Urban Air Pollution Final Report

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## Introduction

Urban air pollution is a serious issue affecting urban regions all over the globe. It is linked to a lower quality of life and is associated with adverse impacts, including contributing to global and local climate change and increased rates of respiratory and cardiovascular illnesses[1]. These climate and health effects make urban air pollution a driving factor behind loss of urban biodiversity and natural ecosystems. Furthermore, these impacts are not distributed equitably throughout cities, with marginalized communities suffering the brunt of the consequences. Perhaps the most important stakeholders in this problem are urban residents, who both produce air pollution and are affected by it. Also essential to the pollution calculus are wildlife and ecosystems, which comprise the natural environment. In balanced and healthy ecosystems, the plant and animal life help absorb air pollution and mitigate its impacts. A third important stakeholder to consider are the regulatory and governing agencies, which create and enforce environmental regulations on air pollution. These agencies also interface with large emission economic sectors like heavy industry, agriculture, and transportation, all of which are prerequisite to a healthy and vibrant economy, but have historically been some of the greatest sources of anthropogenic air pollution and thus its coincident negative effects. The complexity of addressing an issue like air pollution – in which the number of actors are many and the solutions are stymied by geopolitics as much as economic effects like the famed "tragedy of the commons" – means that any analysis of how policymakers should address it must include considerations of all stakeholders and a comprehensive understanding of the interconnectivity of the systems which underlie the interactions between the air and the society. This imperative becomes more essential as rising air pollution is an ever more ominous issue facing wealthy and developing economies alike.

The vast majority of urban air pollution is anthropogenic and on the global scale, overwhelmingly comes from cities. Certain obvious sources of emissions are those which involve the burning of fuels and release of chemicals. For example, open combustion from industrial activity and transportation make up the bulk of greenhouse gas and particulate matter emissions. However, less acknowledged but equally important sources of pollution come from activities like agricultural processes, waste disposal, and the various set of individual actions, such as open fires and the use of natural gas[2]. Atmospheric oxidants, which include carbon monoxide and volatile organic compounds, are produced primarily by vehicle emissions. Acidifying compounds include sulfur dioxide, nitrogen oxides, and ammonia. Sulfur dioxide is mainly produced by industrial processes, transportation, and energy production, while nitrogen oxides primarily come from transportation activity, and ammonia from agricultural emissions[3]. All of these compounds that comprise urban air pollution have significant impacts on the atmosphere, natural environment, and human wellbeing.

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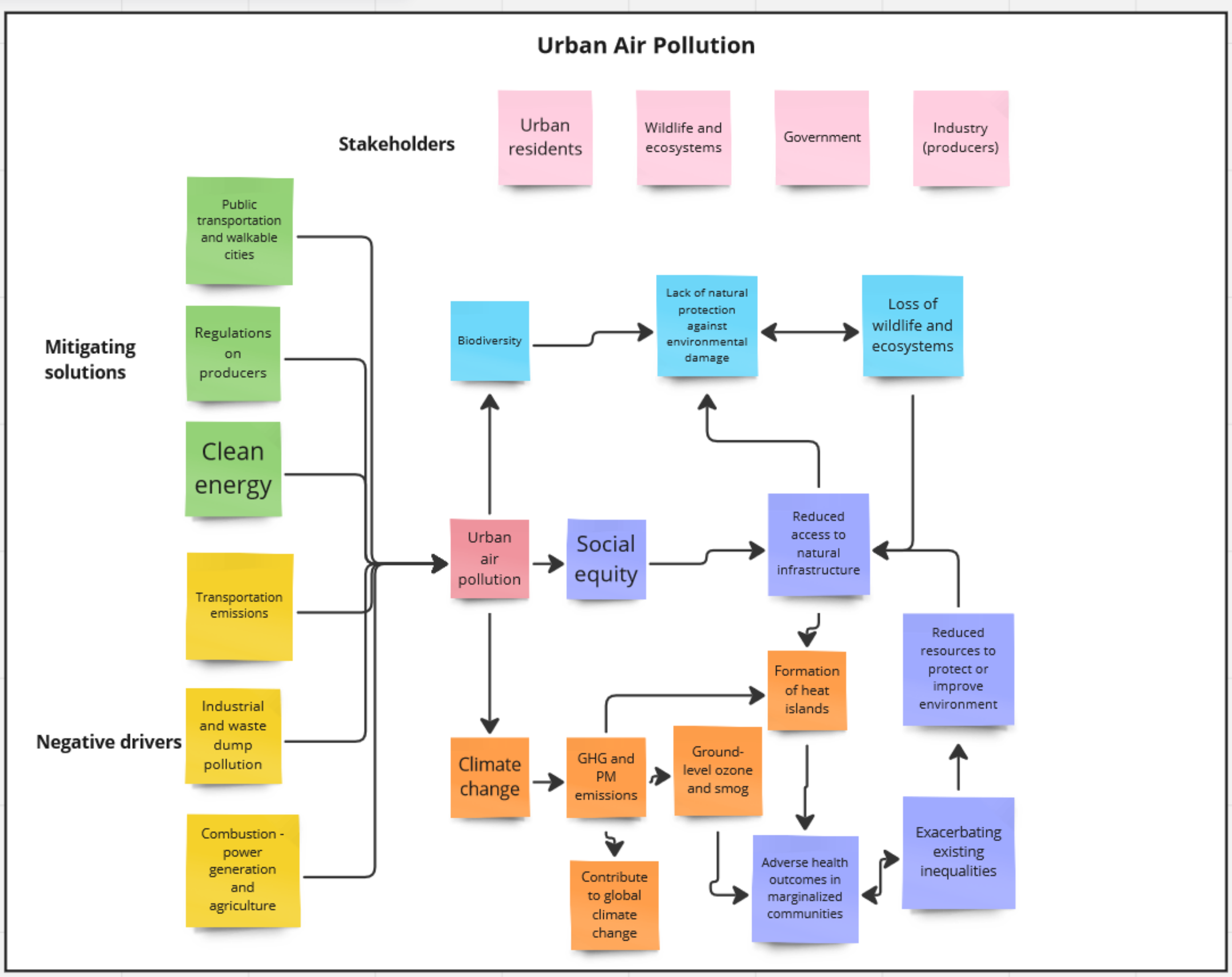
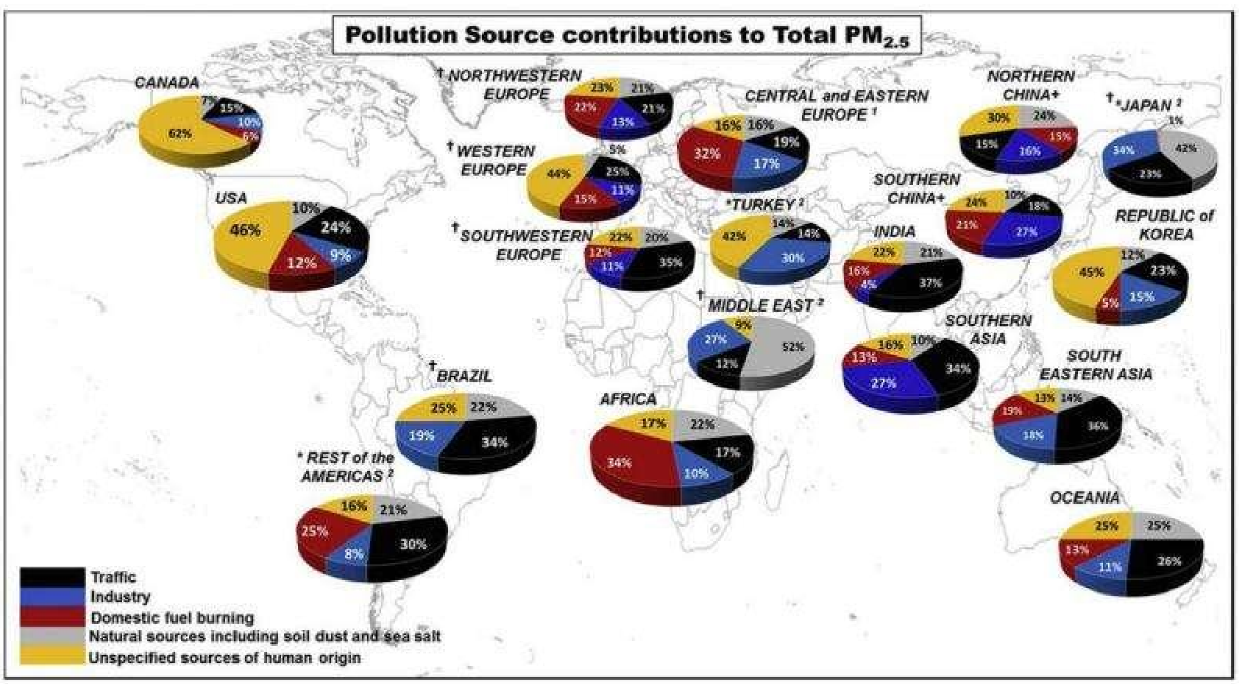
[1] National Institute of Environmental Health Sciences, "Air Pollution and Your Health."

[2] United States Environmental Protection Agency, "Our Nation's Air 2020."

[3] Mcdonald, "11 - Air Pollution in the Urban Atmosphere."

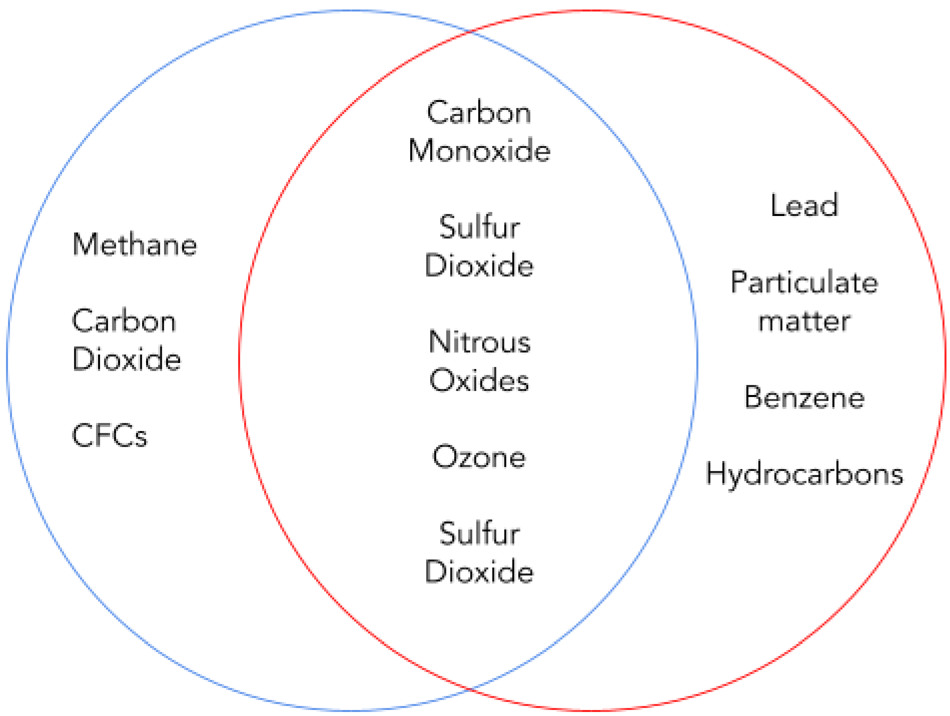

Urban Air Pollution
Stakeholders
Urban residents
Wildlife and ecosystems
Government
Industry (producers)
Mitigating solutions
Public transportation and walkable cities
Regulations on producers
Clean energy
Negative drivers
Transportation emissions
Industrial and waste dump pollution
Combustion - power generation and agriculture
Biodiversity
Lack of natural protection against environmental damage
Loss of wildlife and ecosystems
Urban air pollution
Social equity
Reduced access to natural infrastructure
Formation of heat islands
Reduced resources to protect or improve environment
Climate change
GHG and PM emissions
Ground-level ozone and smog
Contribute to global climate change
Adverse health outcomes in marginalized communities
Exacerbating existing inequalities


Pollution Source contributions to Total PM2.5
CANADA
† NORTHWESTERN EUROPE
CENTRAL and EASTERN EUROPE ¹
NORTHERN CHINA+
† *JAPAN ²
† WESTERN EUROPE
USA
† SOUTHWESTERN EUROPE
*TURKEY ²
SOUTHERN CHINA+
INDIA
REPUBLIC of KOREA
† MIDDLE EAST ²
SOUTHERN ASIA
† BRAZIL
AFRICA
SOUTH EASTERN ASIA
* REST of the AMERICAS ²
OCEANIA
Traffic
Industry
Domestic fuel burning
Natural sources including soil dust and sea salt
Unspecified sources of human origin

*Sources of PM2.5 globally by country*[4]

Urban air pollution contributes to climate change by increasing atmospheric concentrations of greenhouse gasses and particulate matter. In fact, it may be considered that urban "air pollution and climate change are two sides of the same coin"[5]. In an age of petrochemical power and runaway consumption, the constant demand for cheap power, goods, and the handling of human processes in urban environments results in the emission of compounds which are detrimental to overall health. In urban areas, this can result in the formation of ground-level ozone and smog due to heat and other emissions such as particulate matter[6]. These have ramifications for surface-level atmospheric chemistry and the health of urban inhabitants. One of the most destructive types of urban air pollution is short-lived climate pollutants, such as methane and hydrofluorocarbons, which are much more potent than carbon dioxide for accelerating climate change. Therefore, while there is not necessarily a perfect overlap between compounds which are causes for anthropogenic climate change and those which cause air pollution, there is enough match between them that many of the proposed solutions to address them are similar.

Comparison of common greenhouses gasses (left), air pollutants (right), and ones which fall under both (middle)




These impacts on the climate spur biodiversity loss driven by urban air pollution damaging natural ecosystems and harming wildlife through adverse impacts on health and habitats. In particular, sulfur dioxide and nitrogen oxides emitted can create acid rain that causes water and soil to acidify, which can affect the ability of plants sensitive to the pH to live and

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[4] Commission, European, and Joint Research Centre. “Urban Air Pollution – What Are the Main Sources across the World?”
[5] World Bank, “Climate Explainer.”
[6] Centers for Disease Control and Prevention, “Air Pollution.”

grow. The ability of an ecosystem to cycle nutrients and carbon is also affected, leading to less protection against climate change. Furthermore, the formation of ground-level ozone can damage the cell membranes of plants, reducing an ecosystem's ability to filter out pollutants from the air[7]. These all have ramifications for human dependence on nature, such as for water provision, and many of these impacts can create positive feedback cycles, such as the reduced ability of ecosystems to clean out air pollution and fight against climate change.

Urban air pollution also exacerbates social inequity because point polluters, such as factories, tend to be constructed near marginalized communities due to historical redlining[8]. Furthermore, the infrastructure in these communities typically has few green spaces to act as absorbers of or buffers against air pollution[9], nor do these communities have the resources to fight against air pollution. For example, it is estimated by the World Health Organization that 4.2 million premature deaths per year can be attributed to air pollution, with most of these deaths occurring in developing countries[10]. Even within first-world countries, there are socioeconomic and racial disparities. Multiple studies focused on the United States have found that those with little to no income, low education level, or who are people of color tend to have greater exposure to air pollution from transportation and live in areas with higher ambient concentrations of air pollution[11]. All of these factors result in worse living conditions and lower quality of life, widening the gap between social groups and economic classes.

The increasing development of urban regions means air pollution will continue to be an issue and, with current trends, will worsen in the coming fifty years. To combat this, urban areas need to adopt effective policies and implement strategies to reduce urban air pollution and mitigate its consequences. What the most important factors driving urban air pollution are, what the range of possibilities is, and what mitigating solutions people are most likely to desire or be able to adopt will be covered in the following sections.

**Imagining the Future**

Two key drivers of urban air pollution were chosen based on their importance to the issue and the uncertainty in how they might contribute to the problem in the future. Urban development was identified as one because as explained previously, cities account for the majority of anthropogenic air pollution production, especially through transportation, industry, and other activities such as agriculture and waste disposal. Thus, the more cities grow, the greater capacity for emitting urban air pollution. However, the rate at which urban areas will develop and with what kinds of infrastructure are uncertain and will depend on various factors such as population growth and social and environmental policies. These in turn will affect how much air pollution, and what types of air pollutants, will be emitted by a city as it develops.

Likewise, the human-nature relationship, also referred to here as harmony with nature, was designated as the other highly important and uncertain driving factor of urban air pollution because how people will respond to regulations, changes in their environment, and what attitudes towards nature they hold will influence what actions they take that can contribute to or mitigate urban air pollution. Given the global nature of the issue of urban air pollution and the great

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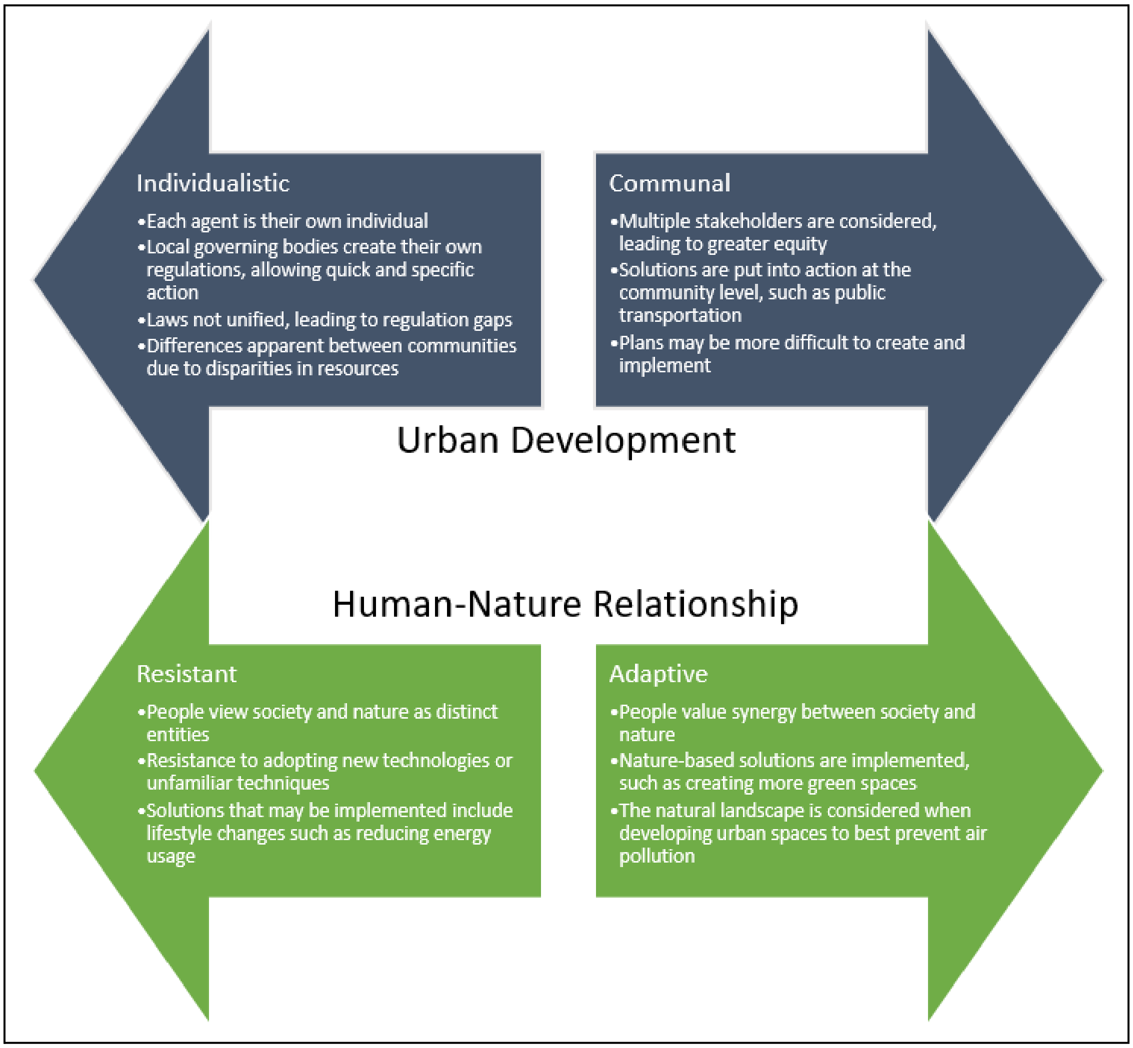
[7] United Nations Economic Commission for Europe, "Air Pollution, Ecosystems and Biodiversity."
[8] Cushing et al., "Historical Red-Lining Is Associated with Fossil Fuel Power Plant Siting and Present-Day Inequalities in Air Pollutant Emissions."
[9] Nowak, Ellis, and Greenfield, "The Disparity in Tree Cover and Ecosystem Service Values among Redlining Classes in the United States."
[10] World Economic Forum, "Best Ways To Reduce Air Pollution & Tackle Climate Change Together."
[11] American Lung Association, "Disparities in the Impact of Air Pollution."

diversity in human cultures and individual lifestyles, there is much uncertainty about what people in an urban area do that affects the local air quality and how their mindsets may evolve in the future.

It is important to note that these drivers do not necessarily correlate with each other and may affect the future of cities in diverse ways. They both encapsulate the top-down nature of governmental regulation of the environment and the bottom-up nature of human behavior, and there are many ways these key drivers may be combined together to create a diverse spectrum of diverging futures. The spectrums designated for the two driving factors encapsulate a wide range of possible futures because they describe how humans contribute to urban air pollution and what kinds of mitigating solutions they would be willing to implement. These dimension endpoints were identified as an individualistic approach versus a communal approach for urban development and a resistant mindset versus an adaptive mindset for harmony with nature.




The individualistic approach focuses on each urban resident as their own entity whose needs are considered independently of those around them or in different communities. Any action taken contributing to or mitigating urban air pollution is done at the personal level, meaning there will be disparities between people and communities with different socioeconomic statuses and attitudes towards the environment. Environmental policies are implemented by each local governing body, which allows for quick action and specific laws tailored to each area but may also lead to gaps in regulation between regions and communities.

In contrast, the communal approach considers each community as the sum of its residents and takes into account the needs of all stakeholders. Mitigating solutions for urban air pollution are implemented at the community level, such as public transportation or walkable and cyclable infrastructure[12], but the exact details of the solutions will depend on the technologies used and the attitudes people hold towards nature. Environmental policies are created with multiple stakeholders in mind and take into account historical and current inequities to narrow the gaps between different social groups and economic classes, although this may add intricacies and make them more complicated to design and put into action.

For people's relationships with nature, a resistant mindset means humans view society and nature as being two distinct entities and that technology should be used as a way for humans to exert control over and extract resources from nature. The "resistant" part of the name comes from people's resistance to innovative ideas and changing the status quo to solve the problem of urban air pollution, such as using indigenous knowledge about the local natural environment[13] or to adopting new, cleaner technologies that would reduce emissions[14]. If efforts are made to combat urban air pollution, they may manifest as lifestyle changes, such as reducing the number of commutes or lowering energy usage, but they may not be substantive enough to counter the air pollution produced.

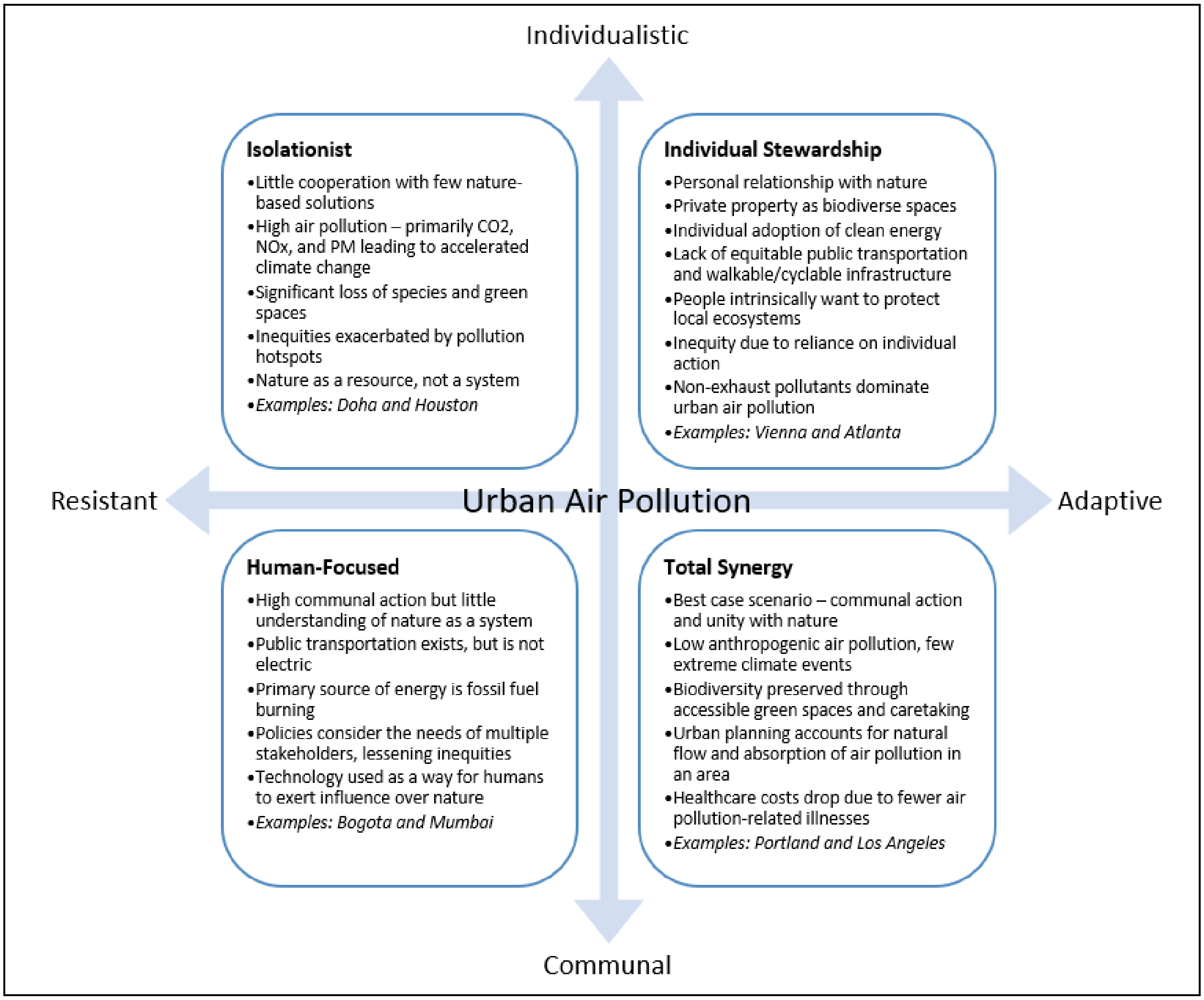
On the other end of the spectrum, an adaptive mindset means people see the value in being in synergy with nature and adapt their lifestyles accordingly to act as a part of the natural ecosystems. This could manifest as implementing nature-based solutions to combat urban air pollution, such as taking into account natural ecosystem services and making existing city infrastructure greener, to best reduce the impact of emissions[15]. Furthermore, people are open to creating and using new technologies to reduce ambient concentrations of air pollutants and to prevent air pollution from being produced in the first place. Together, these endpoints encapsulate a wide range of possible futures which will be identified and elaborated upon in the subsequent section.

**Scenario Logics**

Crossing the two key drivers and their spectrum endpoints, four divergent futures are found, labeled *Isolationist*, *Individual Stewardship*, *Human-Focused*, and *Total Synergy*. Each respectively represents an individualistic-resistant, individualistic-adaptive, communal-resistant, and communal-adaptive scenario, as outlined in the following figure. While useful, there still are some limitations to the comprehensiveness of the descriptions provided by these scenarios. A simplifying assumption made about the interactions between the key indicators and dimension endpoints was that the combination of dimensions represented by each scenario is such that the endpoints are considered mutually exclusive. For example, there would not be a scenario having both robust public transportation (a communal mindset) and significant private vehicle use (an individualistic mindset), even though this may occur in the real world. However, this also allows for identifying the widest range of possibilities concerning how urban areas and their residents

[12] United States Environmental Protection Agency, "Smart Growth and Transportation."
[13] United Nations Environment Programme, "How Indigenous Knowledge Can Help Prevent Environmental Crises."
[14] United States Environmental Protection Agency, "Progress Cleaning the Air and Improving People's Health."
[15] Menon and Sharma, "Nature-Based Solutions for Co-Mitigation of Air Pollution and Urban Heat in Indian Cities."

can contribute to and mitigate urban air pollution because nearly all real-life scenarios should fall within the space defined by the logic matrix. How these four scenarios may play out and what impacts they have on urban air pollution are described in the following paragraphs using details from real-world cities.

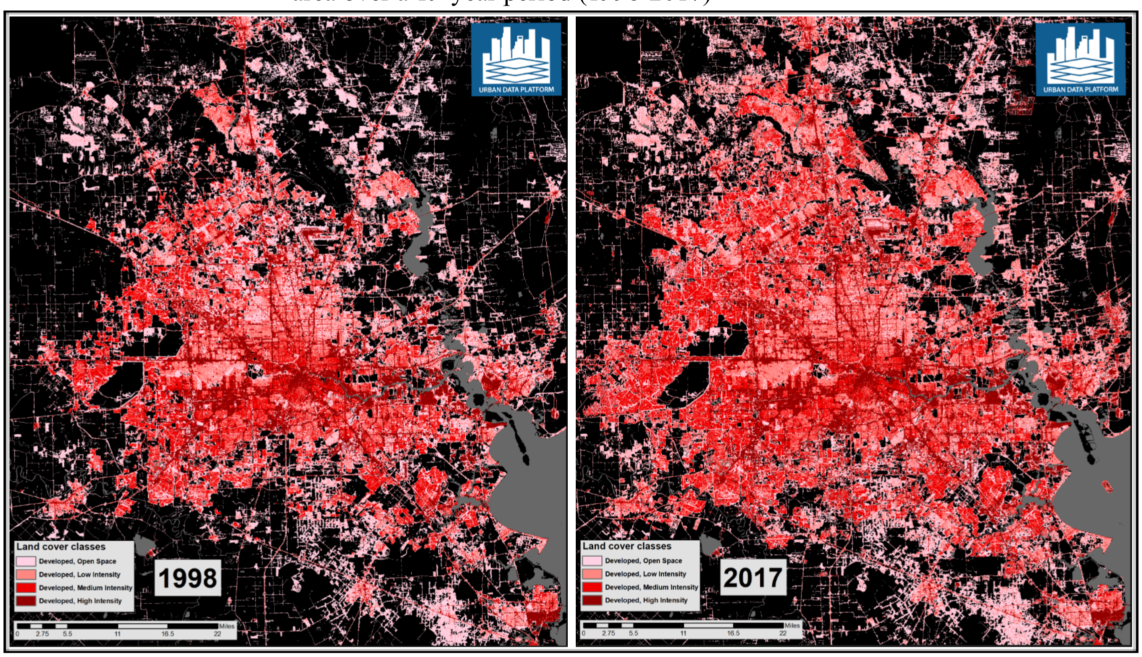



The Isolationist scenario may be likened to the worst-case scenario for urban air pollution, where ambient concentrations of air pollutants are high and few mitigating solutions are being implemented. Details about how this future might play out were taken from two real-world examples, the cities Doha, Qatar and Houston, USA. The primary source of energy is fossil fuel burning, which results in unhealthy concentrations of combustion byproducts[16]. Moreover, car-centric development has been the predominant mode of building typology for decades.[17] This leads to greater exposure to air pollution and incurring higher healthcare costs due to associated illnesses along with accelerating climate change and increasing the risk of extreme climate events. In both of these cities in particular, this type of development has led to

[16] Walker, “Qatar Holds World’s Second Largest Ecological Footprint per Person.”
[17] Kinder Institute for Urban Research, “The Rapid Urbanization of Houston.”

demonstrable increases in health impacts like asthma, cancer, and cardiovascular disease relative to other cities, especially amongst the impoverished and racial minorities.[18] [19] In this scenario, people have an internalized resistance to new technologies and innovative solutions, so there is minimal adoption of clean energy. Additionally, because nature is viewed as a resource for human use instead of collaboration, there are few urban green spaces and most natural ecosystems have been damaged so that their ability to absorb pollution from the air is reduced. This is both caused and by and leads to extensive biodiversity loss, along with poorer urban air quality, especially around marginalized communities. Furthermore, there are evident socioeconomic disparities between communities, resulting in some becoming air pollution hotspots due to being located near or downwind of major polluters.[20] The individualistic mindset people in this scenario hold means there are few community-based solutions, such as public transportation or walkable and cyclable infrastructure.[21] This all culminates in low overall resilience to urban air pollution.

This map shows the rapid expansion of developed land around the Greater Houston area over a 19-year period (1998-2017)[22]




The next future is the Individual Stewardship scenario, which represents an adaptive attitude towards nature and an individualistic mindset for urban development. People value nature as part of human culture and have an intrinsic desire to protect their local green spaces and native ecosystems. In this scenario, environmentally-friendly changes are implemented quickly but are localized to an extreme degree. Actions are performed on an individual level, and thus inequities may be exacerbated if they exist within a context of socioeconomic inequality or differential access to green space. In contrast to the prior scenario, there is less air total air

[18] "Black Children in Houston at Higher Risk for Asthma."
[19] Hussain, "Qatar 'most Affected' Arab Country by Air Pollution."
[20] Union of Concerned Scientists, "Double Jeopardy in Houston."
[21] Al-Thani et al., "Urban Sustainability and Livability."
[22] "The Rapid Urbanization of Houston."

pollution emitted from exhausts, but non-exhaust pollutants are still a concern. Furthermore, if the city in this scenario is located within a developing economy, air pollution emitted from industrial sources can be extremely high and still have extensive health impacts. Examples of this type of city within richer countries are Vienna, Austria and Atlanta. In both of these cities, municipal projects have advanced beneficial policies on a systemic scale, but there is less engagement with questions of equity. The *Klimabonus* (a UBI-like dividend whose funds are appropriated from a progressive carbon tax) and the Beltline green development project both have ambitious goals to advance sustainability and air pollution mitigation, but the bottom-up approach put the success of these projects on the cumulation of many individuals' economic activities.[23]

The third scenario identified is the Human-Focused future, where people value community between humans but have not invested into the relationship humans have with nature. Bogota, Colombia and Mumbai, India were selected as real-world examples of this scenario. The communal mindset means solutions implemented are community-based, such as providing public transportation and building walkable and cyclable infrastructure. However, fossil fuel burning of gasoline and diesel is still the primary source of energy, so the urban air pollution produced by sectors such as transportation remains significant.[24] Barriers to the adoption of clean energy stem primarily from underdevelopment or lack of financial resources to motivate renovating infrastructure and switching to new technologies[25]. However, action plans created by the government to mitigate air pollution take into account the needs of multiple stakeholders and allow for specialized recommendations for specific areas with particularly high concentrations of air pollutants, such as certain villages in Mumbai[26]. The result is that while there is still a substantial amount of urban air pollution, cities in this scenario have the social foundations for combating this problem as a community equitably and effectively. In the case of Bogota, there is significant support from the local government to invest in alternative modes of transportation like electric buses to divest from its current fleet of diesel buses.[27] This effort is especially salient given the rapid urbanization of the city along with the geographic characteristics of the municipal area itself – mostly that Bogota is very high in elevation and is located within a series of mountainous valleys, both of which contribute to high persistent levels of pollutants.[28] In the interim, there are differential impacts of this pollution on the health of the population, but in the long-term, the city may change its trajectory to resemble something more akin to the final scenario, Total Synergy.

The final of the four is the Total Synergy future, which may be considered the best-case scenario for urban air pollution. In this scenario, urban planning is done within a philosophical framework that centers nature as part of development and the planning process, rather than something to work around, against, or merely consider. Cities have a high adoption rate of clean energy, mass transit, and non-motorized infrastructure. The impacts of impervious surfaces on subsurface water tables is minimized due to the presence of bioswales and endemic native plant ecosystems, which also prevents pollutant runoff from being evaporated into the local atmosphere. Point sources of emissions like industrial sites and dumps are either located far

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[23] "Austria's Klimabonus - Citizens' Climate Europe."

[24] World Economic Forum, "Tackling Air Pollution in One of the World's Most Congested Cities."

[25] Copenhagen Consensus, "Colombia Perspective: Air Pollution."

[26] Natural Resources Defense Council, "Clearing the Air: Highlights of City Actions in 2020 to Reduce Air Pollution."

[27] "The Air Quality Crisis in Bogota Is an Opportunity to Rethink Urban Development."

[28] Copenhagen Consensus, "Colombia Perspective."

away from important ecosystem functions and people, or have internalized measures in place to ameliorate the impact of the emissions on local communities. Furthermore, in this future, prevention and treatment of air pollution is performed equitably across the urban geography, without a consideration of the socioeconomic status or perceived importance of the people, animals, and plants which inhabit the space. Lastly, resilience is baked into the core of all planning and development, and is done in coordination with marginalized communities. It was difficult to find truly representative examples of this scenario in the real world, but Portland and Los Angeles were selected for notable actions taken to ameliorate urban air pollution and strengthen the human connection with nature. Portland has been a leader in incorporating activist language into its municipal Climate Action Plans. As an example, it is currently one of five cities in the US to draw an explicit connection between air pollution and environmental justice principles.[29] Portland has also promoted the inclusion of nature in urban spaces through programs such as Ecoroofs, Green Street Stewards, and tree planting, strengthening the relationship between humans and nature[30]. Los Angeles, for its image as a sprawling, low-density metropolis, has recently begun to make clear steps towards decarbonizing and recognizing historical wrongs perpetrated against marginalized communities. The Just Transition Strategy for the city has worked with activist groups to divest away from fossil fuel derricks located within the city.[31] This, while an admirable example of decarbonization, is also being undertaken in light of research which demonstrated that minority communities – which were disproportionately located next to the oil fields – have far higher rates of certain diseases which partially result from chronic air pollution exposure.[32] Los Angeles has also implemented the Green Zones program which focuses on improving the health outcomes and environmental quality in marginalized communities disproportionately impacted by urban air pollution through land use planning and funding business owners to promote the renovation of processes and infrastructure[33]. Together, both cities demonstrate the capacity for humans to improve upon existing conditions and create urban areas that can reduce air pollution in synergy with people and nature.

Given the two drivers of urban development and harmony with nature, the dimension endpoints of individualism versus communality, and the four previous scenarios, there remains a need to identify certain measurable quantities which can help policymakers and strategists determine where on the scenario matrix their city is located. In selecting key indicators, it is important to distinguish between those measurements that are essential to fully understanding the impacts of pollution versus those which are merely useful for developing a more comprehensive apprehension of the situation. Moreover, key indicators should be extremely determinate – in that they by themselves can speak to many of the causative factors which determine overall pollution levels and their impacts. Thus, the key indicator metrics that were determined to measure the impacts of urban air pollution and the effectiveness of mitigating strategies were: first, the ambient air pollutant concentrations in an area, second, the number of urban green spaces supporting a large variety of species, and third, the distance of sources of air pollution from urban communities with respect to socioeconomic status. Each of these key indicators are backed by past research in their predictive capacity; in other words, by merely observing each indicator,

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[29] Diezmartínez and Short Gianotti, "US Cities Increasingly Integrate Justice into Climate Planning and Create Policy Tools for Climate Justice."
[30] "Green Infrastructure | The City of Portland, Oregon."
[31] Angeles, "Los Angeles County and Mayor Eric Garcetti Announce Results of First-Ever Transition Strategy for Oil Extraction Workers – COUNTY OF LOS ANGELES."
[32] McKenzie et al., "Childhood Hematologic Cancer and Residential Proximity to Oil and Gas Development."
[33] Los Angeles County Planning, "Green Zones Program."

any researcher or policymaker can quickly conceive of a hypothetical city's standing with respect to climate change, biodiversity, and social equity in relation to other cities.

Listed here is each key indicator along with a justification for its inclusion in the report. First, monitoring the ambient air pollutant concentrations in urban areas will assist in tracking what kinds of air pollutants are emitted and when and where, helping reduce exposure to urban air pollution and identifying drivers of climate change associated with it[34]. The number of urban green spaces with high biodiversity is a valuable metric because it shows how well natural ecosystems are sustained in urban environments and is a key indicator of how environmentally-conscious and habitable an area is[35]. Lastly, looking at the sources of air pollution with a social equity lens will enable policymakers and other stakeholders to understand how socioeconomic inequity plays into which communities and populations are most impacted by urban air pollution through a quantifiable metric that can inform where environmental action plans should focus their efforts most. These indicators will be used to assess the robustness of the selected strategies because they are all able to be measured reliably and numerically, providing a solid foundation of data to guide policies and benchmarks for a better urban atmospheric environment.

**Simulation Modeling**

The question selected to be explored in the model was "Given different natural landscapes, weather patterns, and urban layouts, what infrastructure design most reduces the air pollution exposure of native ecosystems and urban residents while minimizing the impact on climate change?"

Given the exigencies and time pressures involved with this exploration, there was little time to develop a thorough agent-based model of the complexity required to fully tackle this question. In this report, the relevant agents are numerous: first, the level of air pollution itself, which spreads around the environment and interacts with all other actors in different manners. Second, sources of air pollution are numerous. While the most obvious source of pollution are point emitters like industrial sites and fossil fuel burning locations, the majority of emissions come from dispersed locations like homes and roads. Modeling this behavior is extremely difficult. The presence of green spaces on the level of air pollution is easier to model, since the interaction between pollution and green spaces resembles that of a predator-prey simulation. Lastly, all of these have effects on socioeconomic equity, which is modeled by high and low land values. In the attached screenshots, there is this team's attempt at resolving all of these complex and interactive agents into one simple model.

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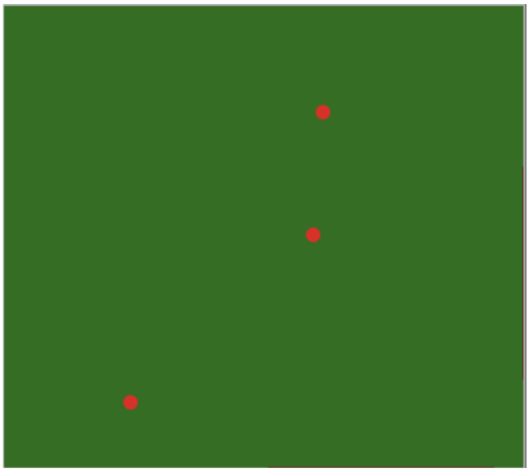
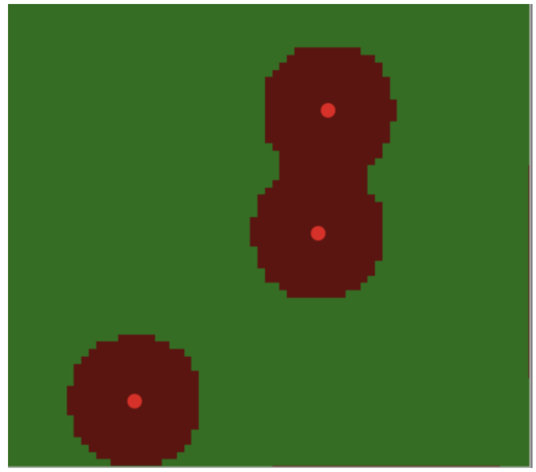
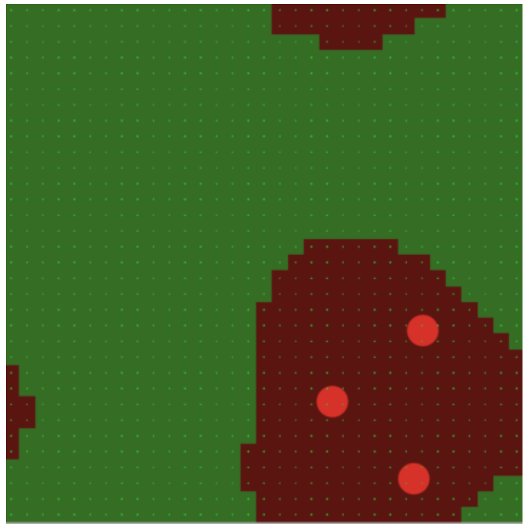
[34] United States Environmental Protection Agency, "Frequently Asked Questions about Air Emissions Monitoring."
[35] International Union for Conservation of Nature. "Embracing Biodiversity: Paving the Way for Nature-Inclusive Cities."

In the beginning state – on the left – there are three randomly placed sources of air pollution. These point emitters will create an expanding cloud of pollution equidistant from themselves. All of the surrounding land is coded as high-value. When the model begins, the land immediately surrounding the point emitters are re-coded as low-value land, in order to demonstrate the detrimental effects of pollution on health and land value. Not pictured here are the green spaces, which are randomly placed around the world. In wealthier areas, the green spaces are set to spawn at a much higher rate than the poorer areas. As the model progresses and time ticks by, there is a dynamic conflict between poor and wealthy areas in which there is a competitive game between the two. The third picture shows one simulation later on, in which the area of low-value land has expanded dramatically. It should be noted that the roughly circular shapes should not be taken as representative of the model's strengths, as the hypotheses created beforehand would have predicted a more amorphous shape to the high and low value areas. This is one of the difficulties and inadequacies of this model.

In another attempt at creating this model, the spawn rate for green spaces was set more evenly throughout the world, which unexpectedly had the effect of creating those more amorphous – and therefore predicted – "clouds" of pollution which the prevailing research has demonstrated exists around emission sites. However, due to the impossibility of evenly spacing green spaces in a grid-like fashion throughout the real world, this should also be considered a weakness of the model.



If more resources were available to the creation of further models, there would be greater emphasis laid on creating a road network with spaces in between that resembled Euclidean zoning. Moreover, the beginning state which has all land valued as high-value does not resemble real-world conditions, and this would be resolved in any future attempts. Ultimately, the scale and complexity of air pollution means that any model – even those which are overly simplified to the point of uselessness – are still extraordinarily complex to model.

**Scenario Strategies**

Three possible strategies identified for dealing with urban air pollution are adaptation, mitigation, and prevention. Adaptation means implementing solutions that make society more resilient to the impacts of urban air pollution. At the individual level, this can mean using air quality monitoring to plan around limiting personal exposure to air pollution and using air purifiers and filters to improve air quality within the home[36]. Solutions at the communal or regional level include strengthening air quality monitoring infrastructure, including determining where people are most likely to be exposed to urban air pollution and establishing pollution stats to understand where to focus efforts[37]. Addressing the health issues associated with exposure to urban air pollution is paramount, raising awareness of how people may be impacted and investing in research to understand the symptoms and possible treatments[38]. Finally, building infrastructure that is more resilient to climate events linked to urban air pollution, such as strengthening structures, can mitigate the difficulties of living with extreme heat and other issues[39].

The second strategy, mitigation, means reducing the effects of urban air pollution directly by decreasing the ambient concentrations of air pollutants in urban areas. One major mitigating

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[36] Wynne Armand, "Air Pollution: How to Reduce Harm to Your Health."
[37] Nyhan, "Coping with Air Pollution in an Age of Urbanisation."
[38] Keswani, Akselrod, and Anenberg, "Health and Clinical Impacts of Air Pollution and Linkages with Climate Change."
[39] American Society of Civil Engineers, "How to Make Infrastructure More Resilient against Climate Change."

strategy is creating urban green spaces, especially those with species proven to be adept at absorbing urban air pollution. Urban forests are particularly good at removing ground-level ozone and sequestering and storing carbon from the atmosphere[40]. Climate change is dependent on the cumulative amount of greenhouse gasses and other air pollutants emitted, so sequestering and storing them is the only way to prevent cascading effects in the future. Carbon dioxide is focused on due to the fact that it remains for a long time in the atmosphere after being emitted[41]. Recognizing and building upon the carbon sequestration and storage ability of urban residential areas is also a potentially viable idea, as the vegetation, soils, and other biogenic materials available in those areas have the capacity to improve the air quality and slow down climate change induced by air pollution[42]. To balance the cost of implementing air pollution sequestering and storing technologies, governments should provide incentives to put those technologies into place or create penalty fees for producing air pollution[43]. Reducing the ability of urban air pollution to spread out from sources of pollution has also been found to be effective. For example, transportation accounts for a significant proportion of air pollution produced. By constructing vegetation barriers and planting them with species adept at absorbing air pollution near roadways, the pollution emitted can be contained to and sequestered within a small area[44].

Finally, the preventative strategy attempts to address the problem by focusing on preventing urban air pollution from being emitted in the first place. Governmental policies that incentivize lifestyle changes, such as implementing free public transportation to reduce private vehicle usage or providing funding to cover the costs of switching household appliances and industrial equipment, are one way to lessen activities that contribute to emissions of urban air pollution. Policies that penalize the production of air pollution are also effective, particularly when enacted in hotspots of pollution[45]. At the technological level, developing and switching to air pollution prevention and control technologies such as mechanical collectors, absorbers, and condensers, as well as using cleaner fuels, less toxic materials, and improving the efficiency of industrial processes can limit the creation and emission of urban air pollutants[46].

Of these three strategies, the adaptive strategy is the most convenient solution to implement because it does not require any momentous change in philosophy or lifestyles. The current modes of energy production and privileged lifestyles which wealthier economies benefit from can be maintained. For these richer societies, adaptation is primarily a means for reducing the impact of air pollution on one's choices. In poorer economies, however, adaptation is done in response to a lack of capital power to make more demonstrative and effective change. It can be cost efficient, but in some respects it speaks to a continuation of socioeconomic inequality across the world. One of the great benefits in these poorer economies is that it is useful for areas that are heavily burdened by the impacts of urban air pollution by directly dealing with the environmental damage and health issues caused. However, this strategy's weakness lies in that it will most likely not maintain any effectiveness in the long-term, nor may it even be able to deal with all the current impacts of urban air pollution, depending on the severity. It also does not address the production of urban air pollution and while it is helpful for managing the fallout, air pollution will be a persistent problem. As it does little to address the long-term causes and effects

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[40] United States National Park Service, "Air Pollution Removal by Urban Forests."
[41] Novoselov, "Carbon Sequestration: A Critical but Less-Understood Piece of the Climate Puzzle."
[42] Kinnunen et al., "Carbon Sequestration and Storage Potential of Urban Residential Environment – A Review."
[43] Clifford, "Carbon Capture Technology Has Been around for Decades — Here's Why It Hasn't Taken Off."
[44] Sacramento Metropolitan Air Quality Management District, "CEQA Guidance & Tools."
[45] Jonidi Jafari, Charkhloo, and Pasalari, "Urban Air Pollution Control Policies and Strategies."
[46] United States Environmental Protection Agency, "Smart Growth and Transportation."

of air pollution on climate change, biodiversity, and social equity, this is the least robust solution of the three strategies outlined.

The second strategy, mitigation, performs well in scenarios where concentrations of urban air pollution are high. This is similar to the first strategy, adaptation, except mitigation means dealing with the air pollutants themselves directly. The strengths of this strategy are its potential for decelerating or reversing climate change while not requiring the wholesale and systemic change of processes, values, and systems which is required for a preventative strategy. Despite this, however, depending on the financial and technological ability of an area, the cost of implementing the technology and processes necessary may be out of reach for even wealthier communities. There are some solutions which are cost efficient, but these are mostly patchwork solutions which do not address the core issue. For poorer economies, the capital required to implement these larger solutions can be exorbitant and thus not feasible. There is also the question of the immediate exigencies of air pollution within the context of advancing climate change. Depending on the level of air pollution that is emitted, it may not be possible to remove pollutants quickly enough to alleviate the most acute effects and negative externalities associated with pollution exposure. This entails a continuation of policies which cause unnecessary suffering and harm to the natural ecosystem, while further impairing future generations' ability to address pollution exposure. Furthermore, there may be difficulty in finding suitable locations for sequestering and storing greenhouse gasses, the capacity of which will vary with the natural landscape and ecosystems of an area.

The preventative strategy is effective for areas not yet heavily affected by or not producing much urban air pollution, such as newly-built urban areas or those with few local pollution sources. It is also useful for slowing down the progression of climate change and other issues worsened by air pollution because it stops the cumulative buildup of pollutants in the atmosphere. At the governmental level, policies which offer incentives for meeting benchmarks and penalties for causing some kind of harm are already common, so creating regulations focused on preventing the production of urban air pollution is not too innovative an idea. Likewise, efforts to design more efficient industrial and agricultural processes and to reduce the use of toxic materials are useful even outside of preventing urban air pollution, so inspiring the motivation and finding the technologies to implement these improvements should not prove difficult. However, this preventative strategy is not nearly as effective for dealing with the impacts of urban air pollution already being experienced, especially biodiversity loss and adverse health outcomes. Furthermore, there may be barriers to implementing this strategy because poorer regions may lack the infrastructure or resources to switch to renewable energy. Even in wealthier areas, depending on physical ability and commuting distance, some people may not have access to convenient or practical alternatives to motorized transportation.

Out of the three strategies discussed, the most robust strategy for solving the problem of urban air pollution is mitigation because it is most effective for urban areas already affected by air pollution, which can be taken to be most cities around the world at this point. It can also be used for those where urban air pollution is present but have not yet experienced serious impacts caused by it, which makes this an effective strategy for numerous scenarios. As previously discussed, reducing the concentration of air pollutants in the urban atmosphere can improve air quality, slow down the progression of climate change, and lessen adverse impacts on the natural environment and human health. In the case of urban areas which have not yet been heavily impacted by urban air pollution, mitigating solutions implemented can act almost preventatively, such as designs which sequester and store or recycle air pollutants right at the source to limit its spread. While depending on the financial and technological resources of each area, there are concerns about the cost and feasibility of designing and implementing the technologies and changes needed to mitigate urban air pollution, as it continues to grow as a problem, the solutions to it are being improved upon as well to be more cost-efficient and effective[47]. Moreover, even implemented solutions which are partially effective will still lessen the burden of urban air pollution, and given how ubiquitous the need is for reducing the pollution in urban areas, the mitigation strategy appears to be the best choice out of the three identified.

**Conclusion**

Given the great complexities inherent and the uncertainties behind the driving factors of urban air pollution, the future may challenge our assumptions about what the best strategy for solving the issue of urban air pollution is. As climate change continues to worsen, extreme climate events associated with or triggered by urban air pollution can become more severe and unpredictable, such as more frequent and intense occurrences of smog. These may put pressure on urban regions to switch to a more defensive method to focus on trying to contain these impacts of air pollution, and thus detract from proactive or offensive efforts to prevent its emission in the first place due to strain on resources. Likewise, advancements in technology can lead to the emergence of new sources of air pollution which may require different regulatory and technological approaches to mitigate their impact on urban air quality, but may also result in innovative and efficient solutions that can greatly enhance the efficacy and plausibility of plans to reduce urban air pollution. Furthermore, the values and attitudes of people may change as human society and culture evolves, along with significant political turning points or crises that can result in substantial impacts on peoples' trust in each other or institutions, willingness to cooperate and take social responsibility, and what quality of life (and likewise, air quality) they are willing to accept before taking action.

The implications of these uncertainties and possible challenges for potential planning and policy recommendations are that solving the issue of urban air pollution requires not only governmental, scientific, and technological resources and knowledge, but also flexibility and creativity to be able to anticipate and adapt to such challenges that may arise in the future. A way to simplify and organize the process of visualizing possible futures and analyzing the interactions between urban air pollution and climate change, biodiversity, and social equity is combining scenario planning with agent-based modeling, as was done in this project. Scenario planning enables identifying the key elements of the issue, such as the stakeholders, driving factors, and dimension endpoints, that create divergent futures. The narrative nature of scenario planning means the futures can be described in relation to real-world examples of how they may play out, which gives a grounded perspective on what actions contribute to urban air pollution. The quantitative approach of agent-based modeling allows for more precisely understanding the interactions between agents and driving factors and provides simulation data that is useful for verifying the details of the futures described and exploring potential mitigating strategies under various conditions. Thus, the complexity and uncertainty in finding solutions to urban air pollution arising from possible progression of climate change, advances in technology, and evolution of mindsets can be handled in a flexible and comprehensive way to aid the creation of planning and policy recommendations.

A surprising find while doing this project was how many possibilities could result from the interactions between agents and driving factors. For example, when constructing the scenario

[47] Clifford, "Carbon Capture Technology Has Been around for Decades — Here's Why It Hasn't Taken Off."

logics matrix, it was difficult at first to envision the exact description of what a resistant and communal scenario would look like, because it is usually thought that either people are open-minded and cooperative (adaptive and communal) or close-minded and independent (resistant and individualistic). However, through creating the scenario logic matrix, it was found that traits thought to go 'hand-in-hand' in fact need not necessarily be that way and numerous real-world examples of such combinations were found that would not have otherwise been considered.

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