Microdata and the Valuation of Natural Capital *

Jonathan Colmer[†], John Voorheis

January 29, 2024

Abstract

The practical valuation of natural capital remains a challenge, despite a strong theoretical foundation and advances in our understanding of coupled natural and human systems. This paper discusses the extent to which advances in the availability of individual-level microdata might relax measurement constraints, and in turn open the door to new methodological and accounting frameworks that incorporate spatial and individual heterogeneity. We discuss conceptual issues, provide an overview of a new prototype microdata infrastructure developed by the US Census Bureau— the Census Environmental Impacts Frame — and present descriptive evidence on the individual-level distribution of urban tree canopy cover in the United States. Our analysis highlights the empirical relevance of aggregation bias and potential for within-location heterogeneity in demand for natural capital.

*Any opinions and conclusions expressed herein are those of the author(s) and do not reflect the views of the U.S. Census Bureau. We thank Eli Fenichel, Nicholas Mueller, Mary Bohman, Corbett Grainger, and seminar participants at the CRIW Conference on Natural Capital Accounting and US Census Bureau for helpful thoughts, comments, and discussion. We thank Surya Menon and Yolande Tra for research support. The Census Bureau has reviewed this data product to ensure appropriate access, use, and disclosure avoidance protection of the confidential source data used to produce this product (Data Management System (DMS) number: P-7505723, Disclosure Review Board (DRB) approval numbers: CBDRB-FY23-CES010-027).

[†]Affiliations: Colmer: Department of Economics, University of Virginia. Voorheis: Center for Economic Studies, US Census Bureau. Corresponding Author: Jonathan Colmer, jonathan.colmer@virginia.edu

1 Introduction

The theoretical basis for valuing natural capital and the ecosystem services they provide is well established (Weitzman, 1976; Hartwick, 1990; Heal, 1998; Daily et al., 2000; Arrow et al., 2004; Nordhaus, 2006; Arrow et al., 2012; Fenichel and Abbott, 2014). However, despite substantial progress in our understanding of ecology and significant advances in quantifying natural capital, the valuation of natural capital has lagged behind.

How much society values the stock of natural capital and the flow of ecosystem services that it provides is ultimately an empirical question, the answer to which is critical for evaluating trade-offs between environmental conservation and use (Krutilla, 1967; Fisher et al., 1972) and for assessing the question of whether society is following a sustainable economic program (Fenichel and Abbott, 2014; Fenichel et al., 2018). The critical challenge to valuing natural capital is determining the appropriate prices to use when evaluating these question. When there are missing or incomplete markets — as is often the case for many critical natural capital stocks – economists have to rely on nonmarket valuation approaches.

Addressing the challenge of valuing natural capital is pivotal to ongoing policy efforts and natural capital accounting. Credible valuation of natural capital is critical to the integration of environmental data into national economic accounts. Therefore, refining natural capital valuation methodologies is not just an academic exercise, but critical for providing evidence that can be used in frameworks that recognize and safeguard the value of the natural environment in policy-making and economic activity.

In this paper we consider the extent to which advances in the availability of microdata might help to relax some of the measurement constraints associated with the valuation of natural capital, and in turn open the door to new methodological and accounting frameworks that incorporate spatial and individual heterogeneity in valuations.

We first discuss some of the current conceptual challenges associated with natural capital accounting, and explore the potential role that microdata could play in helping to address these challenges. Second, using a new microdata infrastructure — the Environmental Impacts Frame (Voorheis et al., 2023) — we provide a case study to illustrate the empirical relevance of these challenges, in the form of evidence on the distribution of urban tree cover across individuals in the United States.

2 Conceptual Challenges

In this section we discuss several key conceptual challenges that Natural Capital Accounting currently faces and discuss the potential role that microdata could play in helping to address these challenges.

2.1 Aggregation Bias and Natural Capital Accounting

To date Natural Capital Accounting has focused largely on producing national accounts at the national level; however, such approaches make very strong assumptions about aggregation, commonly used in other accounting practices, which are unlikely to apply in the context of natural capital. A major conceptual challenge relates to the spatial context of natural capital.

Natural capital accounting has traditionally relied on a "law of one price". This is the approach taken when aggregating physical and financial capital stocks; however, unlike natural capital, physical and finanical capital stocks are generally tradable commodities that can be easily transported and exchanged, meaning that values can be aggregated using a common price. The assumption of a common price is more plausible in such settings because the location of physical or financial capital is less likely to affect its value. By contrast, many stocks of natural capital are immobile and depend critically on their location – natural capital is spatially dependent. If a stock of natural capital is concentrated in one area rather than another, the people living there will value it more highly than the national average (Addicott and Fenichel, 2019). This relative scarcity will lead to a divergence between the total value of natural capital and the sum of its parts.

Spatially resolved microdata provides a platform with which to link spatially explicit natural capital stocks with detailed and comprehensive population and economic data. This can facilitate the definition and measurement of relevant economic jurisdictions, or "market extent", which in turn will facilitate the description, quantification, and valuation of natural capital across locations. This is critical because, as first noted by Smith (1993) differences in market extent are likely far more important than differences in marginal valuations.

2.2 Heterogeneity in Valuations Within a Location

Concern about aggregation bias extend to heterogeneity in how individuals value natural capital within a market. While working with more spatially granular data can help to mitigate heterogeneity across locations, aggregation bias remains if there is heterogeneity in valuations across individuals within a location. Such differences in valuations may arise, for example, due to differences in income or preferences.

Here, confidential microdata provides descriptive details on the distribution of income, wealth, race and ethnicity, age, and other socioeconomic characteristics that will aid researchers and policy makers in understanding how the population within a "natural capital" jurisdiction varies compares to other jurisdictions. This will help to understand the extent to which marginal valuations of natural capital may vary between jurisdictions, as well as the potential for heterogeneity in valuations within a jurisdiction.

2.3 Missing Markets

The previous two conceptual challenges presume that accounting prices for natural capital are available or identifiable. In practice, identifying the appropriate prices needed is the core challenge associated with any natural capital valuation or natural capital accounting exercises.

The main constraint is the absence of observable prices for nonmarket goods and services. Even if prices for a given stock of natural capital were observed at two points in time, the prices used to value a change in wealth must by constant and formed as a convex combination of the two observed prices (Fenichel et al., 2016, 2018).

Restricted-use microdata provides no direct solution to this problem; however, by providing comprehensive economic and sociodemographic context at the individual level, combined with spatially explicit information on quantities of natural capital stocks, it provides necessary information about the economic program. When combined with appropriate methodologies and research designs such data facilitate the identification of marginal valuations based on the actual choices and trade-offs that individuals and society make (Fenichel and Hashida, 2019). Further, large sample sizes mean that heterogeneity in valuations can in principle be recovered when significant heterogeneity in populations exist within or between natural capital jurisdictions.

3 The Environmental Impacts Frame

While advances in technology have improved our understanding of *where* natural capital is located, there remain large gaps in our understand about *who* benefits from natural capital, as well as the consequences for health and well-being. As discussed above, the benefits of natural capital are unlikely to be evenly distributed across individuals within a population, resulting in misleading inferences when using aggregated data sources.

To help mitigate these constraints, we have developed a new prototype microdata infrastructure to facilitate individual-level analyses in the United States – the Census Environmental Impacts Frame (EIF). The EIF uses confidential Census Bureau microdata drawn from surveys, administrative records, and Decennial censuses to provide detailed panel data on demographics, economic circumstances and address-level residential histories for nearly all residents of the United States from the late 1990s forward. This rich microdata (containing more than 6 billion observations) presents new opportunities to advance our understanding of the environmental conditions people face, why differences in exposure to environmental conditions arise, and the distributional consequences of exposure to hazards and amenities in the United States.

The EIF is a modular infrastructure, rather than a single combined file. There are two core modules constructed from confidential data at the Census Bureau: a demographic "spine", which contains basic demographic information, e.g. race, age, sex, date and place of birth, date of death, for the relevant universe of individuals, and an annual residential history file for individuals in the spine, allowing researchers to track individuals over time and space.[1]

The EIF exists to facilitate the description and analysis of exposure to environmental amenities and hazards at the individual-level. The core components described above – the demographic spine and the residential histories – provide the foundation for an exciting and extensive research agenda. Using the EIF, it is possible to incorporate and analyze any environmental data that can be geospatially resolved. As such, the EIF allows researchers to develop a systematic and comprehensive understanding of environmental exposures at a high spatial resolution over a relatively long time series. In the following section we leverage the EIF to highlight the conceptual challenges discussed and illustrate how the EIF could be used to alleviate (at least in part) some of these issues.

4 Urban Tree Canopy in the United States

Urban tree canopy cover – the layer of leaves, branches, and stems that cover land surfaces in urban areas – is an important variety of natural capital in the United States. Urban trees have been argued to provide many important benefits: absorbing carbon dioxide; providing shade and lowering air temperatures; supporting stormwater infrastructure by absorbing large amounts of water and reducing runoff; improving air and water quality; providing wildlife habitats that increase local biodiversity; and providing aesthetic, social, mental health, and cultural benefits.

[1] See Voorheis et al. (2023) for more details on how these modules are constructed.

We incorporate high-resolution data on urban tree canopy cover from the National Land Cover Database (NLCD) into the Environmental Impacts Frame for the year 2016. The NLCD provides satellite-derived data on tree cover at a 30m $\times$ 30m grid and reports the share of each pixel that is covered in by tree canopy. Because this resolution is in many cases smaller than individual parcels, we aggregate the NLCD data to the Census block level, and assign this block-level average canopy measure to each individual's location in the 2016 EIF as their exposure to canopy.

Figure 1 displays the distribution of canopy cover across the United States. As discussed in section 2.1 when natural capital is heterogenous across locations and immobile (as trees are wont to be), a common price cannot be used. Trees are locally non-excludable and have a relatively low marginal cost associated with providing services such as cooling and pollution abatement. This has the additional implication that, all else equal, trees might generate more natural capital services in in more densely populated areas.[2] We see that there is substantial spatial variation in canopy cover across the United States, and so the accounting price may vary substantially.

However, much of this variation may conflate regional differences. Given the density of population in urban areas understanding variation in urban canopy cover is of particular interest. To avoid comparisons between rural and urban tree cover, we restrict our analysis to Core-Base Statistical Areas (CBSAs), geographic areas defined by the Office of Management and Budget (OMB) that contain urban areas and highly integrated adjacent communities. Using this data we provide a systematic description of how urban tree canopy cover varies across space and individuals and relate what we observe to the conceptual issues rasied in section 2.

We first provide systematic evidence on how much variation in canopy cover exists across and within-CBSAs in the United States and how within-CBSA variation in canopy cover correlates with with several key measures of environmental quality. We document that

[2]Of course, forests and larger agglomerations of trees create different services.

there is substantial variation in urban tree canopy cover across the United States. The between-Census block-group standard deviation in urban canopy cover is 18.73. The 90-10 gap is 47.33 – an individual living in a Census block-group at the 90th percentile of the urban canopy distribution has canopy cover that is 47.33 percentage points higher than an individual living at the 10th percentile of the urban canopy distribution. We show that there is substantial variation in canopy cover even with CBSAs. The within-CBSA standard deviation is 14.05. The within-CBSA 90-10 gap is 31.21 – an individual living in a Census block-group at the 90th percentile of their CBSA's urban canopy distribution has canopy cover that is 31.21 percentage points higher than an individual living in a Census block-group at the 10th percentile of their CBSA's urban canopy distribution (Figure 2).

Second, we show that this variation in urban canopy cover is associated with meaningful variation in exposure to a number of socio-economically important margins of environmental quality. One important margin is the role that canopy plays in reducing surface temperatures. Temperatures can vary substantially over short distances due to differences in land cover, which affects local surface energy balance — a phenomenon known as the urban heat island effect (Grimmond, 2007). Pavement and concrete reflect less sunlight and absorb more heat than natural landscapes, such as trees and vegetation. Consistent with this we document that there is a strong negative association between canopy cover and surface temperature within CBSAs. On average, individuals living in census block groups with 10 percentage point more canopy cover than their CBSA mean are exposed to summertime surface temperatures that are 3.5°F (approximately one standard deviation) lower than the CBSA mean (Figure 3a). Chakma et al. (2023b) document the existence of peristent racial disparities in surface temperatures, canopy cover, and imperviousness and show that these disparities exist at every percentile of the national income distribution. Chakma et al. (2023a) shows that the mortality effects of temperature are much higher in neighborhoods with greater imperviousness and that half of the black-white gap in temperature-driven mortality can be explained by differences in imperviousness.

We also estimate a strong negative correlation between canopy and flood risk. Urban tree canopy cover reduces flood risk by intercepting rainfall through the collection of water on branches and leaves, increasing the soil's capacity to absorb and retain water, and by physically slowing down the flow of water. All of these considerations reduce the burden on drainage systems. We estimate that, on average, individuals living in census block groups with 10 percentage points more canopy cover than their CBSA mean are exposed to a flood risk score that is 0.1 points (approximately one standard deviation) lower than their CBSA mean (Figure 3b). Wing et al. (2022) calculate that annualized US flood losses are currently US$32.1 billion on average and are projected to rise to US$40.6 billion by 2050 under the RCP4.5 scenario.

Finally, in Figures 3c, 3d, and 3e we explore the relationship between urban canopy cover and different types of air pollution. In Figure 3c we estimate a strong negative correlation between canopy cover and fine particulate matter ($PM_{2.5}$). Fine particulate matter consists of extremely small airborne particles (30 times smaller than the diameter of a human hair), often generated from combustion sources, that can penetrate deep into the lungs and bloodstream, posing significant health risks. Urban canopy has the potential to affect $PM_{2.5}$ concentrations through direct air filtration (leaves and bark trap and absorb $PM_{2.5}$ particles from the air), and cooling (cooler air can potentially hold fewer particles and reduces energy demand). On average, we estimate that individuals living in census block groups with 10 percentage points more canopy cover than their CBSA mean are exposed to fine particulate matter that is 1.89 micrograms per cubic meter ($\mu g/m^3$) (approximately one standard deviation) lower than the CBSA mean. This association reflects a non-trivial difference in exposure. (Deryugina et al., 2019) estimate that a $1\mu g/m^3$ increase in PM 2.5 exposure for one day causes 0.69 additional deaths per million elderly individuals over the following three-days. This estimate likely reflects a lower bound. Deryugina and Reif (2023) estimate that the long-run effects of acute exposure are higher and calculate that the effect of chronic exposure on life expectancy are 7-8 times larger than the long-run effects of an acute exposure. Colmer et al. (2021) estimate that reductions in early childhood $PM_{2.5}$ exposure are associated with substantial increases in later-life W-2 earnings and document that disparities in exposure play a non-trivial role in shaping broader patterns of economic opportunity and inequality in the United States.

In Figure 3d we also estimate a strong negative correlation between urban canopy cover and Nitrogen Dioxide (NO_2). NO_2 is a highly reactive gas, which forms primarily from the burning of fossil fuels. It contributes directly to smog, reacts with sunlight and other compounds in the atmosphere to form secondary pollutants such as Ozone, and acts like a catalyst to transform primary emissions into secondary particulates, increasing the total amount of particulate matter in the air. Similar to particulate matter, urban canopy cover can affect NO_2 concentrations through direct air filtration and cooling. We estimate that, on average, individuals living in census block groups with 10 percentage points more canopy cover than their CBSA mean are exposed to Nitrogen Dioxide concentrations that are 1.81 parts per billion (approximately one standard deviation) lower than the CBSA mean. These are meaningful differences. Meng et al. (2021) estimate that, on average, a $10\mu g/m^3$ increase in previous day ambient NO2 concentration was associated with a 0.46% increase in all-cause mortality.[3] Khreis et al. (2017) conduct a meta-analysis of 21 studies and generate a summary estimate for the likelihood of developing asthma at some point during childhood. They calculate an odds ratio of 1.05 per $4\mu g/m^3$, i.e., a 5% increase in risk.

In Figure 3e we estimate the opposite relationship – a strong positive correlation between urban canopy cover and Ozone concentrations. Ozone forms through complex chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the presence of sunlight. The consequences of urban canopy cover for Ozone is unclear. On the one-hand, trees absorb Nitrogen dioxide, primary components of Ozone. By lowering air temperature, tree cover could also reduce the efficiency of Ozone formation. On the other-

[3]Assuming 1 atmosphere of pressure (1,013.25 hPa) and an average temperature of 12°C, we convert $\mu g/m^3$ into parts per billion (ppb), using a conversion factor of $1.967\mu g/m^3 = 1$ ppb. $10\mu g/m^3 = 5.085$ ppb.

hand, trees directly emit natural volatile organic compounds (VOCs) a critical percursor to Ozone formation. Our empirical pattern suggests that, all-else-constant, the VOC channel is dominant in our context. We estimate that, on average, individuals living in census block groups with 10 percentage points more canopy cover than their CBSA mean are exposed to Ozone concentrations that are 0.22 parts per billion (approximately one standard deviation) lower than the CBSA mean. The epidemiological literature tilts towards larger damages from fine particulates and NO_x vs. Ozone (Turner et al., 2016; Qian et al., 2017), but without a more detailed comparison of dose response functions that account for the complex relationships between pollutants it is unclear whether the increased damages from Ozone would be offset by improvements in PM2.5 and NO_x.

These facts are helpful for documenting, at least in part, the potential economic value associated with urban canopy cover. However, showing how quantities vary, does not provide any insight into the valuation of this form of natural capital or the extent to which valuations may vary within a location. An important margin that may shape differences in valuations is income. Natural capital engel curves, if they existed, would tell us how demand varies with income holding prices and preferences fixed. However, absent prices, engel curves cannot be estimated for non-market goods and services. Instead, we explore the extend to which canopy cover exposure varies with income, a revealed preference, but reduced form and likely inconsistent approximation for how demand may vary throughout the income distribution.

A common approach to evaluating the role the income plays in shaping differences in environmental quality is to use a place-based average of the household income; however, the use of even granular place-based data severely limits what one can learn about the potential for differences in willingness to pay for natural capital within locations. In our existing and ongoing work we repeatedly document that substantial variation in income within even narrowly defined geographies results in misleading inferences being made about people when using place-based data (Chakma et al., 2023b; Colmer et al., 2023; Voorheis et al., 2023) — a problem known as aggregation bias. Here, we illustrate this in the context of the relationship between income and canopy cover. In Figure 4, we show that within-commuting zone variation in canopy cover exposure is relatively flat through the first half of the individual-level national income distribution before increasing moderately at higher income levels. Individuals at the 90th percentile of the individual-level income distribution experience canopy cover that is 2.7 percentage points higher than individals at the 10th percentile of the individual-level income distribution. By contrast, using average income per capita calculated at the Census Block Group level calculate the distribution of income per capita across locations, we see that there is a much stronger association between place-based average income and canopy cover. We estimate that individuals living in neighborhoods at the 90th percentile of the block group income distribution are experience canopy cover that is 8.6 percentage points higher than individuals living in neighborhoods at the 10th percentile of the block group income distribution, more than tripling the individual-level gap. This is largely driven by differences in the relationship in the bottom half of the income distributions. These differences imply that there are other neighborhood-level factors or amenities correlated with income at the neighborhood level that are not as strongly correlated with the individual-level income distribution. Using place-based data results in a potentially incorrect interpretation of the canopy cover–income relationship. If one were to personify places, rather than using person-level data, one would come to vastly different inferences about the empirical relevance of income for predicting canopy cover exposures.

That there is less variation in expsoure to canopy cover within the individual-level income distribution suggests that within-location heterogeneity in income may not be a first-order determinant of willingness-to-pay for natural capital in this context. We caveat again, however, that these simple relationships do not convey direct information on willingness-to-pay, or the extent of heterogeneity in willingness-to-pay within Census blocks; nevertheless, this finding suggests that the scope for heterogeneity along margins of income are more limited than one may infer from place-based data. This is not because there is limited heterogeneity in income within Census Block groups — within-location heterogeneity is what leads to differences in the two canopy–income relationships (Figure 4). By contrast, it suggests that there may be little scope for individual income as an important determinant of demand for natural capital. Colmer et al. (2023) provide causal evidence that even large changes in individual income lead to only small changes in demand for air quality. Whether this is because the true Marginal Willingness to Pay for air quality is low, or because information frictions or other market failures distort revelead measures of marginal willingness to pay remains unclear.

This highlights the third conceptual challenge that natural capital valuation faces – missing markets. Microdata is not able to do anything directly to address this constraint. Accounting prices are not observed and so can't be "provided" in the same way that data on earnings or housing prices can be made available. The granular variation provided by microdata does, however, create opportunities to credibly estimate accounting prices in a systematic and comprehensive way. This is beyond the scope of this paper, but the application of thoughtful research designs and/or structural models could be used to identify not only average accounting prices or willingness to pay estimates, but also distributions of these economic quantities.

5 Conclusion

In this paper we have raised the prospect of leveraging microdata (and in particular a new restricted–access environmental microdata infrastructure being developed at the Census Bureau) as an input to improve and expand measurement inputs necessary for natural capital accounting exercises. The availability of new microdata products create opportunity for researchers to expand methodologies and accounting frameworks with individual-level data in mind.

We provide several illustrations of how microdata can help to address conceptual issues and inform natural capital accounting exercises. Restricted access microdata can be helpful in defining the extent of the relevant economic jurisdictions when engaging in nonmarket valuation exercises, and address issues of heterogeneity in valuation within locations. Combined with appropriate research designs and structural models, restricted access microdata containing individual-level information about income, wealth, locational choices, alongside information on exposure to natural capital can be used to learn about willingness to pay for natural capital, as well as heterogeneity in willingness to pay. By facilitating the production of new facts and necessary structural estimates microdata has the potential to improve the natural capital accounting endeavor by grounding estimates in the experiences and well-being of individuals, providing new and improved evidence which can inform decisions around how to manage the relationships between people, businesses and the environment.

References

Addicott, Ethan T. and Eli P. Fenichel, "Spatial Aggregation and the Value of Natural Capital," *Journal of Environmental Economics and Management*, 2019, *95*, 118–132.

Arrow, Kenneth J, Partha Dasgupta, Lawrence H Goulder, Kevin J Mumford, and Kirsten Oleson, "Sustainability and the Measurement of Wealth," *Environment and Development Economics*, 2012, *17* (3), 317–353.

Arrow, Kenneth, Partha Dasgupta, Lawrence Goulder, Gretchen Daily, Paul Ehrlich, Geoffrey Heal, Simon Levin, Karl-Göran Mäler, Stephen Schneider, David Starrett et al., "Are We Consuming Too Much?," *Journal of Economic Perspectives*, 2004, *18* (3), 147–172.

Chakma, T., J. Colmer, and J. Voorheis, "The Causes and Consequences of Urban Heat Islands," *Working Paper*, 2023.

Chakma, Tridevi, Jonathan Colmer, and John Voorheis, "Heat Disparities in the United States," 2023. Mimeo.

Colmer, Jonathan, John Voorheis, and Brennan Williams, "Air Pollution and Economic Opportunity in the United States," *Working Paper*, 2021.

_ , **Suvy Qin, John Voorheis, and Reed Walker**, "Income, Wealth, and Environmental Inequality in the United States," 2023. Mimeo.

Daily, Gretchen C., Tore. Soderqvist, Sara. Aniyar, Kenneth. Arrow, Partha. Dasgupta, Paul R. Ehrlich, Carl. Folke, AnnMari. Jansson, Bengt-Owe. Jansson, Nils. Kautsky, Simon. Levin, Jane. Lubchenco, Karl-Göran. Mäler, David. Simpson, David. Starrett, David. Tilman, and Brian. Walker, "The Value of Nature and the Nature of Value," *Science*, 2000, *289* (5478), 395–396.

Deryugina, Tatyana and Julian Reif, "The Long-run Effect of Air Pollution on Survival," *NBER Working Paper No. 31858*, 2023.

_ , **Garth Heutel, Nolan H. Miller, David Molitor, and Julian Reif**, "The Mortality and Medical Costs of Air Pollution: Evidence from Changes in Wind Direction," *American Economic Review*, 2019, *109* (12), 4178–4219.

Di, Qian, Heresh Amini, Liuhua Shi, Itai Kloog, Rachel Silvern, James Kelly, M. Benjamin Sabath, Christine Choirat, Petros Koutrakis, Alexei Lyapustin, Yujie Wang, Loretta J. Mickley, and Joel Schwartz, "Assessing NO2 Concentration and Model Uncertainty with High Spatiotemporal Resolution across the Contiguous United States Using Ensemble Model Averaging," *Environmental Science & Technology*, 2020, *54* (3), 1372–1384.

Fenichel, E. P., J. K. Abbott, and S. D. Yun, "The nature of natural capital and ecosystem income," in V. K. Smith, P. Dasgupta, and S. Pattanayak, eds., *Handbook of Environmental Economics*, North Holland, 2018, pp. 85–142.

Fenichel, Eli P. and Joshua K. Abbott, "Natural Capital: From Metaphor to Measurement," *Journal of the Association of Environmental and Resource Economists*, 2014, *1* (1/2).

_ **and Yukiko Hashida**, "Choices and the Value of Natural Capital," *Oxford Review of Economic Policy*, 2019, *35* (1), 120–137.

_ **, Joshua K. Abbott, Jude Bayham, Whitney Boone, Erin MK Haacker, and Lisa Pfeiffer**, "Measuring the Value of Groundwater and Other Forms of Natural Capital," *Proceedings of the National Academy of Sciences*, 2016, *113* (9), 2382–2387.

Fisher, A. C., J. V. Krutilla, and C. J. Cicchetti, "The Economics of Environmental Preservation: A Theoretical and Empirical Analysis," *American Economic Review*, 1972, *62* (4), 605–619.

Grimmond, Sue, "Urbanization and Global Environmental Change: Local Effects of Urban Warming," *The Geographical Journal*, 2007, *173* (1), 83–88.

Hartwick, John M., "Natural Resources, National Accounting and Economic Depreciation," *Journal of Public Economics*, 1990, *43* (3), 291–304.

Heal, Geoffrey M., *Valuing the Future: Economic Theory and Sustainability*, Columbia University Press, 1998.

Khreis, Haneen, Clare Kelly, John Tate, Roger Parslow, Karen Lucas, and Mark Nieuwenhuijsen, "Exposure to traffic-related air pollution and risk of development of childhood asthma: a systematic review and meta-analysis," *Environment International*, 2017, *100*, 1–31.

Krutilla, John V., "Conservation Reconsidered," *American Economic Review*, 1967, *57* (4), 777–786.

Meng, Xia, Cong Liu, Renjie Chen, Francesco Sera, Ana Maria Vicedo-Cabrera, Ai Milojevic, Yuming Guo, Shilu Tong, Micheline de Sousa Zanotti Stagliorio Coelho, Paulo Hilario Nascimento Saldiva et al., "Short term associations of ambient nitrogen dioxide with daily total, cardiovascular, and respiratory mortality: multilocation analysis in 398 cities," *BMJ*, 2021, *372.*

Nordhaus, William D., "Principles of National Accounting for Nonmarket Accounts," in Dale W. Jorgenson, J. Steven Landefeld, and William D. Nordhaus, eds., *A New Architecture for the U.S. National Accounts*, Chicago: University of Chicago Press, 2006.

Qian, Di., Yan. Wang, Antonella. Zanobetti, Yun. Wang, Petros. Koutrakis, Christine. Choirat, Francesca. Dominici, and Joel D. Schwartz, "Air Pollution and Mortality in the Medicare Population," *New England Journal of Medicine*, 2017, *376* (26), 2513–2522.

Requia, Weeberb J., Qian Di, Rachel Silvern, James T. Kelly, Petros Koutrakis, Loretta J. Mickley, Melissa P. Sulprizio, Heresh Amini, Liuhua Shi, and Joel Schwartz, "An Ensemble Learning Approach for Estimating High Spatiotemporal Resolution of Ground-Level Ozone in the Contiguous United States," *Environmental Science & Technology*, 2020, *54* (18), 11037–11047.

Smith, V Kerry, "Nonmarket Valuation of Environmental Resources: an Interpretive Appraisal," *Land Economics*, 1993, pp. 1–26.

Turner, M. C., M. Jerrett, C. A. 3rd Pope, D. Krewski, S. M. Gapstur, W. R. Diver, B. S. Beckerman, J. D. Marshall, J. Su, D. L. Crouse, and R. T. Burnett, "Long-Term Ozone Exposure and Mortality in a Large Prospective Study," *American Journal of Respiratory and Critical Care Medicine*, 2016, *193* (10), 1134–1142.

van Donkelaar, Aaron, Melanie S. Hammer, Liam Bindle, Michael Brauer, Jeffery R. Brook, Michael J. Garay, N. Christina Hsu, Olga V. Kalashnikova,

Ralph A. Kahn, Colin Lee, Robert C. Levy, Alexei Lyapustin, Andrew M. Sayer, and Randall V. Martin, "Monthly Global Estimates of Fine Particulate Matter and Their Uncertainty," *Environmental Science & Technology*, 2021, *55* (22), 15287–15300.

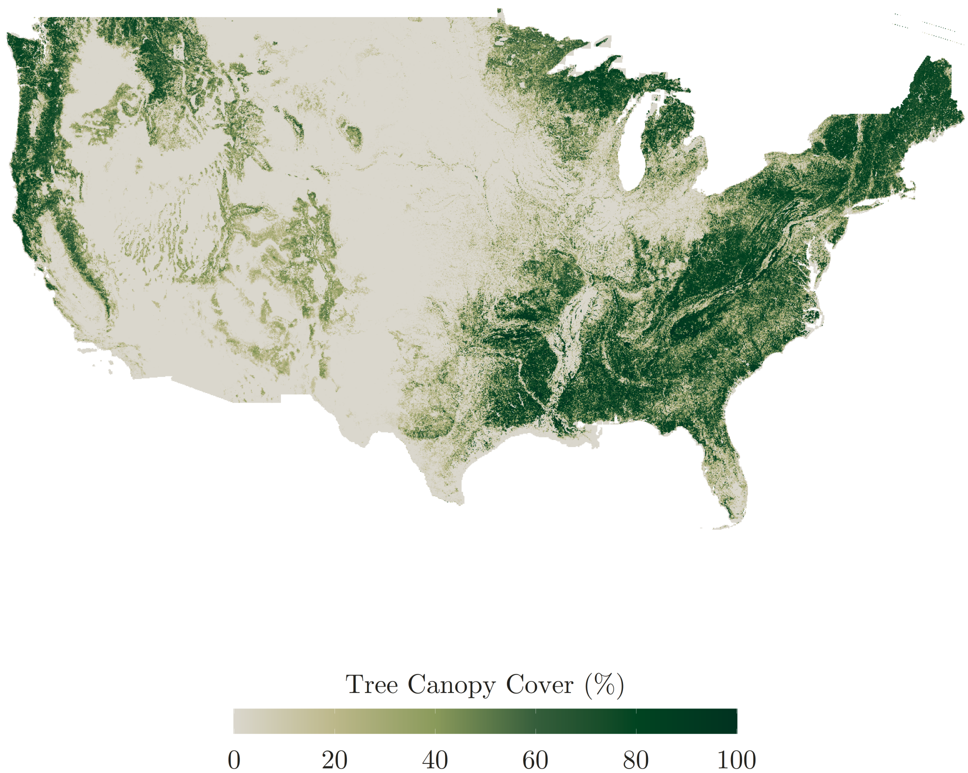
Voorheis, J., J. Colmer, K. Houghton, E. Lyubich, M. Munro, C. Scalera, and J. Withrow, "Building the Prototype Census Environmental Impacts Frame," *NBER Working Paper No. 31189*, 2023.

Weitzman, Martin L., "On the welfare significance of national product in a dynamic economy," *The Quarterly Journal of Economics*, 1976, *90* (1), 156–162.

Wing, Oliver EJ, William Lehman, Paul D. Bates, Christopher C. Sampson, Niall Quinn, Andrew M. Smith, Jeffrey C. Neal, Jeremy R. Porter, and Carolyn Kousky, "Inequitable patterns of US flood risk in the Anthropocene," *Nature Climate Change*, 2022, *12* (2), 156–162.

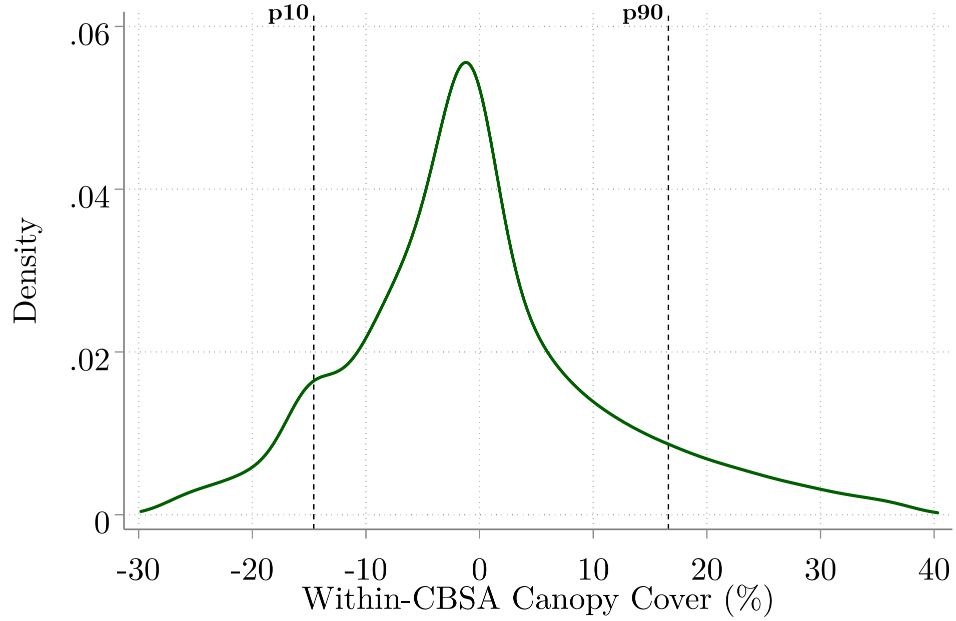
Figures

Figure 1: Tree Canopy Cover in the United States



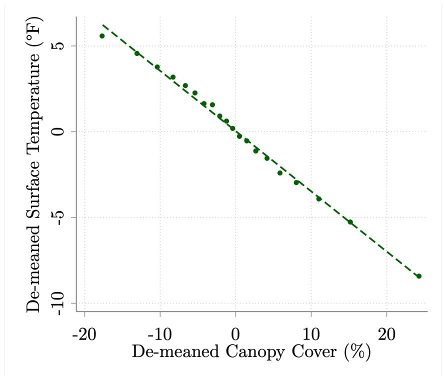
Source: NLCD. Notes: This figure shows tree canopy coverage in the contiguous United States for the year 2016. Data is derived from multi-spectral satellite imagery. The raster data is available at a 30 meter resolution but aggregate to a 480 meter resolution in the figure for visualization purposes. Each 30m grid cell reports the estimated share of land that is covered by tree canopy. Percent coverage increases visually in the figure from light to dark.

Figure 2: The within-CBSA Distribution of Tree Canopy Coverage in the United States

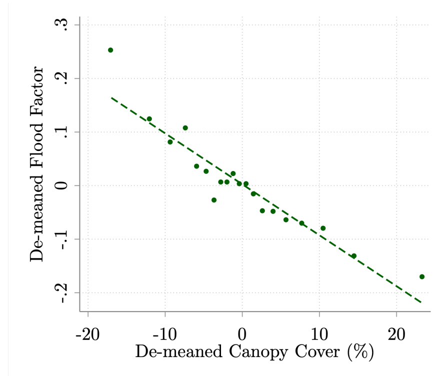


Source: NLCD. Notes: This figure presents a kernel density plot of the within-CBSA distribution of tree canopy coverage for the contiguous United States in 2016. The left dashed line is the 10th percentile of the within-CBSA distribution (-14.59). The right dashed line is the 90th percentile of the within-CBSA distribution (16.61). The within-CBAS 90-10 gap is 31.21 percentage points.

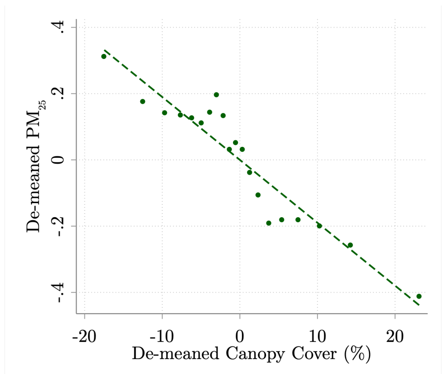
Figure 3: The Association between Canopy Cover and Environmental Risks



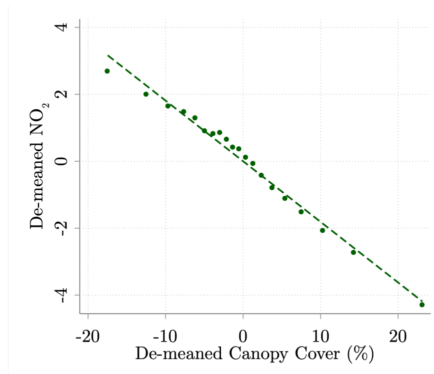
(a) Summer Surface Temperature



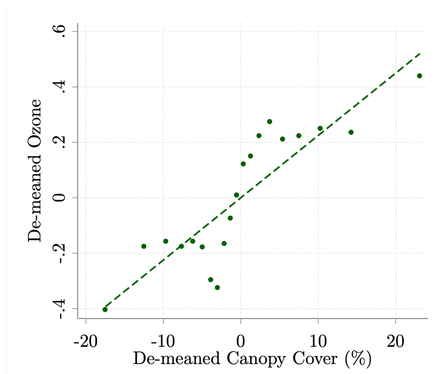
(b) Flood Risk



(c) Fine Particulate Matter ($PM_{2.5}$



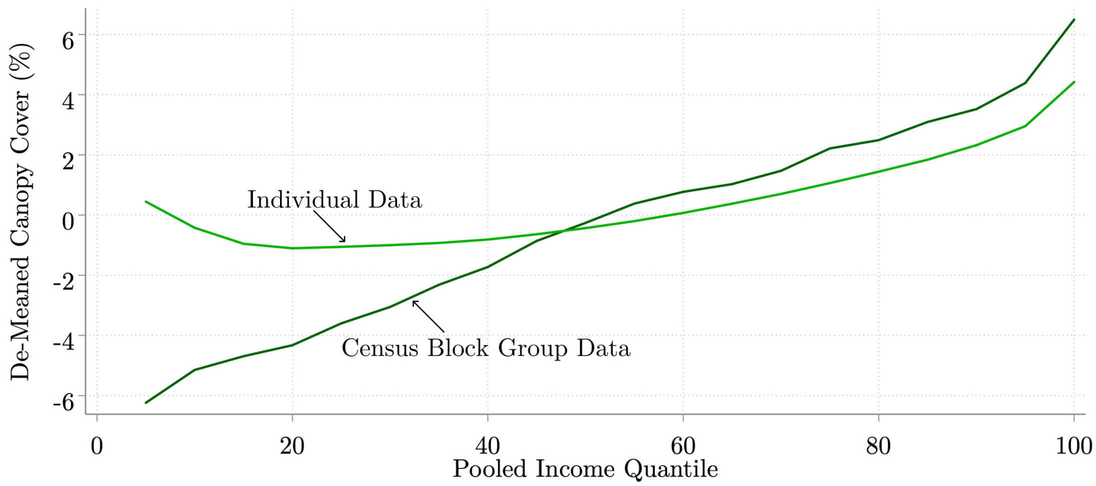
(d) Nitrogen Dioxide (NO_2



(e) Ozone

Source: NLCD, Landsat, First Street Foundation Floodfactor, the Environmental Impacts Frame, Di et al. (2020), Requia et al. (2020) and van Donkelaar et al. (2021). Notes: These figures report the bivariate relationship between within-CBSA variation urban tree canopy cover and within-CBSA variation exposure to environmental risks in 2016. The unit of analysis for the underlying analysis is an individual.

Figure 4: Aggregation Bias and the Canopy–Income Relationship



Source: NLCD and the Environmental Impacts Frame. Notes: This figure shows how within-CBSA variation in canopy cover varies across the individual-level national income distribution (light green line) and the distribution of census block group average income per capita (dark green line). We document a much flatter canopy-income profile when using the distribution of individual income than when using the distribution of census block group average income per capita, indicating that there are other place-based factors correlated with place-based income that result in biased inferences about the importance of income in shaping exposure to urban canopy cover.