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RESEARCH ARTICLE

Advancing sustainable transitions: A spatial analysis of socio-environmental dynamics of landfills across the United States

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Landfills are a kind of environmental hazard, linked to harms, such as the production of greenhouse gases and the accumulation of toxins in natural and human systems. Landfills contribute to climate change through emissions. Yet, the inclusion of socio-environmental dynamics of waste management systems in sustainability research has been understudied. Using a unique dataset of all landfills—construction and demolition, municipal, industrial, and hazardous—this study adds to sustainability research by focusing on waste management systems and to environmental justice research through inclusion of gender indicators and investigation of multiple forms of waste containment beyond solely hazardous facilities. Employing spatial error models, results suggest that communities of color, female-householder families, and disasters are associated with both nonhazardous and hazardous waste landfills. Understanding the relationships between social inequality and landfills improves our ability to plan for and develop more sustainable waste management systems, a key focus for advancing sustainability transitions.

Keywords: Sustainability, Environmental justice, Gender inequality, Spatial analyses, Landfills, Climate change

1. Introduction

One specific system of focus for sustainability transitions that continues to be understudied are waste systems, in particular the role of landfills, in both contributing to climate change (The Intergovernmental Panel on Climate Change [IPCC], 2018; Blair and Mataraarachchi, 2021; Cusworth et al., 2024) and in creating and exacerbating environmental inequality (Bullard et al., 2007; Mohai and Saha, 2015a, 2015b). How we deal with our waste as a society has important implications for transitions to more sustainable systems that reduce harmful impacts on environments and people (Blair and Mataraarachchi, 2021). To better understand the importance of socio-environmental dynamics of waste systems to sustainable transitions, we must first understand the ways in which landfills contribute to climate change and socio-environmental inequality. Such research is necessary to inform more sustainable approaches to waste management.

Waste management, generally, and landfills, specifically, as the predominant form of waste management in the United States (United States Environmental Protection Act; United States Environmental Protection Agency [U.S. EPA], 2008), are important to examine for 3 main reasons. First, all human settlements need a mechanism for discarding waste. Second, landfills are a driver of global climate change as they produce methane that increases the greenhouse gas effect, in which carbon is trapped in the Earth's atmosphere causing the planet to warm (e.g., McKinney et al., 2015; Cannon, 2021; Cusworth et al., 2024). Finally, landfills are a form of environmental inequality in that they produce noxious smells, can create unsafe water and land conditions, and generate air, noise, and water pollution (e.g., Elliott and Frickel, 2011).

Prior research in the social sciences, employing empirical methods, has heretofore focused primarily on hazardous waste facilities as a key form of environmental inequality in their investigations, specifically those of race and socioeconomic status (e.g., Mohai and Saha, 2006, 2007, 2015a, 2015b; Bullard et al., 2007; Smith, 2009; Elliott and Frickel, 2011; Bullard and Beverly, 2012; Cannon, 2020). More generally, utilizing such spatial methods as geographic information systems (GIS) and working cross-disciplinarily, researchers have begun to map social and environmental inequality in the United States in order to analyze variations of socio-environmental disparities across space (e.g., Bullard et al., 2007; Lobao et al., 2007; Elliott and Frickel, 2013; Mohai and Saha, 2015b; McKinney and Thomson, 2022). These methods allow for an operationalization of space in a way that traditional empirical analyses (e.g., ordinary least squares (OLS) regression) have struggled to do so.

The current study adds to the existing literature in 3 main ways. First, this research extends analyses to

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construction and demolition (C&D), industrial, and municipal landfills, which make up roughly 93% of all landfills in the United States—a key area of research needed to advance sustainability. Although not named as hazardous, toxic materials are accepted by all types of landfills, particularly C&D and industrial ones (U.S. EPA, 2008), which means they pose human health and environmental threats (Mattiello et al., 2013). Second, this research employs spatial methods, specifically spatial regression techniques, to uncover significant linkages between social and environmental inequalities to advance our understanding of environmentally just sustainability. Finally, this study utilizes gender indicators in addition to race and socioeconomic variables to assess key relationships between social and environmental disparities.

2. Literature review

2.1. Sustainability, landfills, and environmental injustice

Sustainability is often understood using the 1987 U.N. definition of "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Expanding this definition to encompass social, economic, and environmental systems, sustainability research across the social sciences has investigated social inequality (e.g., Agyeman et al., 2003), global development (i.e., U.N.'s sustainable development goals) (e.g., Sachs, 2009), environmental inequality (e.g., McKinney, 2014), ecosystem services (e.g., Bennett et al., 2015), and nature-based solutions (e.g., Santiago Fink, 2016). Considering this research, sustainability is often understood as ensuring the social, economic, and environmental well-being of communities of the present and future (Agyeman et al., 2003).

One often overlooked area important to sustainability in need of study is that of waste management. Landfills, the predominant form of waste containment in the United States (U.S. EPA, 2008), are themselves drivers of climate change through methane emissions (e.g., Powell et al., 2016; IPCC, 2018; Cusworth et al., 2024) and a source of environmental injustice (Bullard et al., 2007; Bullard and Beverly, 2012). To advance sustainable development goals (SDG) #12—responsible consumption and production—there must also be a focus on responsible disposal, which can reduce inequalities (SDG #10), and help foster sustainable cities and communities (SDG #11). Though frequently considered the "sustainable alternative" to other forms of waste management—such as burning rubbish—landfills contribute to unsustainable systems in that they do not degrade and in their release of greenhouse gases (Allen, 2001; Cusworth et al., 2024), which contributes to the acceleration of anthropogenic global climate change (Saunois et al., 2016). Furthermore, landfills are a driver of a positive feedback loop of unsustainability, wherein landfill emissions accelerate climate change, which causes more frequent and severe disasters, which create more debris that goes into landfills, generating more emissions (McKinney et al., 2015; Blair and Mataraarachchi, 2021). While environmental justice scholars have long studied the relationship among socioeconomic disparities and hazardous waste landfills, as a form of environmental inequality, research into sustainability transitions has been slow to examine the role landfills play in exacerbating both climate change and environmental injustice.

Environmental justice research has employed multiple kinds of methods (e.g., quantitative, qualitative, and spatial) to uncover key relationships between social and environmental disparities including those stemming from proximity to hazardous waste landfills (e.g., Bullard et al., 2007; Lobao et al., 2008; Bullard and Beverly, 2012; Cannon, 2020; Taylor, 2020). Hazardous waste landfills have been found to be one hazard that poses or may pose emotional, mental, and physical health risks to those who encounter it (Brulle and Pellow, 2006) and that disproportionately impacts communities of color and communities with low socioeconomic status (Mohai and Saha, 2015a, 2015b). Yet, recent research suggests that other kinds of landfills—municipal, C&D, and industrial—which make up the overwhelming majority of landfills in the United States pose risks to both the environment through contamination of ecosystems, food webs, and ground and drinking water supplies (Weber et al., 2011)—endangering SDG #15 life on land and SDG #14 life below water—and human health, with exposure likely resulting in high asthma rates and low birth weights (World Health Organization, 2007; Porta et al., 2009; Mattiello et al., 2013). It could be the case that places with hazardous waste landfills may also host nonhazardous waste landfills. This area of research continues to be understudied (Vaverková et al., 2018; Vaverková, 2019). Although not regulated as hazardous waste, these other kinds of landfills pose a threat to sustainability, the environment, and human health necessitating further study.

2.2. Environmental injustice and gender inequality

Although environmental justice scholarship has differed in its findings on the importance of race and socioeconomic status to the distribution of environmental disparities, including hazardous waste landfills and air pollution (e.g., Chakraborty et al., 2011; Mohai and Saha, 2015a, 2015b), few studies have employed gender indicators in addition to race and class variables (see for exception, Downey and Hawkins, 2008; Collins et al., 2011; Cannon, 2021; McKinney and Thomson, 2022). Of the scant research that exists, Downey and Hawkins (2008) found in their tract-level study of different family structures (e.g., female-headed households, male-headed households, married-couple headed households without children) across the United States that female-headed households were overrepresented in tracts with high concentration of air toxics.

Within socio-environmental research that examines gender inequality, scholars have explored how gender inequality intersects with other aspects of social life including age, immigration status/citizenship, and indigeneity to influence disproportionate exposure to such hazards (e.g., Collins et al., 2011; Taylor, 2014; Cannon, 2021). Conceptualizing and operationalizing gender inequality enables greater insight into the ways in which environmental hazards may be linked with race and socioeconomic status. For example, such patterning may be due to the fact that institutionalized housing discrimination impedes housing choices, restricts residential movement, and concentrates women and racial minorities to neighborhoods with high levels of environmental hazards in the United States (Gotham, 2002; Elliott and Clement, 2015).

While most studies investigating gender and environmental inequality have occurred at either the cross-national level (e.g., Austin and McKinney, 2016) or the local level (e.g., Bell, 2013), the current study focuses on the subnational level of analysis, fulfilling calls from leading scholars in the field to better understand regional differences (e.g., Pellow and Nyseth Brehm, 2013). For example, McKinney and Thomson (2022) found that female-householder families were the most robust explanatory variable in their analysis of the percentage of nonhazardous waste landfills in each county in the Southeastern United States. Yet, more research is needed to understand the relationships among landfills as a form of environmental inequality and unsustainability across the United States. Due to systemic oppression women experience in U.S. society (Bell, 2013; Taylor, 2014), it makes sense that women would also disproportionately experience environmental inequality. This article aims to further the fields of sustainability and environmental justice by (1) considering environmental and social inequalities specifically due to gender and (2) examining gender inequality at the subnational level. Doing so provides much needed insights into generalizable trends of the ways in which women may be environmentally disadvantaged across the United States.

2.3. Drivers of spatial inequality

To identify the patterning of socio-environmental inequality across the United States, the geographical distributions of environmental hazards, such as landfills, are necessary to consider (Cutter and Solecki, 1996; Smith, 2009; Elliott and Frickel, 2011; Elliott and Clement, 2015). Taking seriously Tobler's First Law of Geography—everything is related to everything else but near things are more related than distant things (Tobler, 1970)—employing analytic strategies that can adequately operationalize space in socio-environmental research is necessary for assessing such drivers of spatial inequality. Doing so provides empirical means for theorizing pathways in which space matters in the production, expansion, and continuation of social inequality at various scales of analysis (Lobao et al., 2007). Such approaches stress the importance of analyzing spatial inequality subnationally, including under-explored levels of analysis such as counties or regions, and are key to informing knowledge of the geographical distribution of hazards (McKinney and Thomson, 2022).

Especially for investigations into socio-environmental dynamics relevant to sustainability transitions in the United States, some scholars argue for the importance of using spatial methods (e.g., GIS, spatial autoregressive models) to analyze linkages between social stratification and space (Lobao et al., 2008). Defining this spatial gradient is important for identifying trends and processes across the populace and developing strategies for policy development and political action (Lobao et al., 2007, 2008). The current study, following a tradition in the field of identifying resource distribution across race, socioeconomic status, and gender (e.g., McCall, 2001), seeks to show the allocation of environmental hazards across such social axes to advance sustainability research. Analyzing environmental hazards spatially, at this scale, provides insights into disparities across regions in the United States and deepens our understanding of the "missing middle"—a midrange scale that can capture dynamics across different regions without a limiting focus solely on rural or urban areas (Lobao, 2004; Lobao et al., 2008; Cannon, 2020). In doing so, this article fills a gap in the field in its investigation of socio-environmental dynamics of sustainability and environmental hazards that explicitly uses a spatial approach.

2.4. Hypotheses

Based on extant literature reviewed earlier, the following hypotheses were developed to identify the spatial patterning of landfills, as a form of environmental inequality and unsustainability, across the United States.

- H1: Dense concentrations of landfills are concentrated in areas with greater social inequality—counties with a relatively greater percentage of non-white people and percentage of families in poverty.
- H2: Places with greater gender inequality, measured by female-householder families, are located in counties with dense concentrations of landfills.
- H3: Places with dense concentrations of nonhazardous waste landfills are located in counties with dense concentrations of hazardous waste landfills.

3. Materials and methods

In this study, I theoretically specify and empirically analyze how socioeconomic, racial, and gender status, and disasters contribute to unequal risks to environmental inequalities to evaluate the understudied effects of landfills, as a form of unsustainability, across the United States. OLS regression and spatial error models were used to estimate models of a unique dataset of social and environmental indicators for all counties in the contiguous United States. A combination of data from several sources is necessary for this research. Data are reviewed below, followed by a discussion of analytic techniques used in this study.

3.1. Dependent variable: Landfill data

Waste generated from households and through industrial, C&D processes must be disposed of somewhere. Location of landfills maintained by the state is recorded by each state's environmental regulatory agency (e.g., Environmental Management, Natural Resources, Environmental Quality, and Environment and Natural Resources). There is a great deal of variance across landfill records with respect to fill size, accepted materials, and address given municipal, C&D, and industrial waste landfills are regulated and maintained at the state level. Moreover, given such variation across state records, data collection took an extensive amount of time (3 years) and necessitated going to each state's environmental agency to build a dataset of landfill by type and county. Collecting data from individual states, although more time-intensive, proved to be more accurate and thorough than using data from national databases, such as the Toxics Release Inventory (U.S. EPA, 2021), which often lacked the most current and complete data available. Furthermore, federal databases are not always comparable due to inconsistent data collection procedures across federal agencies. As such, this dataset represents the first of its kind to the author's knowledge. Hazardous waste landfill data, since it is regulated and monitored at the federal level, were obtained from the U.S. EPA. Landfills in the United States are typically in use for 50 years until they are permitted to continue operating, expanded, capped, or closed. Because fill size is not recorded across landfills, I am unable to account for the differing sizes of landfills. Similar to much of the environmental justice literature into waste facilities (e.g., Mohai and Saha, 2015b), I treat all landfills as a measure of environmental inequality. All landfills that were listed as open in 2012 are used in the dataset for the 3,108 counties for which there were data.

Counties are used since they represent stable boundaries—a necessity due to the time intensive nature of data collection—and because the disaster data available are measured at the county level (see below). Although the distribution of negative effects associated with waste facilities is not uniformly distributed across a county (e.g., Cole and Foster, 2001; Bullard and Beverly, 2012), these boundaries offer stable, administrative units by which to analyze generalizable trends across the United States (see McKinney et al., 2015; McKinney and Thomson, 2022).

3.2. Independent variables: Sociodemographic data

All sociodemographic data come from the American Community Survey (ACS) 5-year estimate (2009–2013) to include data for all study areas regardless of population size (United States Census Bureau, 2013). This time frame is used so that the dependent variable lags the independent variables—standard practice for the type of analysis employed to test hypotheses. Additionally, total population and population density, or people per square mile (Smith, 2009), are used as control variables. Other independent variables found in the environmental justice literature (e.g., Mohai and Saha, 2015a) include percent non-white as a measure of racial minoritized groups and the socioeconomic variable, percent of families living below the poverty line. To ascertain a unique effect of gender on landfills, following research by Downey and Hawkins (2008) and Collins et al. (2011), percent of female-headed primary households, referred to as female-householder families, is used as a measure of gender inequality. The census defines this measure as "primary families maintained by a female household with no husband present" (United States Census Bureau, 2013). Although certainly not all female-householder families may experience gender disadvantage, given heteropatriarchal society and the limitations of secondary data that have already been collected at this scale, it can provide a good indication of gender inequality. Secondary data analysis is limited by the data collected and future data collection efforts should attempt to collect more information on the experiences and structural disadvantages that are uniquely related to gender to more fully account for gender-related environmental disparities.

3.3. Control variable: Disaster data

Disaster data are taken from the U.S. Federal Emergency Management Agency (FEMA) for each county and include all federally declared disasters for the time period 1961–2011 (i.e., tropical storms, hurricanes, floods, tornadoes, earthquakes, fires, freezes, landslides, droughts, volcanoes, blizzards, water shortages, and tsunamis) (FEMA, 2013). These data are collected by county.

3.4. Analytical approach

A series of multivariate regression models were run to examine relationships among landfills and sociodemographic characteristics, controlling for disasters. Two models—OLS and spatial error—were run for 2 dependent variables, nonhazardous waste landfills (i.e., municipal, C&D, and industrial landfills), and hazardous waste landfills resulting in 4 models. First, an interval variable of landfills was regressed on sociodemographic, disaster, and control variables. This model takes the following form:

$$y_i = \beta_0 + X_i\beta + \varepsilon_i.$$

In this equation, β_0 is the intercept, X_i is the variable, β is the coefficient for that variable, and ϵ_i is the error term.

Second, because landfills can be located in contiguous counties, thus introducing spatial dependency in the dependent variable, a spatial error model was run. Moran's *I*, which is a frequently used measure of spatial autocorrelation (Moran, 1950)—the presence of systematic spatial variation in a variable—is statistically significant and relatively large, 0.216 ($P < 0.001$) for the nonhazardous waste model, and 0.138 ($P < 0.001$) for the hazardous waste model. Following Anselin (2005), Lagrange multiplier (LM) and robust LM tests for spatial lag and spatial error models were run to identify which model would be better specified. The robust LM tests for the spatial error for both dependent variables were statistically significant ($P < 0.001$), thus a spatial error model was run with the same variables as the OLS regression. The spatial error model incorporates spatial dependence in the errors (Saputro et al., 2019). It tests for spatial autocorrelation in the dependent variable, or the association of landfills between geographically proximate counties (Anselin et al., 2013). The model takes the following form:

$$y_i = X_i\beta + \lambda w_i\varepsilon_i + u_i.$$

In the spatial error model, the error term in OLS regression is split into random error, u_i, and a spatially structured error term, which is composed of the spatial error coefficient, λ, and the ε error term weighted by *W*, a row-standardized spatial weights matrix measuring neighbor connectivity, defined as Queen contiguity, which are counties that share a side or vertex. Since $\lambda \neq 0$ in the models, OLS regression coefficients are unbiased and consistent but inefficient, while the standard errors are incorrect. Thus, both OLS regression and spatial error models are presented in **Table 3**. Final analyses were completed using ArcGIS Pro 3.0.1 and GeoDa 1.2.

4. Results

4.1. Descriptive results

Summary statistics are presented in **Table 1**. A diagnostic bivariate correlation table is presented in **Table 2**.

Exploratory spatial data analysis was conducted to better understand the location and distribution of landfills across the United States. **Figure 1** shows a quartile map of the distribution of landfills and a natural breaks map of hazardous waste landfills providing a better sense of where landfills tend to occur in denser and less dense areas.

To further identify spatial clustering of landfills and since Moran's *I*, a measure of spatial autocorrelation, indicates that landfills are clustered, aggregation polygon optimized hotspot analysis calculates a Getis-Ord Gi statistic to ascertain statistically where the dependent variable is spatially clustered at 95%, 97%, and 99% confidence intervals. **Figure 2** presents the results of this analysis. To identify hotspots, this specific type of hotspot analysis allocates point data (i.e., latitude and longitude data of landfills) to the polygon (i.e., county-level data). Doing so reduces a nearest neighbor bias, while accounting for landfills near administrative boundaries. The hotspot analysis assesses the degrees of clustering. **Figure 3** shows the results of this analysis indicating that there are hotspots—a county in which nonhazardous waste landfills are clustered together statistically significantly different from random ($P < 0.01$)—across the Southeastern United States and eastern Texas, Southern California and Arizona, South Dakota, central Florida, and the Illinois–Wisconsin border. Coldspots—or counties that have fewer landfills than if randomly distributed ($P < 0.01$)—were in Virginia, Ohio, Kentucky, Missouri, and the Upper peninsula of Michigan, whereas hazardous waste landfills have fewer clusters but do occur in 3 patches across the Southeast and in the Northeast.

Given the interest in the relationship between landfills and gender inequality, **Figure 3** shows a box map of the calculated risk rate between landfill concentration and percentage of female-householder families using Empirical Bayes smoothing, a spatial averaging approach, to correct for outliers. Darker red colors show where the risk is higher than the average for female-householder families with bluer colors indicating where the risk is less than the average.

In order to statistically test relationships among sociodemographic characteristics and landfills, OLS regression and spatial error models were performed.

4.2. Models

Results from the regression models are presented in **Table 3**. The OLS regression of nonhazardous waste landfills (i.e., municipal, C&D, and industrial) was statistically significant explaining 22.3% of the variance in the dependent variable ($F(7, 3101) = 148.31$, $P < 0.001$). The model shows that the control variables, total population, are positively associated, and population density is negatively associated with nonhazardous waste landfills. These results are consistent with prior research (e.g., Smith, 2009; Cannon, 2020). The independent variables of percent of non-white and percent of female-householder families are also in the

Table 1. Summary statistics with multicollinearity measure, variance inflation factor (VIF), for all counties in the contiguous United States

	Mean	*SD*	Min	Max	VIF
Dependent variable					
Total nonhazardous landfills	1.52	2.09	0	18	–
Hazardous landfills	0.17	0.56	0	6	–
Independent and control variables					
Population density (sq. mile)	258.39	1,724.93	0.12	69,468.42	1.15
Total population	98,479.18	314,016.51	82	9,818,605	1.31
Rural-Urban Continuum Code (RUCC)	4.99	2.7	1	9	1.57
Race					
Percent non-white	16.73	16.32	0.78	97.08	3.83
Socioeconomic					
Percent below poverty	11.97	5.53	0	40.19	2.77
Gender					
Percent female-householder families	11.33	4.28	1.68	38.01	6.38
$N = 3{,}108$					

Table 2. Bivariate correlation table of all measures included in regression models

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Total nonhazardous waste landfills	1.00								
2. Hazardous waste landfills	0.291**	1.00							
3. Population density	0.009	0.055**	1.00						
4. Total population	0.352**	0.256**	0.333**	1.00					
5. Rural-Urban Continuum Code (RUCC)	−0.211**	−0.256**	−0.178**	−0.335**	1.00				
6. All disasters (1964–2011)	−0.003	0.054**	0.025	0.173**	−0.106**	1.00			
7. Percent non-white	0.169**	0.117**	0.162**	0.203**	−0.17**	−0.027	1.00		
8. Percent families below poverty	−0.021	−0.27	0.006	−0.05**	0.175**	0.008	0.532**	1.00	
9. Percent female-householder families	0.133**	0.124**	0.106**	0.133**	−0.24**	0.032	0.84**	0.702**	1.00

** $P < 0.05$.

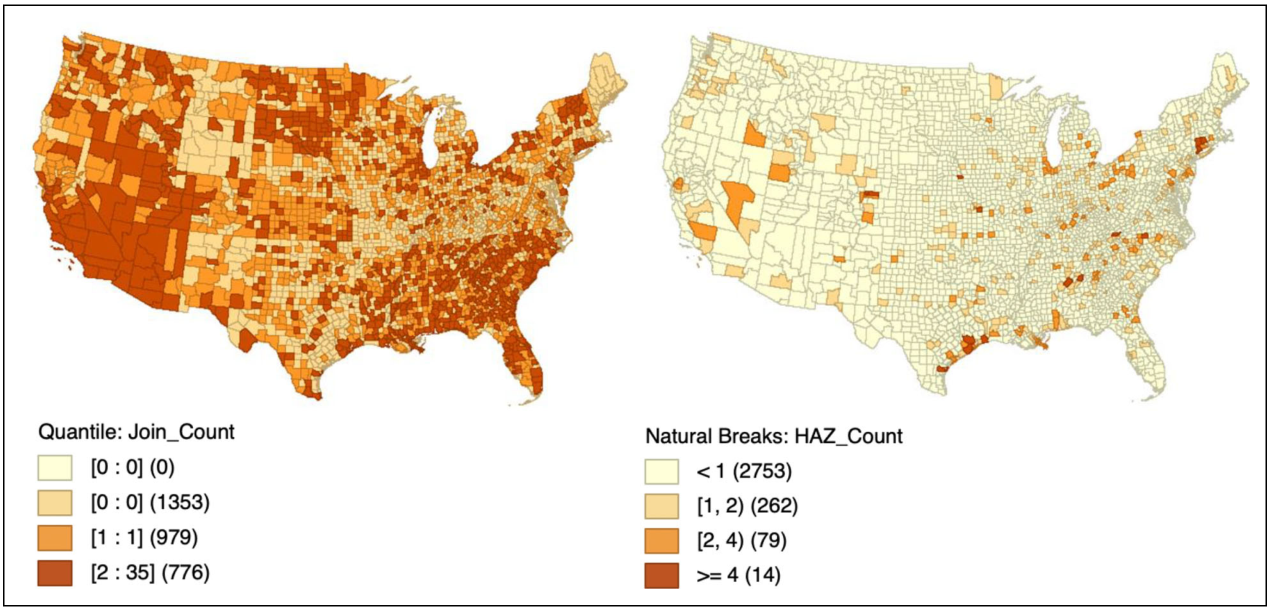

Figure 1. County-level map of landfills on the left and hazardous waste landfills on the right.

expected direction given prior research (e.g., McKinney and Thomson, 2022)—that is a positive association between race as measured by percentage of people of color and landfills and gender inequality, as measured by female-householder families, and landfills. The measures for socioeconomic status and disasters were not statistically significant in this OLS model.

A spatial error model of nonhazardous waste landfills as the dependent variable was also run given the detection of spatial autocorrelation. The spatial error model is interpreted the same as the OLS regression. Looking at model fit statistics, Akaike information criterion (AIC) and Log Likelihood, this model improves on the OLS regression by incorporating spatial dependence of the errors (see **Table 3**). This model was statistically significant, explaining 31.4% of the variance in the dependent variable (AIC = 11,113.7, Log Likelihood = −5,549.85). The spatial error model has a new parameter, λ, which is a lag on the error. The positive direction and statistical significance of λ indicate that when landfills in surrounding areas increase, on average, so do the number of landfills in each county, when adjusting for other explanatory variables in the model. The control variables, total population and population density, were in the same direction as the OLS regression. The explanatory variables, percent of non-white and percent of female-householder families, were also positively associated with landfills confirming the OLS regression results.

Additionally, in the spatial error model, percent of families living in poverty was statistically significant with a negative association to landfills. Although this finding is surprising given environmental justice that has found low socioeconomic status is associated with hazardous

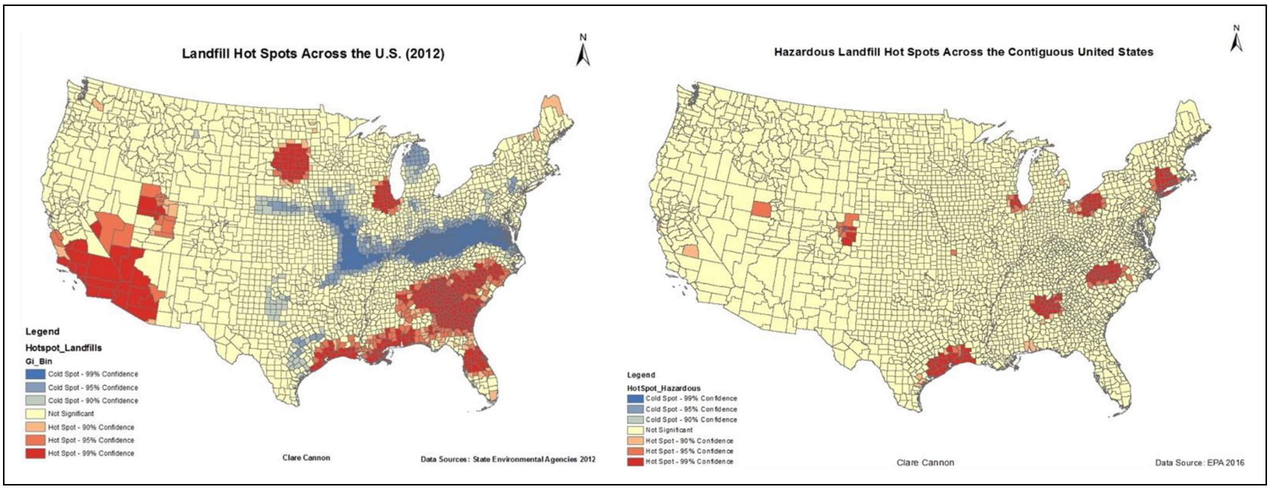

Figure 2. Hotspots and coldspots of nonhazardous waste landfills clustering across the United States on the left and hotspot clustering of hazardous waste landfills on the right.

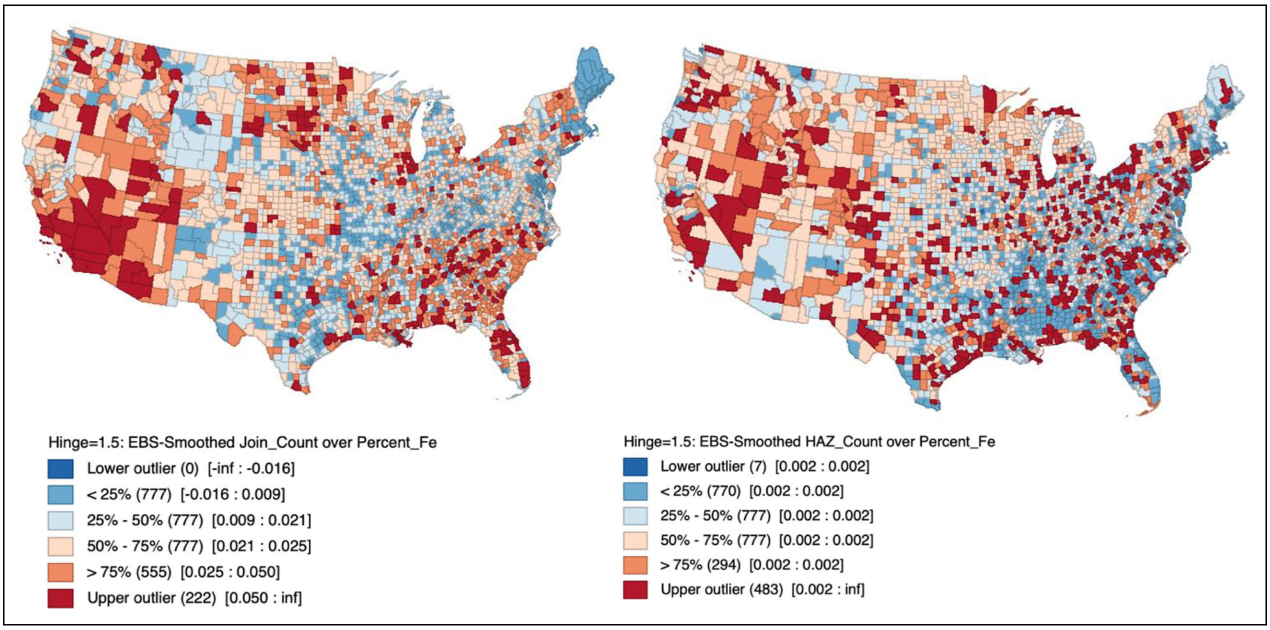

Figure 3. Box map of the risk rate of nonhazardous waste landfills and percentage of female-householder families using Empirical Bayes smoothing method to reduce outliers on the left and the same rate for hazardous waste landfills on the right.

waste landfill location (e.g., Bullard et al., 2007), some research has found that environmental hazards—specifically coal and nuclear host census tracts in the United States—have also not been associated with low socioeconomic status (Kosmicki and Long, 2016). It could be the case that this finding is different from other research due to the scale—other research using different spatial methods, such as creating buffers around a facility for a more fine-grain scale—have found poverty positively associated with hazardous waste landfills (e.g., Mohai and Saha, 2015b). Second, it is likely that there are many people who are not well-off who are not living technically below the poverty line, given the U.S. poverty line is so low. Using a different measure, such as median household income, may capture the relationship between socioeconomic status and landfills more fully. Finally, total number of disasters was also statistically significant in this model and was positively associated with landfills, adding support to McKinney and Thomson's (2022) similar findings between disasters and nonhazardous waste landfills in the Southeastern United States.

OLS regression (3) and spatial error (4) models were also performed with hazardous waste landfills as the dependent variable. Results from these models are also presented in **Table 3**. The OLS regression of hazardous waste landfills was statistically significant explaining 17.5% of the variance in the dependent variable ($F(8, 3100) = 93.71$, $P < 0.001$). The model shows that the control variable, total population, is positively associated with hazardous waste landfills. The independent variable, percent of non-white is in the expected direction given prior research (e.g., Mohai and Saha, 2015b)—that is

Table 3. Regression results

Dependent Variable: Number of Nonhazardous Waste Landfills			Number of Hazardous Waste Landfills	
	OLS	Spatial Error	OLS	Spatial Error
	(1)	(2)	(3)	(4)
Total population	0.002*** (9.833×10^{-5})	0.0023*** (0.0001)	0.0002*** (3.67×10^{-5})	0.00022** (3.78×10^{-5})
Population density	−0.145*** (0.017)	−0.103*** (0.02)	−0.003 (0.006)	−0.001 (0.007)
Percent non-white	0.01*** (0.001)	0.012*** (0.002)	0.001* (0.0005)	0.002*** (0.0006)
Percent poverty	−0.004 (0.006)	−0.013* (0.007)	−0.006** (0.002)	−0.005* (0.002)
Percent female-headed household	0.04*** (0.012)	0.043*** (0.011)	0.016*** (0.004)	0.012** (0.004)
All disasters	0.0006 (0.006)	0.016* (0.008)	0.002 (0.002)	0.005† (0.002)
Nonhazardous waste landfills			0.1*** (0.006)	0.11*** (0.006)
Lambda		0.404*** (0.024)		0.3*** (0.03)
Constant	−1.679** (0.588)	−1.544** (0.569)	−0.757*** (0.218)	−0.61** (0.218)
Observations	3,108	3,108	3,108	3,108
R^2	0.223	0.316	0.175	0.222
Adjusted R^2	0.221		0.173	
Log Likelihood	−5,694.24	−5,545.73	−2,353.21	−2,287.58
Sigma^2	2.287	2.01	0.267	0.25
Akaike information criterion	11,402.5	11,105.5	4,722.41	4,591.16
Residual std. error	1.511 (df = 3,101)		0.52 (df = 3,100)	
F statistic	148.31*** (df = 7; 3,101)		93.71*** (df = 8; 3,100)	
Wald test (df = 6; 7)		11,236.509***		1,623.28***
LR test (df = 1; 1)		288.79***		131.26***

†$P < 0.1$. *$P < 0.05$. **$P < 0.01$. ***$P < 0.001$.

a positive association between percent of non-white residents and hazardous waste landfills. Gender inequality, as measured by female-householder families, is also positively associated with hazardous waste landfills. Socioeconomic status was negatively associated with hazardous waste landfills. Given environmental justice research that has found multiple kinds of environmental hazards tend to be colocated (Kosmicki and Long, 2016), this model included an additional explanatory variable—nonhazardous waste landfills—which was positively associated with hazardous waste landfills. Population density and total federally declared disasters were not statistically significant.

A spatial error model of hazardous waste landfills as the dependent variable was also run given detection of spatial autocorrelation. The spatial error model is interpreted the same as the OLS regression. Looking at model fit statistics, AIC and Log Likelihood, this model improves on the OLS regression model by incorporating spatial dependence of the errors (see **Table 3**). This model was statistically significant, explaining 22.2% of the variance in the dependent variable (AIC = 4,591.16, Log Likelihood = −2,287.58). The positive direction and statistical significance of λ indicate that when hazardous waste landfills in surrounding areas increase, on average, so do the number of landfills in each county, when adjusting for other explanatory variables in the model. The control variable, total population, is in the same direction as the OLS regression. The explanatory variables, percent non-white, percent female-householder families, percent families living in poverty, and nonhazardous waste landfills, were all in the same direction and magnitude as the OLS regression results. Finally, in the spatial error model, total number of disasters was also statistically significant and positively associated with hazardous waste landfills. Population density was not statistically significant.

5. Discussion and implications

Socio-environmental dynamics of waste management systems have been frequently overlooked in research into sustainability transitions and yet remain an important area of focus to advance sustainability. Landfills both contribute to climate change (IPCC, 2018; Blair and Mataraarachchi, 2021) and create and exacerbate environmental inequality (Bullard et al., 2007; McKinney and Thomson, 2022). Though treated as a control variable, both spatial error models suggest that counties with more disasters tend to have more nonhazardous and hazardous waste landfills. It could be the case, as others have posited, that the increased debris from disasters increases landfill impacts (e.g., McKinney and Thomson, 2022), particularly since removing disaster debris as quickly as possible is an important factor in a quicker and more comprehensive recovery (Luther, 2017). More research is needed to test this theory. Moreover, landfills are an environmental hazard that disproportionately impacts communities of color and female-householder families (Bullard et al., 2012; Cannon, 2021; McKinney and Thomson, 2022) and are themselves susceptible to disasters (e.g., Roper, 2008).

The current study adds credence to the call by scholars (e.g., Smith, 2009; McKinney et al., 2015; Mohai and Saha, 2015b; McKinney and Thomson, 2022) to examine and analyze different types of landfills to further our understanding of socio-environmental inequalities. This research builds on the work of others in identifying linkages among social inequality and landfills other than hazardous ones as differences have emerged between relationships among social inequality and hazardous and nonhazardous waste landfills (Cannon, 2020, 2021). For instance, Cannon (2020) found that hazardous waste landfills were more likely to be found in urban areas while municipal, C&D, and industrial ones were more likely to be found in rural ones. The finding in this study—that as landfills in surrounding areas increase, on average, so do the number of landfills in each county, when adjusting for other explanatory variables in the model—helps to explain how landfills as a form of environmental inequality contribute to spatial inequality across the United States. Moreover, the presence of nonhazardous waste landfills such as municipal, C&D, and industrial ones, being associated with the presence of hazardous waste landfills, may suggest multiple kinds of landfills tend to be colocated. By identifying where these clusters occur—specifically across the Southeastern United States and eastern Texas, Southern California and Arizona, South Dakota, central Florida, and along the Illinois–Wisconsin border, we can determine specific regions in need of further study to improve sustainable waste management systems and reduce socio-environmental inequalities.

For instance, these analyses reveal an unequal and uneven distribution of environmental hazards across the Southeastern United States, which supports other research that has explored relationships between social and environmental disparities at such regional levels (e.g., McKinney et al., 2015; Cannon, 2020; McKinney and Thomson, 2022). The Southeast may be a hotspot for landfills due to past land-use patterns that followed and continue to follow a logic of racial segregation (Gotham, 2003; Taylor, 2014). There is additional support for this point in research that has found the more racially segregated a county was between white people and Black people the greater the likelihood the county hosted a nonhazardous waste landfill (Cannon, 2020). This suggests that there may be social, and specifically racial, differences across communities that host different kinds of landfills.

In this way, the high concentration of environmental hazards may support a theory of "path of least resistance," in which areas with high concentrations of people of color may have less political capital to stop such land-use decisions due to social hierarchies supported by patriarchy and white supremacy (Cole and Foster, 2001; Bullard and Beverly, 2012). More research is necessary to determine in what ways land pricing, the historical significance of land use, and segregation practices, particularly in the Southeast and Southwest, play in affecting relationships between social and environmental inequalities. Further investigation at the regional level would provide greater in-depth, historical, and contextual insight into how these landfills developed and identify their effects more locally.

Few studies have explored the effect of environmental inequality on gender disparities at the subnational level (for exception, see McKinney and Thomson, 2022). Adding to the environmental justice literature that has found racial and socioeconomic disparities in exposure to environmental hazards (e.g., Mohai and Saha, 2015b), this study finds that gender inequality is a robust indicator of the location and distribution of landfills across the United States. There is a unique effect of gender as it relates to environmental inequality that is frequently missed in environmental justice research because of a failure to consider gender conceptually and empirically. More research, particularly qualitative approaches, is needed to specify the mechanisms that link gender and environmental inequality. Further unpacking the relationship between gender and environmental inequality is key for advancing equitable and resilient sustainability. Doing so could harness a "pathways approach" developed by the U.N. to advance sustainability by reducing and eliminating gender inequality (Koehler, 2016; Leach et al., 2016) and create synergies with other key areas of focus for sustainability including food security (e.g., Agarwal, 2018).

In addition, the current study suggests that more must be done to correct environmental injustices, specifically the impacts of environmental inequality on women. Using reliable spatial methods such as these to assess racial, socioeconomic, and gender disparities in the location and distribution of environmental hazards adds empirical evidence and improves theorizations of unsustainable and environmentally unjust conditions in the United States.

5.1. Limitations and future research

There are limitations to this study that suggest important areas for future research. First, the current study employs a cross-sectional analysis of secondary data (for critiques, see Mohai and Saha, 2015a). As such, this research is unable to determine causality, future research should include historic census data and landfill permitting dates. Second, the subnational level scope and the county scale might affect estimated relationships (Baden et al., 2007). Similar to many geographic units of analysis, there are limitations in accounting for differences across the unit of analysis (i.e., counties) (Ringquist, 2005). For example, there may be more within-county variation for certain variables. Future research should further test the identified relationships here among sociodemographic characteristics and landfills at a more fine-grained level of analysis (i.e., using census tracts). Future research should also more fully engage with disasters in environmental justice research particularly in relationship to landfills. This research has demonstrated the importance of including measures of gender inequality in socio-environmental spatial analyses. Future research may consider using other measures of gender inequality that are collected at the national level such as female-headed households in poverty. Doing so may shed more light on intersectional axes of social difference across socioeconomic status and gender along with race and in relation to environmental inequality. Such data collection and analysis efforts are crucial to better understanding the role socioeconomic status plays in environmental inequality dynamics. Yet, analyses are limited by the secondary data collected. Subsequently, additional data must be collected to more fully measure and account for gender inequality.

6. Conclusions

Sustainability research has rarely investigated waste management systems as a driver of climate change and environmental inequality. This article advances our understanding of sustainability through a spatial analysis of landfills, race, socioeconomic status, and gender, controlling for disasters, across the U.S. Landfills, as the predominant form of waste management in the United States, are key to developing just sustainable transitions to reduce both their methane emissions and the risks they pose to the environment and human health. Although frequently as a society we do not wish to think about where things go after we dispose of them for sustainability initiatives to be successful, we must think more deeply and holistically about our refuse. As climate change impacts increase in frequency and severity, the urgency of studying waste management systems to develop equitable and sustainable policies continues to grow.

Data accessibility statement

This study utilized the following publicly accessible datasets:

- American Community Survey, U.S. Census, https://www.census.gov/programs-surveys/acs/data.html
- Individual state environmental agencies, see Appendix A
- U.S. FEMA Major Disaster Declaration, https://www.fema.gov/disaster/declarations

I have built a database of landfills for this project from these datasets and this database may be accessed on reasonable request.

Supplemental files

The supplemental files for this article can be found as follows:

Appendix A.xlsx

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There are no competing interests to declare.

Author contributions

Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, software, validation, visualization, writing—original draft, review, and editing: CEBC.

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