SPATIAL ENVIRONMENTAL ECONOMICS

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ABSTRACT

How do environmental goods and policies shape spatial patterns of economic activity? How will climate change modify these impacts over the coming decades? How do agglomeration, commuting, and other spatial forces and policies affect environmental quality? We distill theoretical and empirical research linking urban, regional, and spatial economics to the environment. We present stylized facts on spatial environmental economics, describe insights from canonical environmental models and spatial models, and discuss the building blocks for papers and the research frontier in enviro-spatial economics. Most enviro-spatial research remains bifurcated into either primarily environmental or spatial papers. Research is only beginning to realize potential insights from more closely combining spatial and environmental approaches.

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1 Introduction

How can environmental and spatial economics jointly provide insight on research and policy? In other words, how can accounting for spatial economics change answers to environmental questions, and how can accounting for environmental economics change answers to spatial questions? We argue that environmental and spatial economics have enormous potential synergies. Research exploiting these interactions is in its infancy, and this chapter discusses this emerging subfield. At the same time, the combination of spatial and environmental economics has burgeoning high-quality work, and we forecast expansion in this area.

What is spatial environmental economics? Defining the boundaries of our discussion clarifies our purpose. We cover environmental settings where geography matters and spatial settings where the environment matters. We interpret environmental economics to include analysis of environmental, energy, and natural resource goods. Our interpretation of spatial economics focuses primarily on economic links across regions within a country, such as the movement of people, ideas, goods and services, and externalities like pollution, across provinces or neighborhoods of a city. Research on regional policies with no interactions across space – or using a binary concept of space distinguishing local from "somewhere else" – is not the subfield's primary focus, though we discuss papers with this type of setting. International research making comparisons across countries is also not the core of this subfield, but again we discuss environmental research where geography across countries matters.

The emergence of this subfield reflects a few forces—the increasing use of trade-related methods in economic geography; the broadening availability of high-resolution spatial and environmental data, often derived from remote sensing, business records, or administrative sources; growing recognition that the damages of environmental externalities differ enormously across space; and rising public and academic concern about the intensely spatial challenges of climate change. At the same time, barriers to entry may help explain the limited realization to date of potential synergies between environmental and spatial economics—conducting research at this intersection requires an understanding of methods, institutions, and data in each field. We aim for this chapter to give readers motivation, methods, and references to help understand and contribute to research connecting these fields. It is intended as a resource for environmental and resource economists with limited experience in spatial economics; spatial economists with limited experience in environmental topics; and those considering entering this subfield of research.

Two general examples help illustrate the potential importance of spatial environmental economics to scholars in both fields. The first example describes how ignoring space may provide the wrong answer to important questions in environmental economics. Space plays a central role in adaptation to environmental externalities. When a region experiences an adverse climate shock like a heat wave, reallocating agricultural production across fields accounts for a critical component of the country's adaptive response (Costinot et al. 2016). Similarly, when vulnerable low-lying areas experience flooding, migration and production reallocation can provide important forms of adaptation (Deryugina et al. 2018; Desmet et al. 2021). Accounting for spatial heterogeneity and links is therefore crucial in understanding the aggregate costs of environmental shocks and climate change.

The second example describes how environmental economics can provide insights for spatial economics. Many spatial models describe regional amenities and productivity that benefit households and firms, though are often silent on which features of a region generate these local characteristics. Environmental goods including air pollution, water availability, land quality, climate, and energy resources can help to understand these patterns. Underlying the distribution of productivity across space, Ellison and Glaeser (1999) conjecture that at least half of the concentration of industries across US states reflects natural advantage, including environmental forces, and Hornbeck (2012) finds that natural advantage has large and persistent spatial contributions to agriculture. In terms of amenities, Heblich et al. (2021) also find that pollution transport influences the location of populations within cities. Environmental forces and resources can therefore help explain the distribution of economic activity and agglomeration across space.

Motivated by these complementarities, this chapter considers several broad research questions. First, how do environmental goods shape spatial patterns of economic outcomes? For example, climate differs enormously between countries (e.g., Mali versus Canada), regions within a country (Chile's Tierra del Fuego versus its Atacama desert), and neighborhoods within a city (Santa Monica versus the Inland Empire around Los Angeles). Understanding the amenity and productivity value of climate can help explain divergent economic outcomes across these regions and how the spatial impact of environmental goods may change as climate change intensifies. Understanding spatial patterns of environmental impacts can also shed light on the distribution across different groups of damages from changes in environmental quality, since in many settings, the neighborhood where a person lives provides a proxy for their income, race or ethnicity, and other demographics. We study both exogenous amenities that nature has provided (for example, a location's climate, which is largely exogenous) and endogenous amenities arising from human choices (such as local air pollution, which is primarily endogenous).[1] We discuss both global pollutants such as carbon dioxide (CO_2), which affect global health and welfare equally regardless of where they are emitted,

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[1] Climate change and urban heat islands arguably provide an endogenous component of climate. Dust storms provide an example of potentially exogenous sources of air pollution.

and local pollutants such as particulate matter smaller than 2.5 micrometers ($PM_{2.5}$), which primarily affect health and welfare in the region where they are emitted.

Second, how does the spatial distribution of economic activity and spatial economic forces shape environmental quality? Agglomeration, congestion, commuting, migration, goods transportation, and the flow of ideas all affect the distribution of pollution, natural resource degradation and other environmental goods across space. For example, roads, centers of economic activity, and regional timber prices all drive concentrations of deforestation in the tropics, where rural economic development and valuable services that forests provide (such as flood mitigation and water purification) may be complements in some regions and substitutes in others. Residential growth in many cities around the world is expanding into the wildland-urban interface, where existing population density is low but increased urbanization can result in ecological damage and wildfire risks can increase insurance and property costs.

Third, how do and how should governments design and implement policy in spatial environmental settings? We consider how spatial policies affect the environment, how environmental policies affect spatial patterns of economic outcomes, and how accounting for enviro-spatial interactions affects optimal policy design. This includes, for example, the environmental consequences of zoning, transportation investment, and building restrictions; and the impact of renewable energy subsidies, regional environmental regulations, and regional natural resource protections for both environmental goods and economic activity. Several themes that this chapter discusses can guide optimal environmental policy rules that vary over space, as well as how urban or regional policies should account for air pollution emissions, forest or wetland degradation, and changes in other environmental goods.

Where possible, we draw on data and examples from many different locations and environmental goods. The discussion of existing literature, however, inevitably reflects its geographic focus on the US and, increasingly, China; and its topical focus on particulate matter air pollution and climate change.

This chapter builds on previous reviews. Cherniwchan et al. (2017) and Copeland et al. (2022) discuss trade, globalization, and the environment. Relative to these studies, this review focuses on the relationship between the environment and space *within* countries, where factors are typically more mobile, though we also discuss spatial forces across countries where relevant. Our conclusions highlight several issues that differ between research and policy involving international versus intra-national spatial economics and the environment. Our chapter also complements recent discussions of the emerging literature on environmental and spatial issues—Desmet and Rossi-Hansberg (2024) review spatial climate change research with an emphasis on spatial integrated assessment models, and Dominguez-Iino

(2023) focuses on the implications of spatial factors for environmental policies, for instance regarding leakage and adaptation. We also build on chapters in earlier volumes of this Handbook focused more on interactions of environmental and urban issues (Bartik and Smith 1987; Glaeser and Kahn 2004; Gyourko et al. 1999; Kahn and Walsh 2015; Lakshmanan and Bolton 1987).

Overviewing the chapter may help the reader identify the most useful parts. Section 2 describes stylized facts about the links between spatial and environmental forces—how spatial forces affect polluting activity; how spatial geophysical forces separate the locations where pollution is emitted versus creates damages; and how spatial variation in damage functions influences the welfare impacts of environmental quality. Section 3 discusses insights from, and limitations of, canonical models for understanding interactions between the environment and space. We discuss partial equilibrium models of pollution regulation and natural resource extraction, hedonic models, classic spatial equilibrium models, and richer multi-dimensional equilibrium models. Sections 4 and 5 discuss building blocks underpinning papers at the frontier of spatial environmental economics, with references to relevant literature and open questions. Section 4 discusses broad analysis choices; spatial aspects of household preferences and the environment; and spatial components of interactions between firms and the environment. Section 5 discusses spatial links and policy—connections between environmental goods; agglomeration and dispersion forces; spatial links, including goods transport and migration; and specific policy design challenges at the intersection of environmental and spatial economics. Section 6 summarizes topics for future research. Section 7 concludes.

2 Motivating facts on enviro-spatial links

This section discusses motivating facts about the environment and space.[2] The organization of subsections follows a natural progression from spatial forces that drive polluting activity, to spatial drivers of ambient environmental quality, to spatial variation in environmental damages and contributions to social welfare. This sequence also corresponds to the structure underpinning integrated assessment models, which typically combine modules projecting the distribution of emissions; mapping these to changes in the quality of ambient air, water, or climate; estimating damage functions; and valuing and aggregating damages. The discussion highlights the simultaneous determination of agglomeration of economic activity and environmental outcomes, and the role of underlying environmental resources and the transport of goods, people and pollution in determining these outcomes.

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[2] Appendix B provides details on data sources.

2.1 Spatial forces drive polluting activity

We begin with maps showing spatial patterns of environmental degradation and pollution emissions, which demonstrate how economic forces which vary over space like growth, density, land use change, and transportation drive polluting activity.

Figure 1 reveals large variation in forest cover, deforestation, and emissions across space. Panel (a) shows forested areas in green, and areas deforested between 2000 and 2020 in purple. Earth's forests are concentrated in two bands—a northern band of boreal forests along Canada, Scandinavia, and Siberia, and a southern band of tropical forests concentrated in South America, central Africa, and Southeast Asia. Deforestation can provide local economic benefits, though also contributes to greenhouse gas emissions, erosion, wildfires, biodiversity loss, and water pollution. Because forests represent a stock, deforestation has lasting impacts on these ecosystem services. The map of Brazil on the right reveals recent deforestation at the interface between forested areas and non-forested regions, especially in areas near population centers (shown in red) facing high pressure for land encroachment.

Figure 1, panel (b), maps CO_2 emissions. Emissions come from many economic activities, especially fossil fuel combustion and processing, including for industrial production and home heating. The global map on the left reveals higher emissions in regions with greater population density, like large cities, and with higher incomes, especially in high and middle income countries. CO_2 emissions also reflect transportation, as the map shows clear emissions footprints along major transport routes, such as between the US, EU, and China. The right panel shows similar correlations between emissions, density, and income across US regions.

Figure 1: Spatial variation in forest cover, deforestation and CO_2 emissions

[Insert Figure 1(a) here]

(a) Forest extent in 2020 and Forest Loss in 2000–2020

[Insert Figure 1(b) here]

(b) Tons of CO_2 per cell in 2021

The datasets used in this figure are: GLAD Global Land Cover and Land Use dataset for forest extent in panel (a) and the Global Forest Change 2000-2020 for forest loss in panel (a); GridFed dataset for global map in panel (b); ODIAC dataset for the USA map in panel (b). Appendix B describes each dataset.

Figure 2 maps CO_2 emissions for the Chicago Metropolitan Area at finer spatial resolution. Panel (a) shows predominantly industrial emissions, panel (b) plots total household carbon footprints per cell, and panel (c) shows the mean per-household carbon footprint in each census tract. While aggregate emissions, from both industrial sources and households, concentrate near the city center where industry and populations are densest (panels (a) and (b)), emissions per household are highest in city outskirts and suburban areas (panel (c)), driven by longer commutes, larger housing units requiring more energy to heat and cool, and higher rates of multiple vehicle ownership. Given these differences, the choice of whether analysis measures emissions from consumption versus production may alter conclusions.

Figure 2: Carbon dioxide (CO_2) emissions in the Chicago Metropolitan Area

[Insert figure 2(a), 2(b) and (2c) here in a row horizontally]

(a) Carbon dioxide emissions in 2021

(b) Total household carbon footprint

(c) Average household carbon footprint

The map in (a) uses the GridFED (The Gridded Fossil Emissions Datasets). Appendix B describes this dataset. The map in (b) shows the total household carbon footprint per cell at a 0.01 degree resolution for the Chicago metropolitan area. This map combines data on household carbon footprints (HCFs) for the average household in each US Census tract from Green and Knittel (2020) with data on the number of households per census tract from the US Census Bureau 2019 American Community Survey (ACS) to calculate total carbon footprints. The calculation then distributes these emissions across 0.01 degree cells and rasterizes them for visualization. The map in (c) plots data on average per household carbon footprint in each census tract from Green and Knittel (2020) for the Chicago Metropolitan Area.

Several spatially-varying forces drive the variation in environmental degradation that Figures 1 and 2 show. Following Grossman and Krueger (1993) and then Copeland and Taylor (1994), research has separated determinants of environmental quality into three categories—the scale of output, the composition of output across industries, and the techniques for producing a given good within an industry.

Figure 3 shows how these three categories of scale, composition, and technique relate to population density and $PM_{2.5}$ emissions across US counties, using data spanning all industries, including manufacturing, services, and agriculture. Existing studies, discussed in Sections 4 and 5, report a decomposition into scale, composition, and technique of how pollution changes within an economy over time. Figure 3 instead captures how these channels vary across counties in the cross section. We show population density on the horizontal axis given its connection to many ideas this chapter discusses about rural versus urban areas, patterns of agglomeration, and regional differences within a country. In panel (a), the vertical axis shows the log of county GDP, measuring the scale of economic activity. In panel (b), the vertical axis displays $\sum_s log(E_s/L_s)(L_{sc}/L_c)$, where E_s represents the tons of pollution emitted by industry s, L represents employment, and c identifies counties.[3] Intuitively, this weights each industry's log pollution intensity by its share of county c's employment, and therefore describes the extent to which a county is specialized in clean versus dirty industries. In panel (c), the vertical axis shows county fixed effects from a regression of pollution intensity $log(E_{sc}/L_{sc})$ on county and industry fixed effects. In panel (d), the vertical axis

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[3] We use employment rather than output given publicly-available data on the former at the county×industry level.

indicates whether the Environmental Protection Agency (EPA) designates a county to be in "nonattainment" under the Clean Air Act for having high ambient particulate matter pollution, and consequently subjects it to more stringent regulation.

Figure 3, panel (a), shows a strong positive correlation between population density and scale, measured by county GDP, since densely populated areas have higher income per person and more people. Panel (b) shows that more densely populated counties are also concentrated in dirtier industries, which is intuitive since manufacturing and utilities tend to locate in cities, while agriculture is more concentrated in rural areas. These findings indicate that both the scale and composition of production drives higher levels of pollution in cities. The technique effect in panel (c) shows that, within a given industry, denser areas have lower emissions per worker, suggesting that cleaner production techniques are used to produce output within a given industry in US cities relative to rural areas. This could reflect several mechanisms, including more stringent environmental regulation, greater factor-augmenting productivity, specialization in cleaner goods varieties, or outsourcing dirty production steps to other regions. Panel (d) suggests that stronger regulation may play a role, since more densely populated counties are more likely to have particulate matter nonattainment designations.[4]

Figure 3: Scale, composition, and technique across US counties by population density

[Insert figures 3(a), 3(b), 3(c) and 3(d) here as four panels spanning two rows with two figures in each row]

(a) Scale
(b) Composition
(c) Technique
(d) Regulation

Graphs show binned scatter plots where each underlying observation in the raw data represents a county in the year 2017, the dashed line in each graph shows the linear trend, and the circles in the graph show quantile means. For the x-axes, we measure population using data from the National Cancer Institute's Surveillance, Epidemiology, and End Results (SEER) Program, and measure land area from the Census Bureau's Topologically Integrated Geographic Encoding and Referencing system. The y-axis of panel (a) shows county GDP from the Bureau of Economic Analysis. The y-axis of panel (b) shows $\sum_s log(E_s/L_s)(L_{sc}/L_c)$, where c denotes county, s denotes a NAICS 3-digit industry, E denotes pollution emissions, and L denotes employment. We measure emissions from the National Emissions Inventory (NEI) and employment from the County Business Patterns (CBP). The y-axis of panel (c) shows county fixed effects from a regression of county×industry pollution intensity $log(E_{sc}/L_{sc})$, also measured from NEI and CBP, on county fixed effects and industry fixed effects. The y-axis of panel (d) indicates whether counties are in nonattainment for particulate matter.

The spatial structure of environmental policies, like those shown in Figure 3 panel (d), may therefore both be substantially affected by, and substantially affect, the location of

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[4] Because this graph shows a binned scatterplot, the y-axis shows the share of counties in each density bin which are in nonattainment (since for a given county, nonattainment is binary). Appendix Figure A1 shows even stronger relationships for ozone nonattainment.

economic activity and emissions. Environmental policies may diverge from policies in other domains as they often reflect the spatial structure of environmental externalities—for instance, airsheds, watersheds, and species habitats. China's "War on Pollution" in the last decade provides many such examples which list individual rivers or coastal bays where a policy subsidizes or mandates pollution abatement. Table A1 lists some of the more prominent policies. Environmental policies in other contexts (for instance, the US Endangered Species Act) are similarly demarcated based on geographical features rather than simply following administrative boundaries.

This discussion emphasizes the role of economic activity in determining environmental outcomes across space, and vice versa. Natural resource endowments also vary over space and can be an important driver of both environmental and economic outcomes. Natural resources that affect environmental outcomes, including water access, forests, fertile soils, mineral deposits, solar and wind availability, can change the total scale of production in an area, the composition of industry over space, and the factor intensity of an industry's production. Figure 4 maps the example of coal deposits. Panel (a) maps known coal deposits worldwide and reveals strong concentrations in the central and eastern US, eastern China, eastern Australia, and South Africa. Panel (b) maps the location of coal-fired power plants operating in 2023, which affect both local economic activity and environmental damages. These disproportionately locate near coal deposits, reflecting the fact that coal has high transportation costs. Many "mine-mouth" coal-fired power plants co-locate with coal mines for this reason. A similar correspondence between the location of natural resources and local specialization appears for other endowments, including agro-ecological suitability for crop cultivation (see Figure A2). At a more granular scale, within cities, tree canopy cover can moderate extreme temperatures and reduce energy consumption, increasing local property prices (Han et al. 2024).

Figure 4: Global maps of coal deposits and coal-fired power plants

[Insert figures 4(a) and 4(b) here in a row horizontally]

(a) Location of coal deposits

(b) Location of coal-fired power plants

The figure in panel (a), taken from Suárez-Ruiz et al. (2019), shows the geographical distribution of known coal deposits in the world[5]. The map in panel (b) shows the locations of coal power plants in operation in 2023 using data from the Global Energy Monitor Global Coal Plant Tracker.

Transportation links complicate the simultaneous relationship between the locations of economic activity and environmental outcomes, by altering the composition of economic

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[5] Reprinted from New Trends in Coal Conversion, Vol. 1, Isabel Suárez-Ruiz, María Antonia Diez, Fernando Rubiera, Coal, Pages 1-30, Copyright (2019), with permission from Elsevier.

activity across space and allowing transportation of dirty inputs across regions. Pollutant profiles also reveal the important role that trade and commuting paths play in generating pollution. For global pollutants, the CO_2 emissions profiles in the left-hand panel of Figure 1, panel (b), clearly show global shipping routes. Figure 5 provides another example focused on local pollutants, mapping annual average $PM_{2.5}$ concentrations in London in 2019, from the ADMS-Urban model. Major roads that form the conduits for transportation of goods and workers have the clearest elevated levels. Government-designated "Red Routes" with priority for through traffic have especially high concentrations, with $PM_{2.5}$ levels 35% higher than the mean London road (Camargo and Lord, 2021). While urban and regional models typically predict that increasing trade and commuting flows improves aggregate welfare, accounting for the associated local environmental externalities may temper estimates of the aggregate and distributional consequences of regional integration.

Figure 5: Modeled annual average $PM_{2.5}$ pollution concentrations across London in 2019

[Insert Figure 5 here]

The figure shows a map of modeled $PM_{2.5}$ pollution concentrations across London in 2019. Reproduced with permission from Cambridge Environmental Research Consultants (2024).

2.2 Spatial geophysical forces drive environmental quality

Spatial economic models typically depend on three links between regions—the movement of goods, workers, and ideas. Environmental settings involve a fourth link: geophysical forces that move environmental externalities across space. The spatial impact of pollution emissions depends on the processes by which the environment disperses pollution from one region to others. The areas which are downwind or downstream may have no relationship to county, province, or other administrative boundaries. Similarly, the ways that wildfires spread, or landslides move, or groundwater extraction makes wells run dry, reflect geophysical forces but may have little relationship to administrative boundaries or the flows of goods, workers, and ideas.

Subsection 2.1 discussed spatial variation in the generation of environmental externalities, such as air pollution coming out of a power plant smokestack or water pollution emitted from the discharge pipe of a chemical plant. We here discuss spatial variation in ambient environmental quality, such as the air, water, or climate that people experience. Pollution emissions can occur in different locations than ambient environmental problems both due to pollution transport, and as a result of natural conditions which affect how pollutants transform to affect ambient environmental quality. For example, reactions between nitrogen oxides (NO_x) and ammonia can form ammonium nitrate, a component of $PM_{2.5}$; and heat can interact with organic pollution in surface water to encourage the growth of oxygen-demanding bacteria, which decrease dissolved oxygen and can produce distant "dead zones" where little or no aquatic life can survive.[6]

Figure 6 maps the example of $PM_{2.5}$, which the global map on the left reveals reaches high levels across south and east Asia and northern areas of sub-Saharan Africa. In the map of China on the right, densely populated eastern regions have high industrial $PM_{2.5}$ levels, while northwestern regions have high $PM_{2.5}$ due to dust from the Gobi Desert. Both panels demonstrate that elevated levels of ambient $PM_{2.5}$ coincide with areas where emissions are high, but also appear across neighboring and downwind regions.

Figure 6: $PM_{2.5}$ in 2020

[Insert Figure 6 here]

The figure shows the distribution of ground-level $PM_{2.5}$ globally and within China in 2020 at a 1km spatial resolution. We generate the maps using data from the GlobalHighPM2.5 dataset; Appendix B provides further details.

Analysis of how pollution emissions relate to ambient environmental quality typically requires environmental models of how pollution disperses and is transported over space. Non-linearities in the functions that translate emissions of different pollutants into air quality complicate models of pollution transport. Ground-level ozone pollution (i.e., smog) provides one important example. Ozone formation is nonlinear in its precursor pollutants, NO_x and volatile organic compounds; in some cases, increasing NO_x can *decrease* ozone.

The simplest pollution dispersion models estimate or assume a radius describing how far emissions typically travel from most sources. For example, Currie et al. (2015) find that toxic air pollution from industrial plants primarily falls within a one-mile radius. A second class of pollution dispersion models uses econometric estimation to relate pollutants to areas affected by environmental damages. An example is Rabotyagov et al. (2014), which estimates the relationship between the size of dead zones; pollution sources; and currents, wind conditions, and sea temperature anomalies. A third type of pollution dispersion model, a source-receptor matrix, divides space into a grid and includes coefficients for each pair of regions describing how a unit of pollution emitted in one region affects ambient concentrations in each destination region. The Climatological Regional Dispersion Model provides an example including such a matrix for several air pollutants across about 3,000 US counties.

The fourth type of pollution dispersion model uses detailed information on meteorologi-

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[6] In many countries, dead zones due to agricultural runoff reflect a tragedy of the commons from many agricultural areas draining to a common water basin, and provide an important but underexplored interaction of space and the environment (Rabotyagov et al. 2014; Taylor and Heal 2023).

cal and geophysical processes to describe trajectories of pollution particles from any possible source. Several economic studies use the the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model to trace air pollution particle trajectories across space and time. Figure 7 shows calculations from Hernandez-Cortes and Meng (2023), which illustrates particle trajectories from an industrial facility in Los Angeles. Emissions from one plant, which may occupy less than a city block, impact air quality across much of Southern California. Such dispersion can be even more complex for water pollution, where an industrial plant emits chemicals, an aquatic ecosystem transforms those chemicals into other pollutants, a river transports pollution downstream, a drinking water treatment plant treats pollution, and pipes then distribute the water to household faucets.

Figure 7: Trajectories of air pollution emissions from one pollution source in Los Angeles, California

[Insert Figure 7 here]

Figure reprinted from Hernandez-Cortes and Meng (2023). The figure displays the spatial distribution of particle trajectories every 4 hours originating from a regulated facility during 2016, using the HYSPLIT atmospheric dispersal model.

While it is useful but rare for papers to explain why they use a particular type of pollution dispersion model, this choice often reflects the combination in a given empirical setting of the availability of existing models and requisite data, tradeoffs between desired geographic resolution and coverage, and computational feasibility.

2.3 Spatial variation in damage functions drives social welfare

The previous subsections discuss spatial variation in pollution emissions and ambient environmental quality. Here we highlight that the damages from and valuation of environmental quality also vary over space, so a given level of ambient environmental quality can produce different impacts on firms and households in different locations. Environmental quality represents levels of, for example, pollution, temperature, or natural disaster exposure, while damages refer to mortality, morbidity, productivity, crop yields, and other outcomes more directly pertinent to household utility or firm profits. The spatial patterns that translate environmental quality into damages depend on many firm, household, and regional characteristics.

Figure 8 demonstrates spatial heterogeneity in how environmental quality influences damages from climate change. Climate models predict substantial temperature increases over the coming decades, which differ by region. Panel (a) maps temperature anomalies above 1°C over the period from 2000 to 2019, relative to the mean over 1951-1980, and suggests that far northern and southern latitudes are warming the fastest. Conversely, panel (b), from Carleton et al. (2022), projects that the mortality impacts of future climate change will be concentrated in equatorial regions, with gains accruing at northern latitudes as their temperatures increase. The difference between the spatial patterns in panels (a) and (b) reflects two forces. First, temperature change has nonlinear impacts depending on baseline levels—a one degree temperature increase may create benefits in cold areas at northern latitudes, but costs in equatorial regions that are already hot. This suggests that mean temperatures may measure environmental quality inadequately, and analysis should instead consider more sophisticated measures of the shape of the temperature distributionAn additional force separates the patterns in the two figures—richer regions have more adaptive investments and capacity. For example, high-income regions may have more widespread air conditioning, resilient electric grids, or services employment that allow staff to work indoors or from home during extreme heat. Such adaptation makes welfare in these regions relatively less affected by a given temperature change.

Figure 8: Global temperature anomalies and the mortality effects of climate change

[Insert Figures 8(a) and 8(b) here in a row horizontally]

(a) Temperature anomalies in 2000-2019 relative to the 1951-1980 averages

(b) Figure IV, from Carleton et al. (2022)

Panel (a) shows a map of global temperature anomalies in 2000-2019 relative to the 1951-1980 averages generated using the surface air temperature anomaly field from the Berkeley Earth High-Resolution (Beta) dataset to compute the average number of months per year between 2000 and 2019 with a temperature anomaly higher than 1°C in absolute terms. A description of this dataset appears in Appendix B. The map in panel (b) shows estimated mortality effects of climate change, measured in units of deaths per 100,000 population, in the year 2100, from Carleton et al. (2022) [7]. All values refer to the RCP8.5 emissions scenario and the SSP3 socioeconomic scenario. The map shows the climate model weighted mean estimate across Monte Carlo simulations conducted on 33 climate models; density plots for selected regions indicate the full distribution of estimated impacts across all Monte Carlo simulations. Estimates of the mortality risks of climate change at global scale are based on a novel dataset composed of historical mortality records, historical climate data (from the Global Meteorological Forcing Dataset (GMFD), the Berkeley Earth Surface Temperature dataset (BEST) and the University of Delaware dataset (UDEL)), and future projections of climate, population, and income across the globe.

Aggregating estimated damages across groups and outcomes is challenging, and may draw on both micro-level studies of impacts on particular outcomes such as mortality and productivity, and more aggregate estimates of how the macroeconomy responds (Burke et al., 2015; Dell et al., 2012). Environmental damages may also interact across environmental goods in ways that make aggregate damages differ from the sum across individual pollutants. Bilal and Känzig (2024) highlight that the spatial scale at which damages are estimated is crucial: exploiting changes in global mean temperature yields estimated macroeconomic damages

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[7] Reprinted from Tamma Carleton et al., Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits, The Quarterly Journal of Economics, 2022, Volume 137, Issue 4, Pages 2037–2105, by permission of Oxford University Press.

from climate change that are larger than those implied by studies exploiting country-level temperature variation, which net out common impacts of global temperature through time fixed effects.

3 Canonical environmental and spatial models

The previous section discusses stylized facts describing how enviro-spatial links affect environmental and economic outcomes. This section considers the insights that canonical environmental economics models and canonical spatial economics models provide on these links. For each model, we provide a brief summary, refer readers to other references, and describe a relevant application. These canonical frameworks provide important insights on several interactions between spatial and environmental economics. Because many use only a simple concept of space, however, they leave unrealized opportunities for further progress.

3.1 Canonical pollution models

Canonical models of pollution and its regulation (Chapman, 1999; Kolstad, 2010; Phaneuf and Requate, 2017; Tietenberg and Lewis, 2024) describe firms that generate environmental damage by producing polluting goods. The marginal external cost of pollution emissions is isomorphic to the marginal willingness to pay for environmental quality. Without policy, goods production exceeds the socially efficient level. The planner can obtain socially optimal production by charging a price per unit of pollution emitted, equal to the marginal external cost of emissions (Pigou 1932). Efficient policy equates the marginal costs and benefits of pollution emissions. Cost-effective policy minimizes the cost of achieving a given level of pollution emissions or, equivalently, minimizes pollution emissions for a given cost level. Market-based policy instruments, including price instruments like Pigouvian taxes or quantity instruments like cap-and-trade markets, are cost-effective because they equate the marginal cost of pollution abatement across sources.

Standard public goods models have limited roles for space. Some extensions have a binary concept of space—a pollutant is either local or transboundary; a firm can either face local stringent regulation or move away to avoid it. Canonical approaches assume exogenous definitions of a “market,” which may reflect administrative boundaries or regions with extreme environmental problems. Spatial considerations determine the areas that many of these policies target (e.g., Greenstone and Hanna, 2014), but typical analyses of such policies otherwise have little direct role for space and geography.

Another spatial force underlying canonical environmental economic analyses is firm location choices. Many papers examine how environmental policies affect firm outcomes including sales, input demand, emissions, entry, exit, producer surplus, imports and exports, and (in fewer cases) profits. Studying these outcomes sheds some light on environmental policies' spatial impacts, but does not reveal the full spatial structure of a policy's effects. For example, if a law regulates dirty production in Delhi, do production, workers and capital relocate to suburbs, or to Mumbai, or Shanghai? Standard frameworks typically analyze regulated areas, but focus less on such spatial questions about reallocation to specific other regions. An exception is the literature on "leakage," which examines predominantly international relocation in response to regulation, discussed in Section 5.4.

Shapiro and Walker (2024) provide one example. They study a provision of the US Clean Air Act requiring that a new polluting plant which opens in a city must pay an incumbent plant in the same city, emitting the same pollutant, to decrease its emissions of that pollutant. They use price and quantity data on these decentralized bilateral transactions to compare the marginal benefits and costs of air pollution abatement. The paper concludes that in the average market, the marginal benefits of pollution abatement exceed the marginal costs more than ten-fold, suggesting that air pollution regulation in these markets is more lenient than is optimal. In some areas, however, the opposite patterns suggest that regulation may be too stringent, for instance the Houston market for volatile organic compounds. While the paper analyzes dozens of separate markets and accounts for pollution transmission across space, the analysis otherwise has no role for geography and spatial patterns of reallocation.

3.2 Natural resource models

The classic model of natural resource extraction (Hotelling, 1931) describes a single agent extracting a natural resource over time. This model describes natural resources like minerals or groundwater, where stocks and extraction paths play central roles, and is less relevant for more static environmental goods like air or water pollution. In the optimal extraction path, the resource price rises at the interest rate and the agent maximizes the resource's present value. Common extensions to this classic model account for recharge,[8] resource discoveries, innovation, common pool versus monopoly extraction, institutions to govern commons resources, and other realistic features of natural resource management (Fisher, 1981; Peterson and Fisher, 1977).

Resource models interact with spatial economics in several ways, though few resource papers analyze them. Because resources like oil and groundwater are heterogeneously distributed over space and affect local patterns of production, spatial differences in extraction

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[8] Recharge or renewal of natural resources could include forests growing, fish spawning, or rainfall filling an underground aquifer.

paths will affect outcomes of regional economies and patterns of inter-regional trade. Extraction paths of resources like forests, wetlands, and land quality within a region affect migration between rural and urban areas and locations where land is developed. Additionally, interest rates, resource discoveries, innovation, institutions, and resource ownership structures all vary over space and influence both optimal and actual extraction paths.

To give one example, Timmins (2002) studies groundwater extraction from 13 California municipalities. Using market data and accounting estimates of extraction costs, the analysis estimates both static supply and demand parameters, and the parameters of a dynamic model of resource extraction. The paper estimates deadweight loss of about $110 per household per year (1995 dollars) due to inefficient extraction chosen to achieve unknown political objectives. While separate parameters are estimated for each municipality, there are not geographic relationships between different municipalities, or interactions between their decisions.

3.3 Hedonic models

The classic hedonic model (Rosen, 1974) describes equilibrium in the space of product characteristics. A sample of environmental reviews and applications includes Bajari et al. (2012), Banzhaf (2021), Bishop and Timmins (2018), Bishop et al. (2020), Chay and Greenstone (2005), Davis (2004), Greenstone (2017) and Greenstone and Gallagher (2008). A continuum of consumers in a single market each purchase one differentiated good (e.g., a house), which is fully described by its vector of attributes (e.g., number of rooms, air quality, or quality of local schools). Consumers are fully informed and choose the good which maximizes utility. A consumer's bid function describes isoutility in the space of products and prices. For example, a consumer may prefer a house with less pollution, but such a house sells at a higher price. A consumer's bid function depends on attributes like education and age which shift consumer preferences. Each firm has an offer function describing its isoprofit curve in the space of products and prices. For example, a firm can build a more energy efficient home, but at greater cost. All firms are perfectly competitive and each produces output of given characteristics at constant cost. The hedonic price function describes the market equilibrium price as a function of attributes.

The hedonic model provides an econometric strategy to estimate the marginal willingness to pay for product attributes including environmental quality since, for the product a consumer chooses, the hedonic price function is tangent to the consumer's bid curve. Thus, knowing the slope of the hedonic price function provides information on the slope of the consumer's indifference curve, and makes it possible to estimate marginal implicit prices for product attributes. This has broad applicability in environmental economics because so many environmental goods vary across space within a market. Numerous studies apply the model to housing units within a market in order to estimate preferences for local public goods including environmental quality (e.g., Barwick et al., 2018; Burke and Emerick, 2016; Davis, 2011), often accounting for a home's distance from pollution sources, or environmental amenities within a certain radius. Research has explored many applications, including the amenity value of environmental quality and the value of a statistical life (Viscusi and Aldy, 2003). While the hedonic model is probably the most common framework in environmental economics with a continuous concept of space, spatial links between goods or regions are typically not the focus.

An interesting example is Currie et al. (2015), which estimates how openings and closings of plants that emit toxic pollution affect ambient air pollution concentrations, local real estate prices, and infant health. They find effects on all three outcomes within a one-mile radius; the home value impacts represent a \$4.25 million cost to local residents. While this analysis accounts for local geographic movement of toxic pollution, a metro area like Los Angeles has dozens to hundreds of toxic plants, and their openings and closings may also affect commuting, goods transportation, social interactions, and other spatial forces.

3.4 Classic spatial equilibrium models

While Rosen (1974) studies a single market (land), Roback (1982) adds a second dimension and describes the equilibrium across markets in labor and land. Rosen and Roback models allow the environment to affect both household utility and firm productivity, but Roback allows wages to equilibrate, so is well suited for comparisons across labor markets. Reviews and applications of this classic spatial model include Diamond (2016), Gyourko et al. (1999), Hornbeck and Moretti (2024), Moretti (2004), Notowidigdo (2020) and Shapiro (2006). Homogeneous firms and workers choose one city among many in which to locate. A worker resides and works in the same city. Each city has a wage rate, rental rate for land, and amenities, which can affect worker utility and firm productivity. Workers maximize utility, which depends on land and a numeraire final good; firms minimize costs subject to an output constraint. Workers and firms demand land. In a competitive equilibrium, worker utility is equalized across cities. Although one city may provide better amenities, its higher land values or lower wages make consumers indifferent to relocating there.

This model implies that the marginal willingness to pay for a residential amenity equals the marginal effect of the amenity on land values, multiplied by land's share of consumer costs, plus the marginal effect of the amenity on wages. Many studies use this relationship to estimate the demand for environmental and other amenities. As with the hedonic model, the main insight from Roback models for the concepts in the basic environmental model is therefore its contribution to estimating marginal willingness to pay for environmental goods (e.g., Albouy, 2008; Albouy et al., 2016). The Roback model allows for analysis of many housing markets, some quantification of agglomeration externalities, and effects of environmental externalities operating through both wages and land values. In this sense, Roback models allow for additional spatial environmental insights relative to the classic environmental economics and hedonic models.

These models, however, assume national markets in goods and workers, and differ from the richer models discussed below in assuming frictionless transportation of goods and people. Roback (1982) has other strong assumptions for spatial environmental purposes. For example, the assumption that workers are homogeneous precludes analysis of the fact that workers with asthma may experience greater disutility from air pollution; and workers with skills in heavy industry may have comparative advantage to work in high-paying, fossil fuel-intensive regions like the tar sands in Fort McMurray, Alberta or the West Siberian petroleum basin.

Albouy (2016) provides an illustrative example of the application of Roback models to spatial environmental issues. The paper analyzes how climate and other amenities affect land values and wages across a large set of metro areas, then uses these estimates to construct quality of life indices to rank cities. The analysis finds that productivity accounts for a larger share of inter-city differences in wages and land values than amenities. The analysis includes many cities, though does not analyze spatial relationships between or within cities.

3.5 Richer spatial equilibrium models

Equilibrium sorting models typically focus on household choices of where to locate across neighborhoods. Demand can be a flexible function of local characteristics including employment opportunities and exogenous and potentially endogenous amenities, which may include environmental goods. Reviews and applications include Bayer and Timmins (2007); Epple and Sieg (1999); Ferreyra (2007), and Kuminoff et al. (2013). In such models, estimation of household preferences may build on equilibrium properties of the hedonic model (Ekeland et al. 2004). Applications often focus on one metro area and may hold the housing stock and employment opportunities as given. Barwick et al. (2024b), for example, study transportation policies in Beijing, and find that combining congestion pricing with subway expansion maximizes benefits of intra-city transportation reform.

Quantitative spatial equilibrium models provide a more recent framework. Like Roback, these models account for land and labor markets, and allow the environment to affect household utility and firm productivity. Unlike Roback, these models can incorporate high-resolution geography (e.g., maps of the locations of homes, neighborhoods, and regions relative to one another) and account for migration, commuting and goods markets. Many quantitative spatial equilibrium models build on trade frameworks (e.g., Eaton and Kortum (2002)) by assuming that technology follows a Frechet distribution, preferences are constant elasticity, frictions have iceberg form, and households have limited heterogeneity.

While these models have more markets and mechanisms so are not trivial to learn and work with, helpful reviews and applications include Behrens and Murata (2021); Dingel and Tintelnot (2020); Duranton and Puga (2020); Fajgelbaum and Gaubert (2020); Heblich et al. (2020); Redding and Rossi-Hansberg (2017), and Redding (Forthcoming)'s chapter in this handbook. The basic structure of these models, described in Redding and Rossi-Hansberg (2017), involves assumptions over preferences for goods (which can account for product differentiation, distinctions between industries and local amenities); the technology for goods production (which includes assumptions about market structure, levels and sources of productivity differences, and input-output links); spatial frictions for moving goods, ideas, and people; and factor endowments and their spatial mobility. Applications often study a competitive equilibrium, as well as counterfactual equilibria under alternative policies. Dynamic branches of this literature help to study capital goods, migration costs, and other dynamic forces relevant to the environment.

Quantitative spatial equilibrium models accommodate spatial heterogeneity in local characteristics and complex links between regions, as a result of which they are well placed to address environmental questions. Theory and data for these frameworks are developing rapidly, and research has begun to explore how these models interact with environmental economics.

Many researchers use quantitative spatial equilibrium models to infer amenity and productivity values for each location which are consistent with observed data and estimated parameters. Amenities can reflect environmental and other local public goods and bads. While some studies consider the correlation between model-implied amenities and local environmental characteristics such as pollution, climate, and green space (e.g. Bryan and Morten, 2019; Desmet et al., 2018), few quantitative spatial models analyze environmental quality data in detail. Additionally, few applications consider the links between environmental goods and other local characteristics, including productivity and congestion forces. Congestion externalities play important roles in prominent spatial papers and may implicitly reflect environmental disamenities including pollution, waste disposal and noise, especially important in urban areas of developing countries and historical developed country cities.

A recent strand of the spatial equilibrium literature analyzes the implications of climate change for local characteristics and spatial outcomes. Given that climate change is likely to shift comparative advantage across space, sectors, and products, research has studied channels by which general equilibrium adjustments may influence the impacts of climate change, including migration (Conte et al., 2021), crop production choices and trade (Costinot et al., 2016), and sectoral reallocation (Nath, Forthcoming). Dynamic approaches have also helped project long-run impacts of temperature changes on productivity and amenities; sea level rise on land availability; severe storms on capital depreciation; and how adaptation via dynamic adjustments of migration, trade, innovation and natality rates may influence the aggregate and distributional costs of climate change (Bilal and Rossi-Hansberg, 2023; Conte et al., 2021; Cruz and Rossi-Hansberg, 2024; Desmet et al., 2021; Rudik et al., 2022).

These models can also help in studying interactions between environmental damages and infrastructure investments. Hsiao (2023) studies how investment in protective infrastructure such as sea walls may complicate long-run adaptation to climate change by creating coastal moral hazard. Balboni (2025) considers how accounting for the dynamic costs of sea level rise changes the returns to transport infrastructure investments in Vietnam, finding that investment in coastal areas has considerable static benefits, but that accounting for future sea level rise favors greater inland investment. Beyond dynamic applications to climate change, Kline and Moretti (2014)'s analysis of how the Tennessee Valley Authority's large regional investment in energy and related infrastructure affects long run regional development demonstrates another avenue of dynamic spatial environmental research.

4 Building blocks in enviro-spatial analysis

This section discusses building blocks for theoretical and empirical papers at the frontier of spatial environmental economics. Existing reviews discuss choices in writing an environmental paper, or choices in writing a spatial paper. While it is challenging to specify which components of environmental research should be spatial, and which components of spatial research should be environmental, we focus this and the next section on issues missing from many papers where we think that spatial environmental frameworks may provide particular insight. We discuss three areas: general analysis frameworks, households, and firms. Section 5 builds on this section by considering geography, inter-regional links, and environmental spatial policy. Each area provides an overview, reviews existing approaches, presents novel evidence, and discusses open questions and promising opportunities for future research.

4.1 Environment for studying the environment

This subsection discusses general frameworks for analysis, including the choice of social planner, the role of distributional considerations, and dynamic assumptions.

4.1.1 The choice among planners

Analyses of spatial environmental economics may take the perspective of a local, regional, national, or global planner. Comparing these perspectives can alter welfare conclusions and clarify political economy forces.

Different regions' planners have different perspectives on many intra- and inter-jurisdictional environmental externalities. Surface water pollution increases at inter-jurisdictional boundaries or upon decentralization, potentially because jurisdictions emit pollution near downstream or downwind boundaries, and reflect preferences of local but not national or global planners (Lipscomb and Mobarak, 2016; Sigman, 2005; Wang and Wang, 2021). The asymmetry between a national planner's perspective on industrial policy and a global planner's perspective on climate benefits can help explain tensions underlying international discussions of coordinated green subsidies. For example, for green industrial policies like the US Inflation Reduction Act's electric vehicle tax credits, where policymakers designed the policy to encourage domestic vehicle supply chains and support domestic manufactures, should national welfare analysis treat foreign and domestic producer surplus symmetrically (Allcott et al., 2024)? Similar questions apply to states or provinces competing to attract clean energy firms.

Climate change policy provides a broader example where the choice between planners can affect conclusions. A central concept in measurement of the external cost of greenhouse gas emissions is the "social cost of carbon"—the effect of one metric ton of carbon emissions on damages through all pathways (human health, agricultural yields, etc.) in all regions and future years, discounted to the present. A region's *national* social cost of carbon represents damage to the region's current and future residents. Some countries use the global rather than national social cost of carbon in policy analysis, in part because this may encourage cooperative outcomes for global climate policy (Kotchen, 2018). This decision is not universal; for example, the first Trump Administration revised the social cost of carbon used for US policy analysis to the national rather than global value (Aldy et al., 2021). Figure 8b in Section 2 demonstrates some variation that drives spatial differences in the national social cost of carbon—poor equatorial regions will suffer large costs due to acute impacts of climate change. Rich countries also have a high national social cost of carbon, despite lower proportional damages. For example, Table A2 highlights estimates from Ricke et al. (2018)

of a national social cost of carbon of \$55 for India, \$44 for the US, \$20 for China, and -\$10 for Russia.[9]

In settings involving multiple jurisdictions and planners, it is valuable, though uncommon, for research to discuss and analyze the perspective of different social planners. When environmental externalities cross jurisdictional boundaries, or when firm or consumer profits accrue to regions outside a single jurisdiction, the welfare analyses of municipal, regional, federal, or global planners may differ. Analyses that explain and quantify the implications of these differences for social welfare or optimal policy could help to illuminate the design and political economy of spatial environmental policies.

Welfare analysis must also determine whether the discount rate applied to future years should vary across regions. Discount rates have enormous importance for valuing long-lived natural resources like forests, groundwater, or climate, where a large share of value may occur far in the future. Economists have long debated whether analysts should use market interest rates or normative rates (Ramsey, 1928) for such goods (Gollier and Hammitt, 2014; Goulder et al., 2012a; Nordhaus, 2007). For spatial analyses, market and normative discount rates can differ across regions depending on growth rates, financial development, risk, and other economic fundamentals. Addicott et al. (2020), for example, calculate a Ramsey discount rate of 10.6 percent for India but 4.0 percent for France.

4.1.2 Inequality and the distribution of environmental outcomes

Spatial environmental economics research must decide whether and how to report positive or normative analysis of environmental inequality and its interaction with inequality of income and other outcomes. Levels of many environmental goods differ between households of different income, race, and other characteristics.

Figure 9, panel (a), compares each country's mean level of $PM_{2.5}$ exposure to log GDP per capita. On average, richer countries have lower air pollution, though there is wide dispersion. Some countries like India and China have more pollution than their GDP per capita would predict, while others like Sweden have less. Similar comparisons within regions or countries reveal nonlinear relationships. Panel (b) plots the same relationship across 1 km cells within several countries and regions. In many areas, this relationship also slopes downwards, especially at higher income levels. The US has a somewhat inverted U-shaped relationship between ambient $PM_{2.5}$ and GDP per capita, reminiscent of the Environmental Kuznets Curve (Copeland and Taylor, 1994; Grossman and Krueger, 1993). Appendix Figure

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[9] These numbers describe the Ricke et al. (2018) prediction for Shared Socioeconomic Pathway 1 and Representative Concentration Pathway 60, with a \$305 global social cost of carbon. They project that climate change will benefit Russia due to Russia's cold temperatures today.

A4 presents maps showing the distribution of GDP per capita and $PM_{2.5}$ within the US, EU and China, which illustrate the spatial patterns driving these correlations.

Figure 9: $PM_{2.5}$ versus GDP Per Capita

[Insert Figures 9(a) and 9(b) here in a row horizontally]

(a) $PM_{2.5}$ in 2020 and GDP per capita in 2020 at the global level

(b) $PM_{2.5}$ in 2020 and GDP per capita in 2020 within selected countries

Panel (a) displays a scatter plot of the average person's $PM_{2.5}$ exposure against GDP per capita for each country. Panel (b) presents a binned scatter plot, using quantile-based binning, to illustrate the same relationship within countries—specifically China, the European Union, India, Kenya, the United States, and other non-EU G20 nations. $PM_{2.5}$ exposure for the mean person is given by the population-weighted concentration of $PM_{2.5}$ at the cell level, measured at a 1 km spatial resolution. It is calculated by weighting the ground-level $PM_{2.5}$ concentration in each cell by its population density divided by the total population density across the country or region. $PM_{2.5}$ data are from the GlobalHighPM2.5 (Global High-resolution and High-quality Ground-level $PM_{2.5}$ Dataset over Land) dataset, which combines ground-based measurements, satellite data, and model simulations. Population data are from the GHS-POP (R2023) (Global Human Settlement Layer Population Grid) dataset, which provides high-resolution residential population distribution. GDP figures come from the Global Gridded GDP (Global Gridded GDP under Historical and Future Scenarios, Version v7) dataset, which provides annual global GDP data on a 1 km grid. Recreating the binned scatter plot in Panel (b) using $PM_{2.5}$ data from the van Donkelaar et al (2021) 'Monthly Global Estimates of Fine Particulate Matter and Their Uncertainty' dataset yields similar results; see Appendix Figure A3.

Banzhaf et al. (2019) review the large and growing literature in environmental economics on environmental quality gaps across social groups. This literature examines many different environmental goods and spatial scales, and finds pervasive relationships between locations with vulnerable populations and locations with high exposures to environmental hazards. Environmental Justice is one of the few areas where environmental applied microeconomics research consistently gives geography a central role. Heblich et al. (2021) provide one nice example of how environmental patterns affect inequality through spatial pathways—because the wind in many cities blows to the east, the east sides of many cities have greater pollution. Over several decades, this has increased concentrations of low-income populations. Environmental quality gaps between urban and rural areas, and between cities, can drive urbanization, change aggregate exposures to environmental externalities, and interact with other forces influencing urbanization that have a growing role in determining quality of life, especially in developing countries (Bryan and Morten, Forthcoming).

Environmental inequality has a large and growing role in driving spatial environmental policy. Concerns about how environmental policies would affect environmental inequality generated strong opposition to a carbon tax bill in Washington state, may imperil renewal of California's AB32 carbon cap and trade market, and are an increasing focus of the OECD's discussion with environmental policymakers (Shapiro, 2022). Douenne and Fabre (2022) highlight how beliefs about the distributional impact of carbon taxes shape their political economy, finding that French people would largely reject a tax and dividend policy following the country's Yellow Vests movement. Motivated by these concerns, several papers investigate whether market-based environmental policy instruments produce a different distribution of environmental outcomes across space and demographic groups than traditional command-and-control instruments (Fowlie et al., 2012; Hernandez-Cortes and Meng, 2023; Shapiro and Walker, 2021).

Spatial research can provide both positive and normative analysis of environmental inequality. Much positive analysis compares environmental quality to income, race, or other measures of inequality. For example, Currie et al. (2023) show that predominantly Black US communities have higher $PM_{2.5}$ air pollution exposure than white US communities, and that this gap has declined over time, in part due to the US Clean Air Act's nonattainment designations. Normative spatial analysis of environmental inequality has received less attention – partly due to uncertainty over how inequality enters the planner's decision-making – though does play a role in some studies of climate change damages across countries (e.g., Anthoff and Emmerling, 2019).

4.1.3 Dynamics

As discussed in Section 3, enviro-spatial analyses typically focus on environmental more than natural resource goods. One possible explanation is that exhaustible or renewable resources often involve dynamic forces which complicate models and data. Existing enviro-spatial analyses of natural resources deal with these dynamic issues using a few approaches, each with its own strengths.

Fully dynamic frameworks specify assumptions about agents' information and expectations, as well as stocks, flows, depreciation, recharge, investment, and other dynamic forces, and solve each agent's problem using dynamic programming or related tools. Dynamic analysis may look at a single-agent problem, like a representative agent drawing down a natural resource; or a multi-agent problem, like a tragedy of the commons where several agents are strategically extracting the resource. These frameworks typically require detailed model assumptions and many parameters, but have flexibility to analyze a range of counterfactual scenarios. Computation creates one challenge in such settings, given the high dimensionality needed to study many locations in space, and aggregate uncertainty where environmental goods can generate aggregate shocks, for which machine learning tools may be helpful (Sun, 2024). At the other end of the spectrum, static models of resources add a parameter or moment summarizing critical information from the dynamic aspects of a problem, for instance a parameter representing the marginal value of the resource to future time periods. Hybrid approaches analyze a multi-period problem with interactions across periods but simplify the fully dynamic problem by invoking assumptions such as agents that are partially myopic or that make optimization errors.

The example of groundwater aquifers helps illustrate these tradeoffs. Fully dynamic models like Gisser and Sanchez (1980) solve a dynamic programming or optimal control problem to recover optimal policy and losses from prevailing extraction. Other approaches use a static production function to assess how water affects output, but incorporate a Lagrange multiplier from a dynamic problem solved elsewhere to summarize the dynamic externality that resource extraction in one period increases extraction costs in future periods (e.g., Ryan and Sudarshan, 2022). Intermediate solutions account for increasing extraction costs using a comparative static, spatial equilibrium model (Carleton et al., 2024).

Although natural resources provide one rationale to invoke dynamic forces, dynamic responses to climate change and other environmental shocks provide another. Section 3.5 discusses a recent literature drawing on dynamic quantitative spatial equilibrium models to study climate change impacts and adaptation. Household mobility frictions are also important for studying migration and housing responses to environmental shocks, and dynamic analyses provide one natural way to study them (Bayer et al. 2016).

4.2 Households

This subsection discusses another core element of spatial environmental economics research—spatial aspects of household preferences for, and information about, environmental goods.

We motivate this discussion using two examples of variables related to household demand for environmental goods in the US, shown in Figure 10. Panel (a) shows estimates of the marginal damages from emitting $PM_{2.5}$. The map shows enormous variation across US counties, driven by population density and wind patterns, with the highest values in Southern California, Chicago, and the Northeast Corridor. Globally, such differences aggregate to have vast welfare implications. Greenstone et al. (2022a), for example, estimate life expectancy gains from reducing $PM_{2.5}$ levels to World Health Organization standards of three years in Beijing and six years in New Delhi, but under half a year in US and European cities. Panel (b) shows the market share of another important environmental good that households choose – electric vehicles as a share of all new light duty vehicles – which are highest in coastal California, the Pacific Northwest, and scattered other urban areas.

Such maps raise several important questions. How do marginal damages of pollution or market shares of clean goods relate to utility and marginal willingness to pay? Why does demand for environmental quality and environmental goods vary widely over space? What do these spatial patterns imply for optimal policy design, and what microfoundations drive these patterns?

Many models of environmental goods abstract from direct impacts on utility and focus

Figure 10: Spatial Variation in Marginal Damages and Choices of Environmental Goods

[Insert Figure 10(a) here]

(a) Marginal $PM_{2.5}$ damages, by US county

[Insert Figure 10(b) here]

(b) Electric vehicle shares, by US county

Panel (a) shows marginal damages of $PM_{2.5}$ emissions in each US county, generated using replication data from Holland et al. (2016). Panel (b) shows electric vehicle market share of new light duty vehicles in the year 2022, sourced from the U.S. Department of Energy and based on data from Yip (2023), National Renewable Energy Laboratory.

on how they affect output. The choice of whether and how to model the impacts of environmental goods on productivity or utility influences predictions about the spatial distribution of climate damages and economic outcomes. A recent literature has considered a wider range of environmental goods' impacts on mortality, morbidity, natality, and mental health, which have clear links to utility.[10] Impacts on health outcomes such as these may be highly localized in space (Currie and Walker, 2011) and interact with other local characteristics such as the disease environment (Hanlon, 2024). Models of the utility impacts of environmental goods may assume preferences that are a function of emissions, ambient environmental quality, or health (Freeman et al., 2019; Gao et al., 2023; Pan, 2023; Shapiro, 2016).

An important question with limited evidence is the extent to which observed behavior in relation to environmental goods reflects individuals' true preferences versus imperfect information about levels of environmental amenities and their impacts on well-being. Existing evidence suggests that households do have some information about pollution levels (Peng et al., 2018; Poor et al., 2001), but that this information is incomplete, since household behaviors and outcomes can change substantially due to objective information on pollution or pollution damages (Barwick et al., 2024a; Baylis et al., 2023; Greenstone et al., 2022b). Incomplete information, along with behavioral distortions that may be especially pertinent in environmental economics (Shogren and Taylor, 2008), might therefore render neoclassical estimates of environmental valuations and damages misleading. Even if all households have the same incomplete information about environmental goods, household sorting can make information incur unequal costs across demographic groups (Hausman and Stolper 2021).

Access to defensive, avoidance, or adaptive investments that decrease the costs of environmental problems varies widely across space (Carleton et al., 2022) and influence spatial estimates of environmental preferences. These can include technologies like air conditioning

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[10] A partial list of papers here includes Alexander and Schwandt (2022); Barrage (2020); Barreca et al. (2018); Bishop et al. (2023); Bressler (2021); Chen et al. (2024); Cruz and Rossi-Hansberg (2024); Deryugina et al. (2019); Ebenstein et al. (2017) and Persico and Marcotte (2022).

and asthma inhalers, mobility decisions like where to live or whether to work from home, and investment decisions like seawalls and cooling centers. A common approach to valuing environmental damages assumes that utility reflects personal environmental quality, which depends on collective environmental quality and defensive expenditures. For example, quiet is a function of noise and noise insulation; individuals near loud construction may suffer utility (and hearing) losses due to the decibel level of nearby heavy machinery, but can also purchase earplugs. Analysis can help learn the value of a marginal increase in personal environmental quality from the marginal cost of achieving it via defensive expenditures, assuming that households make optimizing decisions in choosing between investing in defenses versus suffering the direct costs of externalities (Deschenes et al., 2017).

Research devotes limited attention to the microfoundations underpinning household demand for environmentally-friendly goods and its spatial variation, like electric vehicles shown in Figure 10, panel (b). Demand for goods such as green electricity, eco-friendly cleaning products, or organic food could reflect preferences for the quality of these goods, warm glow motives, or the signaling value of conspicuous green consumption (Delgado et al., 2015). Other recent work finds substantial heterogeneity in public support for climate compensation and investment, linked to vulnerability to both climate change and climate policy (Gaikwad et al., 2022). Variation in all of these forces may have an important spatial component, but is complex to quantify systematically.

4.3 Firms

We organize this discussion into three areas: theoretical assumptions about pollution emissions and abatement; impacts of the environment on firms; and impacts of firms on the environment.

4.3.1 Assumptions about emissions and abatement

Research usually takes one of three approaches to model firm emissions and regulation. The simplest assumes that emissions e from any source in industry i equal a fixed coefficient ϕ_i times output q_i:

$$e_i = q_i \phi_i \tag{1}$$

For example, Caliendo et al. (2024) describe an industry's carbon intensity as a fixed function of its unit output. The fixed emissions assumption has the advantages of parsimony and relatively simple calibration and measurement. It may be most useful for estimates of how reallocating production across industries affects emissions in settings with fixed technology. It can also measure the CO_2 emissions from production of fossil fuel varieties, since pollution abatement technologies like carbon capture and sequestration are costly and rare. At the same time, the fixed proportions assumption in (1) abstracts from endogenous pollution control or changes in production technology, so provides less flexible descriptions of settings with changing environmental policy like domestic carbon taxes. Across regions within a country, the fixed proportions approach may not fully capture environmental differences across space, because larger cities tend to have more productive plants and tighter environmental regulations. Thus, equation (1) can capture the scale effect for cities (via which they emit more pollution), and also the composition effect (via which they specialize in different industries), but may miss the technique effect, which can change pollution per unit of output within an industry across regions. Equation (1) also abstracts from variation in pollution emission rates across space due to use of different inputs, especially fossil fuels.

A second approach assumes that firms generate a baseline level of pollution but can invest valuable factors, inputs, or outputs in an abatement technology $a \leq 1$ which decreases emissions:

$$e_i = q_i \phi_i a_i \tag{2}$$

Abatement a_i may be an endogenous function of labor or other inputs dedicated to abatement rather than to producing output. For example, Copeland and Taylor (2004) and Shapiro and Walker (2018) use a functional form for a_i which implies that output is Cobb-Douglas in factors and pollution. The abatement approach typically specifies distinct production technologies for pollution and for output. Firms require some reason for investing in abatement, otherwise they would allocate all resources to producing and selling output rather than to abating pollution. A common approach assumes that firms face environmental policy which either requires abatement or charges firms a price for each unit of pollution they emit.

The abatement approach in (2) requires more detailed assumptions than the fixed proportions approach in (1), involving the structure of the pollution emissions and abatement technologies, captured by a_i. This formulation may be appropriate for air and water pollution, where emission rates depend on a complex and hard-to-specify function of inputs, and where widely used end-of-pipe abatement technologies like scrubbers, selective catalytic reduction, and tertiary wastewater treatment can decrease pollution emission from a given unit of output by over 90 percent. This abatement formulation is less natural for analyzing environmental policies that change CO_2 emissions, since most CO_2 emissions equal a deterministic function of fossil fuel inputs, which can change in counterfactual scenarios. Because this abatement formulation typically abstracts from fossil fuel markets, it also abstracts from the possibility that decreasing coal consumption at one plant could increase coal consumption elsewhere. Additionally, it abstracts from the trade effects of changing fossil fuel demands, and misses global fossil fuel supply and price effects of policy reforms.

Compared to the fixed proportions assumption in equation (1), the abatement approach in equation (2) provides an additional margin to capture spatial variation in environmental policy and polluting inputs across regions within a country. At the same time, the abatement formulation in (2) is less well suited to study the contributions of different inputs within an industry to spatial patterns in emissions, which is most relevant for analyzing greenhouse gas emissions. For example, electricity generation in Eastern Europe generates greater CO_2 emissions per kWh than electricity generation in Western Europe does, due to coal's greater share of inputs in Eastern Europe.

A third approach to modelling emissions and abatement explicitly describes markets for inputs and their impacts on an establishment's emissions. A given unit of a specific fossil fuel may generate a constant emissions rate, as in (1), or the emissions rate ϕ_{fl} for fuel f may differ across extraction location l. For example, Farrokhi and Lashkaripour (2024) describe an industry's physical emissions rate as reflecting its endogenous energy cost share. This approach captures spatial variation in emissions driven by the choice of fossil fuels, or differences in environmental regulations that effectively price fossil fuels. For example, it recognizes that manufacturing in West Virginia generates more CO_2 than manufacturing the same good in Washington state, due to West Virginia's more abundant coal. It can also distinguish petroleum from Alberta's tar sands in Canada, which requires high levels of CO_2 to extract, versus petroleum from the Bakken formation in Saskatchewan and Manitoba, which requires less. This approach is less realistic for local air or water pollution, where end-of-pipe abatement plays a more central role and it is challenging to precisely relate emissions to a firm's inputs.

4.3.2 Impacts of the environment on firms

Environmental quality provides an input to firm production and can affect productivity. One strand of literature uses this feature of environmental goods to help measure the demand for environmental quality (Freeman, 2003). To give a few examples, air pollution and extreme heat decrease labor productivity; microchip and soda production requires clean water; ground-level ozone air pollution decreases agricultural yields; and acid rain and natural disasters depreciate capital stocks (Adhvaryu et al., 2022; Aragón et al., 2017; Bilal and Rossi-Hansberg, 2023; Boone et al., 2019; Chang et al., 2016; Keiser and Shapiro, 2019; Restout et al., 2024; Rode et al., 2022; Saiz, 2010; Somanathan et al., 2021). Because levels of these environmental goods and their marginal impacts on firm outcomes differ across space, such environmental inputs affect the spatial structure of economic activity. For example, historical evidence from British cities suggests that local air pollution reduced long-run city employment and population growth (Hanlon, 2020).

Natural disasters and adaptation to their effects also change the spatial structure of firm activity. Floods, hurricanes, wildfires, drought, blizzards, and extreme pollution decrease output and productivity of the firms that these disasters hit. Effects also propagate upstream and downstream along supply chains, and potentially through vertical and horizontal firm ownership networks (Barrot and Sauvagnat, 2016; Boehm et al., 2019; Carvalho et al., 2021). Firms may respond to the risk of such disasters, for instance by re-organizing production across their networks of plants and by shifting sourcing towards suppliers located in less flood-prone regions or reached via less flood-prone routes (Balboni et al., 2024; Castro-Vincenzi, 2024; Pankratz and Schiller, 2024).

Two environmental factors of production particularly affect the spatial structure of production—land and energy resources. Agricultural productivity depends heavily on land quality, which varies considerably across space. Land quality also influences agriculture's impacts on a wide range of environmental outcomes (Costinot et al., 2016). For example, hydric soils tend to form wetlands, which mitigate floods and purify water to downstream areas. Mass conversion of areas with hydric soils from wetlands to crop cultivation and other land uses, via constructing drainage infrastructure such as ditches, canals, culverts and pumping systems, increases flood damage in downstream areas (Taylor and Druckenmiller, 2022). Logging forests increases output in timber-dependent industries, which can support local economic production, though can also undermine environmental objectives including carbon sequestration, biodiversity, and watershed preservation (Balboni et al., 2023; Hsiao, 2024).

The extraction of energy resources also affects the spatial structure of production. Fossil fuel extraction underpins regional and national economies in many parts of the world. Addressing climate change requires slowing fossil fuel extraction. The costs of extracting fossil fuels, and the associated economic impacts of decarbonization policies, differ across fuels and locations and are important to macroeconomic models of climate change (Arkolakis and Walsh, 2023; Cruz and Rossi-Hansberg, 2024; Welsby et al., 2021). Natural endowments crucial to renewable energy generation, such as solar radiation or wind, also differ greatly across space and affect patterns of local economic production.

4.3.3 Impacts of firms on the environment

Several aspects of firm production change the spatial distribution of environmental quality. Returns to scale in production, product differentiation, input-output links, sunk costs, and market power all generate interactions between the spatial distribution of economic activity and environmental quality.

Plant-level returns to scale drive spatial patterns of output for some polluting industries, many with large plant sizes and capital-intensive investments. In the classic proximity-concentration hypothesis across countries (e.g., Brainard, 1997), firms trade off the productivity of having a few large plants that benefit from returns to scale versus having many smaller plants located closer to customers. Environmental considerations add other dimensions to this tradeoff, both within and across countries. Firms may prefer to have a few large plants located near population centers to benefit from returns to scale, but locating near population centers increases the marginal damages of pollution (since more people breathe or drink a plant's pollution) and may expose plants to stricter environmental regulations. For example, cement production creates the second-largest source of industrial greenhouse gas emissions (behind electricity), emits enormous levels of local pollutants, uses among the largest pieces of industrial machinery in the world (cement kilns), and has high estimated establishment-level increasing returns (Ganapati et al., 2020). Decisions on cement plant size and location may consider not only common variables like access to skilled workers, proximity to customers, and factor costs, but also strictness of environmental policy and the magnitude of environmental damages to local populations, which may be manifested through environmental policy or Coasian bargaining with neighbors. Increasing returns at the equipment level have less clear environmental and spatial consequences. For example, electricity generated by windmills increases in a quadratic function of turbine size, which has led to increasingly large windmills (Covert and Sweeney, 2024), but the size of a wind power plant may matter more for local pollution, land use, or economic activity than the size of an individual wind turbine.

Learning by doing – a form of dynamic returns to scale at the plant, firm, country×industry, or industry level – substantially affects productivity and location choice in energy industries like fracking, wind, and solar. This produces spatially divergent energy investments, depending partly on where natural resources and technology support energy industries, and where pipelines, tankers, and transmission lines can economically transport energy to reach demand (Arkolakis and Walsh, 2023; Davis et al., 2023; Gonzales et al., 2023). Policies encouraging new energy technologies also vary over space due to political economy or distributional concerns. For example, many US Inflation Reduction Act investments subsidize "energy communities," defined as areas that depend disproportionately on certain measures of energy. National and regional manufacturing subsidies substantially shape the location of this production (Banares-Sanchez et al., 2023).

Spatial product differentiation matters relatively more for dirty than clean industries, and differentiation in other product attributes matters relatively less. Many dirty goods like cement, steel, concrete, and coal are disproportionately homogeneous as measured by estimated elasticities of substitution, and have less product differentiation than clean goods. The homogeneity partly reflects the fact that energy-intensive goods are modestly-transformed elements of the periodic table, which have identical molecular structure across the planet. On the other hand, spatial differentiation – local markets for goods with high transportation costs – matters relatively more for polluting industries, which have high weight-to-value ratios and elasticities of substitution (Shapiro, 2023).

Spatial markets for dirty goods also have complex interactions with transportation markets. One interesting example comes from US low-sulfur coal, which is concentrated in the Powder River Basin around Montana and Wyoming. Although the US Clean Air Act increased power plants' demand for low-sulfur coal, because coal is relatively inexpensive to transport overland by rail, Busse and Keohane (2007) find that railroads used market power to capture much of the surplus from the additional demand for low-sulfur coal. In another example, although pipelines provide a durable and cost-effective means to transport crude oil overland, changing political and economic logic behind pipeline investments have led North American crude oil from fracking to increasingly use rail transportation, which changes the environmental externalities and economics of oil extraction (Covert and Kellogg, 2023).

Input-output links can have a strong influence on the spatial economic and environmental impact of polluting industries.[11] Dirty goods are disproportionately upstream, using Antràs et al. (2012)'s or simpler measures of upstreamness, as they disproportionately supply firms rather than final demand (Copeland et al., 2022; Shapiro, 2021). Trade costs give an incentive for downstream firms to locate near their upstream suppliers. For example, many US and European manufacturing establishments justify moving production to Asia by citing the nearby availability of suppliers and customers, including dirty industries. Another topical example is cryptocurrency mining. While the computers that complete cryptocurrency mining themselves emit essentially no air pollution, they demand large amounts of upstream electricity. Some cryptocurrency mining operations locate in Iceland, with clean and inexpensive electricity; others locate near dirty (coal) and inexpensive electricity. Papp et al. (2023) find that the environmental costs of one particularly dirty cryptocurrency mine exceed the value of its revenues.

Sunk costs shape spatial patterns of capital-intensive polluting industries like power plants, oil refineries, airports, and roads. The "rust belt" in many countries partly describes sunk and abandoned dirty capital investments in declining industrial regions, which can be difficult to re-purpose. Some renewable electricity generating plants locate on the

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[11] Input-output links go by many names, including value chains, supply chains, upstream or downstream goods, environmental footprints, or Scope 3 emissions. Accounting measures of greenhouse gas emissions sometimes distinguish three concepts. "Scope 1" represents emissions directly from an establishment. "Scope 2" represents emissions due to electricity, steam, or similar energy utilities than an establishment consumes. "Scope 3" include upstream (and, in some cases, downstream) emissions in the value chain.

site of decommissioned fossil electricity generation, in part to utilize existing transmission and site infrastructure. While re-purposing dirty energy production sites for clean energy does help address public concern about how the energy transition will affect workers in dirty industries, such re-purposing is not always feasible. For example, the Zollverein coal-mining facility, once among the largest in Europe, has now been repurposed to art galleries, exhibition halls and restaurants.

A thin branch of literature on firms and the environment analyzes the structure of market power. Industrial organization papers scrutinizing firm or establishment market power in an industry, with flexible demand and supply structures, tend to occupy a separate literature from spatial models and also from environmental analyses. For example, many spatial papers assume perfect or monopolistic competition and constant elasticity or Cobb-Douglas technology, and many environmental analyses abstract from market power entirely. Yet, as we have emphasized, many dirty industries like petroleum refining and cement are concentrated. Market power typically means that a firm produces less output than is socially optimal, while environmental externalities typically mean that firm production exceeds socially optimal levels. Limited research analyzes optimal environmental policy in the presence of market power and environmental externalities (e.g., Buchanan, 1969; Fowlie et al., 2016; Ryan, 2012), and even less studies its spatial design. Research on electricity and vehicle markets does provide one important set of exceptions.

Another area of research on firms and enviro-spatial economics with scope for further insights involves the roles of scale, composition, and technique effects discussed in Section 2 across regions within a country. Apart from the graphs in Section 2, we are not aware of existing such analysis at the regional level within a country, though the increasing availability of region×industry data provides opportunities to implement such decompositions.

5 Spatial links in environmental analysis and policy

This section moves from the core building blocks discussed in the last section to discuss agglomeration and dispersion, geography and inter-regional links, and policy design.

5.1 Agglomeration forces

Agglomeration forces can benefit the environment in several ways. Population density can improve environmental quality through returns to scale in pollution control technology. For example, the US Safe Drinking Water Act mandates tighter monitoring requirements for drinking water systems serving larger populations, partly reflecting fixed costs of effective pollution control technologies. This has contributed to US cities today having cleaner drinking water quality than rural areas (Keiser et al., 2023). Cogeneration plants ("combined heat and power"), which generate electricity and circulate waste heat as steam, also have competitive costs in dense areas where electricity generation is near other heat-demanding sites.

Agglomeration also changes transportation and housing in ways that have important consequences for environmental outcomes. Denser cities have less driving, smaller housing units, and lower associated energy bills (Duranton and Turner, 2018; Glaeser and Kahn, 2010). Subway system openings, which most reliably serve densely populated neighborhoods, decrease pollution in initially polluted cities (Gendron-Carrier et al., 2022). Agglomeration may become more important for the environment as climate change increases demand for adaptation infrastructure. For example, sea walls, levees, cooling centers, and warning systems for natural disasters all represent local public goods with fixed costs.

An additional impact of agglomeration on the environment occurs through land use. Denser cities have less urban sprawl, which can preserve ecosystem services from undeveloped environments. Some cities have set urban growth boundaries which limit sprawl, in part for environmental reasons, though such land use restrictions can also increase land prices. Koster (2024) estimates that greenbelts, a type of urban growth boundary covering 13% of England, increase both land prices and amenity values.

Set against these benefits, agglomeration increases the marginal damage of pollution emissions. A unit of air pollution emitted in Moscow likely has greater social cost than the same unit of pollution emitted in Siberia, because more people in Moscow breathe the pollution and suffer health damages. This logic does not extend to global pollutants like greenhouse gases, where the social cost depends only on the quantity, but not the location, of emissions. Density can also drive increases in vulnerability to natural disasters, particularly fires and floods, potentially exacerbating a worsening trajectory of fire and flood risk due to climate change. Urban fires spread between homes, especially when older homes have flammable roofs, or adjacent combustible materials like brush, or other lack of "defensible space" (Baylis and Boomhower, Forthcoming). Historical fires have spread through dense urban areas and destroyed infrastructure en masse (Hornbeck and Keniston, 2017). The US Clean Water Act was inspired partly by fires on rivers in dense industrial areas, which occurred regularly between 1870 and 1970 in many US cities (Keiser and Shapiro, 2019). Impermeable surfaces in many dense urban areas prevent drainage, transmitting flood risk downstream (Taylor and Druckenmiller, 2022).

The previous paragraphs discuss how agglomeration affects the environment; environmental goods can also drive agglomeration. The spatial clustering of coal, groundwater, timber, lithium, copper, and other natural resources attracts industries using these resources as inputs (Moreno-Cruz and Taylor, 2017). For example, rapid economic growth in Northwestern North Dakota since 2007 reflects oil in the Bakken shale, which has become economically viable to extract due to innovations in hydraulic fracturing. Other industries may concentrate in such areas because they use these natural resources upstream in value chains or benefit from the agglomeration spillovers (Allcott and Keniston, 2017).

Future research could clarify interactions of the environment with labor market pooling and the flow of ideas. Economic geography research highlights these two channels, alongside input-output links (where environmental research is more active), as driving agglomeration. Mild climates, low natural disaster risks, and good air quality could encourage face-to-face interactions, which enhance the transmission of ideas (Atkin et al., 2023). Some research also studies the limited movement of workers between clean and dirty industries (Colmer et al., 2024) and its potential impacts on communities specialized in fossil energy sources.

Although larger cities have more productive firms (Combes et al., 2012), the aggregate effect of regional productivity on pollution is poorly understood. More productive firms emit less pollution per unit of output (Klenow et al., 2024; Shapiro and Walker, 2018), but also typically have greater market share. Additionally, productivity increases local incomes, which may increase demand for environmental quality, lead to stricter local environmental policy, and change the composition of local industry. The net local effect of productivity on pollution through these channels of physical productivity, scale, endogenous regulation, and composition is a potential topic for future work.

5.2 Dispersion forces

While agglomeration affects the environment through the channels discussed above, it also increases negative environmental externalities through industrial production, transportation, sewage, and related outcomes. In the nineteenth century, rural areas had higher life expectancy than urban areas, due partly to local pollution externalities, especially those affecting drinking water. This pattern reversed by the early twentieth century, largely as a result of local pollution treatment (Anderson et al., 2022; Cutler and Miller, 2005). Rat infestations in megacities like New York and Johannesburg partly reflect the challenges of providing high-quality municipal environmental services like waste and sewage treatment in dense city centers. Urban planners used such arguments to demolish slums in the mid-twentieth century and in many cases build highways through them, in the stated pursuit of urbanism and modernity (Rae, 2005). Informal housing in the dense centers of many megacities today still lacks piped water, sewage conveyance, or trash collection, and can transmit pathogens among households via inadequate waste treatment (Harari, 2024).

City centers can also suffer from increased local temperatures through urban heat islands, wherein dense cities have elevated temperatures due to local energy consumption and non-permeable surfaces like roofs and pavements that absorb solar radiation (Huang et al., 2023). Urban heat islands are probably an amenity in Siberia but a disamenity in the Sahara.

Offsetting the impact of natural resources on agglomeration via input-output links discussed above, natural endowments also produce a classic example of dispersion forces through local supply constraints. Saiz (2010) highlights how geographic constraints on the ability to develop sloped and wetland areas for housing increase housing prices and decrease housing supply elasticities in US metro areas. Harari (2020) studies the economic implications of city shape in India using an instrument based on geographic obstacles encountered by expanding cities.

5.3 Geography and links between regions

Flows of goods, people, and ideas between regions, and frictions to these flows, play central roles in spatial economics. This subsection discusses how such spatial links affect environmental outcomes and how environmental goods influence spatial links.

5.3.1 Spatial links affect environmental externalities

Long-distance transportation of goods and people affect global and local pollution emissions as discussed in Section 2, and can also play an important role in facilitating natural resource extraction. Infrastructure investments accompanying improvements in market access, such as roads, dams and irrigation, often attract attention for attendant damages to local resources such as forests and wetlands. Figure 11, from Araujo et al. (2023), shows the proximity of deforestation in the Brazilian Amazon from 1990 to 2020 to federal roads. The study finds that market access improvements increase deforestation, but that general equilibrium effects complicate the relationship between the locations of road investments and induced deforestation.

[Insert Figure 11 here]

Figure 11: Roads and Deforestation, from Araujo et al. (2023)

The figure shows cumulative deforestation (in orange) in the Brazilian Amazon in 1990 (panel (a)) and 2020 (panel (b)), and its proximity to federal roads in 2010, from Araujo et al. (2023).

Local movement of people via commuting also generates negative externalities, as Figure 5 shows. Higher pollution exposure in cities with larger populations is to a large extent attributable to commuters (Borck and Schrauth 2024), and households near major roads experience greater pollution and noise and worse associated health (Anderson, 2020). At the same time, the combination of commuting and zoning allows people to live in areas with better environmental quality, and can concentrate industrial production in areas with worse environmental quality. For example, Barwick et al. (2022) find that short-term commuting on China's high-speed rail network helps people avoid extreme pollution exposure, saving 21 million life years.

Section 5.1 mentioned the dearth of research on how environmental amenities affect the flow of ideas; slightly more work examines how the flow of ideas affects environmental externalities. Dynamic spatial equilibrium frameworks have examined how firms innovate endogenously, and how local innovation affects energy use, pollution, global warming, and adaptation to sea level rise (Desmet and Rossi-Hansberg, 2014, 2015; Desmet et al., 2021). The flow of ideas across firms, universities, and countries also drives the spread of frontier technologies and innovation for the green transition. Arkolakis and Walsh (2023) develop a spatial growth framework to examine the global consequences of the rise in renewable energy, and find that renewable sources will dominate the world's power system by 2040. Banares-Sanchez et al. (2023) consider the role of barriers to the diffusion of renewable technologies to study global innovation and diffusion of solar technologies. Moscona and Sastry (2023) examine endogenous technological change as a potential source of adaptation to climate change, and find that innovation in US agriculture has in recent decades re-directed towards crops with increasing exposure to extreme temperatures.

5.3.2 Environmental goods and policies affect spatial links

Many environmental policies regulate the transportation sector, partly due to its substantial contribution to emissions. These regulations increase the cost of transportation and improve environmental quality near transportation corridors, both of which affect spatial outcomes. For example, new gasoline vehicles face exhaust standards restricting air pollution emission rates in practically all high- and middle-income countries (Jacobsen et al., 2023). Transportation also faces energy efficiency standards, electrification standards, vehicle remote sensing, inspection and maintenance programs, and fuel content standards. Cities including London, Singapore, and Stockholm have instituted spatially-targeted congestion charges which increase the cost of driving in the central city area, and which have improved environmental quality (Almagro et al., 2024; Leape, 2006).

Natural disasters clearly drive migration, another important spatial link. For example, the US 1930s Dust Bowl and 2005 Hurricane Katrina caused mass migration within and across states (Deryugina and Molitor, 2020; Hornbeck, 2023), labor migration to urban areas was an important coping strategy in the aftermath of Typhoon Ketsana in Vietnam (Gröger and Zylberberg, 2016), and heat stress induces long-term migration in Pakistan (Mueller et al., 2014). Natural disasters also cause international migration, including extreme temperatures' impact on asylum applications to the European Union, migration from Mexico to the United States (Jessoe et al., 2018; Missirian and Schlenker, 2017), and across countries in sub-Saharan Africa (Ruyssen and Rayp, 2014). Both domestically and internationally, migration may mediate the immediate impacts of environmental shocks, and provide an important means for populations to adapt to worsening natural disasters.

Gradual environmental change also drives adaptive migration. Forward-looking studies using quantitative spatial equilibrium models suggest that future changes in climate amenities across locations and time will continue to drive migration, and emphasize the importance of population mobility. Migration and migration frictions affect the spatial transmission and overall levels of climate change's economic costs (Cruz and Rossi-Hansberg, 2024). Desmet et al. (2021), for example, project that sea level rise will displace 1.5% of the global population by 2200, with real GDP losses of 0.1%, compared to 4.5% if populations were immobile. Similarly, Bilal and Rossi-Hansberg (2023) find that migration substantially reduces the variance of climate change's projected welfare impacts across the US.

5.4 Environmental spatial policy and the role of geography

This subsection discusses several policy design issues where enviro-spatial considerations and links between regions play a particularly important role.

Place-based environmental policy and spillovers. Many environmental policies regulate specific polluted locations. More stringent regulation of polluted "nonattainment" counties in the US changes industry location, employment, capital, output, productivity, and wages (Becker and Henderson, 2000; Greenstone, 2002; Greenstone et al., 2012; Henderson, 1996; Walker, 2011, 2013). China's 2013 pollution monitoring program has similarly had important spatial effects on economic outcomes (Xie and Yuan, 2023). Market-based quantity restrictions and tradable performance standards also affect outcomes in the areas they regulate (Convery, 2009; Fowlie and Perloff, 2013; Goulder et al., 2022; Greenstone et al., 2023; Newell and Rogers, 2006; Yeh et al., 2021).

Fewer environmental policies directly reflect environmental spillovers across jurisdictions, despite their importance. Since Montgomery (1972), economists have recognized that cap-and-trade markets can incorporate spatial ratios reflecting heterogeneous damages across sources, though few policies implement such ratios. Similarly, spatially differentiated environmental taxes and regulations rarely directly reflect inter-jurisdictional externalities. To give one example, while nutrient pollution from agriculture in the Midwestern US contributes to a "dead zone" in the Gulf of Mexico, water quality regulation in the Midwest predominantly regulates individual pollution sources or communities, and does not account for flow relationships within the entire Mississippi River watershed.

Environmental federalism. A related issue is that different levels of government often regulate the same environmental problem. Their decisions can interact, not always efficiently. The theory of fiscal federalism suggests that a given environmental problem may have an optimal level of government to regulate it, depending on the structure of the externality. The government actually regulating a specific externality may not correspond to this optimal level.

Governments can negotiate cooperative solutions to environmental challenges that span local and federal jurisdictions. For example, the Chesapeake Bay watershed in the Eastern US, which spans parts of Virginia, West Virginia, Maryland, Delaware, Pennsylvania, New York, and Washington, DC, has long suffered from excess nutrient pollution due to agricultural and municipal discharge. For several decades, an agreement between the US federal government, several governors, and the Washington DC mayor has combined federal funding with regional implementation to address nutrient and sediment inflows (Carey 2021).

Wetland regulation under the US Clean Water Act provides one example of the challenge in dealing with the appropriate level of government to regulate environmental goods. The Act restricts land development in many desert and suburban wetlands, particularly affecting road construction and solar and wind farm development. The US Supreme Court and last several US presidents have repeatedly changed the scope of which wetlands these regulations cover, by up to half of regulated areas. Many states also have their own wetland laws, some of which regulate more than federal regulations and others less. Local governments also operate their own wetland protections which restrict land development. These different levels of stringency at different levels of government may reflect Tiebout sorting and different jurisdictions' preferences for environmental protection. At the same time, because wetland development can contribute to downstream water pollution and flood damage, this environmental federalism may contribute to inter-jurisdictional externalities, and increases uncertainty and costs of regulatory compliance for developers (Aronoff and Rafey, 2023; Greenhill et al., 2024; Keiser et al., 2021).

Leakage. Environmental regulation can cause "leakage" of dirty activities away from regulated regions. Growth in international trade and lengthening supply chains have motivated a literature on offshoring of emissions-intensive production and policy-driven carbon leakage as firms circumvent regulation by moving emitting activities abroad or across domestic regions (Goulder et al., 2012b; Grubb et al., 2022; Kortum and Weisbach, 2022).

This area warrants increasing attention as policy debates advance, such as those around the European Union's Carbon Border Adjustment Mechanism (Ambec et al., 2024; Clausing and Wolfram, 2023; Fowlie et al., 2021).

Leakage can also shape spatial patterns of natural resource exploitation. Leakage concerns may loom large for conservation policies, for instance given concerns that payments for ecosystems services contracts may shift activity to neighboring areas rather than reducing aggregate deforestation (Jayachandran et al., 2017). Adaptive investments such as levees may also have spillover effects if they increase flood risk downstream (Wang, 2021).

Optimal spatial variation in policy stringency. An area that has received limited research focus is the important question of the extent to which the stringency of environmental policy should vary over space. Parry and Small (2005) highlight that gasoline taxes should account for spatial heterogeneity in the externalities from automobile use, for instance driven by the effects of local population density on congestion. More broadly, spatial variation in agglomeration, congestion, and environmental externalities likely play important roles in optimal environmental policy design but have not been a major focus of research.

Land use restrictions. Zoning, development constraints and land use restrictions all affect the environment, by altering spatial patterns of density, polluting activity, and environmental outcomes, and encouraging development in the wildland-urban interface which hosts many human-environmental conflicts (Ostriker and Russo, 2024; Schug et al., 2023). In tropical forested areas, Balboni et al. (Forthcoming) find that land use restrictions implemented via the spatial distribution of concession rights and protected forest areas can also influence patterns of fire-setting, forest loss, and associated environmental costs.

Insurance. Regional insurance policies, as well as disaster aid, can effectively subsidize development in areas prone to natural hazards, and so cause spatial moral hazard (Fried, 2022; Marcoux and Wagner, 2024). The federally-managed US National Flood Insurance Program has for many years subsidized flood insurance in flood-prone areas, encouraging development in these areas. Several US states including California operate state-managed "last resort" homeowners' insurance policies. Other policyholders may subsidize these policies, which can also encourage population concentration in areas prone to wildfires and other natural disasters. Some insurance firms have begun dropping customers out of concern for wildfire exposure (Boomhower et al., 2024).

6 Summary of topics for future research

This section summarizes productive topics for future research, by bringing together topics from the chapter. While far from exhaustive, this list highlights areas where methodological advances and expansions of topical focus might offer exciting avenues for further progress.

6.1 Leveraging innovations in remote sensing and spatial models

We see many opportunities for spatial environmental economics research to utilize recent innovations in remote sensing, machine learning, quantitative spatial equilibrium models and sufficient statistics. Given the insights that the combination of remote sensing and machine learning has provided for environmental and spatial economics separately (e.g., Donaldson and Storeygard, 2016; Faber and Gaubert, 2019; Greenhill et al., 2024; Henderson et al., 2012; Zou, 2021), combining these insights to examine central enviro-spatial interactions in the same setting could provide powerful opportunities for progress.

Many spatial equilibrium papers estimate regional productivity and amenity values which are important to the relevant framework but are challenging to validate. At the same time, many environmental papers struggle to provide generalizable interpretations of the amenity or productivity impacts of environmental goods and policies. The substantial variation in environmental goods and policies across regions and time provides opportunities for the two fields to collaborate—spatial equilibrium models can help interpret estimated impacts of environmental goods and policies, while variation in the latter may provide an opportunity to validate or interpret quantitative spatial models. More broadly, many environmental papers focus on reduced-form approaches, while spatial papers drawing on environmental data are often more structural. Several other areas of economics have productively employed a middle ground between reduced form and model-based approaches, and spatial environmental research may gain insights from building on similar approaches (e.g., Anderson and Sallee, 2011; Meng, 2017).

6.2 Implications of different spatial scales for analysis

Many discussions have raised questions around how different environmental policy evaluation, including optimal policy, might be from the perspective of local, state, national, and global planners. What insights do these differences reveal for the political economy of environmental policy? When and why should analysis and policy use global versus national or regional values of the social cost of carbon, and in what settings should papers report values besides the national social cost of carbon? When do these differences affect conclusions about optimal policy, and can they help explain the political economy of environmental policy?

Related to the spatial scale of analysis is consideration of approaches to managing inter-jurisdictional environmental spillovers. The leakage of pollution away from regulated regions warrants further attention as environmental policy continues tightening in some regions more than others, and policies targeting leakage, such as the European Union's Carbon Border Adjustment Mechanism, continue to advance. Carbon leakage across countries has been one focus of the trade-environment literature, though leakage across regions within countries due to sub-national climate policy is less of a focus (Goulder et al., 2012b is one exception), and spatial and intra-national leakage for non-carbon pollutants is also less widely studied.

Another important approach to addressing inter-jurisdictional spillovers is Coasian bargaining. Despite the spatial relevance of the Coase Theorem (Coase, 1960), little spatial research focuses on it. Given that bargaining parties may locate downstream or downhill, spatial analysis could shed light on the potential effectiveness of Coasian bargaining, and the extent to which it may realize potential gains from trade, which provides one indication of the magnitude of contracting frictions and weakness of property rights. One example with emerging work involves transfer of water use rights (Ferguson and Milgrom, 2024).

6.3 Micro-foundations of cross-regional differences relating to the environment

There is broad scope to develop a more detailed understanding of spatial variation in environmental valuation. For example, how do marginal damages of pollution or market shares of clean goods relate to utility and marginal willingness to pay? Why does demand for environmental quality and goods vary widely over space? What do these spatial patterns imply for optimal policy design, and what micro-foundations drive these patterns?

Additionally, decompositions of environmental outcomes across regions might shed light on the micro-foundations of spatial heterogeneity in environmental quality. Many papers use decompositions of environmental change over time for an entire economy into scale, composition, and technique. We provide a basic application across US counties using publicly available data. Similar approaches might be informative in understanding drivers of differences in environmental quality across regions within a country, and help to frame the types of policies and economic forces likely to affect economic and environmental outcomes.

6.4 Spatial natural resources

Another promising area involves extending environmental and spatial insights to natural resources including fisheries, deforestation, groundwater depletion, mineral extraction, and biodiversity. While some theoretical and empirical papers analyze natural resources (e.g., Brander and Taylor, 1997a,b, 1998a,b; Carleton et al., 2024; Farrokhi et al., 2024; Frank and Sudarshan, 2024; Rafey, 2023; Taylor and Druckenmiller, 2022), work on these topics can face high data burdens and require dynamic models, and remains more limited than research on static environmental goods like air and water pollution, particularly in spatial settings.

Natural resources involve stocks, flows, and other dynamic decisions and forces. Most existing analysis adopts either a fully dynamic approach (solving Hamiltonians or optimal control) or a myopic approach that ignores dynamics. Fully accounting for dynamics imposes a meaningful cost in model complexity, though some settings justify it. Emerging approaches provide a middle ground, where static models use one or a few parameters from other dynamic analysis (e.g. the social cost of carbon, or the shadow price of water) for analyzing dynamics of natural resources.

Further work in this area could yield insights on several policy-relevant questions. Optimal extraction paths for natural resources, and their differences across aquifers, forests, fisheries, and other resource endowments, are important and not widely understood. To what extent do these extraction paths depend on spatial links and spatial variation in economic fundamentals? What are social costs of existing and potentially sub-optimal extraction paths? Another example is the Tragedy of the Commons (Hardin, 1968), which describes many environmental settings we have discussed where a broad spatial area provides a commons, and open access conditions produce inefficiently high environmental damage. Noack and Costello (2024) provides one analysis with fixed institutions but mobile natural resources (fisheries).

6.5 Dynamic adaptation to climate change

Developments in dynamic spatial modeling approaches, and our understanding of the impacts of climate change for a broad range of outcomes, present an opportunity to advance a research agenda on the role of dynamic spatial adjustments in responses to climate change.

The potential role of migration in climate change adaptation has received some attention in the existing literature, but many open questions remain. In the absence of complete global international and intra-national bilateral migration data, quantitative models typically impose functional form assumptions on migration patterns, while quasi-experiments focus on specific settings where appropriate data and research designs are available. Current findings leave open a range of possibilities as to whether migration will be a central or modest component of climate adaptation, depending partly on the magnitude of, and spatial variation in, migration frictions.

The relocation of production as a potential mechanism for adaptation is another area where recent research has begun to make interesting inroads, but where several open questions remain. For example, how might the movement of goods production contribute to adaptation to environmental change? To what extent will within-country relocation in factory locations, farmer crop choice, and goods transactions decrease the aggregate costs of climate change?

6.6 Settings beyond the US and global climate change

Much of this chapter focuses on the US, particulate matter air pollution, and global climate change, reflecting focus of the existing literature. The planet has numerous regions where environmental goods and policies have outsized importance, and many important environmental goods beyond particulate matter and climate change. Expanding focus to other settings will broaden knowledge and advance novel research and policy insights.

7 Conclusions

This chapter highlights complementarities between spatial and environmental economics, and opportunities to advance an emerging literature at the intersection of these two growing fields. Substantial policy challenges from worsening climate change and environmental damages, together with rapid changes in spatial patterns of growth, trade and migration, underscore the importance of this form of intellectual arbitrage.

New methods, alongside the availability of detailed, geographically resolved data for estimation, are advancing rapidly in both environmental and spatial economics. The advent of new analytical tools and high-quality data will permit further progress on questions this chapter explores. This also offers opportunities to explore new areas where we have highlighted that research is still in its infancy, such as the sources of Environmental Justice gaps; the rationality and information behind spatial choices about natural resource exploitation; normative questions of optimal environmental policy design and targeting; and the appropriate level of government to regulate different environmental goods.

Research and policy around trade and the environment has grown in recent decades, and it is natural to ask what features are similar or different between that literature and the analysis we describe on spatial economics and the environment. Many issues we discuss matter for spatial economics, but have less central importance for international economics—commuting, zoning, urban population density, neighborhood choice, local pollution patterns, the wildland-urban interface, agglomeration and congestion forces, and others. At the same time, classic issues such as the Environmental Kuznets Curve, the proximity-concentration hypothesis, spatial market power, and pollution transport play central roles in ways that both international trade and space more broadly interact with the environment, although their roles may differ between the two literatures.

The ideas raised in this chapter have particular relevance for a number of ongoing policy debates where enviro-spatial considerations are central. To name a few, Environmental Justice concerns and the prevalence of "hot spots" with high pollutant concentrations have motivated policies such as the USA's Justice40 Initiative, stipulating that 40% of the overall benefits of certain federal climate, clean energy, affordable and sustainable housing investments should accrue to disadvantaged communities. Enormous investments in infrastructure to help vulnerable regions adapt to the impacts of climate change are under construction or discussion, including seawalls with estimated costs of €7 billion in Venice (Benetton et al., 2024) and $40 billion in Jakarta (Hsiao, 2023). Land use regulation relating to environmental goods often provokes significant local opposition, such as "NIMBY" (Not In My Back Yard) attitudes to the siting of renewable energy projects (Jarvis, Forthcoming). Rapid urbanization and climate changes have culminated in urban water crises brought into stark relief by Cape Town's 2018 "Day Zero," foreshadowing the interruption of essential water services. In these and many other applications, combining tools from environmental and spatial economics can yield important insights into the sources of market failures, and inform policy design and evaluation.

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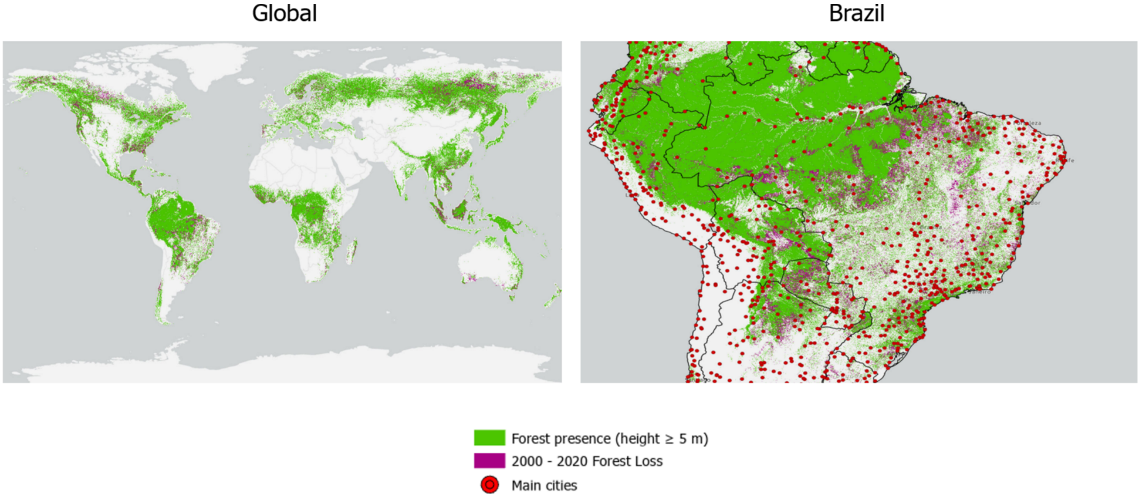
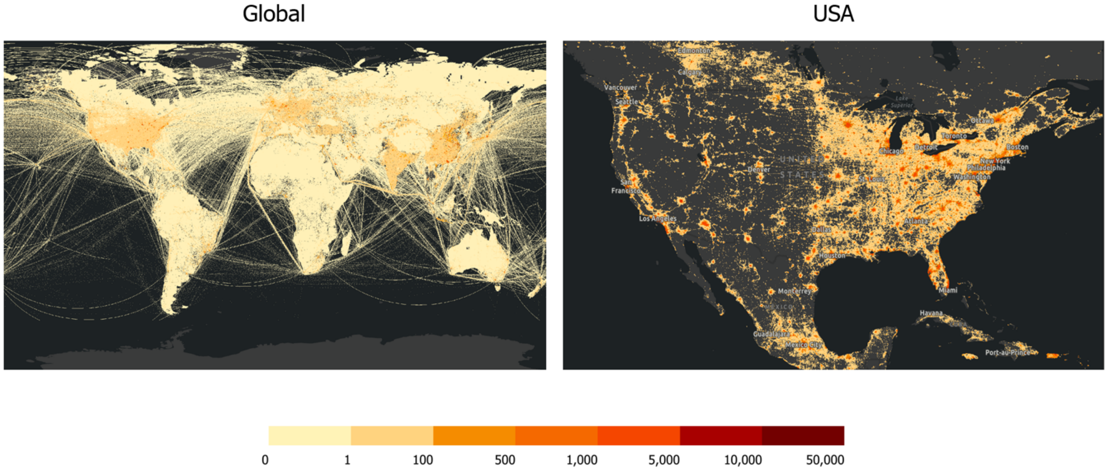
Figures

Figure 1: Spatial variation in forest cover, deforestation and CO_2 emissions



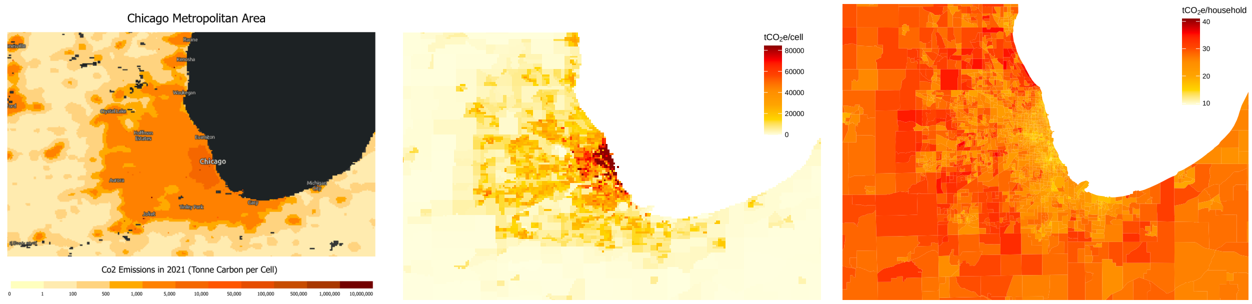
(a) Forest extent in 2020 and Forest Loss in 2000–2020



(b) Tons of CO_2 per cell in 2021

The datasets used in this figure are: GLAD Global Land Cover and Land Use dataset for forest extent in panel (a) and the Global Forest Change 2000-2020 for forest loss in panel (a); GridFed dataset for global map in panel (b); ODIAC dataset for the USA map in panel (b). Appendix B describes each dataset.

Figure 2: Carbon dioxide (CO_2) emissions in the Chicago Metropolitan Area



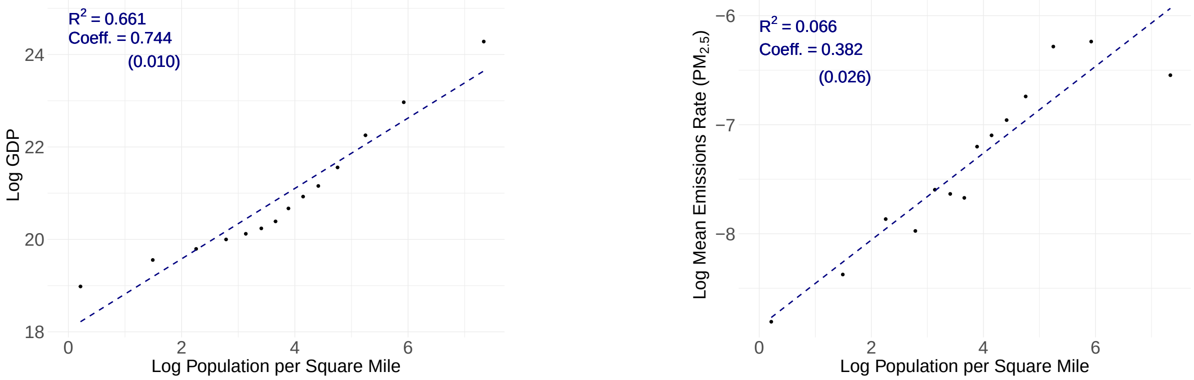
(a) Carbon dioxide emissions in 2021

(b) Total household carbon footprint

(c) Average household carbon footprint

The map in (a) uses the GridFED (The Gridded Fossil Emissions Datasets). Appendix B describes this dataset. The map in (b) shows the total household carbon footprint per cell at a 0.01 degree resolution for the Chicago metropolitan area. This map combines data on household carbon footprints (HCFs) for the average household in each US Census tract from Green and Knittel (2020) with data on the number of households per census tract from the US Census Bureau 2019 American Community Survey (ACS) to calculate total carbon footprints. The calculation then distributes these emissions across 0.01 degree cells and rasterizes them for visualization. The map in (c) plots data on average per household carbon footprint in each census tract from Green and Knittel (2020) for the Chicago Metropolitan Area.

Figure 3: Scale, composition, and technique across US counties by population density

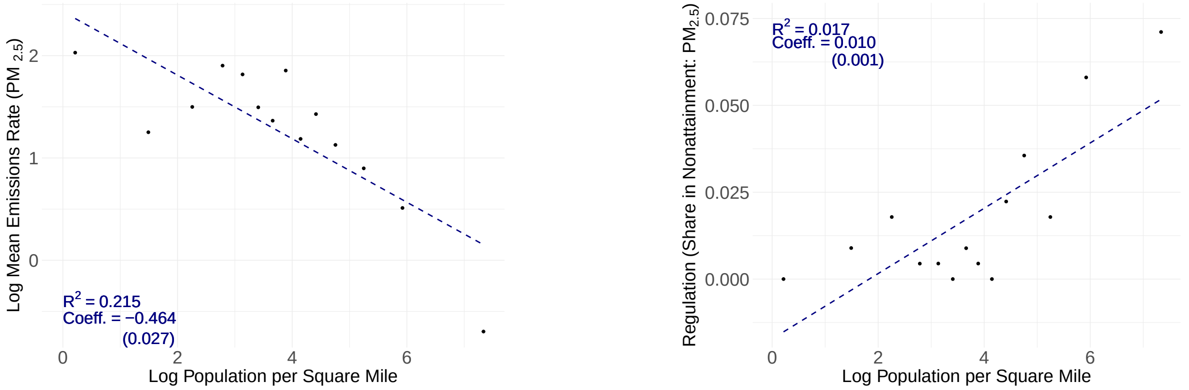


(a) Scale

(b) Composition

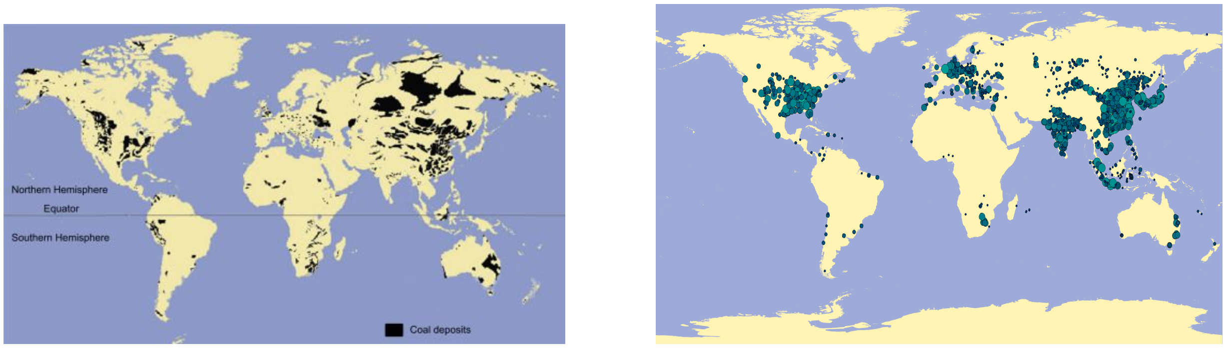
(c) Technique

(d) Regulation



Graphs show binned scatter plots where each underlying observation in the raw data represents a county in the year 2017, the dashed line in each graph shows the linear trend, and the circles in the graph show quantile means. For the x-axes, we measure population using data from the National Cancer Institute's Surveillance, Epidemiology, and End Results (SEER) Program, and measure land area from the Census Bureau's Topologically Integrated Geographic Encoding and Referencing system. The y-axis of panel (a) shows county GDP from the Bureau of Economic Analysis. The y-axis of panel (b) shows $\sum_s log(E_s/L_s)(L_{sc}/L_c)$, where c denotes county, s denotes a NAICS 3-digit industry, E denotes pollution emissions, and L denotes employment. We measure emissions from the National Emissions Inventory (NEI) and employment from the County Business Patterns (CBP). The y-axis of panel (c) shows county fixed effects from a regression of county×industry pollution intensity $log(E_{sc}/L_{sc})$, also measured from NEI and CBP, on county fixed effects and industry fixed effects. The y-axis of panel (d) indicates whether counties are in nonattainment for particulate matter.

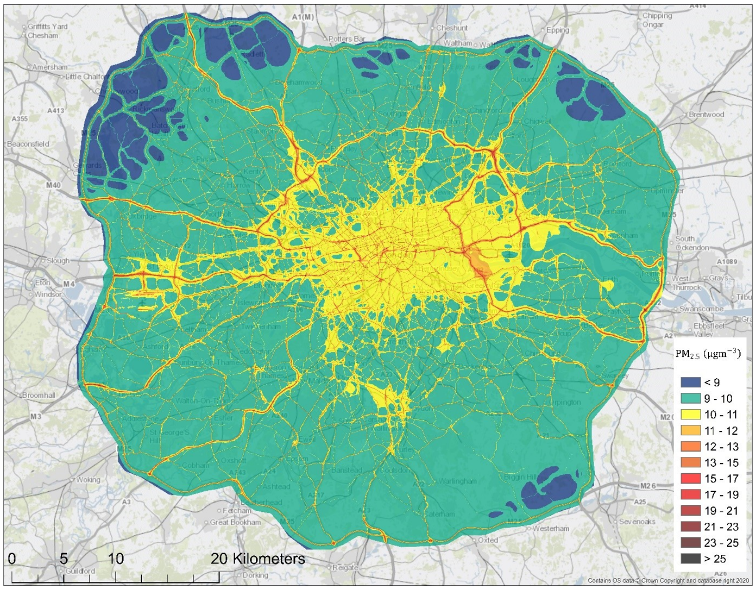
Figure 4: Global maps of coal deposits and coal-fired power plants



(a) Location of coal deposits (b) Location of coal-fired power plants

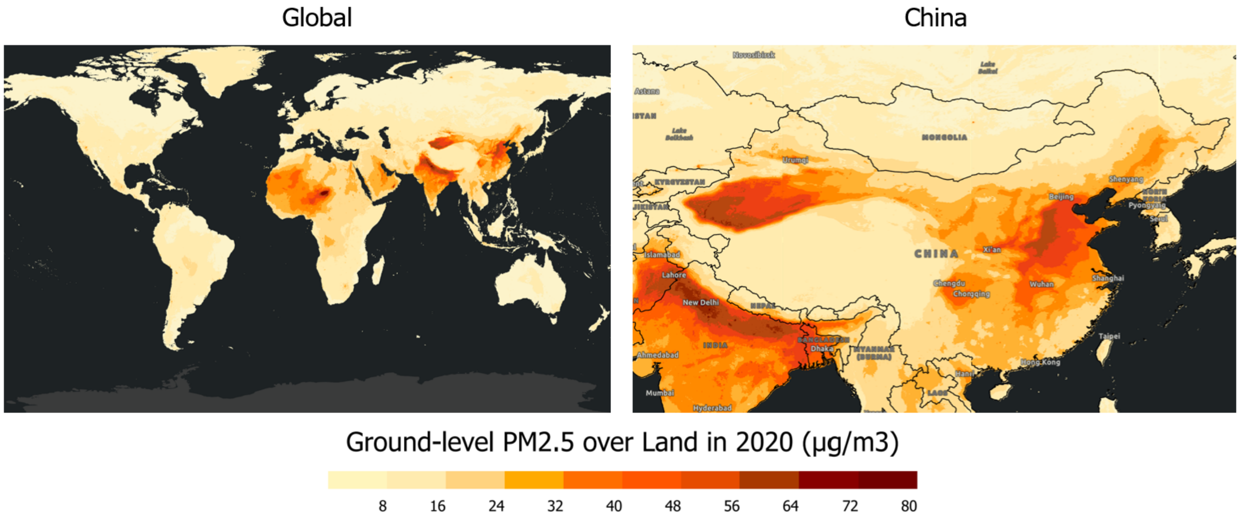
The figure in panel (a), taken from Suárez-Ruiz et al. (2019), shows the geographical distribution of known coal deposits in the world. The map in panel (b) shows the locations of coal power plants in operation in 2023 using data from the Global Energy Monitor Global Coal Plant Tracker.

Figure 5: Modeled annual average $PM_{2.5}$ pollution concentrations across London in 2019



The figure shows a map of modeled $PM_{2.5}$ pollution concentrations across London in 2019. Reproduced with permission from Cambridge Environmental Research Consultants (2024).

Figure 6: PM$_{2.5}$ in 2020



The figure shows the distribution of ground-level PM$_{2.5}$ globally and within China in 2020 at a 1km spatial resolution. We generate the maps using data from the GlobalHighPM2.5 dataset; Appendix B provides further details.

Figure 7: Trajectories of air pollution emissions from one pollution source in Los Angeles, California

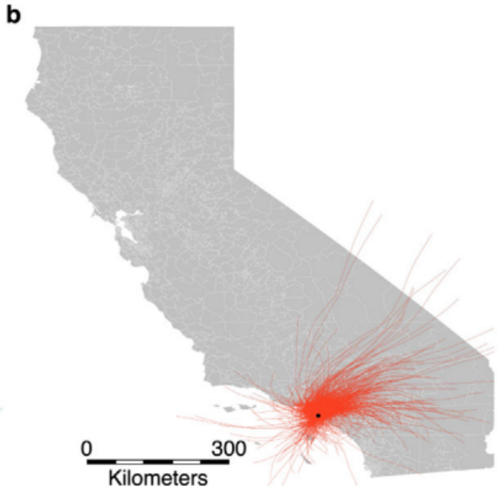
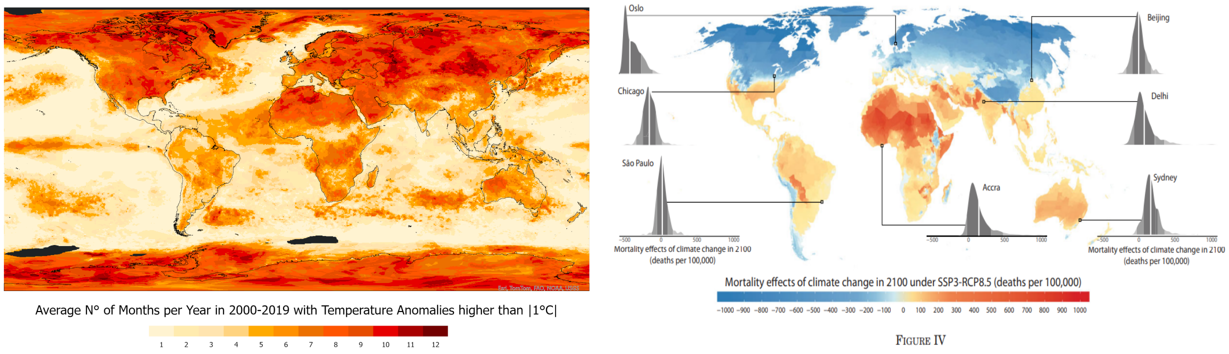


Figure reprinted from Hernandez-Cortes and Meng (2023). The figure displays the spatial distribution of particle trajectories every 4 hours originating from a regulated facility during 2016, using the HYSPLIT atmospheric dispersal model.

Figure 8: Global temperature anomalies and the mortality effects of climate change

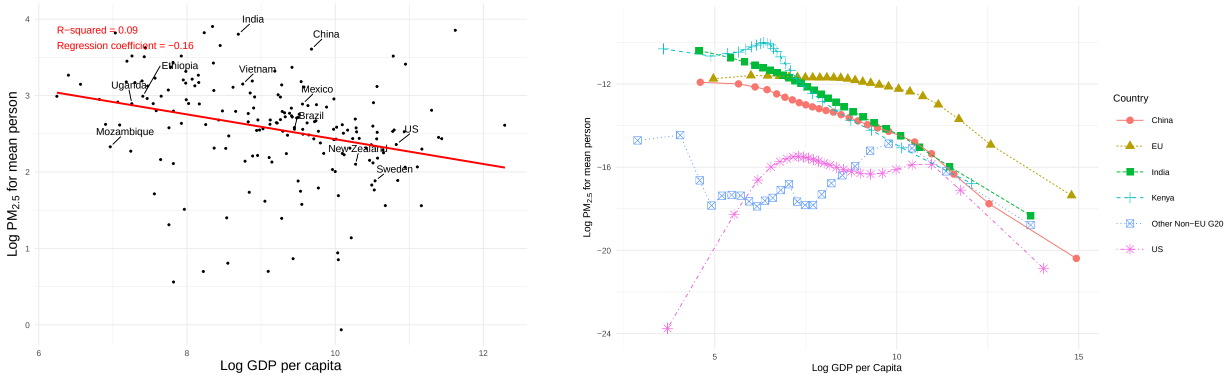


(a) Temperature anomalies in 2000-2019 relative to the 1951-1980 averages

(b) Figure IV, from Carleton et al. (2022)

Panel (a) shows a map of global temperature anomalies in 2000-2019 relative to the 1951-1980 averages generated using the surface air temperature anomaly field from the Berkeley Earth High-Resolution (Beta) dataset to compute the average number of months per year between 2000 and 2019 with a temperature anomaly higher than 1°C in absolute terms. A description of this dataset appears in Appendix B. The map in panel (b) shows estimated mortality effects of climate change, measured in units of deaths per 100,000 population, in the year 2100, from Carleton et al. (2022). All values refer to the RCP8.5 emissions scenario and the SSP3 socioeconomic scenario. The map shows the climate model weighted mean estimate across Monte Carlo simulations conducted on 33 climate models; density plots for selected regions indicate the full distribution of estimated impacts across all Monte Carlo simulations. Estimates of the mortality risks of climate change at global scale are based on a novel dataset composed of historical mortality records, historical climate data (from the Global Meteorological Forcing Dataset (GMFD), the Berkeley Earth Surface Temperature dataset (BEST) and the University of Delaware dataset (UDEL)), and future projections of climate, population, and income across the globe.

Figure 9: $PM_{2.5}$ versus GDP Per Capita

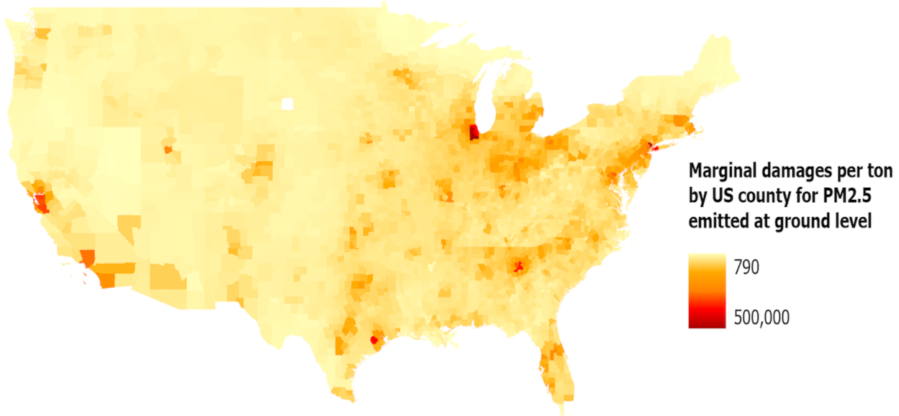


(a) $PM_{2.5}$ in 2020 and GDP per capita in 2020 at the global level

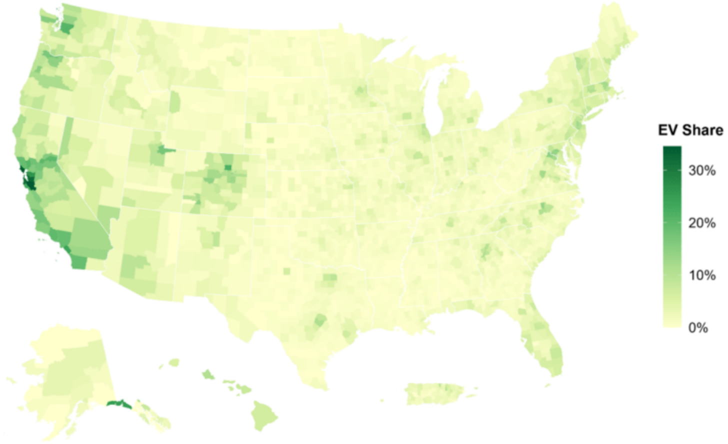
(b) $PM_{2.5}$ in 2020 and GDP per capita in 2020 within selected countries

Panel (a) displays a scatter plot of the average person's $PM_{2.5}$ exposure against GDP per capita for each country. Panel (b) presents a binned scatter plot, using quantile-based binning, to illustrate the same relationship within countries—specifically China, the European Union, India, Kenya, the United States, and other non-EU G20 nations. $PM_{2.5}$ exposure for the mean person is given by the population-weighted concentration of $PM_{2.5}$ at the cell level, measured at a 1 km spatial resolution. It is calculated by weighting the ground-level $PM_{2.5}$ concentration in each cell by its population density divided by the total population density across the country or region. $PM_{2.5}$ data are from the GlobalHighPM2.5 (Global High-resolution and High-quality Ground-level $PM_{2.5}$ Dataset over Land) dataset, which combines ground-based measurements, satellite data, and model simulations. Population data are from the GHS-POP (R2023) (Global Human Settlement Layer Population Grid) dataset, which provides high-resolution residential population distribution. GDP figures come from the Global Gridded GDP (Global Gridded GDP under Historical and Future Scenarios, Version v7) dataset, which provides annual global GDP data on a 1 km grid. Recreating the binned scatter plot in Panel (b) using $PM_{2.5}$ data from the van Donkelaar et al (2021) 'Monthly Global Estimates of Fine Particulate Matter and Their Uncertainty' dataset yields similar results; see Appendix Figure A3.

Figure 10: Spatial Variation in Marginal Damages and Choices of Environmental Goods



(a) Marginal $PM_{2.5}$ damages, by US County



(b) Electric vehicle shares, by US county

Panel (a) shows marginal damages of $PM_{2.5}$ emissions in each US county, generated using replication data from Holland et al. (2016). Panel (b) shows electric vehicle market share of new light duty vehicles in the year 2022, sourced from the U.S. Department of Energy and based on data from Yip (2023), National Renewable Energy Laboratory.

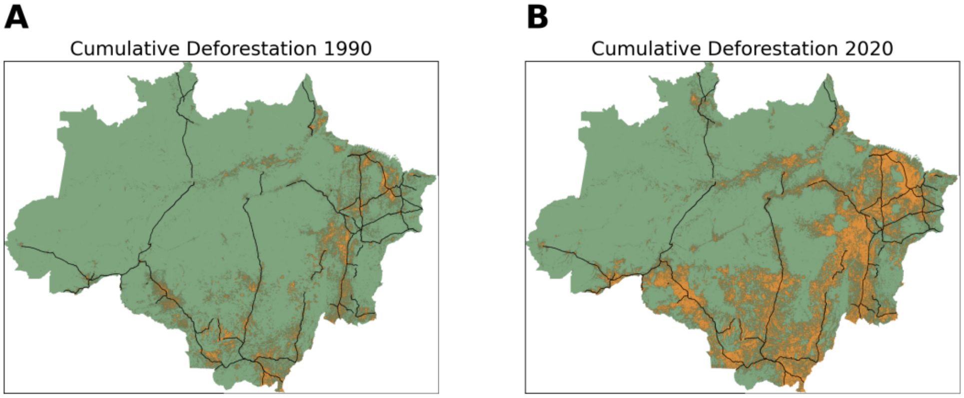


Figure 11: Roads and Deforestation, from Araujo et al. (2023)

The figure shows cumulative deforestation (in orange) in the Brazilian Amazon in 1990 (panel (a)) and 2020 (panel (b)), and its proximity to federal roads in 2010, from Araujo et al. (2023).

A Additional figures

Table A1: Selected Spatially Varying Environmental Policies in China

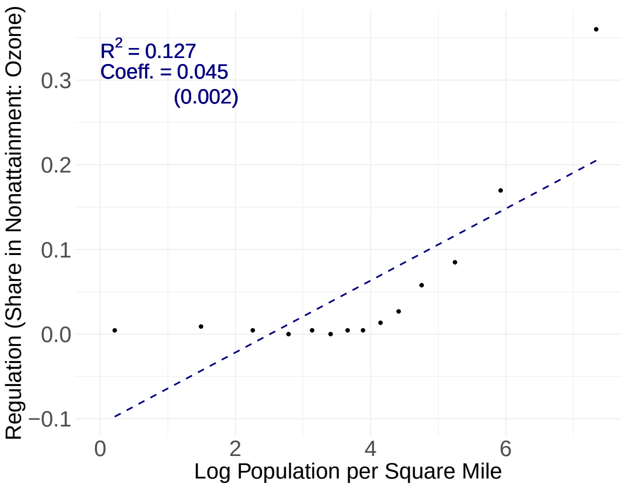
Policy	**Issue**	**Description**	**Initial Year**	**Spatial Variation**	**Sources**
Huai river	Air pollution	Free coal for home heating	1950s-1980s	North of Huai River	Chen et al., 2013; Ebenstein et al., 2017
Air Ten, also called the Action Plan on Air Pollution Prevention and Control; Three-Year Action Plan for Winning the Blue Sky	Air pollution	Retire dirty plants, substitute gas for coal, tighter exhaust standards	2013	Performance contracts between central government and provinces	Karplus et al., 2021; Li et al., 2025
Water Ten, also called Action Plan on Water Pollution Prevention and Control	Surface water pollution	Municipal sewage and industrial wastewater treatment	2015	Lists 7 rivers, 8 coastal bays, 3 regions, and 36 cities for control	Karplus et al., 2021; Ge et al., 2024
Provincial Water Quality Targets, including Water Quality Performance Review (WQPR)	Surface water pollution	Performance reviews of provincial governors depend on meeting provincial water quality targets	2003	Rivers and monitors listed for improvement over specific periods	Wang et al., 2022; Lin et al., 2024
Ecological Compensation Initiative	Surface water pollution	Payments to upstream governments to regulate industrial pollution	2011	Anhui Province rivers flowing into Zhejiang Province	Chen et al., 2021
Pollution Discharge Fees	Air, surface water	Fees to firms for pollution	1992	Varies by province	Karplus et al., 2021
Cap and Trade Pilots	Greenhouse gas emissions	Pilot programs to limit emissions and trade allowances	2013	7 pilot cities and provinces (e.g., Beijing, Shanghai, Guangdong)	Yang et al., 2023
Soil Ten (Action Plan on Soil Pollution Prevention and Control)	Soil pollution	Regulations on contaminated land use and soil monitoring systems	2016	Priority regions and industries for soil contamination control	Karplus et al., 2021

Table A2: Spatial Variation in Environmental Damage Estimates

Type of environmental damage	**High Estimated Damage Location**	**Estimate (High)**	**Low Estimated Damage Location**	**Estimate (Low)**	**Sources**
Social Cost of Carbon (SCC)	India	\$55 per ton of CO_2	Russia	-\$10 per ton of CO_2	Ricke et al., 2018
Life expectancy loss due to particulate pollution (PM2.5)	Pakistan	3.3 years	USA	2.2 months	Greenstone et al., 2024
Projected change in mortality rates due to climate change in 2100 under RCP8.5	Pakistan	376 additional deaths per 100,000	USA	10.1 additional deaths per 100,000	Carleton et al., 2022
Projected increase in the population exposed to heightened drought risk by 2030 under SSP126	Africa	170 million people	Oceania	2 million people	Wang and Sun, 2023
Change in rainfed rice yield in response to an additional day above 30°C	Americas	0.05% increase	Africa	1.1% decrease	Wing et al., 2021
Change in forest loss	Brazil (Amazon)	Reduced from 40,000 km^2 in 2003-2004 to under 20,000 km^2 in 2010-2011	Indonesia	Increased from under 10,000 km^2 in 2000-2003 to over 20,000 km^2 in 2011-2012	Hansen et al., 2013

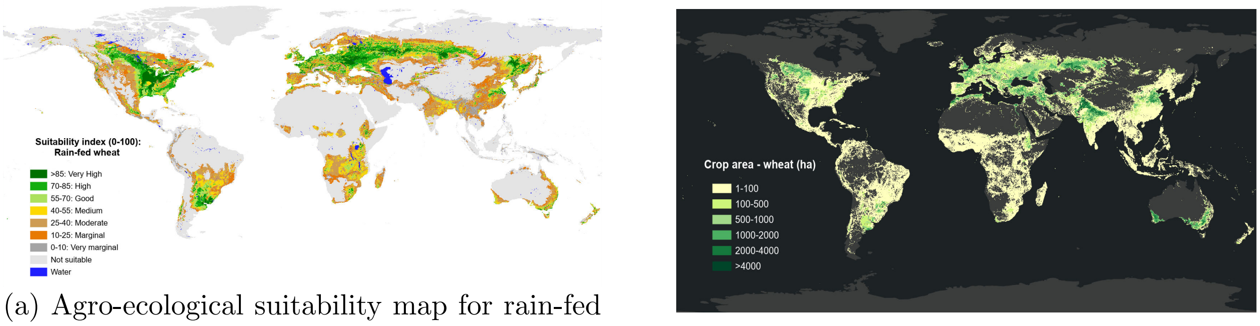
This table presents estimates from the literature illustrating how components of environmental damage functions vary across different regions. High and low estimates were selected based on the highest and lowest values reported in each source, representing countries or regions with the most and least severe estimated impacts under each environmental damage category.

Figure A1: Spatial variation in industrial emissions across US counties by population density: Regulation



All data are from 2017. The x-axis represents population density at the county level. Scatter plot is binned based on quantiles. The figure shows county-level shares of non-attainment records for any ozone category.

Figure A2: Global maps of agro-ecological suitability and cultivation of wheat

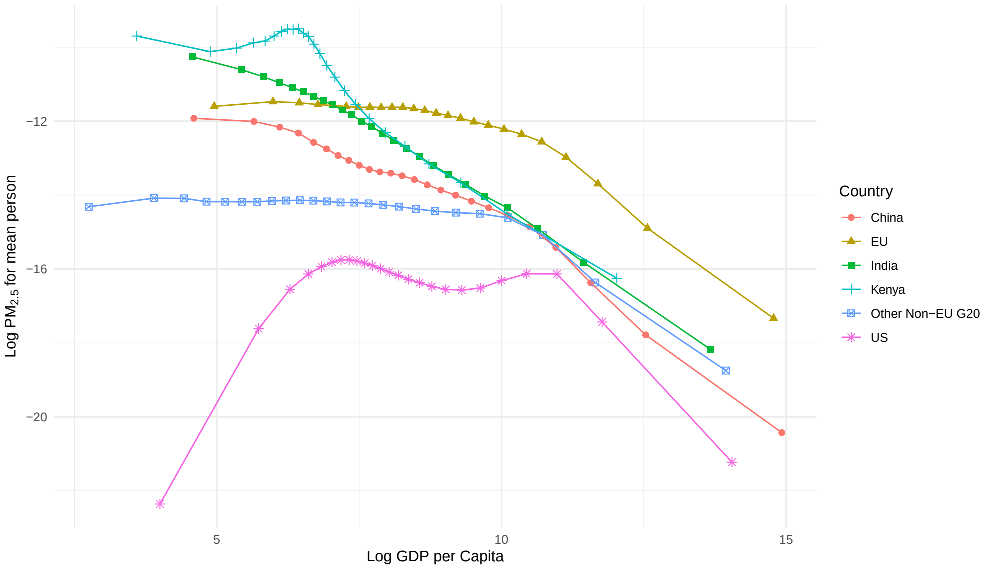


(a) Agro-ecological suitability map for rain-fed wheat

(b) Physical area footprint map for wheat

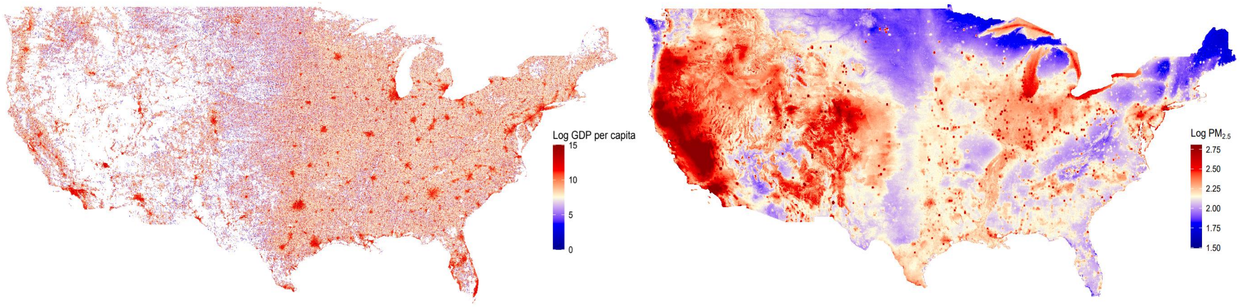
Panel (a) maps the suitability index (range 0-100) by class for rain-fed wheat using data from the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) Global Agro Ecological Zones version 4 (GAEZ v4) dataset. Results are for baseline climate (1981-2010) and assume advanced level of inputs and management. Panel (b) maps the physical area where wheat is grown in hectares (ha) using data from the Spatial Production Allocation Model (SPAM2010) dataset (International Food Policy Research Institute (IFPRI) 2019). It represents the actual area where wheat is grown, not counting how often production was harvested from it.

Figure A3: $PM_{2.5}$ versus GDP per capita within countries, alternative data

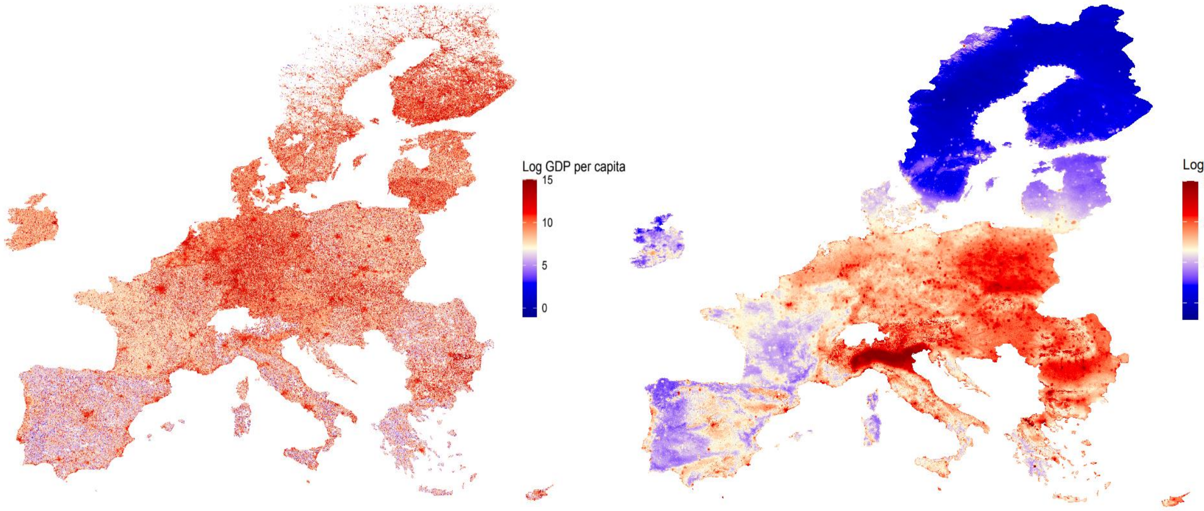


The figure displays a binned scatter plot using quantile based binning to illustrate the relationship between the average person's $PM_{2.5}$ and GDP per capita within selected countries- specifically China, the European Union, India, Kenya, the United States, and other non-EU G20 nations. $PM_{2.5}$ exposure for the mean person is given by the population-weighted concentration of $PM_{2.5}$ at the cell level, measured at a 1 km spatial resolution. It is calculated by weighting the ground-level $PM_{2.5}$ concentration in each cell by its population density divided by the total population density across the country or region. $PM_{2.5}$ data are from the van Donkelaar et al (2021) Monthly Global Estimates of Fine Particulate Matter and Their Uncertainty dataset. Population data are from the GHS-POP (R2023) (Global Human Settlement Layer Population Grid) dataset, which provides high-resolution residential population distribution. GDP figures come from the Global Gridded GDP (Global Gridded GDP under Historical and Future Scenarios, Version v7) dataset, which provides annual global GDP data on a 1 km grid.

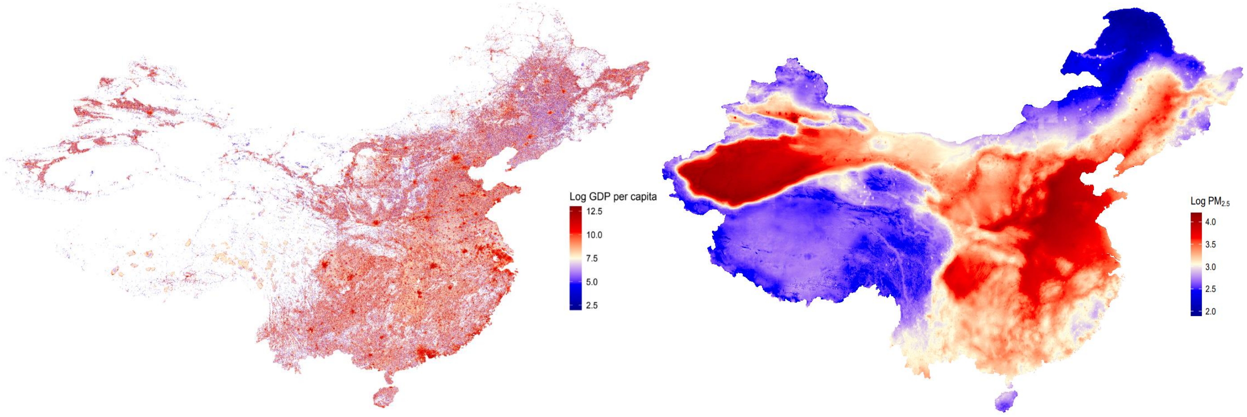
Figure A4: GDP Per Capita and $PM_{2.5}$ in the US, EU and China



(a) GDP per capita in 2020 and $PM_{2.5}$ in 2020 in the US



(b) GDP per capita in 2020 and $PM_{2.5}$ in 2020 in the EU



(c) GDP per capita in 2020 and $PM_{2.5}$ in 2020 in China

The maps in panels A, B and C display the distribution of log GDP per capita in 2020 vs log ground-level $PM_{2.5}$ over land in 2020 at a 1km spatial resolution in the United States, the European Union and China, respectively. GDP figures come from the Global Gridded GDP (Global Gridded GDP under Historical and Future Scenarios, Version v7) dataset. Population data are derived from the GHS-POP (R2023) (Global Human Settlement Layer Population Grid) dataset. $PM_{2.5}$ data are sourced from the GlobalHighPM2.5 (Global High-resolution and High-quality Ground-level $PM_{2.5}$ Dataset over Land) dataset, which combines ground-based measurements, satellite data, and model simulations.

B Data description

B.1 The Gridded Fossil Emissions Datasets

GCP-GridFED (version 2022.2) is a gridded fossil emissions dataset that is consistent with the national CO_2 emissions reported by the Global Carbon Project (GCP; `https://www.globalcarbonproject.org/`) in the annual editions of its Global Carbon Budget (Friedlingstein et al., 2022). It provides monthly fossil CO_2 emissions for the period 1959-2021 at a spatial resolution of $0.1° \times 0.1°$ (roughly 10km x 10km). The gridded emissions estimates are provided separately for fossil CO_2 emitted by the oxidation of oil, coal and natural gas, international bunkers, and the calcination of limestone during cement production. The dataset also includes the cement carbonation sink of CO_2. Note that positive values in GridFED signify a surface-to-atmosphere CO_2 flux (emissions). Negative values signify an atmosphere-to-surface flux and apply only to the cement carbonation sink. GCP-GridFED also includes gridded uncertainties in CO_2 emission, incorporating differences in uncertainty across emissions sectors and countries, and gridded estimates of corresponding O2 uptake based on oxidative ratios for oil, coal and natural gas (see Jones et al., 2021). This dataset is produced by scaling monthly gridded emissions for the year 2010, from the Emissions Database for Global Atmospheric Research (EDGAR v4.3.2), to the national annual emissions estimates compiled as part of the 2022 global carbon budget (GCP-NAE) for the years 1959-2021. The original unit is kg per 1km x 1km cell, but it has been rescaled in this paper to tonne carbon per 1km x 1km cell for consistency with the ODIAC data. See Jones et al. (2021) for a detailed description of this dataset and the core methods used to produce it. This dataset can be downloaded from the following link: `https://zenodo.org/records/7016360`

B.2 Open-Data Inventory for Anthropogenic Carbon Dioxide

ODIAC (version ODIAC2022) is a high-resolution global emission data product for carbon dioxide (CO_2) from fossil fuel combustion released in 2023, originally developed under the Greenhouse gas Observing SATellite (GOSAT) project at the National Institute for Environmental Studies (NIES), Japan. ODIAC pioneered the combined use of space-based night-time light data and individual power plant emission/location profiles to estimate the global spatial extent of fossil fuel CO_2 emissions. It has a spatial resolution of 1x1 km. The original time resolution is monthly, but the data has been processed in this paper to display the annual emissions. The ODIAC2022 dataset can be downloaded from the following link: `https://db.cger.nies.go.jp/dataset/ODIAC/DL\_odiac2022.html`

B.3 GlobalHighPM2.5

GlobalHighPM2.5 is a long-term, full-coverage, global high-resolution dataset of ground-level air pollutants over land. It is generated from ground-based measurements, satellite remote sensing products, atmospheric reanalysis, and model simulations using artificial intelligence, considering the spatiotemporal heterogeneity of air pollution. $PM_{2.5}$ includes secondary formation via chemical reactions from four main precursors of $PM_{2.5}$: ammonia, nitrogen oxides, sulfur dioxide, and volatile organic compounds. This dataset yields a high quality with cross-validation coefficient of determination (CV-R2) values of 0.91, 0.97, and 0.98, and root-mean-square errors (RMSEs) of 9.20, 4.15, and 2.77 µg m-3 on the daily, monthly, and annual basises, respectively. The dataset can be downloaded from the following link: `https://zenodo.org/records/6449741`

B.4 van Donkelaar et al. (2021) $PM_{2.5}$ Dataset (V5.GL.04)

The van Donkelaar et al. (2021) $PM_{2.5}$ dataset (version V5.GL.04) provides global and regional estimates of annual and monthly ground-level fine particulate matter ($PM_{2.5}$) concentrations for the period 1998–2022. This dataset is produced by combining satellite retrievals of Aerosol Optical Depth (AOD) from NASA MODIS, MISR, SeaWIFS, and VIIRS instruments with simulations from the GEOS-Chem chemical transport model. The $PM_{2.5}$ estimates are calibrated using a Geographically Weighted Regression (GWR) against global ground-based observations. V5.GL.04 updates previous versions by incorporating additional ground-based observations, extending the temporal coverage to 2022, and including data from the SNPP VIIRS instrument. The dataset has a high spatial resolution of 0.01° × 0.01° (1 km²). Gridded $\mathrm{PM}_{2.5}$ estimates are provided along with uncertainty estimates. The dataset can be downloaded at the following link: `https://wustl.app.box.com/v/ACAG-V5GL04-GWRPM25`. See van Donkelaar et al. (2021) for a detailed description of the methodology.

B.5 GLAD Global Land Cover and Land Use Dataset

The GLAD Global Land Cover and Land Use Change dataset quantifies changes in forest extent and height, cropland, built-up lands, surface water, and perennial snow and ice extent from the year 2000 to 2020 at 30-m spatial resolution. The global dataset derived from the GLAD Landsat Analysis Ready Data. Each thematic product was independently derived using state-of-the-art, locally and regionally calibrated machine learning tools. Each thematic layer was validated independently using a statistical sampling. It has a spatial resolution of 0.00025° per pixel (approximately 30 meters at the equator). Forest is defined as areas with wildland, managed, and planted tree cover, including agroforestry and orchards. The forest height was mapped globally for woody vegetation taller than 3 m. The dataset employs the global Landsat-based forest height model calibrated for the year 2019 using GEDI observations. For the boreal forests north of 52°N, where GEDI data are absent, it uses a set of regional models calibrated with available GEDI data and manually collected training. The same model was applied to estimate forest height for the years 2000 and 2020. To reduce errors and noise in the model outputs, extensive filtering of the output products were implemented. The forest extent is generated by attributing pixels with forest height taller than 5m as the "forest" land cover class, to ensure consistency with the FAO FRA forest definition. The forest definition employed here differs from the one used by the FAO by the inclusion of trees outside forests (agroforestry, orchards, parks) and the exclusion of temporally unstocked forest areas. Link to access: `https://glad.umd.edu/dataset/GLCLUC2020`

B.6 Global Forest Change 2000-2020 Version 1.8

The Global Forest Change 2000-2020 dataset is the result of time-series analysis of Landsat images in characterizing global forest extent and change from 2000 through 2020. The Global Land Analysis and Discovery (GLAD) laboratory at the University of Maryland, in partnership with Global Forest Watch (GFW), provides annually updated global-scale forest loss data, derived using Landsat time-series imagery. These data are a relative indicator of spatiotemporal trends in forest loss dynamics globally. The dataset has a spatial resolution of 0.00025° per pixel (approximately 30 meters at the equator). Trees are defined as vegetation taller than 5m in height and are expressed as a percentage per output grid cell as '2000 Percent Tree Cover'. 'Forest Cover Loss' is defined as a stand-replacement disturbance, or a change from a forest to non-forest state, during the period 2000–2020. The dataset has been downloaded from the following link: `https://storage.googleapis.com/earthenginepartners-hansen/GFC-2020-v1.8/lossyear.txt`

B.7 Berkeley Earth High-Resolution (Beta)

The Berkeley Earth High-Resolution (Beta) dataset provides high-resolution global monthly gridded mean temperature anomalies, covering the entire Earth from 1850 to the present. The dataset has a spatial resolution of 0.25° x 0.25°, which is roughly equivalent to 27km x 27km. Temperature anomalies are calculated relative to the 1951-1980 averages. It is important to note that this data has not yet undergone peer review. Files based on this new data set are being provided as part of an early preview to aid in the identification of any remaining bugs or errors.

Temperature project for high resolution gridded data fields. These fields contain reconstructed monthly temperature anomaly values generated by the Berkeley Earth project based on our method of climate analysis. A surface air temperature anomaly field is provided, in degrees C, for each pixel. Missing values are reported as NaN. A value is reported as missing if the coverage diagnostic indicates that the locally available data provides less than a 20% constraint on the anomaly. Link to access: `link:https://berkeleyearth.org/data/`. For academic publications and other permissions requests please contact permissions@berkeleyearth.org.

B.8 Global Human Settlement Layer Population Grid

The GHS-POP (R2023) spatial raster dataset depicts the distribution of residential population, expressed as the number of people per cell. Residential population estimates between 1975 and 2020 in 5-year intervals and projections to 2025 and 2030 derived from CIESIN GPWv4.11 were disaggregated from census or administrative units to grid cells, informed by the distribution, volume, and classification of built-up as mapped in the Global Human Settlement Layer (GHSL) global layer per corresponding epoch. This dataset is available for different epochs, resolutions and coordinate systems but the version used here contains data on 2020 with a spatial resolution of 30 arcsec and WGS84 coordinate system. The dataset has been downloaded from the following link: `https://human-settlement.emergency.copernicus.eu/download.php?ds=pop`. More information can be found in the following report: European Commission, GHSL Data Package 2023, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/098587, JRC133256

B.9 Global Gridded GDP

"Global gridded GDP under the historical and future scenarios (Version v7)" is a global gridded dataset that includes annual global GDP from 2000 to 2020. The unit is PPP 2005 international dollars. This dataset consists of a total of 101 tif images with spatial resolutions of 1 km (in 7 zip files) and 0.25-degree, respectively. The gridded GDP are distributed over land, with Antarctica, oceans, and some non-illuminated or depopulated areas marked as zero. The spatial extents are 90S - 90N and 180E - 180W in standard WGS84 coordinate system. The dataset has been downloaded from the following link: `https://zenodo.org/records/7898409`

B.10 Global Agro-Ecological Zones version 4

GAEZ v4 (Global Agro-Ecological Zones version 4) is the most comprehensive global dataset for agro-ecological and natural resource assessments, offering detailed spatial data and insights into agricultural potential and resource use. Developed to support global users, it provides consistent, high-resolution spatial data on agro-ecological conditions and crop performance.

The dataset includes spatial data in raster format with a standard resolution of 5 arc-minutes (approx 9 x 9 km at the equator) and finer-resolution maps (30 arc-seconds, approx 0.9 x 0.9 km) for specific features such as AEZ classification, soil suitability, and terrain. It incorporates baseline data from 2010, including global land cover, harmonized soil databases, terrain information, and biodiversity-rich areas. Climate data are derived from historical trends (1961–2010) and future simulations using IPCC AR5 Earth System Models for four Representative Concentration Pathways (RCPs). The dataset has been downloaded from the following link: `https://gaez.fao.org/`

B.11 The Spatial Production Allocation Model

The Spatial Production Allocation Model (SPAM2010) is a global dataset providing disaggregated estimates of crop production patterns. It uses a variety of input data and a cross-entropy approach to map the spatial distribution of 42 crops across two production systems (subsistence and commercial). The dataset disaggregates data from coarse administrative units, such as countries and subnational provinces, to finer grid cells with a resolution of 10 x 10 km.

SPAM data highlights spatial patterns in crop performance, offering a global view of agricultural production systems and land use. This information is useful for analyzing crop distribution trends, informing agricultural policies, and supporting rural development and food security initiatives. The dataset has been downloaded from the following link: `https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/PRFF8V`

C Data References

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