Estimating Consumption-Based Carbon Emissions at the ZIP-Code Level

Evidence from Berkeley, California

Vaidehi Srinivasan

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Executive Summary

Local consumption patterns provide a meaningful way to understand a city's carbon footprint beyond emissions generated by its production. This project examines how consumption-based emissions vary within Berkeley, California, by estimating and visualizing emissions associated with household consumption across nine ZIP codes.

Project Context and Motivation

Standard municipal carbon accounting typically relies on production-based inventories, measuring emissions at the geographic point of release. However, as modern global supply chains increasingly separate production from consumption, territorial emissions accounting provides an incomplete picture of local carbon footprints. Often, a reduction in locally reported emissions does not necessarily signal a net global decrease, but instead reflects "carbon leakage": the relocation of carbon-intensive industries to regions outside the city's accounting boundary.

In contrast, a consumption-based emissions inventory (CBEI) attributes emissions to the goods and services consumed within a community (C. Jones and CoolClimate Network 2020). This methodology provides a comprehensive view of the demand-side forces driving emissions around the world. Using publicly available census, expenditure survey, and emissions intensity data, this project roughly estimates a CBEI for Berkeley, California. With this data, it constructs synthetic ZIP-level consumption profiles to examine within-city variation in per-capita emissions.

A city with ambitious municipal climate goals, including a target of net-zero emissions by 2045 (City of Berkeley 2009), Berkeley may typically perform well on standard production-based inventories due to its lack of heavy industry (Dinkelspiel 2019). However, its affluent population, high cost of living, and significant income inequality suggest that consumption-driven emissions may tell a different story. By focusing on this specific municipality, this project aims to reveal the 'hidden' carbon footprint of a wealthy, post-industrial city and demonstrate how consumption-based metrics can inform more equitable local climate policy.

Scope

This project measures emissions at the ZIP code level. Household consumption behavior is modeled using area-level averages, rather than direct observations. This design imposes standard ecological inference constraints: the findings of this analysis describe differences across areas, not individual households. Additionally, this project excludes ZIP code 94720, since this area encompasses the University of California, Berkeley campus and lacks household-level data.

Researchers such as the UC Berkeley CoolClimate Network employ Environmentally-Extended Input-Output (EEIO) models to derive lifecycle emission factors. These models require complex national economic supply-chain matrices to calculate the carbon intensity of every dollar spent in the economy. As this project focuses on the spatial distribution of emissions, the full EEIO model was not replicated. Instead, established intensity factors were adopted and applied to local demographic data.

ZIP-Level Emissions Estimation Model

The estimation methodology functions as a mapping process. For a given ZIP code z, estimated total household emissions E_z are calculated as a function of the area's median income I_z. A mapping function $M(I_z)$ assigns the ZIP code to a specific income bracket b. Total emissions are then derived by summing the product of bracket-specific expenditures and carbon intensities across all consumption categories k:

$$E_z = \sum_k \left(C_{b,k} \cdot \beta_k \right)$$

Where:

- I_z represents the median household income for ZIP code z.
- $b = M(I_z)$ denotes the specific income bracket corresponding to that median income.
- $C_{b,k}$ is the average expenditure (share of wallet) for consumption category k within income bracket b.
- β_k is the carbon intensity (emission factor) associated with category k.

Data and Variables

This project sources demographic data from the 5-year estimates of the American Community Survey (ACS) as of 2022 (US Census Bureau 2022). ZIP Code Tabulation Areas (ZTCAs) represent conventional ZIP codes and provide geographic data. Other variables utilized are median household income, number of households, and total population.

Household-level consumption data was sourced from the Consumer Expenditure Survey (CES) by the Bureau of Labor Statistics (BLS) (Bureau of Labor Statistics 2025). These data reported the national average household expenditures by income bracket, reflecting household-level consumption. Thus, spending patterns are assumed to vary along with income.

Emissions intensity data was estimated using research by the Coolclimate Lab at UC Berkeley (Christopher M. Jones and Kammen 2011) and the Center for Sustainable Systems at UMichigan (Center for Sustainable Systems 2017). These data reflect upstream supply-chain emissions associated with household consumption of five different categories: transportation, food, housing, goods, and services.

Model Application: Berkeley Case Study

To demonstrate the utility of the estimation methodology, the model was applied to nine ZIP codes within Berkeley, California. The following results illustrate the model's capacity to capture aggregate consumption profiles, spatial heterogeneity, and sectoral drivers of emissions.

Figure 1 presents the aggregate consumption based emissions inventory (CBEI) for the modeled area. The analysis identifies Transportation (28%) and Housing (25.3%) as the primary drivers of the local carbon footprint, cumulatively accounting for over half of total household emissions. Food consumption constitutes the third largest share (19.4%), a wedge driven largely by the carbon intensity of animal based products rather than transport distance.

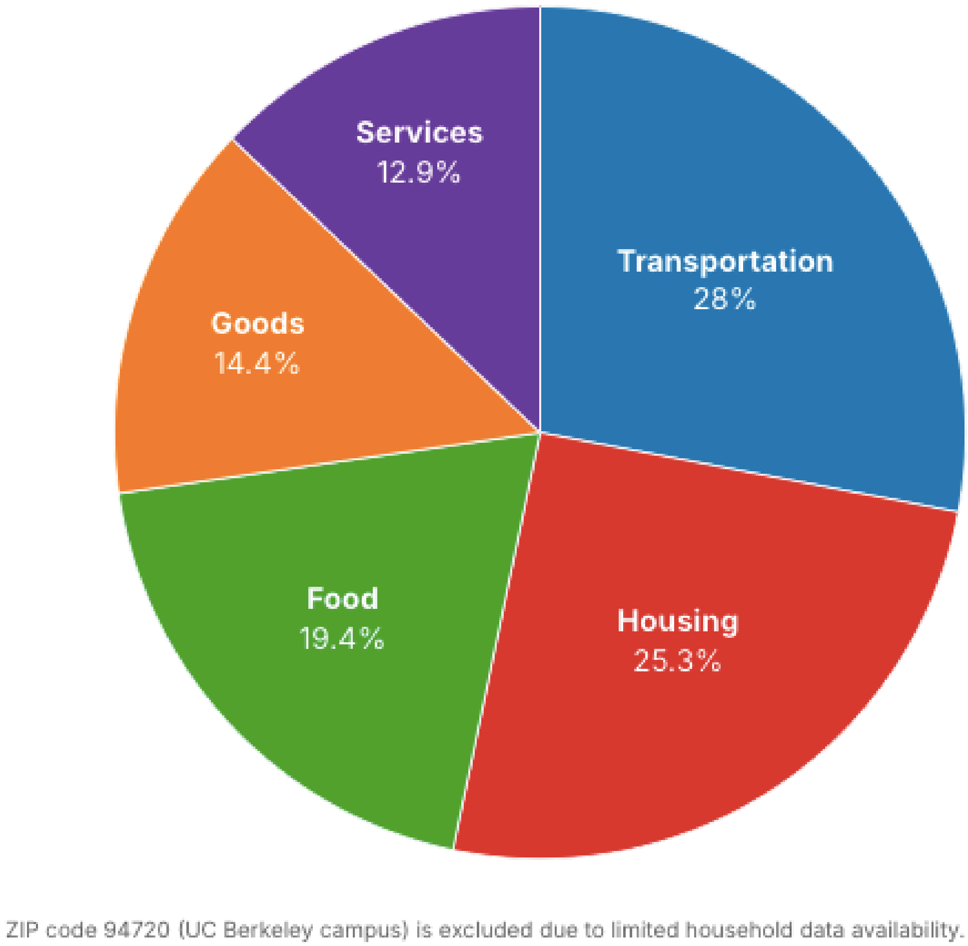

Figure 1: Aggregate sectoral breakdown of consumption based emissions across all modeled Berkeley households.

When these estimates are projected into space, significant heterogeneity emerges. As shown in Figure 2, modeled per capita emissions vary by a factor of four across the city. The lowest footprints are concentrated in dense, transit rich neighborhoods such as 94704 (Downtown/Southside), where estimates average approximately 5,200 kg CO2e per capita. In contrast, emissions peak in the lower density hillside communities of 94708, reaching nearly 24,000 kg CO2e per capita.

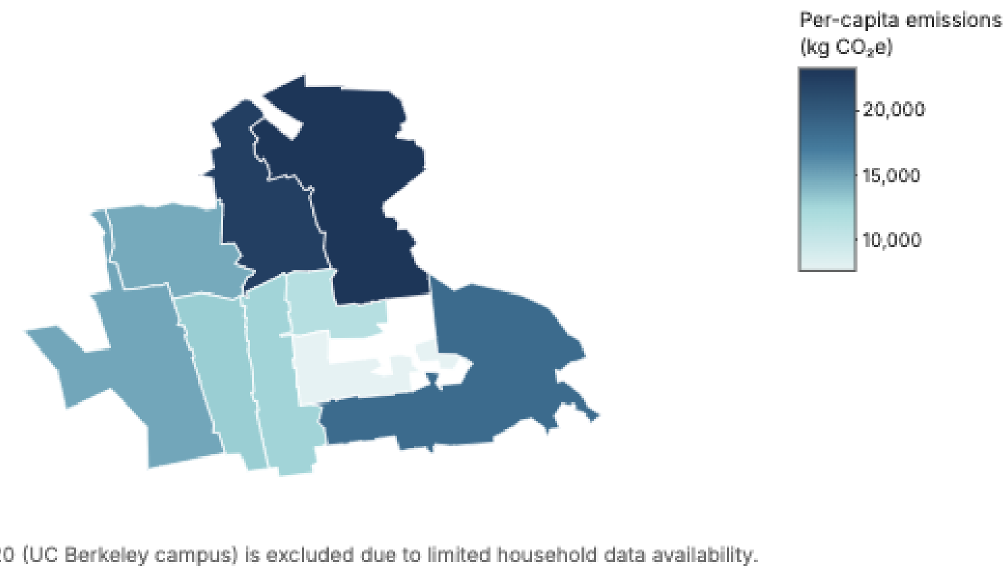

Figure 2: Spatial variation in estimated per capita carbon footprints by ZIP code.

Figure 3 decomposes these disparities to identify the specific drivers of high emission neighborhoods. The chart displays sectoral deviations from the citywide average. While consumption of goods and services grows linearly with income across all ZIP codes, the highest emitting neighborhoods are distinguished by disproportionate deviations in Transportation and Housing. This output suggests that the carbon gap is not driven solely by discretionary spending, but also by structural differences in the built environment, specifically vehicle dependence and home energy intensity. These findings suggest that efforts to lower city-wide emissions must address both consumer preferences and infrastructural gaps within the city.

Project Limitations

Income-Based Consumption Mapping: Household consumption patterns are inferred by assigning each ZIP code to a national income bracket based on reported median household income. This approach assumes that the median is a representative measure for every household, and that households with similar incomes exhibit similar average expenditure shares across locations. In practice, both are untrue. There may be significant intra-neighborhood heterogeneity in income, and consumption behavior may vary within income groups themselves due to differences in housing markets, transportation infrastructure, local prices, and consumer preferences. As a result, estimated consumption profiles should not be interpreted as direct observations of household behavior.

Household microdata would provide a more robust framework to understand consumer behaviour and consumption-based emissions. In this project, all estimates are constructed using area-level

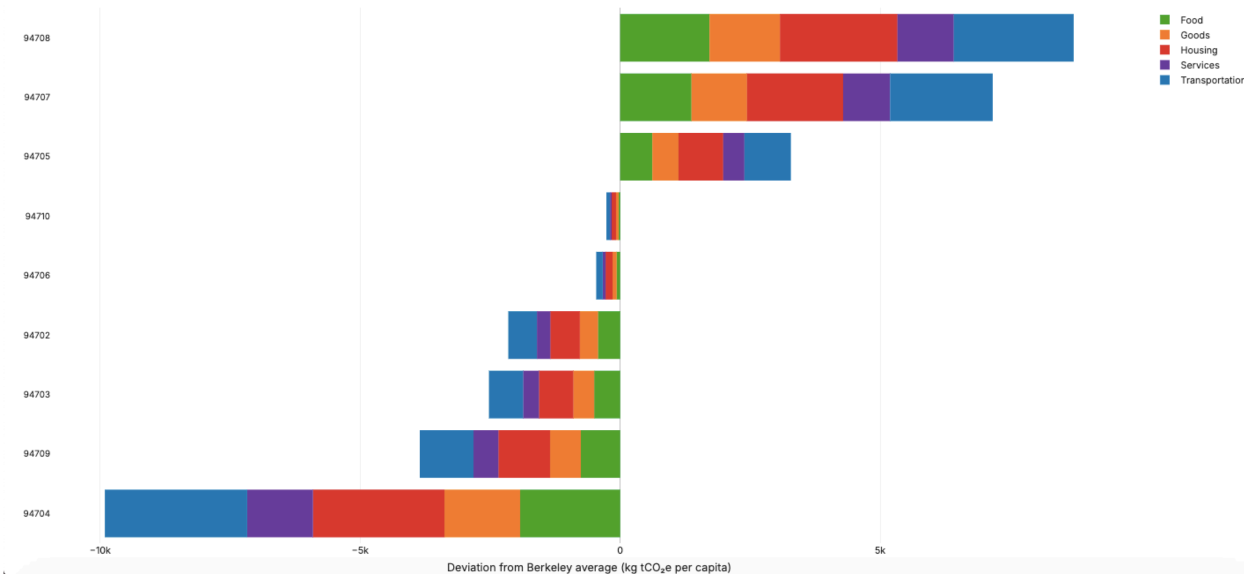

Figure 3: Sectoral contributions to emissions deviations relative to the Berkeley citywide average.

aggregates and modeled averages. As a result, within-ZIP heterogeneity in income, household size, and consumption behavior is excluded from the analysis.

Use of National Average Expenditure Data: Household expenditure shares are sourced from national averages reported in the Consumer Expenditure Survey. These averages may not reflect local consumption patterns in high-cost urban areas such as Berkeley. In particular, the CES does not capture regional price variation or city-specific differences in access to goods and services. Consequently, modeled expenditures may diverge from actual local spending, especially for housing and transportation.

Emissions Intensity Assumptions: Emissions intensities are estimated from secondary research and represent average upstream supply-chain emissions per dollar of expenditure. Actual emissions associated with specific goods or services may vary substantially depending on production methods, sourcing, and energy mixes. As such, category-level emissions should be interpreted as rough approximations.

Utilization of ZTCAs: ZIP Code Tabulation Areas (ZCTAs) are used to approximate conventional ZIP codes. ZCTAs may not perfectly align with residents' lived experiences or with administrative boundaries relevant for policy implementation. Spatial aggregation at the ZIP-code level may therefore also mask variation within neighborhoods.

Interpretation and Policy Use

This analysis was conducted as an independent personal project intended to demonstrate technical proficiency in spatial analysis, data visualization, and reproducible reporting. It represents an academic exercise for skill development rather than a formal institutional policy evaluation.

Consequently, emissions estimates should be interpreted as illustrative rather than definitive. The primary contribution of this analysis lies in highlighting relative differences across neighborhoods and encouraging discussion of demand-side climate policy, rather than encouraging specific regulatory interventions.

Future Work

This project serves as a proof-of-concept for spatially explicit consumption-based emissions modeling. Future iterations of this work could improve upon the current limitations through three key improvements:

Integration of Microdata: To resolve the ecological inference problem, future analysis could incorporate anonymized household-level microdata (e.g., PUMS) rather than relying on ZIP-code aggregates. This would allow for the analysis of within-neighborhood heterogeneity and a more precise understanding of how variables beyond income influence carbon footprints. These variables may include household size, age, employment status, etc.

Regional Calibration of Coefficients: To address the reliance on national averages, future models could adjust expenditure profiles using the San Francisco-Oakland-Hayward Metropolitan Statistical Area (MSA) data from the BLS.

Policy Scenario Analysis: Formulating a model to include hypothetical scenario testing would increase utility for policymakers. For example, the model could simulate the emissions impact of specific local interventions, such as transit-oriented development, public transit expansion, or subsidies for home electrification, leveraging machine learning methods to inform climate action planning.

Conclusion

This project demonstrates that municipal carbon accounting must extend beyond geographic boundaries to fully capture the climate impact of a community. By constructing a consumption-based inventory for Berkeley, California, this analysis reveals that local emissions are significantly driven by both infrastructural gaps and consumer lifestyle choices.

While the use of aggregate data and national coefficients imposes necessary constraints on precision, the methodology establishes a replicable framework for identifying spatial inequalities in carbon footprints.

Use of Generative AI

Generative AI (Claude) was used during development as an editorial and programming assistant. It was used primarily to draft and refine CSS and HTML for layout and interactivity, improve narrative wording for clarity, and debug R code by suggesting fixes for syntax and rendering issues in the Quarto/Plotly workflow. All modeling decisions, analytical choices, and interpretation of results were made by the author, and any AI-suggested changes were reviewed and validated before inclusion.

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