demographic index scores, indicating that the most and least vulnerable communities in Puerto Rico are living in close quarters near the capital and that inequality is acute in the San Juan region. Both the southwest region and the central mountainous region have high demographic index scores because of low education rates, low household median incomes, and high rates of linguistic isolation, suggesting that there are multiple different pathways for vulnerability, with potentially different implications for recovery. This highlights one of the possible limitations of relying on a singular index (whether that index is the environmental, demographic, or environmental justice index) without also studying the relationship of each indicator within the index to the recovery metric. Still, use of an index allows for some measure of cumulative effects to be utilized in policy recommendations.

5.2. Environmental justice index

The environmental justice index, which was constructed by averaging the environmental index and demographic index values for each census tract, is displayed in Fig. 5. San Juan, Arecibo, Guayama, Vieques, and the southern coast outside of Ponce score high on the environmental justice index, indicating higher vulnerability to environmental injustice. The west coast and other areas outside urban centers (including San Juan, Caguas, Mayagüez, and Ponce) have low environmental justice index scores. San Juan in particular has many census tracts with low demographic index scores and high environmental index scores, highlighting the inequity that exists within urban spaces, an inequity that complicates a disaster recovery analysis without highly granular spatial data.

5.3. Electricity restoration regression

We conducted a multivariate linear regression analysis using the electricity restoration data as the dependent variable, and the demographic and environmental indices as independent variables. We conducted a second linear regression analysis using the individual demographic and environmental indicators as independent variables in order to identify important relationships. The results of the regressions are found below in Tables 3 and 4. Data limitations are discussed in the Methodology section, above.

Table 3 shows the results of the regression analysis using the environmental and demographic indices as independent variables predicting the electricity restoration time. Both the demographic index and the environmental index have highly significant relationships with the electricity restoration wait time. The adjusted R^2 value for this regression model is 0.031, indicating that these two indices do not explain the majority of the variation in the electricity restoration time among communities in Puerto Rico. A traditional environmental justice

Table 3
Linear regression results for demographic and environmental indices.

	Unstandardized Coefficients		Standardized Coefficients		Collinearity Statistics	
Model	B	Std. Error	Beta	Sig.	Tolerance	VIF
(Constant)	1.011E-14	.034		1.000		
Dem. Index	.154	.034	.154	.000	0.998	1.002
Envr. Index	−.105	.034	−.105	.002	0.998	1.002

Table 4
Linear regression results for all indicator variables.

	Unstandardized Coefficients		Standardized Coefficients		Collinearity Statistics	
	B	Std. Error	Beta	Sig	Tolerance	VIF
(Constant)	−1.514	.469		.001		
% Non-white**	−.106	.033	−.106	.001	.968	1.034
HH median income	.050	.060	.050	.404	.294	3.401
% No HS education	.028	.051	.028	.581	.403	2.479
% Ling. Isolated**	.124	.042	.124	.003	.603	1.660
% Youth in poverty	.067	.040	.067	.094	.662	1.511
% Elderly in poverty**	.130	.045	.130	.004	.520	1.922
% Lead poisoning risk**	−.153	.034	−.153	.000	.898	1.113
Air Quality*	.404	.167	.083	.016	.892	1.121
RMP sites	−.004	.141	−.001	.975	.958	1.044
NPL sites	.149	.194	.025	.443	.989	1.011
TRI sites**	.255	.073	.115	.000	.970	1.031

** $p < 0.01$ *$p < 0.05$.

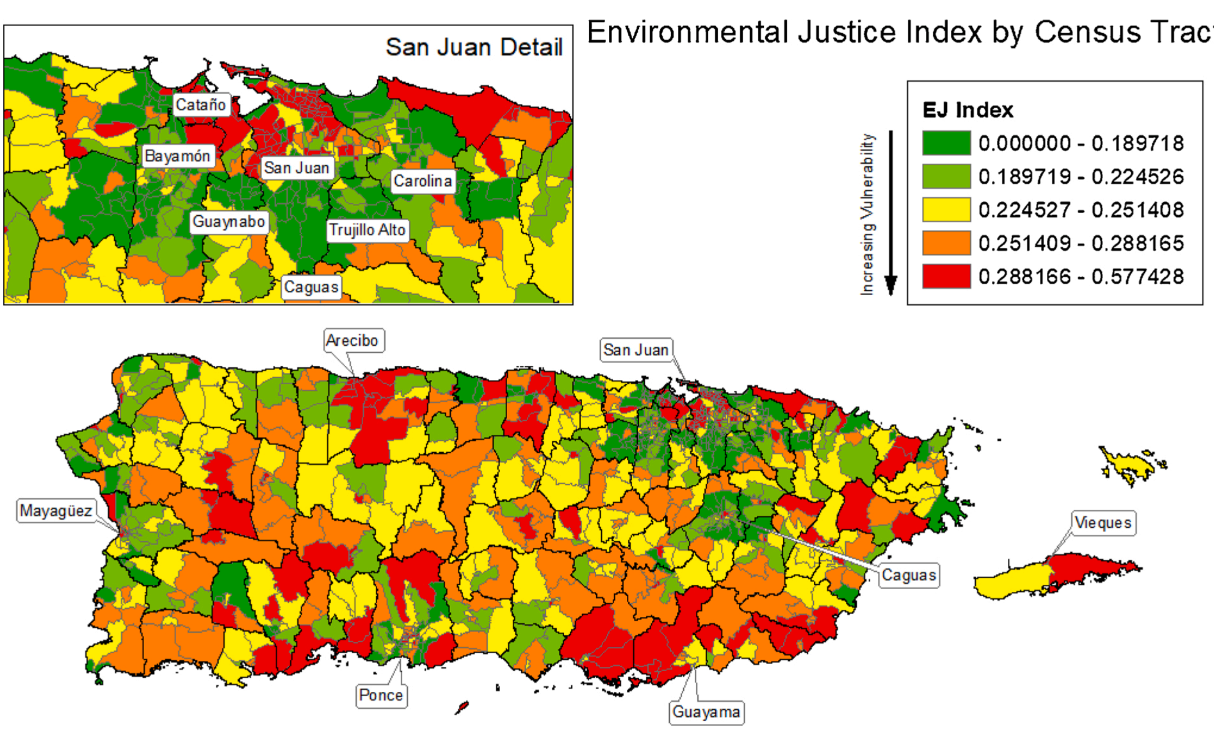

Fig. 5. Environmental justice index indicating the areas of Puerto Rico at risk of environmental injustice.

approach, therefore, is not sufficient for understanding the electricity restoration process post-hurricane – other factors, such as institutional prioritization, geography, the path of the hurricane, and energy infrastructure conditions are likely important variables in explaining the restoration pattern. However, the significant results we found indicate that environmental justice, even if not sufficient, is a useful framing for analyzing disaster recovery. To explore which indicators are contributing towards these significant results, we conducted a second regression analysis using the indicator variables as independent variables. The results are found in Table 4 below.

According to this analysis, the indicators driving the predictive value of the demographic index in electricity recovery are the percent of the population that identifies as nonwhite, the percent of the population considered linguistically isolated, and the percent of the elderly in the population living in poverty. The household median income, the educational attainment of the population, and the percent of youth living in poverty do not seem to predict electricity recovery. The indicators driving the predictiveness of the environmental index in electricity recovery are the percent of the population at risk of lead poisoning due to the age of their home, attainment with the NAAQS, and the number of TRI sites within the census tract. RMP sites and Superfund sites do not predict electricity restoration, which is an important finding, given the wide use of these indicators in the environmental justice literature.

6. Discussion

6.1. Island-wide results

Using an environmental justice framework to analyze the vulnerability of certain populations to natural disasters, such as hurricanes, requires a contextualization of environmental justice across multiple indices, and incorporating multiple demographic and environmental variables into cumulative scales or indices.

Overall, demographically vulnerable communities typically suffered longer wait times for electricity restoration than environmentally vulnerable communities, as seen from the significant relationship between the demographic index and the electricity restoration wait time. However, different forces in the demographic index compete to produce this significant result. Communities with high rates of poverty among the elderly and communities that are linguistically isolated (primarily-Spanish speaking, as opposed to primarily-English speaking or bilingual) were more likely to have longer electricity restoration wait times. These results support the body of the environmental justice literature, which uses these demographic indicators to define communities at risk of environmental injustice. Surprisingly, the household median income indicator did not significantly predict electricity restoration. This may be due to the spatial proximity of communities with high poverty rates in the San Juan area to communities with high household income in the same census tracts. More spatially-granular data would likely shed light on this unexpected result, and illuminate further the pattern of electricity restoration within urban areas. It would also illuminate why the interior region of the island was without power for so long. We hypothesize, based on news reports of the electricity restoration process, that transporting energy infrastructure equipment over the mountainous terrain of the interior region may have led to these long electricity restoration times. The question of why southeastern coastal communities were also the last to have their electricity restored would require an alternative explanation, other than geography.

Our analysis also indicates that communities with larger non-white

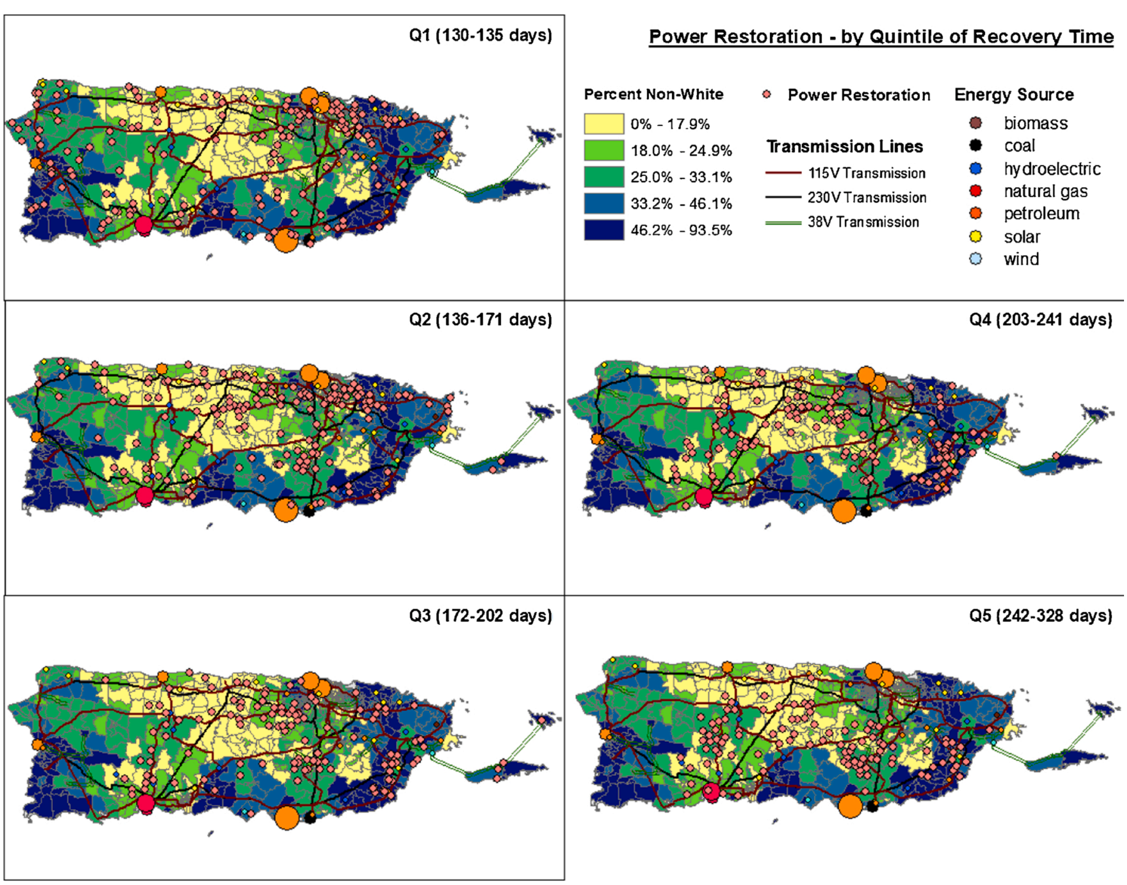

Fig. 6. Race/ethnicity by census tract, with powerplants by energy source and generation capacity, overlaid with recovery data separated into quintiles based on recovery time.
Source: IEEE and RPPR.

populations actually had shorter electricity restoration wait times. This is unexpected; we would expect these communities to have longer electricity restoration wait times according to traditional environmental justice results. To explore this further, we disaggregated the electricity restoration data and mapped the data overlaid with the demographic index (see Fig. 6).

Communities with shorter electricity restoration times were generally concentrated around the San Juan region, or scattered around the rest of the island in areas in close proximity to electricity infrastructure (see Fig. 6, Quintiles 1 and 2). The last 60 percent of communities to have their electricity restored tended to be clustered near transmission lines in the central region of the island (see Fig. 6, Quintiles 3 and 4), or in communities north and northeast of Guayama (see Fig. 6, Quintiles 3, 4, and 5). Roughly, the communities whose electricity restoration wait time was longest tended to be clustered in two demographic profiles – non-white communities in the southeastern region, and white communities in the central mountainous region. We propose that the non-white communities in the southeast present as a classic case of environmental injustice, traditionally understood within the U.S.-centric environmental justice frame; the poor, rural, majority-white communities in the central mountainous region complicate the environmental justice narrative, and require an expansion of how we conceptualize environmental injustice in Puerto Rico, especially in the context of disaster recovery. This may align better with emerging understandings of the marginalization of rural, white communities in the U.S. such as in Appalachia.

The environmental index indicates that communities classified as environmentally vulnerable also had longer electricity restoration wait times. The statistically significant relationship between lead poisoning risk and long electricity restoration wait times is negative, indicating that communities at risk for lead poisoning saw shorter electricity restoration wait times. This is likely because communities in dense, urban areas, which generally had homes built before 1960, experienced shorter wait times than the rest of the island. Urban areas have high levels of income inequality and are vulnerable to specific environmental health effects (such as the risk of lead poisoning from aging housing); however, our analysis shows that the vulnerabilities of the urban poor may be offset by their spatial proximity to wealthier urban communities.

The communities that were not in attainment with the NAAQS and communities located near a TRI site were more likely to experience longer electricity restoration wait times, a conclusion in line with existing environmental justice research which links vulnerability to proximity to environmental hazards. These communities experienced multiple intersections of vulnerability in the wake of Hurricane María. Poor air quality and pollution led to respiratory and other health concerns among affected populations; these health concerns were exacerbated by the lack of energy and water due to damage by the hurricane, and by the use of diesel generators as backup power sources (García-López, 2018; Willison et al., 2019).

Both the demographic and environmental indices, therefore, were useful predictors in identifying communities that were at risk of longer electricity restoration wait times; however, the relationship is not straightforward. Our findings that rural communities are especially vulnerable to long recovery times corroborates other research on natural disaster recovery among urban and rural communities in the U.S., which finds that housing density is correlated with electricity restoration (Mitsova et al., 2018; Román et al., 2019). These results also show the need for environmental justice to expand its understanding of vulnerability in the context of natural disasters – as climate change continues to wreak destruction on coastal and island communities, more nuanced understandings of how environmental factors may intersect with socioeconomic vulnerability is increasingly necessary.

6.2. Regional results

San Juan provides an interesting case of demographic vulnerability interacting with recovery – the region contains some of the most demographically and environmentally vulnerable populations on the island, but generally experienced quicker electricity restoration then other areas that had similar demographic and environmental vulnerability values (including the region surrounding Guayama and the central mountainous region). This is likely due to these neighborhoods' close proximity to the least vulnerable communities on the island, which were also located in San Juan, and the political and economic power of these areas. However, recovery within San Juan was not evenly distributed – the data used in this analysis is not comprehensive or granular enough to corroborate this finding, but our conclusion that environmental justice vulnerability correlates with long electricity restoration wait times seems to support this conclusion. While it may have been reasonable to prioritize the recovery of San Juan, as the capital, the major population center, and the economic engine of the island, enacting environmental justice requires that vulnerable communities be prioritized in disaster recovery, as they have fewer personal resources (such as backup generators and the ability to buy food and clean water) to fall back on. Despite the overall faster recovery in San Juan, disparities within the region are still possible.

The concentration of power plants on the southern coast of the island may have facilitated recovery in these communities compared to other areas, where the distribution networks have been neglected. Communities near Ponce benefitted from their proximity to the main power plants on the island (Román et al., 2019). Román et al. (2019) concluded that the Ponce region recovered electricity relatively quickly after Hurricane María due to the recent upgrades in the region's distribution grid and backup electricity supplies. Our analysis indicates that power plant proximity and ease of access to transmission lines likely facilitated faster recovery; a more comprehensive analysis of power restoration may further illuminate this hypothesis, including the varying level of damage caused by the hurricane in different parts of the island. In such cases, there is a tension between vulnerability caused by proximity to the power plants, and the associated public health impacts, as classic environmental justice analyses would suggest, and the reduced vulnerability afforded by this proximity in the event of electricity losses. Data limitations don't allow us to consider disparities within communities located near the power plants; therefore, even though these communities overall had their electricity restored more quickly, it does not necessarily mean that every household regained electricity access at the same time.

Southeastern Puerto Rico did not experience a similar benefit – high demographic index values in the southeast correlated with a high nonwhite population, and long electricity restoration wait times. The southeast, in addition, had a similar density of transmission lines and proximity to power plants, though these factors did not lead to faster restoration times for these communities. An estimate of damage caused by the storm would be an additional useful variable to include in this analysis, especially in exploring the damage in the southeastern region in comparison to the San Juan region. Further study and more comprehensive data would be needed in order to support this explanation. What is clear from our analysis is that communities in Yabucoa with large Black populations were hit first and hardest by Hurricane María and suffered the longest electricity restoration times on the island. In this case, environmental justice provides a useful frame for exploring the structural factors that led to such inequitable electricity restoration. A deeper analysis into the extent to which the physical damages from the hurricane correlated with the electricity restoration wait time would help elucidate these relationships, while recognizing that the damages are linked to the pre-existing condition of the infrastructure, not just the path of the hurricane.

The remoteness of central mountainous communities resulted in low environmental index values, as air pollution and lead poisoning risks are generally higher in urban areas, or near polluting facilities. However, our findings make it clear that these communities are vulnerable in a way that the environmental index fails to illustrate. Rural communities in Puerto Rico remained without electricity for longer than most of the urban regions of the island. Including indicators measuring terrain, road access, or proximity to transmission lines and power plants may have improved the predictive value of the environmental index. The demographic index for the central mountainous region did a better job of capturing vulnerability, as low incomes and education levels, and high rates of linguistic isolation and poverty affected these communities. Integrating insights from the natural hazards literature with environmental justice literature could prove a promising avenue for future research.

7. Policy and research recommendations

Our research shows the importance of using an environmental justice frame in the context of natural disasters. As the effects of climate change continue to unfold, natural disaster response and recovery will continue to be important in the public policy sphere. We argue that environmental justice provides an institutionalized frame that is useful for analyzing natural disaster recovery. The Biden administration has promised to incorporate environmental, energy, and climate justice into its policies, highlighting the continuing political salience of the environmental justice framework. In addition, environmental justice is rooted in community-led social and economic justice activism; it also has been woven into existing government policy, as evidenced by the environmental justice screening tools we utilize in this paper. These existing environmental justice mapping tools, such as EJSCREEN, could identify communities at risk of environmental justice whose recovery should be prioritized. At the same time, we recognize that traditional understandings of environmental justice (based on race/ethnicity, income, and proximity to polluting sites) may not be the optimal way to identify vulnerable communities in Puerto Rico. Geographic factors, such as proximity to energy infrastructure, flooding, and terrain intersect to affect community recovery, and can make accessing these communities with supplies and equipment more difficult.

Our policy recommendations therefore focus on the use of an environmental justice frame in natural disaster recovery; this frame centers those who are more vulnerable, and makes explicit the relationship between vulnerability and race, income, geographic, and ecological factors. Researchers, first-responders, disaster aid agencies, and policy makers should engage in a vulnerability analysis rooted in environmental justice long before disaster strikes to help drive disaster recovery approaches. Such an analysis should have been included in Puerto Rico's Economic and Disaster Recovery Plan (EDRP); however, the EDRP does not prioritize justice, equity, or vulnerability in its plan for energy infrastructure transformation. The recovery plan has four goals – to promote an educated, healthy, sustainable society; to rebuild the economy so that it is sustainable and competitive; to enhance Puerto Rico's resilience; and to strengthen Puerto Rico's critical infrastructure (COR3, 2018). None of these goals include mention of justice or equity. In light of scholarship regarding the inherent inequity when resilience is framed as the sole goal of disaster recovery (Baker, 2019), the EDRP's lack of commitment to justice and equity only further highlights the need for an environmental justice lens in the island's recovery. The EDRP does include recommendations to enhance the resilience of the island's electricity system by relying on decentralized solar infrastructure that can be islanded from the grid (COR3, 2018); however, the plan does not prioritize vulnerable communities in this system transformation. Our analysis highlights two communities in particular that were disproportionately affected by the power grid's failure post-Hurricane María: rural communities in the center of the island, and Black communities in the southeast. We recommend that resources should be targeted towards these communities.

Our research recommendations include further study to identify possible environmental variables that might better correlate with natural disaster resilience, such as land ownership and green space, or natural resources such as nearby running water and local food sources, in addition to indicators mentioned above. Traditional environmental justice indicators consist of demographic variables and proximity to polluting sites. We recognize that the drivers of vulnerability to natural disasters differ from the drivers of vulnerability to classic environmental injustices (such as disproportionate exposure to pollution), and therefore advocate for a set of environmental indicators that are more contextually appropriate to natural disasters. However, the EDRP's discussion of environmental factors that can increase resilience to natural disasters is sparse, consisting of a section on natural capital (such as coral reefs, seagrass, wetlands, and forests) that can reduce the effects of flooding. Further research on how natural capital can be utilized in the southeast of Puerto Rico and how these considerations fit into disaster policy and planning is critical to ensure that such natural capital is not ignored in vulnerable communities. Further, the remoteness of the central region of Puerto Rico is not discussed in the context of resilience or natural disaster recovery, even though terrain and public infrastructure in this region affected recovery after Hurricane María. Qualitative case studies of areas that have high environmental and demographic index values, and experienced long electricity restoration wait times (such as the southeast and central mountainous regions) would further illuminate the relationship between a history of environmental hazards and injustice, and natural disaster resilience.

Author statement

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Laura Kuhl: Conceptualization, Resources, Writing – Original Draft, Writing – Review & Editing, Supervision, Project Administration, Funding Acquisition.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2021.04.004.

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