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New Methods for Assessing Sustainability of Wood-Burning Energy Facilities: Combining Historical and Spatial Approaches

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Abstract: Methods to assess wood-based bioenergy projects have tended to focus on technological and physical constraints. Less is known about how longer-term environmental, economic, and social systems—the three pillars of sustainable development—have influenced technological development in the context of woody biomass energy. This research offers new methods for assessing the sustainability of wood-based energy projects by combining spatial analysis, semi-structured interviews, and archival data analysis. By integrating quantitative and qualitative methods, this project offers ways to understand how social and environmental dynamics from the past shape technological development in the future. A propensity analysis of biomass energy plants in Michigan, USA was performed using US Census data grouped by social, economic, and environmental categories. This quantitative analysis helped to characterize community and landscape types in which woody biomass plants were developed in Michigan in the late-twentieth century. To help illustrate some of the often-hidden social and political dimensions of energy development, such as access to decision-making and attitudes toward bioenergy projects, transcripts of public hearings, media coverage, and other archival sources were examined, and 30 stakeholder interviews were conducted. By integrating these qualitative and quantitative approaches, this paper aims to provide a more comprehensive approach to assessing the sustainability of wood-based biofuel technologies.

Keywords: wood energy; sustainability assessment; circular bioeconomy; biomass; decision-making; propensity analysis

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1. Introduction

Wood is humanity's oldest fuel source and one that may fit well into circular economies of the future. Yet to use wood-based energy technologies sustainably, developers and policymakers must consider a wide range of factors that are specific to particular locations. Since the 1970s, renewable energy advocates have emphasized the importance of understanding the broader context in which new energy technologies are developed. The terms "renewable energy," "alternative energy," "appropriate energy," and "clean energy" arose at different moments, but all aimed to provide alternatives to fossil-based fuels, which tended to concentrate the distribution of economic benefits and environmental burdens [1–4]. More recently, many energy developers have embraced the idea of sustainable development, as articulated in the 1987 Brundtland Report "Our Common Future." This report defined sustainable development as that which meets the needs of the present without compromising the ability of future generations to meet their own needs [5]. Most conceptions of sustainability emphasize three overlapping spheres: Economic viability, environmental protection, and social wellbeing (Figure 1).

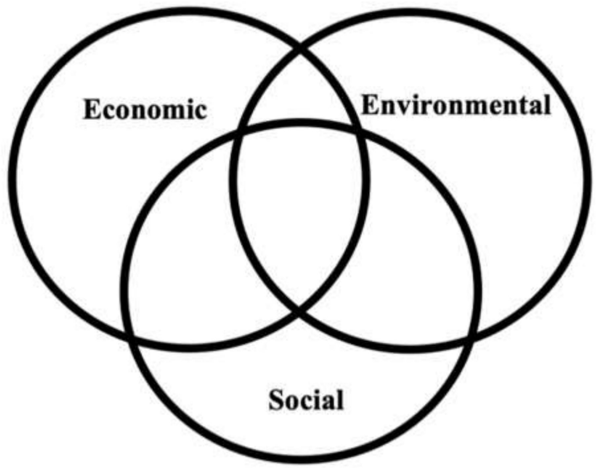

Figure 1. Standard concept map of factors involved in sustainability.

Research on the assessment of bioenergy projects has tended to focus on technical or physical supply factors [6–8]. Studies on the economic dimensions of bioenergy assessment have examined macro-scales and have focused on the development of different types of economic indices [9–11]. In terms of social dimensions, studies have tended to focus on landowner preferences regarding harvesting for woody biomass, generally finding that willingness to supply biomass is dependent on the size of forest holding and species mix [12–14]. Additionally, landowners in the southern US were more interested in markets for low-value wood than their northern counterparts [15,16]. Few studies have combined quantitative, spatial, and qualitative methods to examine underlying historical patterns that have shaped biofuel development. This research combines spatial and historical analysis to assess a range of indicators in the context of woody biomass development.

This paper builds on prior scholarship that used Multi-Criteria Analysis (MCA) and Geographic Information Systems (GIS) to account for a wide range of variables involved in the siting of biomass facilities [17–19]. For example, Woo et al. (2018) combined supply chain cost analysis with resource availability and land use factors to generate optimal locations for biomass siting in Tasmania [20]. Such approaches have integrated social factors such as population change, economic factors such as feedstock availability, and environmental factors such as slope and elevation. These kinds of analyses are useful for providing a comprehensive snapshot of quantitative variables that contribute to the sustainability of bioenergy. Yet, they are still somewhat limited because they fail to illustrate change over time or to provide deeper understandings of some of the underlying cultural and political factors that influence community acceptance of bioenergy projects.

Other approaches to bioenergy assessment have focused on land-use suitability. Suitability analyses have been used by planners and developers to identify appropriate patterns for a wide range of future land uses, including energy development. Malczewski (2004) and others have distinguished "hard" versus "soft" information involved in land-use suitability analysis as a part of planning processes. The former typically refers to quantifiable, objective information such as remote sensing data, census data, or standardized survey data. "Soft" information refers to subjective things such as the opinions and attitudes of local residents or decision-makers [21]. In the context of energy planning and bioenergy in particular, "hard" types of information have been used to identify places that might be good for siting a variety of biomass technologies [6,22]. Yet "soft" dimensions have proved difficult to address through quantitative spatial analysis. For example, how can quantitative analyses engage with factors such as "access to decision-making," "influence over local zoning decisions," or "cultural identity tied to unique land use histories"? These types of social factors are essential to the siting and sustainability of new energy facilities yet are not easily captured in traditional land-use suitability assessments.

Studies on the shift to the circular bioeconomy and renewables in general have demonstrated the need for inclusive and equitable approaches to energy development [4,23]. Early conceptions of the circular economy focused on the intersection of economic and environmental dimensions of technological development [24]. More recently, advocates of the circular economy have emphasized the importance of integrating social perspectives to align efforts with the UN's Sustainable Development Goals (SDGs) and popular conceptions of sustainability [25]. To do this, recent research on the circular economy suggests that policymakers and scholars need to engage more fully with the challenges of environmental justice [26].

As a movement, policy directive, and field of study, environmental justice has come a long way since its focus on toxic pollution in the late 1980s and 1990s. Environmental justice is defined as the meaningful involvement and fair treatment of all people regardless of race, class, or national origin in environmental decision making. It is often characterized as having both distributive and procedural elements. Distributive justice tends to address how environmental burdens and benefits are distributed across a landscape and how they affect different populations. Procedural justice has more to do with decision-making processes that lead to specific environmental outcomes and ensuring those processes are fair and equitable. As noted by Antonio Moreno-Jiménez et al. (2016), methods for assessing environmental injustices have become increasingly sophisticated over the last decade. These include spatial matching analysis, quantitative coefficients, regression models, spatial autocorrelation, and other statistical tests [27]. In a study on geographic disparities in the transition to renewable energies, Carley et al. (2018) argue that there has been little research on the distributional consequences of adverse impacts of energy policies on different populations [28]. They develop a broad framework for delineating possible harmful effects but acknowledge the limitations of such a large-scale approach that tends to paint in broad brushstrokes. The authors note that understanding more nuanced, location-specific social factors are an important focus for future analysis. Yet standard qualitative methods—or mixed methods approaches—for assessing disparate impacts of energy development and environmental injustice remain somewhat illusive.

Historical perspectives have demonstrated how patterns of both distributive and procedural injustice have emerged in the context of energy production and consumption [29–31]. Energy historians have shown how over a century of increasingly centralized fossil- and nuclear-based energy systems led to the creation of landscapes that separated the production of energy from where energy was consumed [32,33]. In doing so, conventional energy systems that ran on fossil and nuclear fuels were remarkably good at producing winners and losers [2,34]. Energy historians have had less to say about how renewable energy technologies have distributed benefits and burdens since the energy crises of the 1970s and relatively little to say about biofuels in particular.

This research aims to fill research gaps on environmental justice and the circular bioenergy economy by coupling the assessment of standard spatial metrics of social, economic, and environmental variables with qualitative methods including semi-structured interviews and analysis of historical documents related to decision-making structures and processes in specific case-study communities in Michigan. Research questions were as follows: How did different environmental, social, and economic variables influence the location of woody biomass plants in Michigan, USA? What kinds of factors tended to characterize communities that embraced wood-based power generation and what factors tended to shape opposition to these new technologies? What patterns emerge when historical perspectives are combined with quantitative spatial analysis? To what extent do socioecological dynamics from the past constrain technological development in the future? By examining these questions, this research puts environmental justice at the center of sustainability assessment for the circular bioeconomy and offers new ways to integrate social dimensions along with traditional economic and environmental considerations.

2. Materials and Methods

Quantitative, spatial, and qualitative data were combined to determine how different variables shaped the technological development of woody biomass systems in Michigan, USA. Researchers examined documents from state and regional archives—including local news media, public transcripts, and correspondence between state officials, developers, and citizens—and developed a GIS database to examine spatial trends through a propensity analysis between locations throughout the state of Michigan. In addition to spatial statistics, researchers conducted semi-structured interviews with bioenergy developers, foresters, local residents, state officials, and other stakeholders to gain a deeper understanding of the social, economic, and environmental factors that shaped biomass development in Michigan. Triangulating research methods in this way provides a more nuanced and accurate account of the factors that have influenced woody biomass development projects in Michigan and allows bioenergy assessment to engage more fully with questions pertaining to environmental justice and sustainability.

This study focused on the state of Michigan for several reasons. First, Michigan has been a center for environmental justice research and methodological development since the 1990s. Michigan held the first Conference on Race and the Incidence of Environmental Hazards in 1990 where Paul Mohai and Bunyan Bryant presented pioneering work to establish methods for assessing disproportionate risk [35]. Second, in terms of bioenergy, Michigan is one of the United States' largest consumers of wood energy and is representative of the broader Great Lakes region. As Figure 2 shows, wood and wood waste has been the largest contributor to Michigan's energy portfolio since the 1960s according to the US Energy Information Administration.

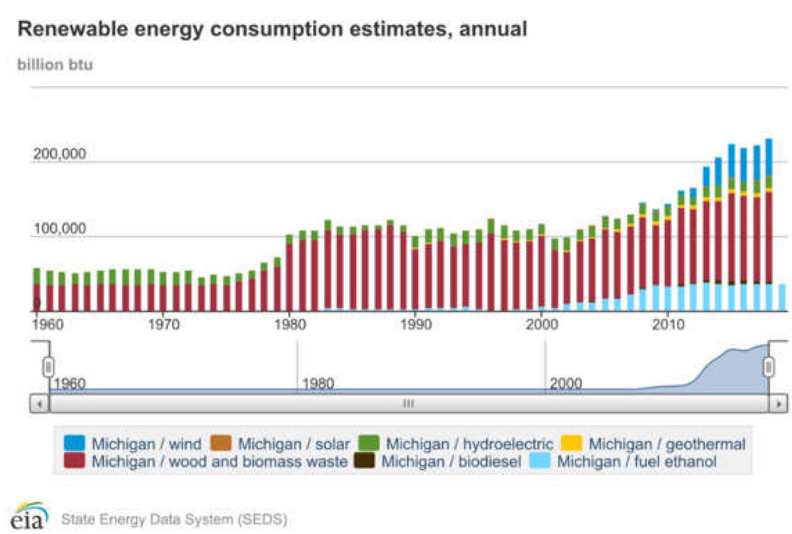

Figure 2. Michigan Renewable Energy Consumption Estimates. Source: US Energy Information Administration. https://www.eia.gov/state/search/#?1=104&2=203&a=true&r=false, accessed on 18 November 2021.

Like the rest of the US, Michigan's economy was powered primarily by wood until the late nineteenth century. From domestic use to industrial applications, wood sustained nearly all aspects of life. Although wood continued to heat homes in many rural, forested communities throughout the twentieth century, its role as a major economic driver subsided as coal and oil took on greater economic and cultural importance. Post-WWII growth and prosperity were largely based upon the extracting, refining, and combusting of fossil fuels, and the political infrastructure that surrounded and reinforced fossil fuel industries [36]. As fossil fuel consumption increased, particularly in the southeastern part of the state, wood-based energy consumption in Michigan was relegated to poorer rural areas, particularly in the north. Although wood provided three-quarters of the US energy supply in 1870 and a quarter of the supply in 1900, by 1972 wood provided less than two percent of the country's total energy [37]. Instead of using trees to feed, heat, and transport themselves, Americans had become increasingly dependent on oil produced in the Middle East by the final decades of the twentieth century.

In response to waves of energy crises in the 1970s and the threat of energy insecurity, biofuel developers began to explore new ways to produce energy from wood. New wood-burning technologies included more efficient woodstoves, new types of wood-fired boilers, cogeneration facilities that could produce both heat and power, and mechanisms that could help convert large coal- and oil-fired power plants to wood and other biofuels. As more advanced technologies were developed in the final decades of the twentieth century, wood became biomass, and an ancient fuel was rebranded with a new sense of technological modernity and purpose. Some of these new wood-fired technologies included combined heat and power (CHP) facilities, industrial power plants, and district heating systems based on European designs. Community responses to new wood-burning technologies varied widely and greatly influenced technological adoption.

This paper focuses on the development of seven biomass power stations in Michigan and combines historical and spatial analysis to provide deeper understandings of the range of reactions to biomass development throughout the state. Figure 3 shows the location of these electricity-producing facilities along with the location of regulated wood-burning boilers used primarily for thermal applications. The map also shows the percentage of households that use wood as their primary heat source by census tract. Project counties that have biomass power facilities are outlined in orange.

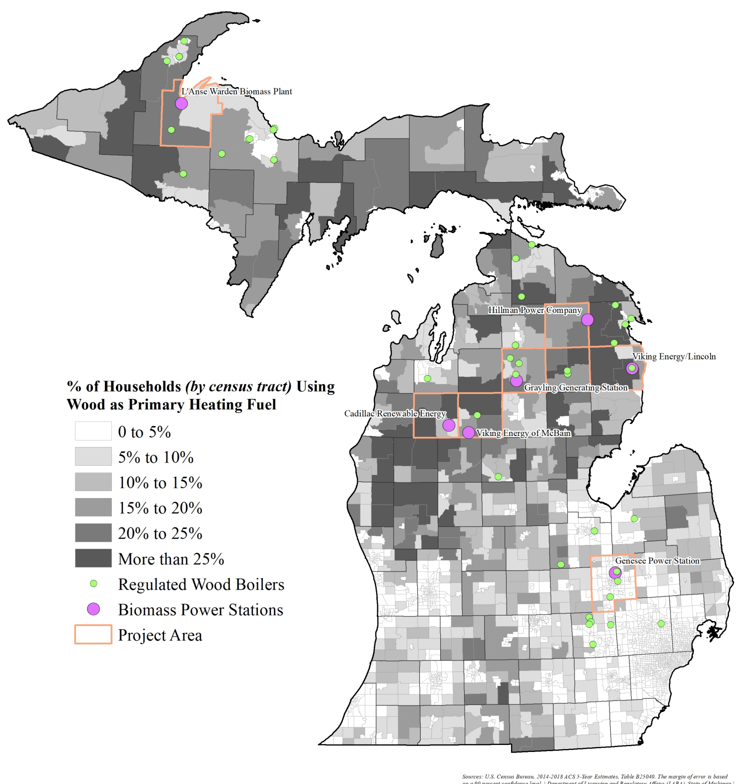

Figure 3. Map of three scales of wood energy in Michigan. 1. Shaded areas represent percent of households that use wood as a primary heat source. 2. Location of commercial-scale boilers in green. 3. Location of wood-burning power plants in purple. Counties that have biomass power plants are outlined in orange.

This analysis focused on the development of woody biomass power stations and the use of wood to produce electrical power. Novel propensity analysis was used to characterize those communities that had biomass power facilities as compared with communities with no wood-fired power station. There are several statistical approaches used to understand relationships between an event or phenomenon and socioeconomic variables. The propensity analysis used in this study is a form of spatial analysis that creates social, environmental, and economic profiles of communities with and without biomass facilities using a set of variables. The analysis uses statistical means to determine an individual variable's importance and the overall model importance in understanding the profile of a community. More specifically, researchers coded 33 variables into three categories: Social, economic, or environmental, to create profiles of communities with and without biomass plants in Michigan. See Figure 4 for the list of variables and how they were coded.

Variables	Description	Variable Coding 1 - Environmental 2 - Social 3 - Economic
Per_For16	Percent Area Classified as Forest 2016 CCAP (Percent)	1
Per_For85	Percent Area Classified as Forest 1985 CCAP (Percent)	1
Per_ForChange	Percent Change in Area Classifed as Forest (CCAP) between 1985 and 2016 (Percent)	1
Per_AreaCF	Percent Area of county enrolled in Commerical Forest Program (Percent)	1
Num_Threatened	Number of Threatened or Endangered Species in County (Count)	1
Per_Wetland16	Percent Area Classified as Wetland 2016 CCAP (Percent)	1
Total_Roads	Total mileage (all road classifcations) in County (Count)	1
Pop_2019	County Population recorded in 2019 American Community Survey (ACS) - 5-Year Estimates	2
PopDensity	Population per Square Mile (2019 Pop ÷ County Area)	2
Pop_1990	County Population - 1990 Census	2
PopChange_90_19	Percent change in county population from 1990 to 2019 (Percent)	2
PerHighEd	Percent of people 25 and older with a Bachelor's degree or higher (Percent)	2
Tot_Housing	Total Housing Units (Count)	2
Per_Uninsured	Percentage of People without Health Insurance Coverage (Percent)	2
Num_Households	Total Households (Count)	2
MedAge	Median Age	2
Per_Over65	Percent of Population over 65 Years Old (Percent)	2
Per_HighSchoolEd	Percent of High School Graduates or Higher (Percent)	2
Per_Disabled	Percent of Population that is Disabled	2
Per_Native	Percent of Population that is American Indian and Alaska Native Alone (Percent)	2
Per_Asian	Percent of Population that is Asian Alone (Percent)	2
Per_Black	Percent of Population that is Black or African American Alone (Percent)	2
Per_Latino	Percent of Population that is Hispanic or Latino Along (Percent)	2
Per_OthRace	Percent of Population that is Some Other - Not Listed Above (Percent)	2
Per_MultiRace	Percent of Population that is Two or More Races (Percent)	2
Per_White	Percent of Population that is White Alone (Percent)	2
SVI18	CDC Social Vulnerability Index 2018	2
Medincome	Median Household Income	3
EmployRate	Employment Rate (Percent)	3
PovRate	Poverty Rate (all ages) (Percent)	3
Per_ChildPoverty	Percent of Children Under 18 in Poverty (Percent)	3
Med_Rent	Median Gross Rent	3
Median_HomeVal	Median Housing Value	3
Model_Key	Various classifications of counties. • 1 = Project County • 0 = Adjacent County	No Code
County	County Name	No Code

Figure 4. Environmental, social/demographic, and economic variables involved in the development of woody biomass facilities in Michigan. Data from the 2019 American Community Survey and 2016 Coastal Change Analysis Program (C-CAP).

Propensity analysis was used to help determine the factors that may influence whether or not a community had adopted woody biomass energy technologies. Propensity analysis is a type of statistical analysis that highlights the environmental and socioeconomic patterns related to an event. These propensity profiles were compared with the profiles of surrounding counties to highlight the potential difference that may have arisen from the facility. Comparing propensity profiles in this way cannot determine cause-and-effect relationships but can highlight correlative patterns.

The propensity analysis is a Random Forest (RF) model. RF is an ensemble machine-learning technique developed by Breiman et al. (1984) that models response variables from a set of covariates by generating hundreds of classification trees [38,39]. The RF response is determined by evaluating the response of all the trees. Outputs from RF analysis include variable importance plots highlighting the mean decrease in accuracy and the Gini coefficient. RF models use a test and train approach in their statical analysis. Roughly two-thirds of the reference data are sampled with replacement to build each tree, while one-third of the data are withheld from tree construction [40]. Withholding such data allows for the assessment of out-of-bag-error and is used to obtain a running unbiased estimate of the model errors as more trees are produced. The outputs of the RF analysis will show statistically significant variables and their ranks across study counties.

The RF model was developed in R using the "ModelMap" and "randomforest" packages [41,42]. Inputs to the RF are shown in Figure 4 and include the three categories of variables: Environment, social, and economic. Such data came primarily from two data sources: The American Community survey (2019) and Coastal Change Analysis Program (C-CAP, 2016). The C-CAP data represent land use and land cover across the study area whereas the American Community Survey represents recent census data. At the time of this analysis, the new 2020 census data had not been released. These variables were analyzed in tandem to assess the multivariate propensity profile. Additionally, the models were run by variable category.

To enhance the Random Forest (RF) assessment, we examined the social and land use histories of three communities in Michigan that had woody biomass facilities: The L'Anse Warden Plant in Baraga County in Michigan's Upper Peninsula, the Grayling Generating Station in Crawford County in Michigan's northern Lower Peninsula, and the Genesee Power Station in Genesee County in Southeastern Michigan (see Figure 3). These three case studies were chosen because they represent different contexts in which woody biofuel development has occurred. Focusing the historical analysis on these three case studies reveals how different cultural and environmental factors have interacted to influence the development of woody biomass technologies not only in terms of biophysical constraints, but social, economic, and cultural constraints as well.

In combination with spatial analysis of land cover and land use change over time, this research incorporated historical methods, including document analysis at state and regional archives and semi-structured oral history interviews. Documents related to the case-study communities were identified through databases at the Michigan State Archives, the Bentley Library at the University of Michigan, and finding aids at regional history centers such as the Baraga County Historical Museum Archives. Potential interview candidates were selected using online search tools that helped to identify individuals who lived or worked in the case-study communities and through the researchers' professional networks. The interview script was pre-tested and adjustments to the interview script were made based on discussion with the research team. Thirty interviews were conducted via the web platform Zoom and lasted approximately one hour. All questions were open-ended. In the process of collecting data, conceptual categories were developed to identify patterns [43]. Researchers also used GIS databases to examine demographic changes in the case study communities. Study procedures were approved by the Northern Michigan University Institutional Review Board, #HS19-1045.

3. Results

The propensity analysis compared counties with biomass plants to adjacent counties without biomass facilities. This analysis revealed important differences and helped to illustrate broad-scale statistical trends as explained below. Analysis of historical documents from three case-study communities and semi-structured interviews with stakeholders provided a detailed account of local dynamics that contributed to broader-scale patterns. The results section will first explain statistical patterns, then explain the results of the historical analysis and interviews in relation to state-level changes.

3.1. Propensity Analysis

The RF analysis shows that mainly social and economic variables were important in determining the profile of counties in Michigan with biomass plants when compared with adjacent counties without biomass facilities (Figure 5a,b). Where biomass plants occurred, the population (change and density), employment rate, percentage of child poverty, and the total number of households were significant to the RF-derived profile (Figure 5a). However, some of those same variables resulted in being significant for counties without biomass plants (Figure 5b). When observed in conjunction with other variables, certain demographic patterns were differently ranked between the biomass counties and adjacent counties (e.g., percent high school educated is highly significant for non-biomass counties; Figure 5b). Environmental data led to differences between counties with and without biomass plants. Percentage forest cover at multiple dates and, to a lesser degree, wetland area were significant variables to the profile of biomass counties. Conversely, those variables were not as critical to adjacent counties (Figure 5b). Overall, the top 10 variables related to the profile of biomass counties included the population in 1990, number of households, percentage of child poverty, employment rate, population density, population change, percentage of forest cover (1985), total housing units, median age, and percentage of forest cover in 2016. Figure 5 shows the variable importance for counties in Michigan with biomass plants (Figure 5a), counties without biomass plants (Figure 5b), and cumulatively for all counties (Figure 5c).

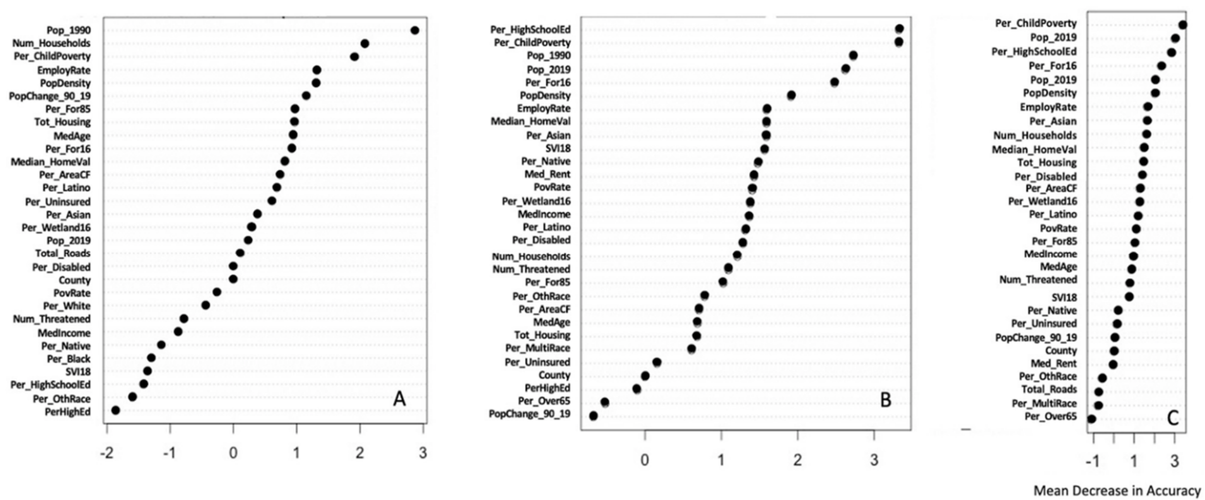

Figure 5. Variable importance by class. (**A**) Represents seven Michigan counties with biomass plants; (**B**) represents Michigan counties without biomass facilities but adjacent to ones with such facilities; (**C**) cumulative model highlighting overall variable importance through mean decrease in accuracy.

Variable importance is related to the difference between counties with biomass versus those without. Looking at the cumulative propensity profile (Figure 5c), we see that other variables are significant. This means that if this RF model were to be used to classify regions with biomass versus those without, we would need more cumulative variable inclusion. For the cumulative model, the top variables include the percentage of child poverty, population, percentage educated, percentage of forest cover, population density, and employment rate. Other variables were significant, but these were more highly significant.

The RF analysis is ideal for assessing the cumulative effect of multiple variables with differing scales, types, and temporal extents. However, the models were additionally run by variable type (economic, social, and environmental) to determine whether the cumulative effects of each category differ from the whole model (Figure 6). In terms of the economic model, the percentage of child poverty, median household value, and median income were most significant, as seen in the mean decrease in the accuracy statistic (Figure 6). Such figures highlight what would happen to the model without those variables included. It should be noted that they are also important to the full model. Overall, this analysis shows that economic variables such as the percentage of child poverty, median household value, and median income are significant. However, to truly understand the profile of such communities, more data are needed to improve the statistical power of the model. Qualitative methods such as historical analysis and in-depth semi-structured interviews can provide a deeper understanding of local dynamics related to economic variables as well as social and environmental characteristics.

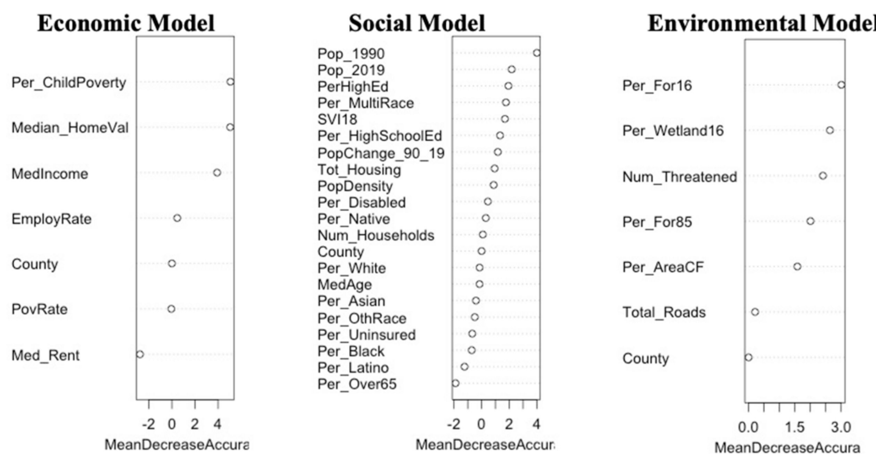

Figure 6. Variable importance for models run by data type (social, economic, and environmental).

For the social variables modeled through the RF analysis, there are again strong similarities to the full model, indicating trust in the full analysis. Variables on population and the percentage of higher educated individuals are highly significant. Lastly, but along the same lines as the full model, the environmental model shows forest cover as significant. Additionally, the percentage of wetland and number of threatened species are influential. Overall, these models show that we can classify communities with and without biomass facilities with certain sets of data (e.g., social, environmental, and economic) but to truly understand the profile of biomass communities, one must look across scales and disciplines.

To complement the spatial analysis and help explain some of the broad environmental, economic, and social patterns revealed in the RF analysis, we examined local and regional variation using semi-structured interviews, documentary analysis, and additional spatial analysis in three case-study communities: Baraga County in Michigan's Upper Peninsula where the L'Anse Warden Plant is located; Crawford County in the northern Lower Peninsula, home of the Grayling Generating Station; and Genesee County in southern Michigan where the Genesee Power Station is located (see Figure 3).

3.2. Case Study—Baraga County: Woody Biomass Development in Michigan's Upper Peninsula

Wood-burning energy facilities have been embraced and criticized depending on the particular social and environmental contexts in which they have been built. The case of Baraga County helps to illustrate a range of resistance and support for different forms of wood-burning energy technologies. Like many other communities along Lake Superior in Michigan's Upper Peninsula, Ojibwe people developed extensive settlements in the area now known as Baraga County over a thousand years ago. French fur traders were the first Europeans to explore the Keweenaw Bay in the early 1600s, followed by others who were attracted to the region's large mineral deposits and vast forests. The region experienced boom and bust cycles associated with copper and iron mining, but forestry remains one of the oldest, most long-standing industries in the region since the beginning of European colonization.

By the beginning of the twentieth century, most of Michigan's Upper Peninsula had been cutover. In response to growing national and local concerns about the timber famine, conservation practices began to take hold. Throughout the twentieth century, conservation-minded organizations such as active chapters of the Sierra Club, the Michigan League of Conservation Voters, and Friends of the Land of Keweenaw (FOLK) began to organize in the area [44].

The county seat of Baraga County, the Village of L'Anse, borders the L'Anse Reservation, Michigan's largest and oldest reservation. The reservation is home to the Keweenaw Bay Indian Community (KBIC) of the Lake Superior Band of Chippewas. The Chippewa, or Ojibwe, people were once the largest cultural group in what is now the United States. The Treaty of 1854 created the L'Anse Reservation, and KBIC officially became a sovereign nation in 1936. Today, KBIC is the largest employer in Baraga County.

In 1959, the L'Anse Warden Electric Plant was built to produce "power for future expansion of the territory [45]." Local residents celebrated the opening of the coal-fired plant, hoping that it would attract other industries. However, in 1993, the plant was closed, only running on an as-needed basis. Like other industrial ports in the Great Lakes region, communities such as L'Anse experienced rapid deindustrialization in the late twentieth century. By 2007, L'Anse had one of the highest unemployment rates in Michigan at 12.5%.

The White Pine Electrical Power bought the defunct coal plant from the Upper Peninsula Power Company in 2007 with plans to convert it to biomass. The plant would use low-grade wood, including railroad ties, mill waste, wood chips, logging slash, and construction waste to produce power. The conversion to biomass occurred with little fanfare. Many residents in the county were accustomed to using wood to heat their homes, and approximately 17% primarily heated with wood [46]. One resident from Michigan's Upper Peninsula noted that wood energy could provide positive environmental outcomes stating that "Clean energy means the least amount of impacts from harvest to utilization . . . . Wood is definitely among the cleanest because there are so many environmental benefits [47]." Furthermore, due to existing treaty rights and the plant's location on the shore of Lake Superior, the KBIC's forestry and natural resources department would play a role in environmental monitoring in addition to state and federal regulatory oversight.

When the converted biomass plant began operating in 2008, complaints from community members were few. Local leaders and residents welcomed new economic development opportunities. However, when pollution became apparent and the plant began burning tire-derived fuel (TDF), complaints to the EPA and MDEQ led to two violation notices in 2015. The ensuing controversy played out in the local newspaper, with the debate centered around public health and employment. Many thought the health risks were not worth the jobs provided. KBIC spoke directly to the EPA and MDEQ and expressed their concerns while local environmental groups protested and expressed their concerns in local media. In 2016, the plant's permit was revised and many of the community concerns were mitigated. Today, many residents distrust the EPA and MDEQ and are still concerned about the environmental and health impacts of the plant, while others appreciate employment opportunities at the facility and enjoy its economic benefits.

3.3. Case Study—Crawford County: Woody Biomass Development in Michigan's Northern Lower Peninsula

As with other parts of the Great Lakes region, Michigan's vast white pine forests drew eastern timber interests in the 1800s. The pattern of forest change in Crawford County was typical of northern Michigan's forests on both the upper and lower peninsulas. In 1857, the area was mostly hemlock-white pine or mixed pine forest. By 1927, pine forests were cleared, and by 1978, aspen-birch forests were feeding a thriving pulp and paper market. The forests of Crawford County continued to support diverse wood markets at the end of the twentieth century and into the twenty-first. In 1990, CMS Generation proposed a $60 million wood-burning co-generation plant that would produce 34 MW of electricity for the state's largest utility, Consumers Energy. Seventy percent of the fuel for the plant would come from sawmill residues, primarily wood chips and sawdust, and 30% would come from logging slash.

When the Crawford County Board of Commissioners started to hold meetings about the proposed Grayling wood-burning cogeneration plant, the local newspaper *Crawford County Avalanche* reported only one resident expressed concern about the health impacts of emissions and deforestation. In 1990, County Commission Chairman Robert McLachlan favored the construction of the plant but expressed concern that a new biomass energy plant might quickly burn through available waste wood and compete with other local wood industries. He estimated that 30% of the Generating Station's fuel would need to come from stumpage within two years [48]. According to archival sources and interviews, the plant was generally "welcomed with open arms" in Crawford County in 1990. One local resident, whose great-grandfather was a logger and whose grandfather planted trees in the area with the Civilian Conservation Corps, emphasized the importance of wood to the regional economy. He noted that just as "West Virginia has coal. We have trees [49]". Figure 7 uses C-CAP data to show the extent of forest cover within a 12.5-mile radius of the Grayling Generating Station.

Figure 7. Forest land cover near the Grayling Generating Station, Crawford County, Michigan.

Crawford County, where the Grayling Generating Station is located, has only about 14,000 residents but several forest product industries including ADJ Forest Products established in 1975, the Weyerhaeuser flooring and sheathing mill (est. 1992), the Georgia Pacific mill (est. 1986), and Arauco North America, a particle board manufacturer (est. 2018). Some of these mills have used their own wood-fired boilers to heat their buildings for several decades. The county also has relatively high levels of residential wood heating, whereby about 15–25% of homes in Crawford County use wood as their primary heating fuel [46].

The historical and widespread use of wood for energy and other forest products seemed to make the community more accepting of the use of wood for industrial-scale power generation. These economic factors and a cultural identity tied to working in woodlands seemed to make most residents in Crawford County more receptive to all scales of wood-burning energy technologies. These factors are particularly noteworthy when compared to the case of the Genesee Power Station, where a much different set of environmental, economic, and social changes led to resistance against industrial-scale biomass power.

3.4. Case Study—Genesee County: Woody Biomass Development in Southeastern Michigan

Right after the Grayling plant opened in 1990, CMS Generation proposed a nearly identical plant in Flint, Michigan—the Genesee Power Station. The 35 MW facility would bring electricity to over 25,000 homes, create over 200 jobs, and net $1.8 million in annual tax revenues to the township. To assess the impact of the proposed power plant, a group of Flint residents rented a bus to tour the recently constructed Grayling Power Plant in Grayling, MI. Although the two plants were nearly identical, one resident noted that the Grayling station was located among the forests of northern Lower Michigan, and it would burn only raw—or green—wood chips. The Genesee Power Station would be more dependent on waste wood from construction and demolition projects in the southeastern part of the state.

Although southeastern Michigan once had vast forests and thriving forest products industries, by the mid-twentieth century the Detroit and Flint areas became hubs for the automobile manufacturing industry and major metropolitan centers. As Figure 8 shows, the area surrounding the Genesee Power Station was more developed with much less forest land cover than its northern counterpart in Crawford County. In 1978, General Motors employed over 80,000 workers, many of whom worked in the manufacturing plants on the northeast side of Flint, where the Genesee Power Station was later built. By 1992, the year the plant was proposed, the number of those employed by General Motors declined to 50,000. The process of deindustrialization had left those who stayed in Flint struggling to make a living at a number of polluting industries such recycling centers, a fuel storage facility, and asphalt and cement plants [50]. In the 1990s, unemployment soared to 20% in Flint, making local leaders eager to accept new industry in the area [51].

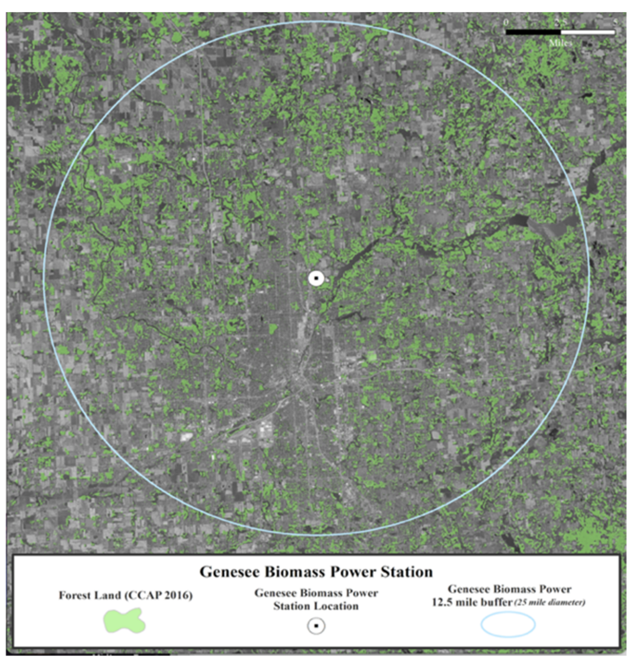

Figure 8. Forest land cover near the Genesee Power Station, Genesee County, Michigan.

Broader demographic changes occurred alongside the decline of economic opportunity in the Flint area during the late twentieth century. According to the US Census, 9.9% of Genesee County residents were considered non-white in 1960. That percentage grew to 29.5% in 2018. In the area immediately surrounding the power plant, 73% of residents were African American. The Flint Water Crisis and the poisoning of the city's predominantly African American population by lead brought national attention to environmental justice concerns in the area. However, Flint had become an industrial sacrifice zone long before the public outcry about the city's water supply in 2015. Figure 9 shows the location of the Genesee Power Station relative to other hazardous waste sites in the predominantly African American city.

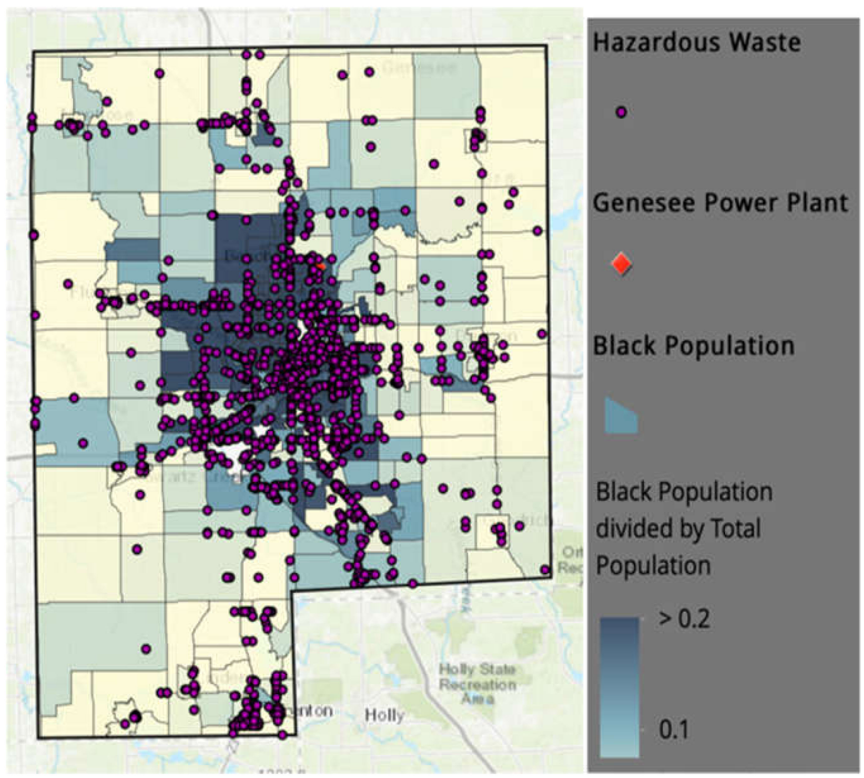

Figure 9. The central and northern parts of Flint are home to predominantly African American populations as well as a number of hazardous waste facilities.

When local residents learned that the Genesee Power Station would be burning construction and demolition wood in addition to green woodchips, they expressed concern about the possibility of lead and other toxins in the wood waste. According to a study by the Michigan Department of Natural Resources, depending on the level of sorting, burning construction and demolition wood could release 110–500 times more lead into the air than burning whole tree chips [52].

Local residents argued that the siting of the plant in their community was an act of environmental racism. When an EPA administrative law judge ruled that racial discrimination was "beyond the scope of Air Quality's rules and regulations" in 1993, activists turned to the courts [53]. The Flint case became one of the first to apply US civil rights laws to an environmental health issue in Michigan. In 2017, a twenty-five-year-long investigation by the US Environmental Protection Agency's Civil Rights Compliance Office concluded that the state's permitting process for the biomass facility in Flint had discriminated against the predominantly African American residents in the area, many of whom had resisted the plant in the early 1990s [54].

The story of the Genesee Power Station, where a large energy utility company installed a polluting facility that burned hazardous demolition and construction wood in a predominantly low-income, minority community, supports an all-too common narrative of environmental injustice. However, in other communities in Michigan, the story of wood energy complicates the story of environmental justice. For many small rural schools and residential users, using wood to heat their institutions and homes was a source of empowerment. For users of distributed thermal applications, wood offered financial benefits and independence from fossil fuels. One interviewee explicitly recommended that Combined Heat and Power (CHP) plants should be located in poor communities not because it would be easier to get away with environmental or public health problems, but because people living in poorer rural communities embraced an ideology that was favorable to using wood for energy, and people there were more comfortable with extractive industries such as logging and forest products manufacturing [47]. Understanding how different ideological orientations interact with different racial demographics is an important area of future research.

4. Discussion

The combination of quantitative spatial statistics and qualitative historical data highlight the influence of social, economic, and environmental variables that influence woody biomass plant locations in Michigan. In terms of environmental factors, the results of the spatial and historical analysis indicated that counties with greater forest cover were more likely to have biomass technologies. This is not a surprising finding but reinforces the idea that wood-based energy technologies, like other forms of renewable energy, fit best in particular biophysical locales.

In terms of the economic and social variables, the results of the Random Forest (RF) analysis highlight the role of the population (change and density), number of households, employment, and age variables as major factors that have characterized counties with biomass power facilities. Qualitative data from interviews and archives also suggest that biomass plants in Michigan have been located in predominantly rural counties with relatively fewer economic opportunities in terms of employment and with aging populations. Historical research on the three case-study communities revealed that because industrial-scale biomass technologies were often linked to the physical and political infrastructure created in the era of fossil fuels, the politics of industrial-scale renewable energy projects often mirrored that of a prior era. As revealed through spatial analysis, the southeastern part of the state experienced greater and more rapid forest change in the late twentieth century and into the twenty-first century. This region had a more diverse economic landscape, and the area immediately near the Genesee Power Station had already become a kind of sacrifice zone for hazardous industries and land uses before the wood-fired plant had been proposed.

Yet in case-study communities in the forested, rural northern parts of the state, such as Crawford County, which tended to have predominantly white, lower-income populations, this research suggests that community members were more receptive to accepting the risks and benefits associated with wood-fired energy facilities, especially when biomass plants could be fueled by green wood chips from existing forest products industries and not waste wood from construction and demolition projects. Individuals in these northern areas were generally more accepting of commercial-scale boilers for heating applications and had higher rates of residential wood heating as compared to the more urbanized southern parts of the state. This is likely the result of biophysical and economic factors such as the availability of forest residues as well as cultural factors such as an identity tied to working woodlands. People in the northern parts of the state often viewed different forms of biofuels as part of an economic development strategy that was consistent with the area's history of logging, milling, and forest management.

Combining historical perspectives with spatial analysis can help illustrate some of the often-hidden dynamics within communities that might not be apparent when looking at large quantitative datasets. For example, the RF analysis did not show variables on race to be particularly significant. However, records of public hearings, newspaper articles, and policy memos indicate that in the case of Genesee Power Station, questions about environmental racism were at the heart of the conflict over the plant. Incorporating methods that use the different disciplinary lens to address multiple scales of social, economic, and environmental dynamics enables research on the circular bioeconomy to engage more fully with questions related to environmental justice. Understanding both broad-scale trends and regional variation in characteristics of communities with bioenergy technologies in the past can help developers and policymakers make more informed siting decisions in the future.

Although this paper focuses on seven communities in Michigan, USA, the approach used in this study may be useful to decision-makers and scholars in other communities outside of the US because it shows how specific cultural, political, and environmental factors interacted to shape the implementation of new bioenergy technologies. These factors can vary significantly not only throughout the US, but especially when considering broader international contexts. One of the limitations of this study is that tightly focused analyses of community dynamics in Michigan, USA may not apply directly to international contexts. However, the goal of this study was not to prescribe how other places should approach bioenergy development. Instead, what international scholars and decision-makers can take away from this research is the importance of understanding specific characteristics and dynamics of local communities, and why certain communities might embrace the circular bioeconomy while others resist particular models of bioenergy development. Combining historical and spatial data can be an effective methodology to illustrate how complex social and environmental systems change over time, and how hidden human histories can influence technological development in specific locales. Like all forms of renewable energy, there is no one-size-fits-all model that yields social acceptance. Historical perspectives, coupled with statistical spatial analysis, can help provide deeper understandings of why communities have reacted to bioenergy development in vastly different ways.

5. Conclusions

This research combined spatial tools and historical perspectives to help provide a more complete assessment of the sustainability of woody bioenergy projects in Michigan. Spatial analyses that examined the geographic distribution of social, economic, and environmental factors were enhanced by qualitative methods that helped to illustrate some of the hidden human dimensions involved in woody biomass development. This integrated approach for assessing the sustainability of biofuel projects revealed that using wood to produce power was generally more acceptable in forested areas with low levels of forest cover change and labor histories still connected to current wood products industries. Locations that had ongoing histories of wood as an energy source tended to react more favorably to new wood-based bioenergy technologies. In locations such as southeastern Michigan, which had higher rates of forest conversion and more racially diverse populations, new wood-based bioenergy technologies faced greater opposition and contributed to ongoing struggles for environmental justice.

By combining historical and spatial methods, this research reveals how social and environmental dynamics from the past constrain technological development in the future. Traditional suitability analysis for wood-based bioenergy systems can provide information about how certain biophysical and socioeconomic factors influence the viability of wood energy. However, like all forms of analysis, these spatial and quantitative methods have limits. To understand how different communities have interacted with the implementation of bioenergy systems, and how decision-making processes have influenced bioenergy development, historical methods and perspectives can complement and enhance established approaches for assessment. This research offers new ways of evaluating the sustainability of bioenergy development and reveals how community responses to bioenergy development have been—and continue to be—inextricably linked to changing social, economic, and environmental conditions. Taking a holistic methodological approach that incorporates both qualitative and quantitative data for assessment can help ensure that the shift to the circular bioeconomy is done in a more just and sustainable manner.

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Data Availability Statement: All spatial data used in this study are freely available to the public for download. The American Community survey data from https://www.census.gov/programs-surveys/acs (accessed on 18 November 2021) are collected yearly and are similar to census data collections though on a lesser scale. The data were downloaded for 1990 and 2019 and minor summations were completed such as calculating the population change between the two years. The C-CAP data are available from https://coast.noaa.gov/digitalcoast/tools/lca.html (accessed on 18 November 2021) This land use and cover data are available for MI given the extensive Great Lakes coastline. The multidate data were downloaded and cleaned during the data pre-processing stage though no major changes were made. Land cover classes were lumped together in some instance. Data sheets, historical documents, and interview transcripts can be provided upon request.

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