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# The Mobile Monitoring of Particulate Matter through Wearable Sensors and Their Influence on Students' Environmental Attitudes

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**ABSTRACT** While we have a comprehensive understanding of air pollutants, and their spatiotemporal characteristics across global, and even regional, scales, we are quite limited in our capacity to monitor neighborhood-scale emissions. The mobile monitoring of air pollution is a growing field, prospectively filling in these gaps while personalizing air quality-based tools and risk assessment. In the present study, we developed wearable sensors for particulate matter (PM); and through a citizen science approach, students of partnering Chicago schools monitored PM concentrations throughout their commutes over a five-day period. While their recorded findings would be used to explore the relationship between PM concentrations and urban vegetation, we were also interested in the degree to which mobile monitoring influenced their environmental attitudes. PM readings were processed as GIS point features across 8 survey sites, while urban vegetation was determined through a true normalized difference vegetation index (NDVI) using Landsat 8 OLI/TIRS satellite imagery. As expected, our linear regression indicated a negative correlation between PM and vegetation. Survey responses were scored on the basis of their environmental affinity. Although there was no significant difference between cumulative pre- and post-survey responses, changes within certain attitudinal subscales may possibly suggest that students were inclined to practice more sustainable behaviors, but perhaps, lacked the resources to do so. Further research on the social and environmental implications of mobile monitoring may improve our capacity to collect, model, and interpret air quality in the city; and do so in a way that promotes a political discourse around these issues.

## INTRODUCTION

Air quality is a global concern that imposes a direct threat to the health of those within the urban environment; and does so in a way that disproportionately impacts the marginalized communities of the industrialized world, as they are most often in closer proximity to threatening emission sources (Pearce et al. 2010). Coming from a range of stationary and mobile sources,

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such as fuel-combusting power plants and on or off-road vehicles, respectively, air particulate matter (PM) is a very common concern within our cities. PM refers to a mixture of organic and inorganic particles or liquid aerosols that, upon inhalation, have been known to cause serious obstruction to heart and lung function for those with long-term exposure or preexisting conditions such as asthma (Phalen 2002). In order to mitigate the imposed hazards of PM and other urban air pollutants, it is imperative that we first understand when and where we are at high risk of exposure.

Today, air quality data, including that of PM, is predominately collected through large and expensive stationary monitors (Snyder et al. 2013). The use of remote sensing instrumentation is another common approach, and while it is highly effective at observing the spatial distribution of air pollutants on global and national scales, these instruments are currently limited in their capacity to obtain more localized, near-surface readings. Furthermore, through these current approaches, there is not a direct connection between archived observations and the general public. As a result, most of these individuals often fall short of understanding the imposed health concerns specific to their own surroundings; and in turn, how and why those may differ from the prospective concerns of a much broader scale.

Therefore, there is interest in expanding on the modes through which atmospheric data is collected. One such method may be the extensive mobile monitoring of our air through citizen science: a model of scientific investigation that incorporates the public in the processes of posing questions, collecting data, and interpreting and communicating results. With air quality monitoring tools directly in the hands of the general public, the implications of air quality data should resultantly become a more personal matter. By bringing these

observations to a more localized scale, concerned individuals or communities may be better equipped to bring matters of environmental health into a political context. On the other end of this collaborative process, scientists could more thoroughly study the social and geophysical dynamics of air pollutants in areas where stationary monitors may not currently exist.

Successful 'crowdsourcing' projects, such as the Environmental Monitoring Assessment Network (EMAN)'s, *NatureWatch,* and the Cornell Lab of Ornithology and National Audubon Society's, *eBird*, have demonstrated how we can promote education and awareness on ecological issues while concurrently expediting the process of widespread data collection (Mueller and Tippins 2015). Research from Bouvier-Brown (2014) furthers this notion, implying that we develop a much stronger connection to air pollution and other issues of environmental justice when we engage in hands-on learning, directly working with these data sets. She also addresses the lack of affordable mobile monitoring devices, and the promising future they may have in the field of citizen science-based research.

In this study, we expect engagement with wearable sensors to reflect a heightened environmental affinity and sense of responsibility for issues surrounding anthropogenic pollutants; and additionally, that data acquired on these pollutants can be integrated with other forms of data to further understand matters of public and ecological health. Some research has already been established in forecasting the potential of these intersections—those of which may include air quality-selective rerouting and other real-time mobile alert services for map applications (Kelly et al. 2011). With this in mind, our study examined both the social and environmental implications of mobile monitoring.

Wearable PM sensors were designed through the collaboration of Dr. Mark Potosnak and Dr. Eric Landahl of DePaul University's Environmental Science and Studies Department and Physics Department, respectively. The sensors (Figure 1) detect the presence of particulates through a dynamic light scattering technique. When turned on, the optical devices pulse a beam of infrared light once per minute, recording a time-stamped PM concentration based on the total area of disrupted light flow. These measurements are recorded in volt units that have not yet been standardized in common parts-per notation. As it stands, they will be referred to as monitor units. Though the sensors do not distinguish between PM classes (e.g. $PM_{2.5}$, $PM_{10}$), they effectively monitor cumulative concentrations linearly across all particulate size ranges.
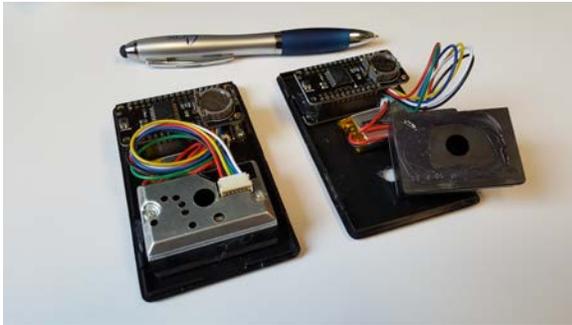


**Figure 1:** Internal design of two wearable PM sensors.

Students of partnering Chicago high schools were able to take the mobile monitoring of PM into their own hands, posing questions, collecting data, and interpreting their findings. They were thoroughly instructed on the process of collecting data through the wearable sensors and logging spatiotemporal observations. Collectively, we investigated the relationship between Chicago's concentrations of PM and urban vegetation. Pre and post-surveys were allocated to assess the influence of mobile monitoring on participating students' environmental attitudes and knowledge.

Ultimately, we tested two hypotheses: 1) Students' scores on the post-survey instruments will indicate a heightened environmental affinity and knowledge, and 2) PM concentrations will be lower in more vegetated study areas. In efforts to limit any respondent bias in survey performance, the details of this former hypothesis were temporarily withheld from students. Upon completion of the post-surveys, this role of deception was disclosed to all participants.

## METHODS

SURVEYING PROCEDURES

Josephinum Academy of the Sacred Heart is an all-girls high school in Chicago, Illinois' Wicker Park neighborhood. Nine students of a predominately senior-level environmental science course agreed to participate. First, they completed a pre-survey by hand. For the purpose of confidentiality, each student was administered an ID code (1-9) from their teacher to eventually link the results of their surveys with that of their PM sensors.

The survey instrument was an adaptation of the Children's Environmental Attitude and Knowledge Scale (CHEAKS) (Leeming et al. 1995). The original 66-question instrument was selectively narrowed down to 20 questions, which focused the survey primarily on issues surrounding anthropogenic pollution. Both the adapted and the original CHEAKS surveys (see Appendix) split evenly into four subscales, assessing verbal commitments, actual commitments, affect, and knowledge. The former three criteria were measured on a 5-point Likert-type scale, ranging from "(1) very true," denoting a firm agreement with a statement, to "(5) very false," denoting a firm disagreement. Knowledge-based questions, however, were strictly objective (e.g. "Most of the lead in our air is caused by:").

All pre-surveys were completed and collected at the beginning of the initial classroom intervention. Following the period of PM data collection, the same CHEAKS instrument was distributed as a post-survey. Upon completion of both instruments, all students were debriefed on the role of the surveys, and how their responses would be processed to study the changes on environmental attitudes through wearable sensing.

For the 15 questions of the Likert-type scale, students' responses were scored 1-5, with scores representing the least and greatest environmental affinities coded as "1" and "5," respectively. A two-tailed paired t-test was run, pairing each student's cumulative pre-survey score with their cumulative post-survey score (n = 9 pairs). For the 5 knowledge-based questions, responses were scored with a binary "0" or "1" code representing a correct or incorrect answer. The same t-test procedure was run for these responses, pairing each student's total of correct responses from pre-survey to post-survey.

## MOBILE MONITORING, GIS, AND REMOTE SENSING PROCEDURES

Though marketed for detecting dust (Sharp GP2Y1010AU0F), these sensors have been used in a number of other air quality projects. The sensor data was logged through a microcontroller with a microSD card interface from Adafruit, containing a real time clock on a daughter board (Adafruit Feather 32u4 Adalogger; DS3231 Precision RTC FeatherWing – RTC Add-on For Feather Boards). A small (350 mAh) LiPo battery provided power.

Students were introduced to our hypothesis addressing PM concentrations and urban vegetation, and were encouraged to consider hypotheses of their own over the several following weeks. A standardized method of mobile data acquisition was covered. This involved each student attaching their sensor to a strap of their backpack with a carabiner clip. Establishing this standard design would increase airflow through the device's aperture while walking, and minimize the likelihood of some students collecting more airflow than others.

The PM data collection took place over a five-day period. On the first day, students collected data between school and their homes, recording the times in which they had exited and entered, respectively. Each student was given a blank map of the study area, in which they illustrated their routes for each day by hand. On days two through four, this procedure was repeated, in addition to logging their times and routes from home to school. Sensors were collected upon entering the school on the final day. With a 24-hour battery life, the sensors continuously collected PM concentrations once every minute with the exception of school hours, in which they were each connected to a charging port.

In accordance to students' spatiotemporal data logging, a total 93 points of certain time and location were determined across 8 different sites (i.e. Josephinum Academy and home locations for sensors 1, 3-8). PM readings for sensor 2 and sensor 9 were discarded due to insufficient data logging. For each of the 93 points, a mean average of PM concentration was recorded over an 11-minute window in which each logged time served as the average's centermost point. This window minimized the chances of recording sampling error while also focusing our analysis on the brief periods in which students entered or exited a known location. This was done in an effort to limit the interference of indoor PM concentrations (i.e. at home, at school, in cars, buses, or trains). While indoor PM is an outstanding contributor to an individual's exposure to air pollution, accounting for it would introduce many unique challenges to the spatial component of this analysis.

A cumulative average PM concentration was calculated for each survey site based on each of its derived averages. Because the sensors currently measure concentrations with arbitrary monitor units, survey sites were classified relative to one another opposed to any baseline or regulatory standard. Three sites were classified as low PM (0 – 0.030 units), two as medium PM (0.031 – 0.039 units), and three more as high PM (0.040 – 0.043 units).

A set of coordinates were approximated for each survey site, and plotted as point features in ArcMap. For each site, a zone of a half-mile radius (804.7 m) was created with its respective PM classification symbolized by a colored perimeter.

We acquired a Landsat 8 OLI/TIRS (combined Operational Land Imager and Thermal Infrared Sensor) image. The imagery was selected based on minimal cloud cover and its proximity to the time frame of the wearable sensor data acquisition (October 17th – October 21st, 2016). In order to determine the relative amount of urban vegetation, we used a true normalized difference vegetation index (NDVI). Accounting for the intensities of visible red and near-infrared light (NIR) reflected by vegetation, this index calculates the density of a landscape's foliage through the spectral differencing formula below.

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

Spaces of healthy vegetation in our study area should have absorbed a greater amount of visible red light (around 650 nm) and reflected a greater amount of near infrared light (700 nm – 1100 nm). Through analyzing a histogram of these tabulated values, a binary NDVI threshold was determined to distinguish vegetation from non-vegetation for our entire study area.

By overlaying the NDVI and zoned PM point features, we were able to quantify the total space of vegetation for each of our 8 sites. Since Landsat 8 imagery has a known spatial resolution of 30 m per pixel edge, and each pixel was classified as either vegetated or non-vegetated, the total number of vegetated pixels for each zone was multiplied by a factor of 900 $m^2$. These values were then converted to hectares (ha)—a more applicable metric unit of square measure, in which 1 ha = 10,000 $m^2$.

With these figures, we ran a linear regression, with the sample of our viable survey sites (n = 8), modeling the changes in PM concentrations in response to our tabulated areas of vegetation.

## RESULTS AND DISCUSSION

SURVEY DATA ANALYSIS

Based on the standard alpha level, α = 0.05, we found no significant differences between students' responses to the pre and post-survey instruments. This was the case for the assessment of environmental attitudes (Table 1a; t = 0.4015, p = 0.6986, df = 8), as well as that of environmental knowledge (Table 1b; t = 0, df = 8).

Although the pre and post-survey responses did not yield any significant differences, the consistency between the mean scores of these surveys does seem to indicate that the CHEAKS instrument serves as a robust assessment tool for studying the variables of our qualitative hypothesis. Expanding considerably on the sample size of n = 9 may reveal more insightful evidence of the relationship between wearable sensors, environmental affinity, and the knowledge-based response to anthropogenic pollution.

**Table 1: CHEAKS Survey Results and t-Test Table.** A two-tailed paired t-test analyzed the changes in survey response before and after engaging with mobile monitors. The Likert-type figures were scored out of a total 75 points in Table 1a, while the binary knowledge-based figures were scored out of 5 in Table 1b.

| Sensor ID Code | Attitudes Scores (a) | | Knowledge Scores (b) | |
|---|---|---|---|---|
| | Pre-Survey | Post-Survey | Pre-Survey | Post-Survey |
| 1 | 55 | 54 | 2 | 3 |
| 2 | 64 | 66 | 2 | 2 |
| 3 | 47 | 49 | 3 | 3 |
| 4 | 42 | 45 | 2 | 3 |
| 5 | 53 | 54 | 3 | 3 |
| 6 | 65 | 67 | 3 | 3 |
| 7 | 48 | 41 | 4 | 4 |
| 8 | 45 | 42 | 2 | 2 |
| 9 | 41 | 38 | 2 | 0 |
| Mean | 51.11 | 50.67 | 2.56 | 2.56 |
| Std. Error | 2.95 | 3.51 | 0.24 | 0.38 |

Among other potential sources of error may have been the sequencing of our methodology. The interpretation of data and results is a component of the citizen science process that ideally should be included in our analysis. Although it may have jeopardized our attempts to dismiss respondent bias, revealing the results of the PM analysis prior to the post-survey may have significantly influenced students' responses.

In building on this study, there may also be implications of the changes in response (or lack thereof) to particular types of survey questions. Of the Likert-type prompts assessing attitudes, the subscale measuring affect yielded the greatest amount of change toward environmental affinity, while the actual commitment questions yielded the least (see Figure 2). After completing the five days of air quality monitoring, 5 of the 9 respondents indicated a heightened affirmation that, "[they are] frightened to think people don't care about the environment." Concurrently, only 2 of the 9 respondents indicated a heightened affirmation that "[they] would be willing to ride the bus to more places in order to reduce air pollution." Such a trend may suggest that these students are well inclined to practice more environmentally-conscious behaviors, but perhaps, are lacking the resources to do so. A deeper analysis with a greater sample size will be required to adequately investigate the relationship between a student's behavioral responses to changes in environmental affect.
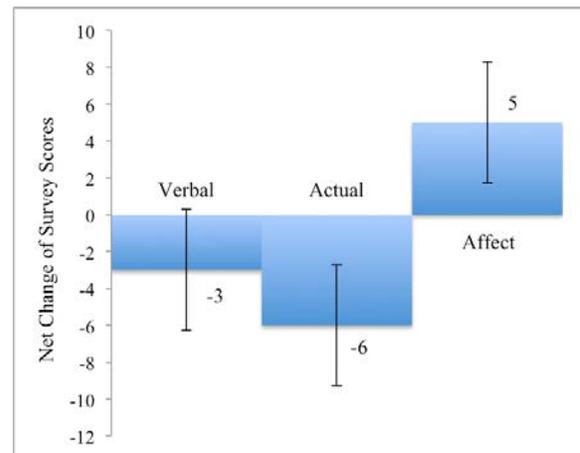


**Figure 2: Changes of Environmental Attitudes Sorted by Assessment Type.** Results are based on the net change of survey scores for each attitudinal subscale—each with a sample size of n = 45 responses. No statistical test was run to measure the significance of these observed changes.

In addition to gathering a greater sample size, a more representative sample group may yield more replicable results. Since the sample group at Josephinum Academy all belonged to an environmental science course, these subjects may have held a broader knowledge of environmental issues than their peers, and perhaps had stronger opinions about them. While still focusing on youth, this study could be supplemented by expanding to classrooms and after-school programs of disparate subjects. To thoroughly understand how the general public responds to the mobile monitoring of air quality, continued research should also incorporate intergenerational sample groups.

In further studies, it may also be of interest to analyze whether or not these heightened affinities of environmental affect withstand or regress over time; and furthermore, if actual commitments have a tendency to build over time, acknowledging that several students identified an increased verbal commitment without any evidence of increased actual commitment. Similarly, there could be significant changes across all attitudinal subscales when extending the periods in which participants collect air quality data. With these concepts in mind, future approaches to this project may involve amending the duration of PM data collection, the chronology of survey data collection, and perhaps, the addition of a third survey phase after a greater period of reflection and habit formation.
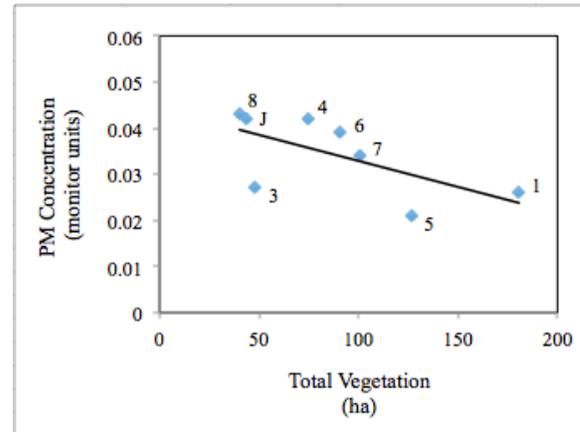


**Figure 3: Total Vegetation versus PM Concentration for Each Survey Site.** The linear regression model indicates an inverse proportionality between average PM concentrations and total vegetation across each of our viable survey sites (n = 8). Point labeled 'J' indicates data collected at Josephinum Academy. (y = -0.0001x + 0.0442; $R^2$ = 0.4019).

## PM DATA ANALYSIS

As we had expected, our correlational analysis of PM concentrations and NDVI values suggested an inversely proportional relationship, in which PM concentrations were lower in more vegetated study areas (see Figure 3). According to our linear regression with an $R^2$ value of 0.4019, our linear model can explain 40.19% of the variation in PM concentration.
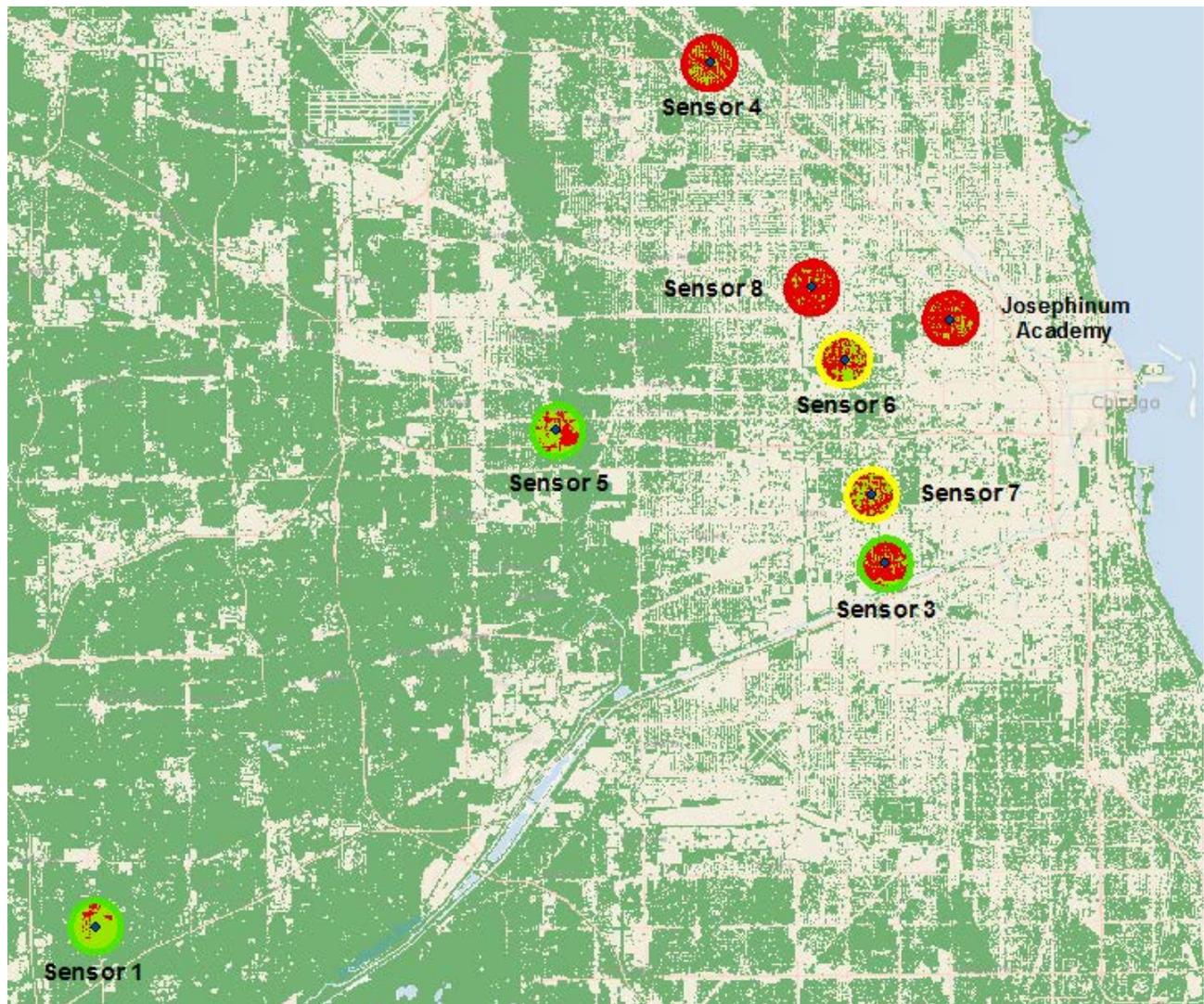
**Figure 4: Spatial Analysis of Chicago, IL's Vegetated Area and PM Concentrations.** Within each of these surveyed zones, the PM concentrations have been classified as low, medium, or high, as indicated by a green, yellow, or red perimeter, respectively. The binary NDVI layer depicts vegetation as green both inside and outside of the zoned survey sites. The Landsat 8 OLI/TIRS imagery from September 12th, 2016 was acquired through the U.S. Geological Survey's EarthExplorer.

Through a more generalized observation of our broader study area, the inverse proportionality of PM and vegetation appears to hold true. Sensor 1's site, for example, clearly encompassing the most green space, is characterized by low PM concentrations. Conversely, the sites of sensor 8 and Josephinum Academy are characterized by high PM concentrations, and seem to occupy some of the most industrialized areas of the city. A closer look at Figure 3, however, does indicate that some of these zones deviate from our study area's general pattern. Most notably, the site of sensor 3, ranking among the lowest PM concentrations despite ranking among the lowest total vegetation. This observation is also highlighted in Figure 3, in which sensor 3 deviates the greatest from the linear regression's trend line.

These observations provoke a number of questions—one of which may pertain to the transportive nature of PM. Regardless of an emission's origin, it is important to note that, within the urban landscape especially, previously settled PM is susceptible to re-suspension through vehicle-induced turbulence (Thorpe and Harrison, 2008). Although the residence time of tropospheric PM does not tend to exceed a few days to a few weeks, a more temporally extensive approach may be necessary to standardize the interference of the atmospheric advection, and even trans-boundary, potential of particulates (Seinfeld and Pandis, 2016; Langer et al. 2014). For similar reasons, it would be highly beneficial to expand PM observations to a broader range of vegetation types and densities. While this study took a binary approach to identifying urban vegetation, a classified analysis may reveal that certain types of vegetation suppress the suspension of PM more effectively than others.

Finally, it is also important to consider that not all outdoor air pollutants—PM included—should be attributed to clusters of population and industry. We ought to also question how and why air pollutants independently persist in less urbanized spaces. As the accessibility and compactness of mobile monitoring devices advance through research and technology, answers to such questions, as well as potential modes of civil action, should grow increasingly transparent.

## ACKNOWLEDGEMENTS

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**APPENDIX**

Modified Surveying Instrument (CHEAKS)

1. I would not be willing to save energy by using less air conditioning.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

2. I would be willing to ride the bus to more places in order to reduce air pollution.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

3. I would go from house to house to pass out environmental information.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

4. I would be willing to write letters asking people to help reduce pollution.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

5. I would not be willing to separate family's trash for recycling.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

6. I have not written someone about a pollution problem.

(1) very true
(2) mostly true
(3) not sure
(4) mostly false
(5) very false

7. I have talked with my parents about how to help with environmental problems.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

8. To save energy, I turn off lights at home when they are not in use.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

9. I have asked my parents to recycle some of the things we use.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

10. I have asked others what I can do to help reduce pollution.
    (1) very true
    (2) mostly true
    (3) not sure
    (4) mostly false
    (5) very false

11. I am frightened to think people don't care about the environment.

    (1) very true
    (2) mostly true

(3) not sure
(4) mostly false
(5) very false

12. I get angry about the damage pollution does to the environment.
(1) very true
(2) mostly true
(3) not sure
(4) mostly false
(5) very false

13. It makes me happy to see people trying to save energy.
(1) very true
(2) mostly true
(3) not sure
(4) mostly false
(5) very false

14. I do not worry about environmental problems.
(1) very true
(2) mostly true
(3) not sure
(4) mostly false
(5) very false

15. I am not frightened about the effects of pollution on my family.
(1) very true
(2) mostly true
(3) not sure
(4) mostly false
(5) very false

16. Burning coal for energy is a problem because it:

(1) releases carbon dioxide and other pollutants into the air.
(2) decreases needed acid rain.
(3) reduces the amount of ozone in the stratosphere.
(4) is too expensive.

(5) pollutes the water in aquifers.

17. The most pollution of our water sources is caused by:
　　(1) dams on rivers.
　　(2) chemical runoff from farms.
　　(3) methane gas.
　　(4) leaks in the sewers.
　　(5) human and animal wastes.

18. Where does most of the garbage go after it is dumped from the garbage trucks?
　　(1) to an aquifer where it is buried.
　　(2) it is dumped into the ocean.
　　(3) it is recycled to make plastic.
　　(4) to a landfill where it is buried.
　　(5) to farmers to use for fertilizers.

19. Most of the lead in our air is caused by:
　　(1) cars.
　　(2) industrial plants.
　　(3) airplanes.
　　(4) burning refuse.
　　(5) cigarettes.

20. Most air pollution in our big cities comes from:
　　(1) cars.
　　(2) jet planes.
　　(3) factories.
　　(4) big trucks.
　　(5) landfills.

The original version of the Children's Environmental Attitude and Knowledge Scale (CHEAKS) can be found at (http://www.meea.org/melab/CHEAKS.pdf).