UNIVERSIDAD AUTÓNOMA DE BAJA CALIFORNIA

DOCTORADO EN MEDIO AMBIENTE Y DESARROLLO

Tesis:

Distribución, percepción y gestión de la calidad del aire en México: el caso de la ciudad de Mexicali, B.C

Para obtener el grado de

DOCTORA EN CIENCIAS EN MEDIO AMBIENTE Y DESARROLLO

Presenta:

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TESIS

QUE PARA OBTENER EL GRADO DE

DOCTORA EN MEDIO AMBIENTE Y DESARROLLO

PRESENTA

DALIA MARCELA MUÑOZ PIZZA

APROBADO POR:

Dra. Mariana Villada Canela

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RESUMEN

Antecedentes: La contaminación del aire es un problema de salud pública a nivel mundial. En esta investigación interdisciplinaria se analiza el problema ambiental de la calidad del aire en México, y en el caso particular de Mexicali, Baja California. Estudios previos han señalado a Ciudad de México en especial como un referente en la gestión de la calidad del aire, sin embargo, existe un estancamiento en la reducción de los contaminantes criterio. El caso de Mexicali es especial por sus características geográficas, fuentes puntuales de contaminación, dinámica económica y social que requieren ser explorados. A nivel local, existen pocos estudios que direccionen aspectos como el estatus socioeconómico y la percepción pública de la calidad del aire como factores que pueden incidir en la exposición y planteamiento de políticas públicas.

Objetivos: Evaluar como inciden el estatus socioeconómico y la percepción de la calidad del aire en la exposición a contaminantes atmosféricos en Mexicali y cómo estos factores se introducen en el planteamiento de políticas públicas para mejorar la calidad del aire a nivel nacional. Para esto se plantea: 1) Analizar resultados sobre el rol del estatus socioeconómico como un efecto modificador en la relación contaminación del aire y salud e identificar brechas en investigación; 2) Evaluar e identificar las zonas donde confluyen una alta exposición a PM_{10} y población socialmente vulnerable, así mismo analizar la percepción pública de la calidad del aire para las zonas identificadas; 3) analizar el rol de factores socioeconómicos, percepción de la calidad del aire y conocimiento de efectos en salud sobre una escenario para mitigar las concentraciones de PM_{10} en Mexicali y estimar el valor económico por mejoras en la calidad del aire a través de la estrategia propuesta; y 4) Explorar la manera en que la vulnerabilidad social es tomada en cuenta dentro del proceso de toma de decisiones para mejorar la calidad del aire e identificar las barreras y facilitadores para ampliar el rol de la evidencia científica dentro del planteamiento de políticas públicas en el país.

Métodos: En el documento se usó un método mixto para direccionar los objetivos de investigación, comparar perspectivas y ampliar el entendimiento de los temas evaluados. Para el objetivo 1, se condujo una revisión de literatura entre los años 2000 a 2017. Para el objetivo dos, se realizó un análisis estadístico y espacial, usando el método de distancia

inversa ponderada IDW, auto correlación espacial local y un modelo logístico ordenado, con datos a nivel de AGEB para estimar la exposición y vulnerabilidad social, a nivel individual para direccionar el análisis de percepción. En el objetivo 3, se aplicó una encuesta a residentes en la zona urbana de Mexicali y los datos coeficientes se estimaron a través de un modelo de elección dicótoma con seguimiento. Para el objetivo 4, se condujeron entrevistas a tres grupos de actores clave en la gestión de la calidad del aire: tomadores de decisiones, científicos y representantes de organizaciones no gubernamentales. Los datos de las entrevistas se analizaron mediante teoría fundamentada.

Resultados: La revisión de literatura internacional puntualiza que los factores socioeconómicos tienen un efecto modificador significativo en el riesgo de efectos a la salud por exposición a contaminantes atmosféricos, riesgo que se incrementa en personas de bajo estatus socioeconómico. Resultados de auto correlación espacial y modelos estadísticos indican la existencia de clústeres en el Noroeste y Sureste de Mexicali donde confluyen una alta exposición a PM_{10} y una alta vulnerabilidad social. El análisis estadístico sobre percepción de la calidad del aire de los habitantes de Mexicali, indica una subestimación del riesgo y poco conocimiento de los efectos severos en salud asociados a la contaminación del aire, principalmente en el clúster de alta vulnerabilidad social. Se encontró un amplio soporte público para mejorar la calidad del aire a través de forestación urbana, estimado en 0.8% del ingreso promedio anual de los hogares, además de un rol significativo de la percepción local de la calidad del aire y sensibilización sobre efectos en salud en la disposición a pagar por mejorar la calidad del aire. Un amplio reconocimiento de la protección a la salud pública como argumento principal en el diseño de las políticas públicas fue encontrado, sin embargo, los actores puntualizan la dificultad de priorizar acciones en poblaciones con desventaja socioeconómica. Factores como la poca capacidad técnica, incipientes sistemas de vigilancia epidemiológica, reducida capacidad institucional, grupos de interés, fondos insuficientes y limitada gestión interinstitucional, dificultan la incidencia de la evidencia. Las áreas de oportunidad van dirigidas a promover investigación interdisciplinaria en este tema, generar espacios de encuentro formales e informales, promover convenios en las instituciones académicas y de gestión pública que otorguen recursos económicos y formalicen una logística apropiada para la producción e intercambio del conocimiento.

Conclusiones: El uso de métodos mixtos para el desarrollo de los objetivos de esta investigación permitió un mejor entendimiento del problema. Los resultados del análisis cuantitativo dan evidencia de la existencia de la población en mayor grado de vulnerabilidad. El análisis cualitativo permitió poner en contexto los factores que deben ser fomentados para que dicha evidencia logre incidir en la implementación de políticas públicas con un mayor impacto en la comunidad.

Palabras clave: contaminación del aire, estatus socioeconómico, percepción, PM_{10}, valoración contingente, política basada en evidencia, Mexicali.

ABSTRACT

Background: Air pollution is a concern for public health worldwide. This interdisciplinary research analyses the problem of air pollution in Mexico, and particularly in Mexicali, Baja California. Previous studies have signed Mexico City as a referent in air quality management; however, no substantial changes have been achieved in recent years. The case of Mexicali is distinctive due to its geographical characteristics, specific sources of contamination, and economic and social dynamics that require exploration. At the local level, few studies address aspects such as socioeconomic status and public perception of air quality as factors that can influence exposure and public-policy design.

Objectives: Evaluate how socioeconomic status and perception of air quality influence exposure to air pollutants in Mexicali and how these factors are introduced in the design of public policies to improve quality at the national level. For this, we propose: 1) Analyze results on the role of socioeconomic status as a modifying effect on the relationship between air pollution and respiratory children's health and identify gaps in research; 2) To evaluate and identify areas where high exposure to PM_{10} converge with socially vulnerable population clusters, as well as analyze the public perception of air quality on these areas; 3) Investigate the role of socioeconomic factors, perception of air quality and knowledge of health effects on a scenario to mitigate PM_{10} concentrations in Mexicali through urban afforestation and estimate the economic value of improvements in air quality; and 4) Explore how the social vulnerability is taken into account in the decision-making process and identify barriers and facilitators to expand the role of evidence within the country's public policy design.

Methods: This research conducts a mixed-methods approach to address the objectives. It compares perspectives and increases the understanding of the analyzed issues. For objective 1, a scoping review between 2000 to 2017. For objective 2, statistical and spatial analysis (inverse distance weighted, bi-variate local autocorrelation, ordered logit model) using data at the AGEB level to estimate exposure and social vulnerability and at the individual level to conduct the analyses of perception. For objective 3, a survey was applied to residents of the urban area of Mexicali, and the data were modeled using a double bounded dichotomous choice model. In objective 4, interviews were conducted to stakeholders in air quality management, including decision-makers, researchers, and NGO representatives. The data from interviews were analyzed using grounded theory.

Results: The results pointed out that socioeconomic factors have a significant effect on the risk of respiratory health issues related to air pollution in low socioeconomic groups. Findings from the spatial and statistical analyses showed the presence of clusters with high exposure to PM_{10} and high social vulnerability in the Northwest and Southeast of Mexicali. Information about public perception yields an underestimation of risk and little knowledge of severe health effects related to air pollution, mainly in the cluster of high vulnerability. It was found broad public support to improve air quality through urban afforestation. The economic value of air quality improvements with this strategy was estimated to be 0.8% of the average annual household income. Also, perception at the local level and closeness to health effects associated with air pollution show a significant role in the willingness to pay to improve air quality. Broad recognition of public health protection was the main argument in the design of public policies; however, the actors pointed out the difficulty of prioritizing actions in populations with socioeconomic disadvantages. Factors such as low technical capacity, deficient epidemiological surveillance systems, reduced institutional capacity, interest groups, insufficient funds, and limited inter-institutional management hinder the incidence of evidence. Opportunity areas aim to promote interdisciplinary research on this topic, generating formal and informal meeting spaces, promoting agreements in academic and public management institutions that grant economic resources, and formalize appropriate logistics for the production and knowledge exchange.

Conclusions: The use of mixed methods to develop the objectives of this research allowed us to understand the problem better. The quantitative analysis results gave evidence on the existence of a population with a higher degree of vulnerability. The qualitative analysis helped us to bring into context, the factors that must be strengthened to improve the role of evidence in the implementation of public policies and the factors that should be accounted for the design of strategies with a broad community impact.

Keywords: air pollution, socioeconomic status, perception, PM_{10}, contingent valuation, evidence-based policy, Mexicali.

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PREFACIO

Los capítulos II y III de esta tesis provienen de manuscritos ya publicados. El capítulo IV se encuentra bajo revisión y el capítulo V es un manuscrito a ser sometido a la revista Environmental Science & Policy, de la editorial Elsevier.

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4. Muñoz-Pizza, D. M.., Rivera-Castañeda, P., Osornio-Vargas, A., Texcalac-Sangrador, J. L., Villada-Canela, M. Analysis of evidence-based policy in air quality management in Mexico: a stakeholder's perspective. Por ser sometido a Environmental Science & Policy. Factor de impacto: 4.767

ÍNDICE

Lista de acrónimos

CALINE 4: California Line Dispersión Model

CVM: Método de valoración contingente

CONAPO: Consejo Nacional de Población

DBCD: modelo de regresión Double-Bounded dichotomous choice, modelo de respuesta binaria con seguimiento.

EBP: política basada en evidencia

HR: hazard ratio

IDW: modelo de interpolación de distancia inversa ponderada

IC: intervalos de confianza

IMECA: Índice Metropolitano de Calidad del aire.

INEGI: Instituto Nacional de Estadística, Geografía e Informática

LUR: modelo de regresión a través de uso de suelo.

NDI: neighbourhood depreviation index, índice de marginación a nivel vecindario

OECD: Organización para la Cooperación y el Desarrollo Económicos

ONG: Organización no gubernamental

ONU: Organización de Naciones Unidas

OR: odds ratio

PCA: análisis de componentes principales

PM_{10}: Material particulado con menos de 10 micrómetros de diámetro

Proaire: Programa de gestión para mejorar la calidad del aire

RR: risk ratio

RETC: Registro de Emisiones y Transferencia de Contaminantes

SEMARNAT: Secretaría de Medio Ambiente y Recursos Naturales

SES: estatus socioeconómico

SPA: Secretaría de Protección al Ambiente

TRAP: contaminación del aire asociada al tráfico

WHO: World Health Organization

WTP: disposición a pagar

CAPÍTULO I

INTRODUCCIÓN

I.1 Antecedentes y justificación

La contaminación del aire constituye uno de los principales riesgos ambientales para la población mundial. Los procesos de urbanización en los países de bajo y medio ingreso, el cada vez mayor consumo de energía, combustibles y la laxitud de las regulaciones, han conducido a exposiciones tóxicas para la población rural y urbana en estos países (OMS, 2016).

Los cambios en los centros de industrialización intervienen en el uso del suelo y la energía. La mayor demanda por recursos naturales ante una infraestructura y planeación que no se desarrolló paralelamente han tenido consecuencias en el deterioro de la calidad del aire, cuyos efectos se manifiestan en la salud pública, daño a los ecosistemas y daños materiales.

La conexión entre los sistemas económico, político, social y ambiental hacen ver la complejidad y la necesidad de un enfoque interdisciplinario para un mejor entendimiento de esta problemática, que hasta ahora, se ha caracterizado por un enfoque reduccionista en la gestión local de la calidad del aire. La Figura I.1 muestra algunas características de los sistemas complejos en la problemática de la contaminación del aire. La atmósfera es un sistema abierto sujeto a reacciones en las que tienen incidencia fuentes antropogénicas y fenómenos naturales. En este sistema se integran el subsistema ecológico o ambiental, social, económico y político -y está sujeto a gran incertidumbre en parte por condiciones meteorológicas y en parte por conductas de la sociedad en general y el accionar de políticas públicas.

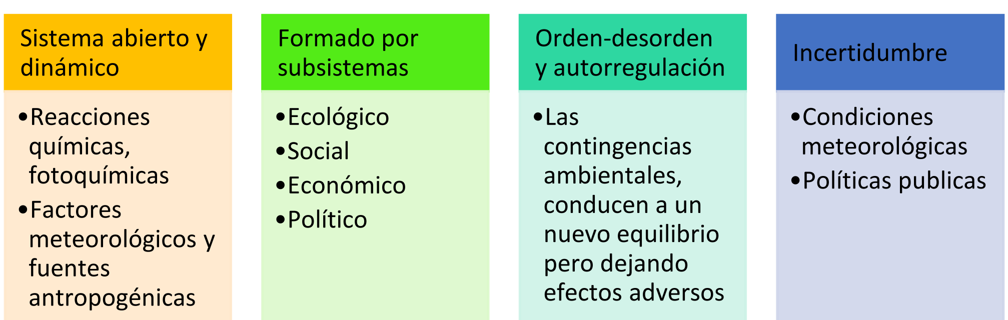

Figura I.1. Conceptos de complejidad aplicados a la contaminación del aire

Las respuestas a esta problemática, que en México inició desde los 80s, se han focalizado principalmente en mejoras en los combustibles, reubicación de las industrias y restricciones vehiculares (Molina y Molina, 2002), cuya gestión se ha caracterizado por una visión técnica centrada en el monitoreo de contaminantes criterio (O_3, CO_2, NO_2, PM_{10} y $PM_{2.5}$). Sin embargo, de acuerdo a Coloballes (2018), incluso los aspectos técnicos conllevan una gran carga política, y los riesgos ambientales, como señala Irwin (2002), no existen aisladamente, sino que son resultado de la realidad social.

Mientras la contaminación del aire es un problema que afecta a toda la población la mayor afectación a grupos socialmente vulnerables son un ejemplo de las interrelaciones entre los sistemas económicos, sociales y ambientales. Un ejemplo son los programas de gestión de la calidad del aire, cuyo mayor énfasis se ha dado hacia situaciones de contingencia (Flamand y Rojas-Bracho, 2015) sin direccionar estrategias específicas para proteger la salud de la población fisiológicamente y socialmente vulnerable. En relación a la contaminación atmosférica, la atención prioritaria a grupos vulnerables y temas de justicia ha sido poco documentado y menos aún plasmado en acciones de política pública.

La evidencia científica de la contaminación atmosférica ha constituido un empuje importante y se considera una condición necesaria en la toma de decisiones, sin embargo, para que se considere como problema público, se requiere de la construcción social (Lezama, 1997). Ngo et al (2017) destacan la importancia de la movilización social y presión de los expertos para que los problemas sean considerados dentro de las prioridades del gobierno y de incorporar las interpretaciones públicas de la contaminación del aire, de modo que se logre una mayor sensibilidad y compromiso (Bickerstaff y Walker, 2001) cambiando el enfoque de reactividad ante el problema.

En esta tesis se aborda la problemática de calidad del aire integrando componentes del sistema social, económico y ambiental que inciden en la exposición a contaminantes atmosféricos y aspectos asociados a la toma de decisiones, con énfasis en la protección a grupos socialmente vulnerables. En este sentido, un marco que permite integrar los diversos aspectos mencionados y que eventualmente puedan ser considerados en la práctica es el de la política basada en evidencia (PBE). El enfoque PBE parte de que una evidencia efectiva debe incluir datos cuantitativos y cualitativos. Brownson et al. (2009) añaden que la evidencia puede ser vista como un continuo que abarca tres dominios: proceso, integrado por investigaciones que permitan direccionar opciones probables de política; contenido, constituido por estudios que buscan identificar algunos elementos específicos para que esta sea más efectiva y tercero, resultados, donde se documenta el potencial impacto de determinada política.

A lo largo de estos dominios, se buscan incorporar las tensiones que dificultan la puesta en marcha de ciertas estrategias, los valores, intereses e incertidumbre en estos procesos para transitar en la generación de evidencia que considere estas características de la complejidad (Ansell y Geyer, 2017). En términos de la gestión de la calidad de la calidad del aire, esto implica introducir aspectos de cómo se distribuye el riesgo, percepción pública, preferencias y visiones de los actores clave.

Se seleccionó como caso de estudio la ciudad de Mexicali, al presentar una de las peores condiciones atmosféricas en relación a material particulado (PM_{10}) en el país (INECC, 2017). La calidad del aire en Mexicali permanece comprometida por diversas actividades económicas y procesos deficientes de planificación urbana, aunados a las características geográficas y climatológicas de la región. La Figura I.2, muestra la relación entre factores sociales, económicos y políticos que inciden en el deterioro de la calidad del aire.

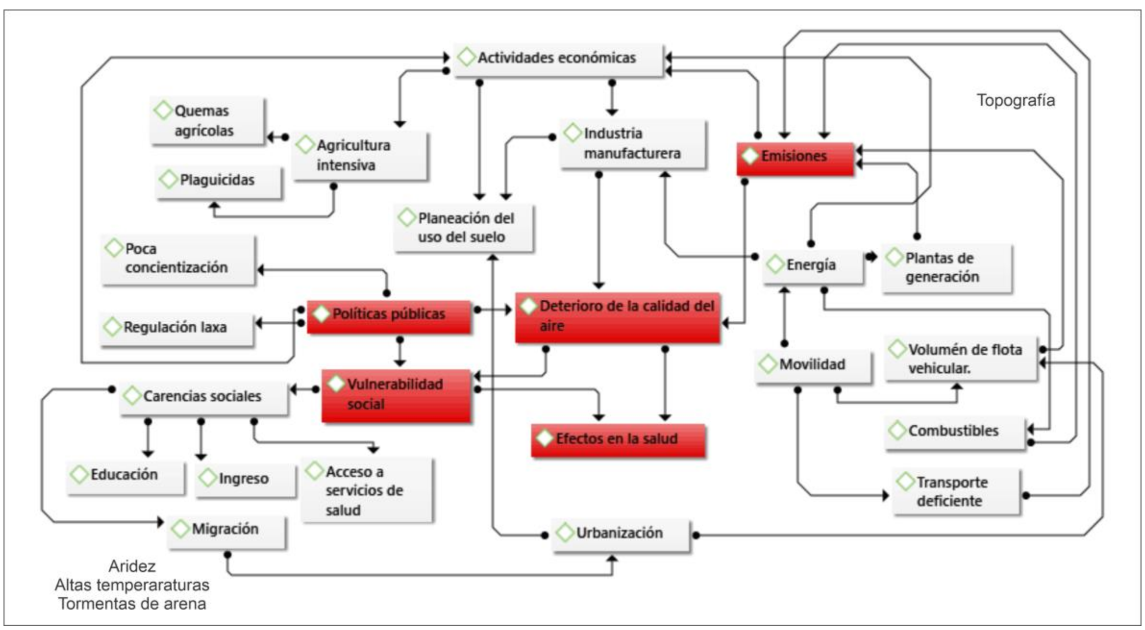

Figura I.2. Factores sociales, económicos y políticos que inciden en la calidad del aire en Mexicali.

La concentración de industria manufacturera -debido en parte a las altas ventajas comparativas como una ligera regulación ambiental-, la actividad agrícola sin prácticas sustentables, el deficiente manejo de desechos sólidos e inadecuada planeación del uso de suelo, además del importante número de calles que permanecen sin pavimentar, constituyen fuentes antropogénicas importantes en los elevados niveles de material particulado (Ramos y Reyes, 2006; Corona-Zambrano y Rojas-Caldelas, 2009). Estas elevadas concentraciones tienen además una asociación muy importante con fuentes naturales de emisión como la propia topografía de Mexicali, las altas temperaturas, y factores asociados con el ambiente desértico (Quintero-Nuñez and Sweedler, 2004). La Figura 2 muestra las interrelaciones entre factores sociales, políticos y ambientales que muestran la complejidad del problema de calidad del aire y su asociación con determinantes socioeconómicos.

Programas para atender la degradación ambiental y efectos en la salud pública en la frontera norte de México y en relación al aire en la cuenca atmosférica Mexicali-Valle Imperial, fueron impulsados desde los años noventa. Algunos acuerdos que fueron fundamentales para el planteamiento de programas locales son el “Acuerdo de la Paz” en 1983 y otros posteriores, como Frontera XXI y Frontera 2020 (SEMARNAT, 2016), en donde se reconoció la importancia de incorporar la percepción de los ciudadanos y su participación, dado el carácter intersectorial y complejidad que implica la gestión de la calidad del aire.

Una de las respuestas gubernamentales, y hasta el momento la principal, es el Programa para mejorar la calidad del aire “ProAire”, creado en el 2000 y firmado por autoridades de los tres niveles federal, estatal y municipal. No obstante, este programa fue cuestionado por la falta de gestión estratégica (Ramos García, 2011), que prevalece en el ProAire 2011-2020. Recientemente se dio a conocer el ProAire 2017-2026 para Baja California (SPA, 2019), el cual busca un manejo intersectorial más amplio e incorpora, aunque de manera incipiente, la perspectiva social en la evidencia científica que lo sustenta.

El deterioro en la calidad del aire que experimenta la población, aunado al contexto de rezago económico y social que viven ciertos grupos en Mexicali, motivan su incorporación dentro de los objetivos de esta investigación, para la generación de evidencia que contribuya en el sustento científico desde una perceptiva social en la toma de decisiones. Hasta el momento, en Mexicali y en general en el país, no hay estudios que integren mediciones de calidad del aire con aspectos sociales y de percepción pública. Esta investigación, por tanto, busca ofrecer una visión integral para los tomadores de decisiones, y a su vez, hacer contribuciones científicas para ampliar el conocimiento de estas interrelaciones dentro del contexto de un país en desarrollo.

I.2 Hipótesis y preguntas de investigación

Existe una relación significativa entre los factores socioeconómicos, la exposición a los contaminantes atmosféricos y la percepción pública de calidad del aire, la cual debe desempeñar un rol relevante en la gestión de la calidad del aire en México.

Preguntas de investigación

1. ¿Existe un efecto significativo entre las condiciones socioeconómicas y los efectos en salud por exposición a contaminantes atmosféricos?
2. ¿En Mexicali existen áreas donde confluyen una alta exposición a PM_{10} y alta vulnerabilidad social?
3. ¿La valoración económica de la calidad del aire, a través de métodos con preferencias reveladas, constituyen un soporte científico importante de los factores sociales que inciden en la implementación de estrategias para la gestión de la calidad del aire a nivel local?
4. ¿La percepción pública de la calidad del aire tiene un rol significativo para el diseño de políticas públicas encaminadas a mitigar la contaminación del aire en Mexicali?
5. ¿Cómo se integra el tema de vulnerabilidad social en el diseño de los programas para mejorar la calidad del aire en el país?
6. ¿Cuáles son los principales factores que favorecen y obstaculizan una mayor incidencia de la evidencia científica en la gestión de la calidad del aire a nivel local?

I.3 Objetivos

Teniendo en cuenta estas características, se plantea como objetivo general producir evidencia desde una perspectiva social, sobre la vulnerabilidad diferenciada de la población por condiciones socioeconómicas y la exposición a contaminantes atmosféricos, incorporar la valoración de la calidad del aire por parte de los ciudadanos e integrar la visión de los actores clave que permitan dar sustento a una gestión de la calidad del aire, entendida como un problema público.

Objetivos específicos:

1. Revisar los elementos socioeconómicos que están involucrados en la vulnerabilidad diferenciada a los efectos de la contaminación del aire en la salud respiratoria infantil.

2. Identificar áreas de confluencia de población socialmente vulnerable bajo una alta exposición a material particulado (PM_{10}) en la zona urbana de Mexicali.

3. Valorar económicamente la disposición de los ciudadanos por mejorar la calidad del aire en Mexicali e identificar el rol de la percepción y factores sociales relevantes en el soporte público para un programa de forestación urbana como estrategia para mitigar la contaminación del aire por PM_{10}.

4. Determinar los obstáculos y las áreas de oportunidad para incrementar la incidencia de la evidencia científica y la incorporación de temas de vulnerabilidad social en la gestión de la calidad del aire en el país.

Los objetivos de esta tesis abarcan diferentes contextos geográficos con la finalidad de comparar resultados arrojados a través de la evidencia internacional (Capítulo II) con los resultados del caso de estudio (Capitulo III y IV). La información recopilada a nivel nacional (Capítulo V) en áreas metropolitanas con ProAire vigente, permite además comparar la visión de los actores clave en lugares que tienen diferentes contextos sociales, políticos y capacidad científica y técnica.

I.3 Métodos

El desarrollo de la presente tesis implicó una propuesta metodológica que sigue el enfoque de métodos mixtos, planteada en la Figura I.3. Hernandez-Sampieri (2014) y

Johnson et al. (2007) describen el enfoque de métodos mixtos como un conjunto de procesos sistemáticos, empíricos y críticos de investigación que implican recolectar y analizar datos de carácter cuantitativo y cualitativo, integrarlos y generar inferencias a partir de los resultados obtenidos.

La complejidad del problema a investigar determina en gran medida el optar por métodos mixtos en el desarrollo de este trabajo interdisciplinario. Entre las principales ventajas de esta metodología, Creswell y Creswell (2018) enfatizan: una mayor robustez a las inferencias científicas, poder comparar desde diferentes perspectivas, presentar resultados cuantitativos con un seguimiento y análisis de la información cualitativa, mayor aplicabilidad de los resultados al incorporar perspectivas de los individuos y grupos marginados y poder evaluar intervenciones *ex ante* y *ex post* de políticas públicas.

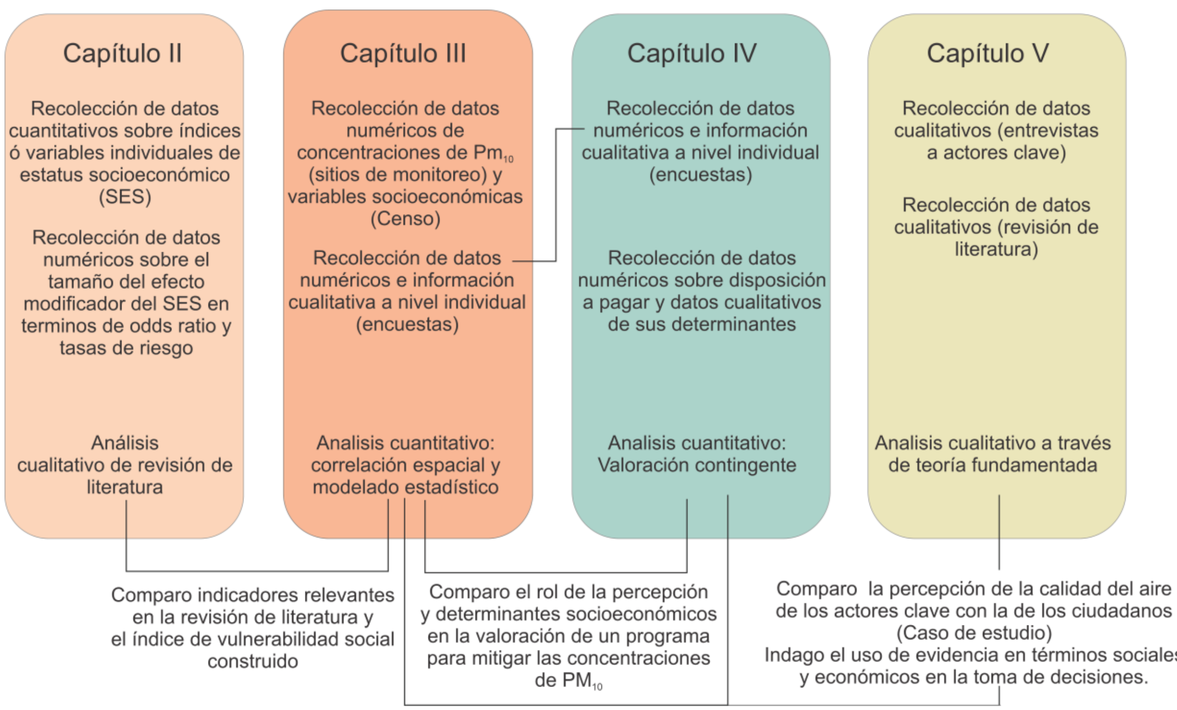

Figura I.3 Secuencia metodológica usando métodos mixtos concurrentes

Se optó por un diseño de métodos mixtos multinivel, el cual integra la fase secuencial y paralela. En este tipo de diseño no se prioriza el análisis cuantitativo o cualitativo, y los resultados obtenidos en dichos análisis permiten crear inferencias para responder a las preguntas de la investigación (Schoonenboom, and Johnson, 2017). Cada herramienta metodológica presentada en la Figura I.3 se explica en los capítulos correspondientes.

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CAPITULO II

EL ESTATUS SOCIOECONÓMICO COMO EFECTO MODIFICADOR EN LA RELACIÓN CONTAMINACIÓN DEL AIRE Y SALUD RESPIRATORIA INFANTIL.

Muñoz-Pizza, D. M., Villada-Canela M., Reyna, M. A., Texcalac-Sangrador, J. L., Osornio-Vargas A. (2020). Air pollution and children's respiratory health: a scoping review of socioeconomic status as an effect modifier. International Journal of Public Health, 65, 646-660. https://doi.org/10.1007/s00038-020-01378-3.

Resumen.

Objetivo. La contaminación del aire es uno de los principales riesgos ambientales, y el estatus socioeconómico (SES) se ha postulado como un efecto modificador, especialmente en los niños. Existe un creciente interés en explorar este efecto. El siguiente trabajo revisa el estatus socioeconómico como un efecto modificador en la salud respiratoria infantil por exposición a contaminantes atmosféricos.

Métodos. Se condujo una búsqueda en las bases de datos PubMed y SCOPUS en septiembre de 2017 para identificar aquellos estudios que cumplieran los siguientes criterios de inclusión: estar centrados en los niños, evaluar efectos respiratorios, y plantear medidas de estatus socioeconómico.

Resultados. Un total de 17 artículos fueron incluidos. Doce usaron medidas individuales de SES, y los restantes incluyeron índices compuestos. El ingreso de los hogares (9) y la educación parental (8) fueron evaluados frecuentemente. Se encontró significancia en el efecto modificador en 9 estudios que demostraron un mayor riesgo en niños viviendo en bajo SES. Las fuentes de heterogeneidad en los resultados se asociaron a las medidas de SES, la manera en que se reportan los efectos en salud y la agregación en términos geográficos.

Conclusiones. Los resultados sugieren una alta modificación en el efecto del SES hacia un incremento en el riesgo de los niños en bajo SES. Las características de los niños deben ser cuidadosamente teorizadas e incluir el uso de aproximaciones transdisciplinarias

Palabras clave: contaminación del aire, salud infantil, enfermedades respiratorias, efecto modificador, estatus socioeconómico, evaluación de exposición.

International Journal of Public Health
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REVIEW

Air pollution and children's respiratory health: a scoping review of socioeconomic status as an effect modifier

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Abstract

Objectives Air pollution is a leading environmental risk, and socioeconomic status (SES) is postulated as an effect modifier, especially in children. There is a growing interest in exploring this modifier. The present manuscript reviews SES as an effect modifier in children's respiratory health.

Methods A search in the PubMed and SCOPUS databases was conducted in September 2017 to identify studies with the inclusion criteria of being centred on children, respiratory outcomes, air pollutants and SES measurement.

Results A total of 17 studies were included. Twelve used single SES variables, and the remaining studies included composite SES indices. Household income (9) and parental education (8) were frequently evaluated. The significance of the effect modifier was found in nine studies that demonstrated a higher risk for individuals living in a lower SES. Sources of heterogeneity included SES measurement, health outcomes and geographical aggregation.

Conclusions The results suggest a higher modification in the effect of SES, generally indicating greater risk for children in lower SES. Children's characteristics need to be more carefully theorized and measured in this area, including the use of transdisciplinary approaches.

Keywords Air pollution · Children's health · Respiratory diseases · Effect modifier · Socioeconomic status · Exposure assessment

Introduction

Air pollution is one of the leading environmental risks challenging human health. Around 300 million children live in urban areas, principally in low-income zones, where the air is considered toxic (UNICEF 2016). The stages in which children are physiologically vulnerable to physical, chemical and biological factors are known as windows of susceptibility (Selevan et al. 2000; Makri et al. 2004), which are related to the development of their respiratory, nervous, immunological and endocrine systems and have been subject to intensive investigations (Kessler 2014).

In the case of children's respiratory systems, the time of exposure during the windows of susceptibility could favour the development, exacerbation and prevalence of asthma (Clark et al. 2010; Samoli et al. 2011; Zeng et al. 2016), as well as an increase in hospital admissions due to respiratory infections, pneumonia, bronchitis (Ostro et al. 2009; Lothrop et al. 2017) and reduced lung development and

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function (Gauderman et al. 2002; Barraza-Villarreal et al. 2008; Hernández-Cadena et al. 2009).

Health disparities due to air pollution have been associated with socioeconomic status (SES) (Martenies et al. 2017; Thakur et al. 2013). Although SES attempts to capture an individuals' social position, welfare and potential to access certain goods and services (Campbell 1983), in this review, we include papers based on the variable name, regardless of the definition. Those disparities have documented material and social factors such as restricted access to healthcare services, limited access to higher education levels, unemployment and maternal conditions (Lee and Marmot 2005; Evans and Kantrowitz 2002; Evans 2006) as potential effect modifiers. Likewise, psychosocial stress, independent of or in synergy with SES, has a modifying effect on the health outcomes attributed to air pollution (Clougherty and Kubzansky 2009).

The link air pollution–SES is part of the environmental justice framework. Hornberg and Pauli (2007) refer to environmental justice as the "uneven distribution of environmental quality between different social groups", making specific mention of an inverse relationship between SES and exposure to environmental hazards. Regarding air pollution, this relationship has been linked to transportation infrastructures in poor neighbourhoods where people are more exposed to traffic-related air pollutants (TRAP) (Pratt et al. 2015) and in proximity to industrial zones (Holifield et al. 2009). In the case of children, there is more concern because they do not decide the conditions in which they live (Kessler 2014).

The studies mentioned above identified an increased vulnerability in low SES through different pathways. However, some studies reported that this effect could also be observed in high-SES groups or even a lack of effect modification of SES for respiratory health outcomes (Cakmak et al. 2006; Wilhelm et al. 2009). In this sense, it is relevant to understand the context under which the effect of SES is observed on children's health. In the coming decades, the prevalence of diseases such as bronchitis and asthma will significantly increase due to the increasing worldwide air pollution problem (OECD 2016), which could have a considerable impact on children living in conditions of poverty and deprivation (UNICEF 2016).

To broaden our knowledge about the context of and the gaps that contribute to the heterogeneity of those results, we conducted a review of the recent literature on the role of SES as an effect modifier in the relationship between air pollution and children's respiratory health.

Methods

We conducted a search of scientific papers published between January 2000 and December 2017 in environmental, public health, medical and social science journals. Since this period includes the years in which the United Nations, World Health Organization (WHO) and UNICEF promoted the development of children's environmental health indicators (WHO 2004), we expected to find a significant number of publications on this topic. PubMed and SCOPUS bibliographic databases were used. Only peer-reviewed papers in English were considered. Reviews and reports were excluded.

Search terms in the abstract, title and keywords that were related to the following terms ("air pollution") AND ("socioeconomic status" OR "socioeconomic" OR "vulnerability" OR "effect modifier" OR "neighbourhood" OR "deprivation" OR "poverty") AND ("children's health" OR "respiratory diseases" OR "health effects") were used to identify relevant publications. After applying it, we retained 203 papers that contained any of the terms. These studies were filtered according to the following inclusion criteria: respiratory effects, outdoor air pollution, role of SES and children; 57 articles were eligible.

Finally, an in-depth evaluation was conducted to identify the specific discussions of SES as an effect modifier, as stated by the authors in their results. Seventeen studies were finally chosen (Fig. 1). We extracted the following data to compare these studies: author, publication year, study area, age group of children, study design, methods to evaluate exposure and SES effect, SES measurement, health outcomes, limitations and key findings. We grouped the selected papers according to categories in terms of the

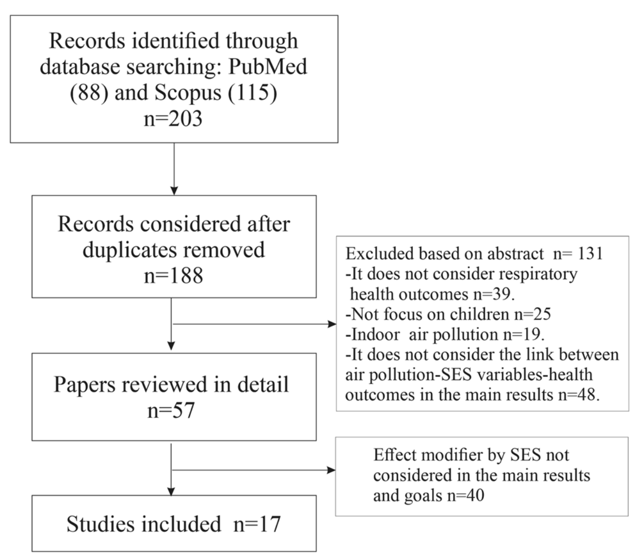

Fig. 1 Flow chart of the scoping review

SES measurement used (single-indicator variables or composite indices), the pollutant evaluated and health outcomes.

Results

Among the 17 selected articles, nine provided evidence of a statistically significant role of SES as an effect modifier (Lee et al. 2006; Lin et al. 2008; Burra et al. 2009; Delfino et al. 2009; Shankardass et al. 2009; Grineski et al. 2010; Alwahaibi et al. 2016; O'Lenick et al. 2017a, b) on the risk to suffer air pollution-related respiratory health outcomes. The overall evidence reflected a consistent pattern of an increased risk for children in low-SES groups, despite heterogeneity in the SES measurements used and the pollutants evaluated. The selected studies were conducted mainly in developed countries: the USA (10), Canada (3), South Korea (2), Oman (1) and Germany (1). We observed an increase in the number of studies in recent years: two between 2000 and 2006, eight between 2006 and 2012 and seven between 2012 and 2017.

SES measurements to assess the effect modification

SES is a complex concept, and in the reviewed papers, it was evaluated through either individual variables or composite indices. The impact of SES on the health of children has been evaluated by the following factors: structural (average household income, poverty level, insurance status, parental education level, unemployment, social cohesion) and material (material of walls, roof and floor of the dwelling, age of the house, infrastructure, material goods) (Lynch et al. 2000). Studies assessing psychosocial factors such as parental stress were included too.

We identified 12 articles that used a single-indicator variable as the SES measurement (Table 1), four studies that employed both single-indicator variables and a composite index for measurement and one study using only a composite index (Table 2).

The papers using composite indices usually include a mixture of variables focused on structural and material factors. Two used the Townsend index and two the neighbourhood deprivation index (NDI). In this group, we also included studies that used a set of variables from the psychosocial pathway (Shmool et al. 2014).

Among the 12 studies that used a single-indicator variable measurement of SES, six used an individual-level variable (through questionnaires applied to the parents) and six used a community-level variable (regional or postal code through census). Those studies conducted at the individual level reported more significant differences between strata than those studies performed at the community level.

Seven of the 12 studies that used single-measurement SES variables (Table 1) identified low SES as a potential effect modifier of respiratory health outcomes related to air pollution. Structural factors such as income (7), parental or maternal education (6) and health insurance (4) are frequently used. Household income was used as a proxy for other characteristics that influence living conditions; thus, the evaluation of this measure depicts different results. In studies at the community level (Lin et al. 2004; Burra et al. 2009), an association was found between mean income household, hospital admission for asthma and a large risk for children whose parental income is under the poverty line; however, effects in the opposite direction, i.e. a high risk for children in a high-SES strata (Delfino et al. 2009), were also reported. For the remaining studies that considered both income as a measure of SES at the individual level and different health outcomes (Hoffmann et al. 2009; Ebisu et al. 2011; Cakmak et al. 2016; Yi et al. 2017), there was a tendency towards a higher modifying effect on risk for low-SES strata. However, most associations were not significant, except for that of allergic rhinitis (Yi et al. 2017).

Concerning health insurance indicators and education level, we found a tendency to report substantial effect modifiers in the odds ratio (OR) of low-SES groups. For example, a birth cohort study (Lin et al. 2008) reported that children of mothers with a low education level and without health services guaranteed by Medicaid or self-payment present higher OR for asthma admission. This pattern was also noted by the examination of the new onset of asthma and respiratory symptoms assessed through parental education level (Shankardass et al. 2009; Ebisu et al. 2011; Cakmak et al. 2016).

Regarding composite indices, four studies used census data and one used variables directly obtained at the individual and family levels (Table 2). Two studies showed evidence of effect modification in the low SES (O'Lenick et al. 2017a, b). The studies using the Townsend index and NDI (Yap et al. 2013; O'Lenick et al. 2017b) for potential SES effect modification of respiratory health outcomes through counties/cities showed mixed results.

Among the studies, the inclusion of variables from the psychosocial pathway yielded mixed results. A higher modifying effect for low-SES strata was found in Shankardass et al. (2009) and Shmool et al. (2014), while Wilhelm et al. (2009) found it for high SES.

Additionally, the importance of stratifying the SES measurement was highlighted for both single-indicator variables and composite indices (O'Lenick et al. 2017a). When using a composite index, there was evidence of significant SES effect modification across strata. The

Table 1 Effect modifier evaluated through single-indicator variables of socioeconomic status (SES) in North America, Germany, South Korea and Oman from 2000 to 2017

Reference, location	Health outcomes	Age group	Air pollutant/exposure method	SES measurement	Level	Main results
Lin et al. (2004), Vancouver, Canada	Hospitalization by asthma	Children aged 6 to 12 years old	CO, SO_2, NO_2, O_3, monitoring sites	Average household income	Community	Risk of asthma hospitalization higher in children living in lower-SES areas. Risk modification by SES was divergent due to pollutants and lags
Lee et al. (2006), Seoul, South Korea	Hospital admission by asthma	Children under 15 years old	PM_{10}, SO_2, NO_2, CO, O_3, monitoring sites	Average health insurance rate	Community	Effect modifier statistically significant by health insurance. Relative risk of hospitalizations larger in lower-SES districts
Lin et al. (2008), New York City, USA	First admission by asthma	Children aged 1 to 6 years old	O_3, monitoring sites	Race, health insurance education level, living under the poverty level	Individual	Significant effect modifier by health insurance, education, poverty. Patterns of higher OR were reported in low-SES areas
Burra et al. (2009), Toronto, Canada	Medical visits by asthma	Children aged 1 to 17 years old	$PM_{2.5}$, SO_2, NO_2, O_3, monitoring sites	Mean income household	Community	Heterogeneous results for the effect modifier by income. Larger effects for low-socioeconomic groups were significant for NO_2 and $PM_{2.5}$
Delfino et al. (2009), California, USA	General hospital admission and emergency room visit by asthma	Children aged 0 to 18 years old	NO_x and CO; California Line Dispersion Model (CALINE4)	Household income, living in median or below poverty line, insurance status	Community	Higher effects in block groups with more families at the poverty level. Household income showed higher HR for strata greater than the median. No significant effect modification by health insurance
Hoffmann et al. (2009), Westphalia, Germany	Respiratory infections, allergic diseases, laboratory test (lung function, and allergic sensitization)	Preschool children	Total suspended particles; small-scale interpolation model	Migratory status, education level, household income, poverty line, unemployment	Individual	Heterogeneous results were found. Higher effects in high SES measured by education level. Higher effects among unemployed population for respiratory infections and abnormal lung function measured by health outcome
Shankardass et al. (2009), Southern California, USA	Asthma (new onset in a cohort study)	Preschool children	NO_x as a proxy for traffic-related air pollutants (TRAP); California Line Dispersion Model (CALINE4)	Psychosocial stress, parent's education level	Individual	Higher effects associated with TRAP for high parental stress compared to subjects with low parental stress. For parental education, the HR was higher for low-SES strata. Significant effect found in both variables for low-SES strata
Grineski et al. (2010), Arizona (Phoenix), USA	Hospitalizations by asthma (at least one night)	Children fourteen years old or younger	NO_2, monitoring sites	Insurance status and race	Community	Insurance status and race are modifiers of the impact of NO_2 on the risk of asthma hospitalizations. A greater effect in low-SES strata

Table 1 (continued)

Reference, location	Health outcomes	Age group	Air pollutant/exposure method	SES measurement	Level	Main results
Ebisu et al. (2011), Connecticut, USA	Wheeze symptoms (0, < 30 and > 30 days)	Children aged 0 to 4 months old	NO_2, monitoring sites and land-use regression	Family income and maternal educational attainment	Individual	SES can modify the effect of urbanity on health. Effects between urban land-use and severity of wheeze differed by SES, with higher effects in lower-SES areas
Cakmak et al. (2016), Windsor, Canada	Cough without cold, chest congestion, asthma, wheeze with dyspnoea, chest illness	Children in the fourth and sixth grades	SO_2, NO_2, $PM_{2.5}$ (TRAP); land-use regression, traffic density parameters	Income and education (parental/family)	Individual	Effects associated with exposure to traffic and respiratory symptoms were higher in low-SES groups when measured by education and income but not significant. Greatest effects for chest congestion, wheeze with dyspnoea and chest illness
Alwahaibi and Zeka (2016), Oman	Daily patient visits for acute respiratory diseases (ARD) and asthma	Individuals aged 0 to 20 years old	Industrial pollution; proximity model	Education level, employment status	Community	Higher effects in the lower strata with a higher percentage of the population without education and with unemployment. Effect modifier significantly increased the risk in both low- and high-SES strata
Yi et al. (2017), Seoul, South Korea	Allergic symptoms for atopic eczema, asthma, allergic rhinitis	Children aged 1 to 12 years old	TRAP, proximity density of vehicles on major roads	Monthly household income, economic strata of residence area	Individual	Heterogeneous results were reported by health outcome. Asthma and allergic rhinitis show a pattern of higher effect for low-SES households and regions

modification in the risk level was higher for low-SES groups than for high-SES groups. An exception was found in Wilhelm et al. (2009).

Despite the lack of consistency in the results, all authors identify SES as a factor that increases the vulnerability to air pollution. Seven of the 12 studies that used a single-indicator variable and two of the five studies that used a composite index found significant associations. The composite indices yielded more consistent results than the single-indicator variables. Notwithstanding, individual variables of the structural type, such as education level and insurance status, reflected significant associations and substantial differences in effect size among the SES strata. Based on the effect sizes, studies using education level as a SES measurement showed that the difference in risk between the low- and high-SES groups was 0.52 (Cakmak et al. 2016), 0.4 (Alwahaibi and Zeka 2016) and 0.35 (Shankardass et al. 2009), respectively. Concerning insurance status, the three highest differences were 0.2, 0.16 and 0.15 (Lee et al. 2006). Among the composite indices, the NDI reported wider differences between the strata compared to the others, such as the Townsend index. On the other hand, the smallest differences in the effect size were 0.001 and 0.002 (Burra et al. 2009; O'Lenick et al. 2017a) for income and the Townsend index, respectively. The effect sizes are presented in Table S1 (Supplementary Material).

Exposure assessment: influence of the exposure estimation in the identification of the effect modifier

Seven of the 17 analysed studies included statistical models to estimate exposure; ten included spatial analysis. A multi-pollutant evaluation was conducted in nine studies. Exposure to NO_2/NO_X was the most evaluated (11),

Table 2 Effect modifier evaluated through composite indices of socioeconomic status (SES) in North America from 2000 to 2017

Reference, location	Health outcomes	Age group	Air pollutant/exposure method	SES measurement	Level	Main results
Wilhelm et al. (2009), California (L.A.), USA	Asthma with or without attacks	Children aged 0 to 17 years old	PM_{10}, CO, NO_2, O_3, monitoring sites	Individual (child's insurance status); family (income, education, employment); neighbourhood (social cohesion)	Individual and community	Psychosocial factors modified the effect of O_3 exposure on risk of asthma. A higher effect was observed in high-SES strata. No significant effect modification when measured by child's insurance status, and education level
Shmool et al. (2014), New York City, USA	Emergency department (ED) visits by asthma	Children aged 0 to 14 years old	NO_2; New York City Community Air Survey with land-use regression	Psychosocial stress (violence, crime, abuse), education level, unemployment, income and overcrowding	Community	Heterogeneous results. Effect modifier in the NO_2–asthma exacerbation was significant for Factor 2 (crowding and poor access to resource, including healthcare indicators). Slight modification in the effect by Factor 1 (psychosocial stress). No significant effect modification by poverty rates
Yap et al. (2013), South Coast California, USA	Hospital admission for acute respiratory infections, pneumonia, asthma	Children 1 to 9 years old	$PM_{2.5}$, monitoring sites	Townsend index	Community	Consistency of the effect modifier is variable by region and health outcome. The South Coast areas present greater effects in lower SES (Townsend index score)
O'Lenick et al. (2017a), Atlanta, USA	ED visits for asthma and wheezy	Children aged 5 to 18 years old	$PM_{2.5}$, NO_2, O_3, elemental carbon, monitoring sites	Education, income, poverty, unemployment, the NDI and the Townsend index	Community	Identified a pattern of modification on the risk due to SES (education level). Higher effects in low-SES strata. Effect modification by the NDI and Townsend index was significant and higher in low-SES strata except for O_3
O'Lenick et al. (2017b), Atlanta, Dallas, St. Louis, USA	ED visits for respiratory diseases	Children aged 5 to 18 years old	O_3, monitoring sites	Education, living below the poverty line, the NDI	Community	Found evidence of effect modification. Significant effect modification by education, poverty and the NDI with higher effects in the low strata in each city

followed by ozone (7), $PM_{2.5}$ (4), proxy measures for industrial and TRAP (4), CO (4), SO_2 (4) and PM_{10} (1). Significant associations were obtained in five studies that used time-series analyses and four that used dispersion models. The studies that found a significant role of SES as an effect modifier in the children's respiratory outcomes tended to use finer temporal (Lee et al. 2006; Lin et al. 2008; Grineski et al. 2010) and spatial scales (Delfino et al. 2009; O'Lenick et al. 2017a) than those of other studies. A few studies assigned similar aggregation units for exposure and SES measurements.

We explored the differences in the effect sizes through OR, risk (RR) and hazard ratios (HRs), according to the SES measurements, for the most frequently evaluated pollutants in the 12/17 papers that reported them numerically. Figures 2, 3 and 4 only include asthma-related outcomes because there are a sufficient number of studies available. The effects on the association proximity to industrial zones, TRAP and asthma are presented in Fig. S1 (Supplementary Material). Additional health outcomes considered in the reviewed studies are displayed in Fig. S2 (Supplementary Material).

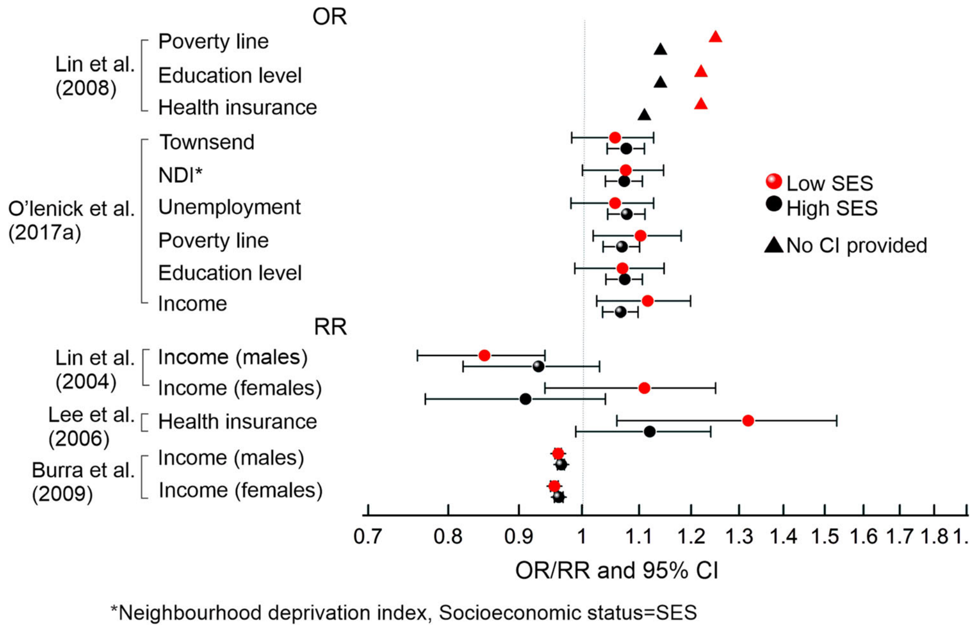

Fig. 2 Socioeconomic status (SES) as an effect modifier for associations between exposure to ozone and asthma-related outcomes in children in North America and South Korea from 2000 to 2017. *OR* Odd ratios, *RR* relative risk. *CI* 95% confidence interval

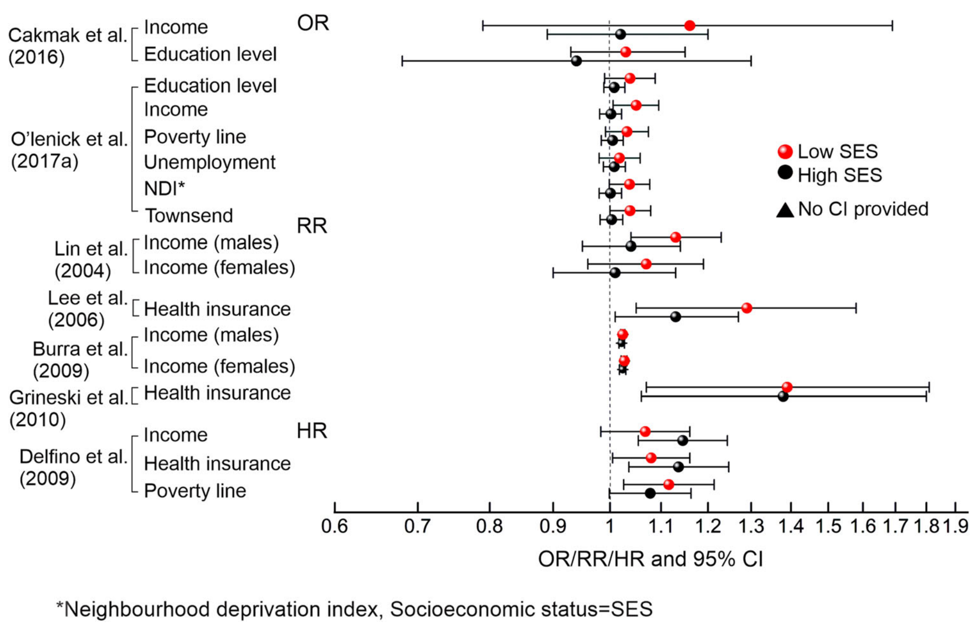

Fig. 3 Socioeconomic status (SES) as an effect modifier for associations between exposure to NO_x, NO_2, traffic-related pollution and asthma-related outcomes in children in North America and South Korea from 2000 to 2017. *OR* Odd ratios, *RR* relative risk, *HR* hazard ratio. *CI* 95% confidence interval

The estimates on the role of SES as an effect modifier in the risk of asthma-related outcomes (hospitalizations, emergency visits, department visits and reports of symptoms) were statistically significant for exposure to O_3 in most cases (Fig. 2) among the five presented studies; however, divergent results were observed in the modification of risk due to income (Lin et al. 2004; Burra et al. 2009). The most considerable effect was observed for the low-SES strata using health insurance as the SES measurement (Lee et al. 2006). This tendency was also observed for education level (Lin et al. 2008; O'Lenick et al. 2017a), with a statistically significant effect (Lee et al. 2006; Lin et al. 2008).

Reports for NO_x/NO_2 exposure (Fig. 3) showed narrower CIs, mainly when using composite SES indices (O'Lenick et al. 2017a) and income (Burra et al. 2009). In most instances, the low SES was identified as effect modifier which leads to a greater risk of asthma in children. Once again, the individual variables, such as medical insurance or parental education level, demonstrated more considerable differences between the strata than the other SES measurements (Lin et al. 2004; Lee et al. 2006; Cakmak et al. 2016). An exception was found in Grineski

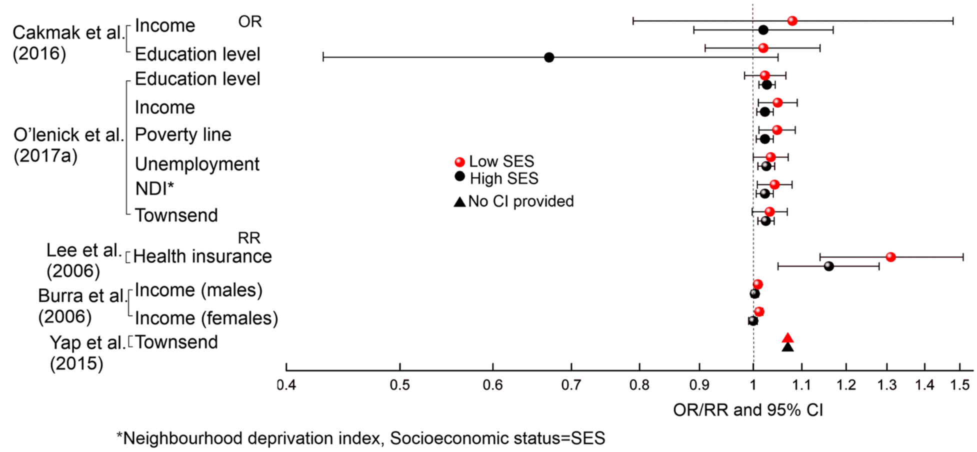

Fig. 4 Socioeconomic status (SES) as an effect modifier for associations between exposure to $PM_{2.5}$ and asthma-related outcomes in children in North America and South Korea from 2000 to 2017. *OR* Odd ratios, *RR* relative risk. *CI* 95% confidence interval

et al. (2010), where smaller differences between strata were reported. The exposure estimation methods used in these studies did not seem to influence the finding of a statistically significant effect modification through SES strata.

In Fig. 4, we summarize the results from four studies focussed on $PM_{2.5}$ and one that assessed PM_{10} exposure (Lee et al. 2006). The analysed papers reported mixed results on the significance of the effect modification among SES strata; for O'Lenick et al. (2017a), Yap et al. (2013) and Lee et al. (2006), the results were significant for all SES indicators, while Burra et al. (2009) and Cakmak et al. (2016) found significance only for low-SES strata. Nevertheless, the results point in the same direction, increasing the risk in low-SES strata. The study by Cakman et al. (2016) reported the most substantial differences in risk between the strata when using education as a family-level variable and estimating $PM_{2.5}$ exposure by land-use regression models and traffic density parameters. Using composed indices yielded narrower CIs and higher consistency on the effect modifier identified among strata.

The reports of three papers that used proxy measures of exposure to fixed and mobile sources (Cakmak et al. 2016; Yi et al. 2017; Shankardass et al. 2009) are displayed in Table S2.

(Supplementary Material) and exhibited heterogeneous statistical significance. Differences in exposure assignment using individual/residential versus neighbourhood levels may explain this heterogeneity. However, both the OR and RR measurements show a clear pattern: Children living in low-SES strata had an increased risk of asthma due to SES.

Four papers evaluated exposure from mobile sources through dispersion models (Shankardass et al. 2009; Delfino et al. 2009) and parameters such as proximity and density of major roads (Cakmak et al. 2016; Yi et al. 2017). Significant associations with this exposure assessment and low education levels were reported by Cakmak et al. (2016) and Shankardass et al. (2009). However, Yi et al. (2017) reported heterogeneous results using major road density, income as an indicator of SES and different health outcomes. Although these variables of exposure provide precise information on children's exposure, in many cases, the SES information covered a larger scale. These aspects possibly contribute to the heterogeneity in the results.

Most of the studies considered in the previous section concluded that exposure to outdoor air pollutants has a significant effect on low-SES children, regardless of the analysed pollutant. The models used to estimate the exposure could influence the identification of SES as an effect modifier, mainly when the aggregation assigned to the exposure differs from the one assigned to the SES measurement.

Health outcomes

Regarding the respiratory health outcomes included in this review, six studies relied on information obtained directly through questionnaires and laboratory testing, while the remaining 11 used information from health information systems, hospital records and health insurance databases. Asthma was the most evaluated outcome (14); either individually (9) or in conjunction with acute respiratory infections (5). Only three studies evaluated upper and lower respiratory infections, including wheeze, allergies and lung function.

Interesting results were found in two studies that evaluated different health outcomes using individual self-report data and laboratory testing (Hoffmann et al. 2009; Cakmak et al. 2016). When using the self-reported health outcomes, the estimated risk measures were more extensive in the high-SES strata for allergic, respiratory diseases and cough without cold. When using laboratory tests for abnormal lung function and chest illness, the higher risks were found for the low-SES strata.

In the four studies that assess different health outcomes, namely Hoffmann et al. (2009) (allergic diseases, respiratory infections, markers of allergic sensitization, abnormal lung function), Alwahaibi and Zeka (2016) (acute respiratory diseases), Cakmak et al. (2016) (cough without cold, chest congestion, current asthma, wheeze with dyspnoea, wheeze, chest illness) and Yi et al. (2017) (asthma, allergic rhinitis), the reported results were heterogeneous. Hoffmann et al. (2009) and Alwahaibi and Zeka (2016) found a significant association in the combined effects for acute respiratory and allergic diseases, while Cakmak et al. (2016) only found associations with chest congestion. In Yi et al. (2017), there was not a clear pattern.

Discussion

In this review, we explored the existing published evidence of SES as an effect modifier in the relationship between air pollution-related children's respiratory health. We found a statistically significant effect-modifying role in nine out of the 17 studies. These studies showed a higher modification in the risk measure for lower socioeconomic groups, but the modification was not uniform.

The role of SES as an effect modifier has often been based on parent's information. Measures such as household income, insurance status and parental education level remain the most used despite the initiatives to look for a more child-oriented specific indicator, as presented in "The Global Initiative on Children's Environmental Health Indicators" (Kessler 2014; Wendee 2018; WHO 2004). Since 2009, there has been an increase in the number of studies devoted to obtaining SES information at the individual level, looking to give more emphasis to information that focuses on children (Hoffmann et al. 2009; Shankardass et al. 2009; Wilhelm et al. 2009; Ebisu et al. 2011; Cakmak et al. 2016; Yi et al. 2017).

The lack of consistency in the results exploring the role of SES as an effect modifier of pollution-related health effects has been explored in systemic reviews (Vinikoor-Imler et al. 2014; Rodríguez-Villamizar et al. 2016), where evidence seems to be weak. In this paper, we found evidence that points towards an increased risk for children in low-SES groups. However, the results are not unanimous, and the measures to evaluate SES may act differently from one health outcome to another. In addition, the exposure metrics and the aggregation of the data have an important role. Attention to these issues is necessary to understand the strength of the effect modification reported for these conditions.

Selection of SES measurement

There is controversy over which SES indicator better reflects health outcome disparities, and our literature review found gaps related to the chosen measure. The chosen SES measurement should not be entirely defined by the statistical significance; it must be carefully selected. Houweling et al. (2003) pointed out that the choice of SES measurement often affects the estimates of the health outcomes and the differences reported between countries or time intervals.

In comparative studies between regions, even if the selected SES measurements are similar, they can lead to different results (Yap et al. 2013; O'Lenick et al. 2017b). The geographical, climatic, political and cultural factors could influence these differences. Additionally, theoretical support concerning the correlation with the health outcomes, the differentiation between direct and indirect measures of SES and the inclusion of both single-indicator variables and composite indices are necessary to consider when designing a study (Wagstaff and Watanabe 2003; Van Vuuren et al. 2014). We considered that the selected SES measurement should capture the relevant conditions for children related to their care and activities that may lead to increased exposure to air pollutants. For example, in single-variable analyses, income showed heterogeneity in the significance of the effect modifier. The authors recognized that using it may overlook some other factors that interact in socioeconomic status and attenuate the effects seen (Lin et al. 2004; Cakmak et al. 2016).

Regarding composite indices, Oakes and Rossi (2003) mentioned that although separate variables are preferred for statistical modelling, composite indices (which condense a large quantity of information) have advantages in stratified analysis and the communication of results. In this review, we identified that the results from papers using composite indices showed narrower confidence intervals and high consistency in the differential effects between the SES strata than studies using a single-indicator variable.

Measurement units

The current evidence showed another gap related to the scales used for exposure assignment; in this sense, there is consensus, i.e. the higher the resolution used for the geographical and temporal analysis is, the more precise the approximations will be.

When using data from monitoring sites in bulk/average over a large geographical area, such methods overlook the different sub-regional levels of exposure at the municipal level; this is known as the modifiable areal unit problem (MAUP) (Maantay 2007). As we noted in the reviewed studies (Shankardass et al. 2009; Ebisu et al. 2011; Cakmak et al. 2016), similar levels of aggregation between the spatial units assigned to the exposure and the SES measurements can contribute to a more precise estimate of the modifying effect of SES.

Another gap exists concerning the exposure measured through proxies such as traffic density. Children living within the same distance to large roads may be exposed to different levels of TRAP depending on the built environment and geographical characteristics of each place (Yi et al. 2017).

On the other hand, the presented results concerning exposure to $PM_{2.5}$ did not analyse information about its composition. Such characterization could contribute to the overall analysis by integrating the socioeconomic measures with $PM_{2.5}$ exposure (Bell and Ebisu 2012) and considering the relationship between the toxicity of specific components and personal exposure (Peng et al. 2009; Lippmann et al. 2013), which can significantly differ in intra-urban levels (Kassomenos et al. 2014).

Information on health outcomes

Overall, SES measurements assessed in low strata evidenced a significant effect modifier role on asthma, acute respiratory infections, chest congestion and combined effects related to outdoor air pollution. However, there was no definitive consensus, as heterogeneity was observed in the statistical significance and the direction of the effect; for example, a more substantial effect on the high-SES group was found in the studies of Lin et al. (2004) and Yi et al. (2017) compared to those that found a more substantial effect on the low-SES group.

Health outcomes assessed by questionnaires about asthma, allergic diseases and registered asthma hospitalizations displayed certain results. For the low-SES population, a considerable number of less severe cases are either not reported in questionnaires or not receive medical attention; only the severe cases are notified (Corburn et al. 2006; Hoffmann et al. 2009; Wilhelm et al. 2009). Therefore, it is difficult to determine the prevalence of such cases in the low-SES groups.

These differences in health outcomes are also observed depending on the use of self-report data and laboratory testing. Significant associations were found when using laboratory testing, in contrast to self-report data (Wilhelm et al. 2009). Under-reporting in low-SES strata may be associated with education or cultural factors; however, an explanation for these differences remains scarce. Selection bias, subject-based reporting bias and biologic interaction were noted by Hoffmal et al. (2009) and Maantay (2007).

Additionally, the results pointing high-SES as an effect modifier of the risk of asthma and allergic diseases have suggested the hygiene hypothesis as a potential mechanism for lower incidence in children living in low-SES strata. This hypothesis related the prenatal and early childhood exposure to viruses, bacteria and endotoxins from older dwellings and overcrowded conditions as factors against the sensitization of these diseases (Corvalán et al. 2005; Uphoff et al. 2015). The evidence for this outcome has been controversial and requires a deeper understanding of the contextual differences and long-term assessments.

Further work requires better integration of data and theorization based on different disciplines. Transdisciplinary research can contribute to offering a broader perspective of the links between social, economic and ecological systems and including the knowledge and perception of the community, to have a better understanding of behavioural and contextual factors that lead an increased exposure of children living in poor conditions. This research would provide valuable support for the interventions of public policies to reduce air pollution considering equity, which, according to Benmarhnia et al. (2014), persists as a challenge in evidence-based public health.

An important fact is that most studies included in this review are from developed countries, thus highlighting the necessity to evaluate SES, as an effect modifier of the risk of health outcomes in developing nations. Nonetheless, challenges to this evaluation are in place, such as the limited number of monitoring stations, the lack of knowledge about the air quality status in many cities, the lack of robust epidemiological and poverty surveillance systems, and pronounced inequalities.

Conclusion

This scoping review summarized the evidence on the complex relationship between children's respiratory health and outdoor air pollution exposure modified by SES. A statistically significant effect was found in nine out of the 17 studies. Associations between respiratory health outcomes, mainly children's asthma, and ambient pollutants yield a tendency of larger effects in low-SES groups, but the results are not consistent.

We found mixed results related to the lack of convergence among the temporary or spatial units assigned to the exposure, the SES measurements and the source of information on the health outcomes. These factors possibly influence underestimation or generalizations that go beyond the specific context.

The majority of the studies used a structural SES variable; income was the most frequently employed and provided heterogeneous results. Indicators such as parental/maternal education level and insurance status showed more sensitivity and clearer patterns when detecting the SES effect modification for children in low-SES strata. Composite indices were often used to explore the effect modifiers between cities but without a definitive consensus.

The complexity of analysing socioeconomic status, health outcomes and exposure suggests the need to explore these aspects from different disciplines, including new qualitative and quantitative data collections, mainly in regions that face vast economic inequalities and poor air quality and where studies remain scarce.

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Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interests.

Ethical approval Statement ethical approval was not required. The authors declare ethical responsibility. This is not published nor under consideration in any other journal. The data extracted for review have been properly cited.

Human and animal rights This article is a review and it does not require human or animal data.

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Consideraciones para el Capítulo III

Los hallazgos de la investigación plasmada en el capítulo II mostraron la importancia de considerar el estatus socioeconómico como factor que incide en los efectos en salud asociados a la contaminación del aire. Los resultados en cuanto a las variables usadas y métodos de estimación fueron usados para direccionar aspectos sobre la creación de un índice de estatus socioeconómico, el cual a nivel local permitiera identificar las áreas de mayor vulnerabilidad social y donde confluyen una alta exposición a PM_{10} en nuestro estudio.

Se tomaron en cuenta las siguientes consideraciones:

- Aunque los indicadores individuales mostraron ser más eficientes en la identificación del SES como efecto modificador, la disponibilidad de datos y la búsqueda de un mayor acercamiento al contexto de los habitantes en Mexicali fueron determinantes en optar por la construcción de un índice.
- El estatus socioeconómico (SES) medido a través de índices presenta intervalos de confianza más estrechos, los índices permiten capturar diferentes características en un solo valor y son más efectivos en la comunicación de los resultados.
- Una brecha identificada se asoció a la escala de agregación, con el propósito de brindar congruencia en la estimación de áreas socialmente vulnerables y en la exposición a $PM_{10,}$ se seleccionaron periodos de análisis que permitieran estimar a nivel de área geoestadística básica (AGEB) ambas variables y que además tuvieran mayor suficiencia estadística.

CAPITULO III

EVALUANDO LA INFLUENCIA DEL ESTATUS SOCIOECONÓMICO Y NIVELES DE CONTAMINACIÓN DEL AIRE EN LA PERCEPCIÓN PÚBLICA LOCAL DE LA CALIDAD DEL AIRE EN UNA CIUDAD DE LA FRONTERA MÉXICO – ESTADOS UNIDOS.

Muñoz-Pizza, D. M., Villada-Canela, M., Reyna, M.A., Texcalac-Sangrador, J.L., Serrano-Lomelin, J., Osornio-Vargas A. (2020). Assessing the influence of socioeconomic status and air pollution levels on the public perception of local air quality in a Mexico-US border city. International Journal of Environmental Research and Public Health, 17 (13), 4616. https://doi.org/10.3390/ijerph17134616.

Resumen.

La contaminación del aire en los países en desarrollo es una preocupación creciente. Este problema ambiental está asociación con la urbanización y estructuras sociales y económicas. El entendimiento de cómo los factores sociales pueden incidir en la percepción y los impactos atribuidos a la contaminación del aire no han sido direccionados de manera suficiente.

Este estudio direcciona la asociación entre vulnerabilidad social y exposición a PM_{10} y la manera que estos factores inciden en la percepción de la calidad del aire de los residentes de Mexicali. Este estudio usa variables individuales y datos del censo de población, también, análisis estadístico y espacial. Se encontró un clúster de población socialmente vulnerable y con alta exposición a PM_{10} en áreas periféricas de la ciudad. La distribución espacial de la percepción local de la calidad del aire difiere entre las zonas de exposición a PM_{10} estimadas. Los encuestados que viven en zonas de muy alta exposición, perciben la calidad del aire como “mala”, contrario a la percepción que manifiestan en áreas de exposición intermedias y bajas donde se percibe como “muy mala” por varios de los encuestados.

La proximidad a fuentes fijas de contaminación fue asociada con una percepción de la calidad del aire como “mala” o “muy mala”. Los resultados también indican que a nivel individual un nivel de ingreso bajo y la percepción de la calidad del aire como “mala” en el lugar de residencia, incide negativamente en los cambios percibidos sobre el tiempo. El conocimiento de los efectos de salud crónicos relacionados a la contaminación del aire fue escaso en la población encuestada, especialmente en zonas de muy alta exposición y alta vulnerabilidad social. Estos hallazgos pueden servir como soporte en la gestión de la calidad del aire a nivel local.

Palabras clave: Contaminación del aire; vulnerabilidad social; PM_{10}; percepción; Mexicali, desarrollo sustentable.

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Assessing the Influence of Socioeconomic Status and Air Pollution Levels on the Public Perception of Local Air Quality in a Mexico-US Border City

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Abstract: Air pollution in developing countries is a growing concern. It is associated with urbanization and social and economic structures. The understanding of how social factors can influence the perception and the potential impact of air pollution have not been addressed sufficiently. This paper addresses the social vulnerability and exposure to PM_{10} association and its influence on the air quality perception of residents in Mexicali, a Mexico–US border city. This study used individual variables and population census data, as well as statistical and spatial analyses. A cluster of socially vulnerable populations with high exposure to coarse particulate matter (PM_{10}) was found in the city's peripheral areas. The spatial distribution of the local perception of air quality varied by the exposure zones of the estimated PM_{10} concentrations. Respondents living in very high exposure areas perceive air quality as "poor," contrarily to a worse perception in areas of intermediate and lower exposure to PM_{10}. Proximity to stationary sources of pollution was associated with a poor perception of air quality. Results also indicate that low household income and poor air quality perceived at the place of residence negatively influences the perceived changes in the air quality over time. The knowledge of chronic health effects related to air pollution was scarce in the sampled population, especially in the areas with very high exposure and high social vulnerability. These findings can serve as a support in local air quality management.

Keywords: air pollution; social vulnerability; PM_{10}; perception; Mexicali; sustainable development

1. Introduction

1.1. Air Pollution in the Context of Sustainable Development

Air pollution is recognized as a threat to public health with significant social, economic and material consequences [1]. Ambient air pollution, mainly due to fine particulate matter ($PM_{2.5}$) has been associated with three million deaths annually from no communicable diseases [2]. It mainly affects the quality of life and the economy of people living in low-middle income countries [3,4]. This issue has an essential relationship with the Sustainable Development Goals (SDGs). In particular, air pollution is linked to Goal 3 (good health and well-being), Goal 7 and 9 (clean energy, industry innovation and infrastructure) and Goal 11 (sustainable cities and communities) [5]. It also contributes indirectly to Goal 1, related to no poverty, building the resilience of people in vulnerable situations and reducing their vulnerability to economic, social, and environmental impacts [6]. A representation of such relationships is found in developing countries where the rapid urbanization process has led to a widening of the economic inequalities, growth with disordered changes in land use, industrial expansion, and a noticeable deterioration of the air quality [7–9]. High concentrations of particulate matter (PM_{10} and $PM_{2.5}$) remain a concern in low-and middle-income communities in several countries of Latin America due to the existing levels exceeding the World Health Organization Air Quality Guidelines (an annual mean of 20 $\mu g/m^3$ for PM_{10} and 10 $\mu g/m^3$ for $PM_{2.5}$) [4,10]. The high levels of particulate matter in Chile and the upper middle-income nations of Brazil and Mexico have been associated with an increase in respiratory and cardiorespiratory morbi-mortality risk, where people living in lower socioeconomic groups are at a higher risk [11–13]. There is evidence supporting the role of socioeconomic status as a significant effect modifier of air pollution-related health outcomes in disadvantaged populations [14–16]. However, the evidence is still scarce in Latin American countries [17], and consequently, there is an even a scarcer number of public policy initiatives [18]. Public policy programs to mitigate air pollution are widely supported by the technical information of the sources, levels and health issues. Factors related to social vulnerability (the capacity of individuals or communities exposed to environmental hazards to resist, cope with, and recover from these hazards [19]) have received less attention. Social vulnerability is a complex concept and involves socioeconomic status, demographic factors, perception, social networks, access to infrastructure, and political power [20]. However, when addressing air pollution, it has been overlooked, despite its relevance in sustainable development [21]. Policies to improve air quality represent opportunities to advance in SDGs [22,23], especially if they integrate relationships between social, economic and environmental factors. In this sense, effective policies to control air pollution with a broader socioeconomic impact require the understanding of the factors that influence the social vulnerability and the perception of air quality as evidence needed in the communication and implementation of appropriated strategies [24].

1.2. Air Quality Perception

Air quality public perception is a relevant input for evidence-based decision making. It influences the behavioral response to interventions and the choices that can lead to increasing or reducing exposure to air pollutants [25,26], as well as to new technological developments and regulatory strategies. Furthermore, public perception may be influenced by trust in institutions and socioeconomic characteristics such as income, education and age, and by contextual factors such as proximity to fixed sources of pollution or the presence of green areas in neighborhoods [27,28].

Studies conducted in Nanchang, Shanghai, and Wuhan (China) [24,29,30], southern Chilean cities [31], Colombian cities [32] and Mexico City [33] have demonstrated the importance of such socioeconomic and geographical factors in the decision making and implementation of air quality control strategies. Despite these efforts, there is a gap in the knowledge of the relationships among socioeconomic disparities, environmental degradation, and public perception [34]. This situation requires addressing in order to support air quality policies in the context of sustainable development. In this paper, we evaluated patterns of PM_{10} exposure levels, air quality perception, and social vulnerability in Mexicali, a representative city of the social and environmental problems present at the Mexico–US border region. Mexicali is a city affected by problems such as a marginalized migrant population and low-income communities exposed to multiple risks related to water and air pollution [35,36].

Explicitly, we modelled and characterized a city-wide exposure to PM_{10}. PM_{10} concentrations compromise the air quality in Mexicali city. In addition to its geological origin, PM_{10} levels also reflect other persistent problems in the region. Local sources of PM_{10} relate to deficient urban solid waste management, agricultural waste burning, increased road traffic (abrasion, erosion, and exhaust emissions), resuspension from unpaved streets, and emissions from maquiladoras [37,38]. We developed a socioeconomic index to evaluate the spatial patterns of social vulnerability related to PM_{10} exposure, and we evaluated the association between the spatial distribution of the population's air quality perception and the estimated exposure. All these were to analyze the factors that influence air quality perception using data from surveys and previous estimations of exposure and social vulnerability. These analyses seek to provide policy-relevant evidence to local air quality management in the context of sustainable development goals.

2. Methods

Exposure patterns to PM_{10} across the city were developed using 2015 PM_{10} data, a socioeconomic index was built on 2010 Census data, and the air quality perception at the individual level in inhabitants of Mexicali was approached by a survey performed in 2019. A detailed description of the methods is found below.

2.1. Study Site

More than 15 million inhabitants live in the US–Mexico borderlands [39]. This region is affected by poverty, marginalization, social inequities, and crucial environmental pollution issues [40]. In addition to the natural characteristics of the region, such as aridity, high temperatures, and scarce precipitation, the establishment of manufacturing and power-generating plants have brought consequences in sustainable development [41]. On the one hand, the establishment of the maquiladoras has had a positive impact as a substantial source of manufacturing jobs [42]; however, the weak environmental regulations imposed on these maquiladoras have negatively impacted the quality of water, air, and soil [43]. Mexicali is a remarkable example of this situation. The city is on the northern Mexican border, adjacent to Imperial Valley, California (Figure 1). It has a population of 689,775 inhabitants [44], dry weather and precipitation of around 75 mm/year [45]. One of its leading environmental problems is air pollution [46]. It is ranked as the ninth most polluted place on the American continent due to the high concentration of PM_{10} [4]. Within Mexico, it is the second city with the highest 24-hour average PM_{10} concentration (274 $\mu g/m^3$) just after Torreón city (276 $\mu g/m^3$) [47].

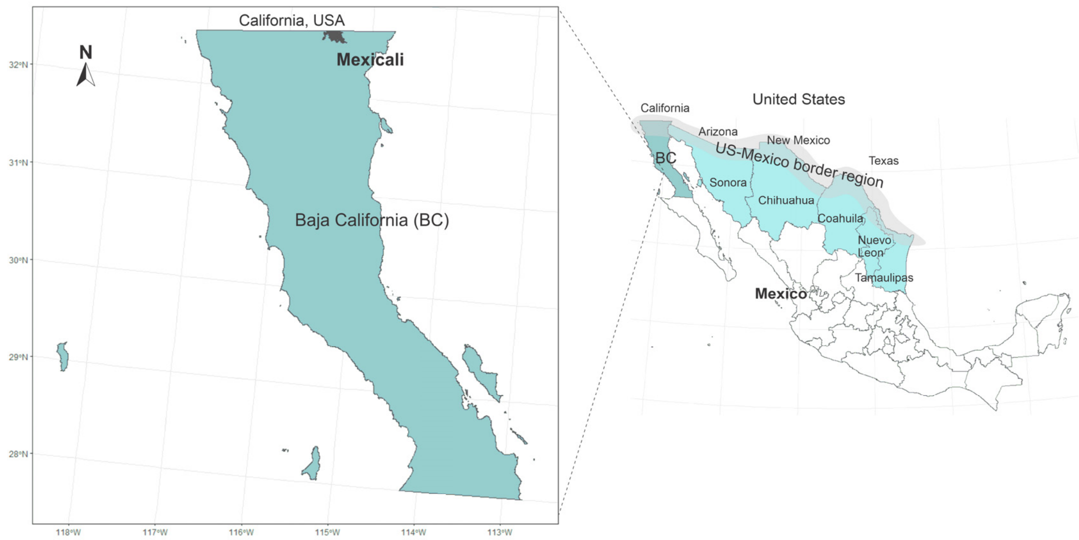


Figure 1. The geographic location of Mexicali within the US–Mexico border region.

Binational programs have been established through the US–Mexico Border 2020 Program to promote sustainable development in the border regions, including the Mexicali–Imperial Valley region. One of the main objectives is to improve air quality. The programs have advanced in the establishment of guides and strengthening the installed technical capacity. However, agricultural and industrial unsustainable practices, as well as natural sources (mainly erosion caused by wind) have contributed to the deterioration of environmental conditions [48,49]. The study of the PM_{10} chemical composition when the 24-hour average concentration exceeded 120 μg/m^3 (national index) identified multiple additional sources such as construction activities, burning of wood and household waste, unpaved roads, and dust crushing due to traffic. Those sources share participation in the urban areas at the Mexico–US border [50]. Local strategies to improve air quality in the city are addressed through PROAIRE ("Programa para mejorar la calidad del aire"), which includes scientific and technical information and a set of strategies to reduce the pollution from the identified sources. However, social vulnerability and perception are factors that are not considered in-depth, even though air pollution can disproportionately impact the communities of this area with high migration and poverty rates [51]. Within this context, we explored the social vulnerability and public perception of air quality as relevant factors in local air quality management.

2.2. Air Pollution Data and the Exposure Estimation Model

We worked with the concentrations of PM_{10} for 2015, since the data from previous years (2010 to 2015) were statistically insufficient (>25% missing), and in the subsequent years (2016 to 2019), several monitoring stations were out of operation. Thus, the data from 2015 was the most consistent in whole the 2010–2019 range. The data included measurements obtained at the monitoring stations of the National Air Quality Information System (SINAICA) and provided by the Secretaría de Protección al Ambiente, Baja California. We estimated the exposure levels using an interpolation inverse distance weighting (IDW) model. The model used as a base the point data from the monitoring sites. To obtain the possible values of exposure over the space between all the data points, and the visualization of spatial patterns [52], we constructed circular buffers of 5 and 10 km radius. These centered at the monitoring sites and measured the distance to the centroid of each basic geo-statistical area (AGEB by its acronym in Spanish) (Figure S1 in Supplementary Material). AGEBs represent the minimal geographic region where census data is accumulated and reported. The urban area of Mexicali city has 412 AGEBs. Then, we weighted the 24 h average PM_{10} concentrations from monitors that had ≥75% of hourly measurements. In a first interpolation, we assigned the daily AGEB PM_{10} concentration using the IDW raised to the power value of two to those centroids that intersected within 5 km buffers. A second interpolation used the centroids within 10 km buffer intersections for those AGEBs not included in the first, and also raised to the power of two. As a third approach, the centroids outside any 10 km buffer intersection received the PM_{10} concentration of the closest monitoring site. Lastly, for the AGEBs outside the buffers, the IDW raised to the power value of 1 was used, taking as reference the 24 h average concentrations of all the monitoring sites. Téllez-Rojo et al. [53] provided the procedure and validation of this method. We created and used categories based on exceedance days for each AGEB in the subsequent analysis. Exceeded days were those with PM_{10} concentrations above the WHO Air Quality Guideline (AQG) mean value of 50 μg/m^3 in 24 h. Exposure estimation was obtained for all 412 AGEBs. The analyses were performed using software R, version 3.5.2. (R Foundation for Statistical Computing, Vienna, Austria).

2.3. Social Vulnerability Index

We analyzed social vulnerability through socioeconomic status (SES), based on the variables reported in literature linking socioeconomic status and air pollution [15,54,55], as well as data availability. We included variables such as education level, individual economic status (unemployed), health insurance status, women head of household, and access to long lasting consumer goods at the AGEB level from the more recent national population census [44]. The selected variables included the dimension of susceptibility and adaptability, as described by Ge et al. [21]. We used principal components analysis (PCA) to obtain an aggregated value for the range of considered variables. Given that single variables may be autocorrelated, we used the PCA to reduce redundancies and dimensionality. We only included those variables with minimal missing values to minimize the potential for clumping or truncation [56]. We retained the components whose percentage of variance was higher than 10%. Additionally, we used the scree plot based on the eigenvalues proposed by Cattell (1966) [57] (Figure S2 Supplementary Material). The Kaiser–Meyer–Olkin (KMO) index was used as a measure of sampling adequacy (Table S1 Supplementary Material). The index resulting from the PCA analysis was used as a categorical variable based on the standard deviation from the mean, allowing a better visualization of AGEBs with extreme values of social vulnerability. The analysis was performed using Stata version 11.2. (IBM, Armonk, NY, USA).

2.4. Spatial Analysis

To analyze the spatial association between PM_{10} exposure and social vulnerability, we used the local bi-variate spatial auto-correlation through Moran's Index. This indicator quantifies the spatial association between these two variables, the identification of spatial clusters, and their statistical significance [58]. We selected the first order "Queen" spatial weight matrix; this measure of contiguity is based on spatial units that share boundaries and vertices. The variables used to obtain the SES index were not available for the 412 AGEBs; thus, the Queen's measure was more appropriate. We carried out this spatial analysis using the Geoda 1.12 software (free and open source software) [59].

2.5. Data Collection and Statistical Models of Individual Socioeconomic Characteristics and Air Quality Perception

2.5.1. Data Collection from the Survey

We conducted a survey to capture additional individual socioeconomic characteristics and the perception of the air quality among the inhabitants of Mexicali. The survey was part of a contingent valuation study to assess the socioeconomic, perception, and health concerns as potential determinants towards a program of urban afforestation to improve air quality [60]. The questionnaires were applied, face to face, in open spaces (streets, commercial establishments, parks, supermarkets) in January 2019. Pedestrians were randomly selected, and the survey was applied to individuals over 18 years of age and that provided consent. The questions sought to gather quantitative and qualitative information. The items first addressed the demographic and socioeconomic attributes (age, sex, education level, average household income, health insurance, ownership) and the place of residence (street, postal code, and neighborhood) of the respondents. Moreover, the individuals were asked about their concerns for air quality, capturing their perceptions at the local and city level. We used a Likert scale with the categories of very good, good, regular, poor, and very poor air quality. We also explored their perceptions of air quality changes in the last few years (during 2015–2019), presenting them with three scenarios: do you think the air quality in Mexicali has improved; remains unchanged; or worsened? In a third section, we explored another essential aspect, their knowledge about the health effects related to air pollution and pollution sources. We also asked if at least one of the household members presented frequent respiratory symptoms. Two hundred and seventy surveys were applied (sample size has an error type I of 5%). Two inclusion criteria were applied to this sample to select the surveys included in the analysis. First, the respondents must be people with more than four years living in Mexicali, and they must provide some reference for their place of residence. We considered this inclusion criterion essential so that the respondents could provide us with information on the changes observed in recent years. One hundred and ninety-nine surveys were retained. The information about their place of residence allowed us to assign the perception responses to a specific AGEB when the reference was within the polygon. To assess the potential association between air pollution perception and the presence of stationary sources of pollution, we first geocoded the medium-large industries with more than 30 employees and were registered in the National Statistical Directory of Economic Units [61]. We constructed 1.6 km radius buffers centered at the respondent's place of residence and counted the number of industries within each buffer. The used distance is frequently employed in environmental hazard assessments [62,63]. The assessment of the spatial association between perception and the presence of stationary sources of pollution also used the Queen spatial weight matrix and Moran's Index. Figure S3 (Supplementary Material) present the buffers used to assess the spatial association between the number of nearby industries and air quality perception.

2.5.2. Statistical Analysis

To identify the association between the estimated variables of exposure and social vulnerability, with the perception of air quality, we used the three categories of the question about the changes perceived in air quality over time (during 2015–2019) as the dependent variable. An ordinal logistic regression model was employed to determine the factors that influenced the perceived changes in the air quality at the individual and neighborhood level. This model is especially relevant when the dependent variable is ordered, in this case:

$$y = \begin{cases} 1\ \textit{improved} \\ 2\ \textit{unchanged} \\ 3\ \textit{worsend} \end{cases} \tag{1}$$

The selection of the included independent variables was based on previous studies [64–67] and the Kruskal–Wallis H test [68]. The test was used to determine if the dependent variable differs significantly between each group of the independent variables (Table S2, Supplementary Material). The model was as follows:

$$\begin{aligned} p_{ij} = \Pr\left(y_j = i\right) &= \Pr\left(\mu_1 < x_j\beta + u + \mu_2\right) \\ &= \frac{1}{1+\exp\left(-\mu_2+x_j\beta\right)} - \frac{1}{1+\exp\left(-\mu_1+x_j\beta\right)} \end{aligned} \tag{2}$$

where p_{ij} is the change perceived by the individual j, i corresponds to the ordered categories ("improved," "unchanged," "worsened"), x_j are the independent variables, β are the estimated coefficients, μ_1 and μ_2 are the thresholds, which divide the ranges of possible values for the dependent variable, for instance, μ_1 is the estimated threshold on the ordered variable used to differentiate the "improved" category from the "unchanged" and "worsened" categories when the values of the independent variables were assessed at zero, μ_2, is the estimated threshold used to differentiate "improved and "unchanged" categories from "worsened" when the independent variables are evaluated at zero, and u is the error term. The model assumes that the three choices follow the same distribution. Thus, the effects of the independent variables are constant across the choices. This assumption is the well known parallel regression assumption for the proportional odds ratio [69,70] and it was proven in our estimations.

3. Results

3.1. Estimation and Spatial Distribution of PM_{10} Exposure

The average days with exceedances of the AQG established by the WHO in the AGEBs studied was 60%. Twenty-one days represented the minimum days with exceedances, and 44 days was the maximum. They correspond to 42% and 88% of the days with valid measurements for 2015. The estimated annual median concentration was 77.35 μg/m^3, the minimum was 59.32 μg/m^3, and the maximum was 101.93 μg/m^3. Figure 2 presents the spatial distribution of exposure based on the exceedance days at the AGEBs level. These results show that high concentrations of PM_{10} regularly impacted the general population of Mexicali. AGEBs with higher PM_{10} exposure were located mainly in the West and Southeast regions of the city. These peripheral areas are close to agricultural activities and industrial zones (electric power generation, metallic and nonmetallic mineral products manufacturing, meat processing, and conservation).

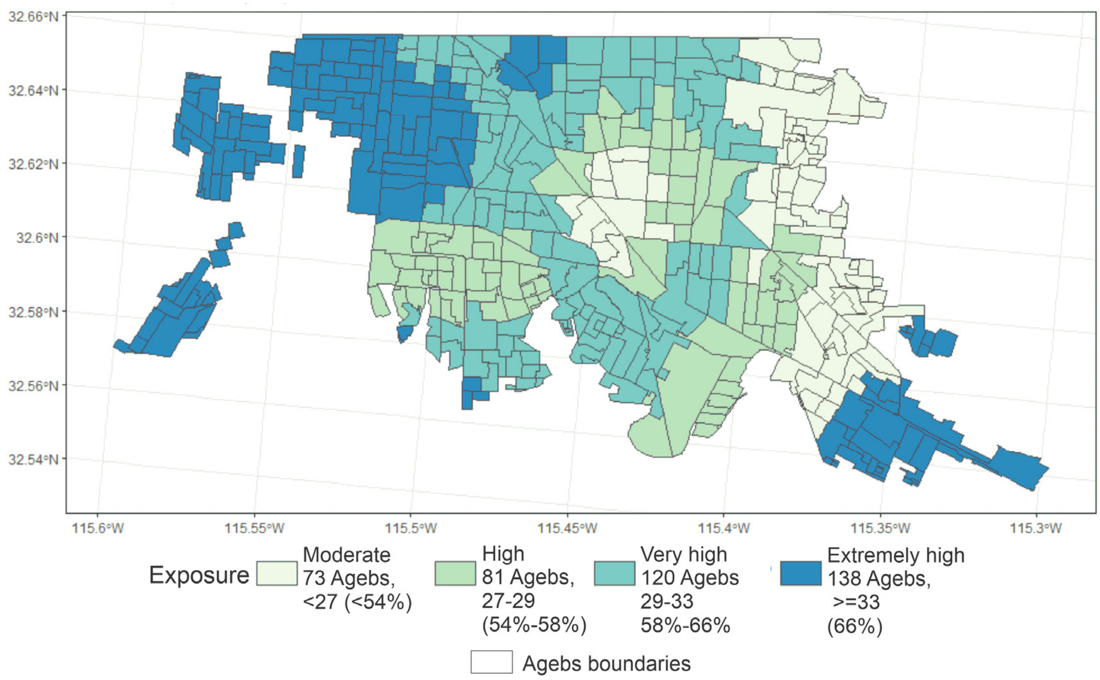


Figure 2. Exposure areas by exceedance days in the urban areas of Mexicali, B.C., at the basic geo-statistical area (AGEB by its acronym in Spanish) level. Parentheses are the percentages of exceedances in days based on 50 days as the maximum measurements available in all the monitoring stations during 2015—categories by quartiles.

3.2. Estimation of Social Vulnerability

An initial set of 13 variables from the 2010 Census, including economic, social, and material conditions, were selected, based on the least number of missing values, higher variance, and significance, according to a literature review. The PCA only included six variables (Table 1). This set of variables showed good sampling adequacy (KMO: 0.85).

Table 1. Description of the socioeconomic variables included in the principal component analysis.

Variables [1]	*N*	Mean	Std. Dev.	Min	Max
Population without post-basic education [2]	370	687.43	540.49	1	4290
Population without employment [3]	357	42.11	30.69	0	168
Population without health insurance (public/private)	370	458.70	301.12	0	1503
Number of households headed by women	370	149.54	100.19	0	470
Number of people per room (overcrowding proxy)	370	3.43	0.51	2	4
Household without a car	370	136.46	115.07	0	750

[1] The variables are based on metadata defined by National Institute of Statistic, Geography and Informatics (INEGI), 2010 Census [44]. [2] People more than 18 years old without post-basic education (bachelor's degree, master or doctoral studies, complete or incomplete grades). [3] People over 12 years old who did not had job, but they looked for a job in the reference week of the census.

We assigned these variables as proportions to each AGEB before the PCA, due to differences in the population size among AGEBs. Two components with an accumulated variance of 84% were extracted. The first component combined the variables related to social (education, access to health services), and material factors (access to long-lasting consumer goods). Component 2 gave higher weight to financial conditions (unemployment, female-headed households, and overcrowding). Figure 3 shows the correlation of the variables included in the analysis to each one of the selected components.

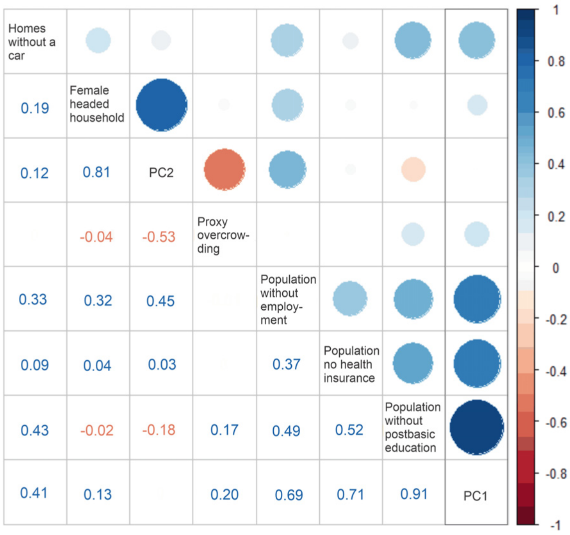
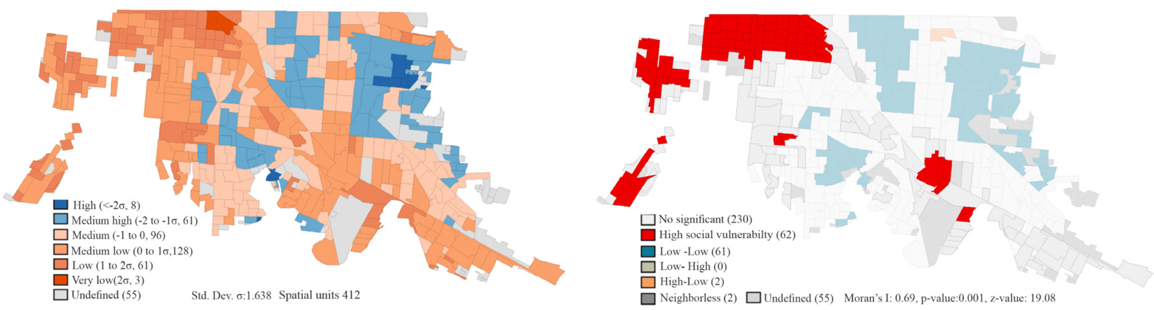


Figure 3. Component loads and correlation among the included variables for principal component 1 (PC1) and principal component 2 (PC2). The blue colors correspond to positive correlations; the red colors correspond to negative correlations. The color intensity and size of the circle are proportional to the component load.

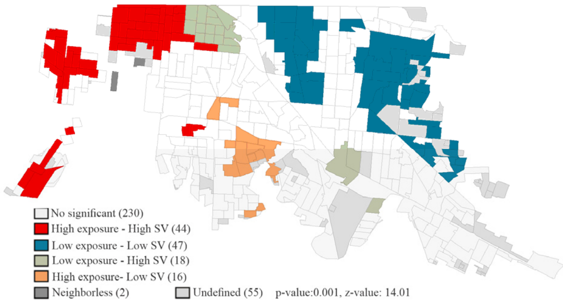
3.3. Spatial Distribution of Social Vulnerability and Autocorrelation with Estimated Exposure to PM_{10}

The PCA identified two principal components, Component 1, which includes the variables associated with the susceptibility and adaptive capacity. It also has the statistical power to serve as the SES index used in this study. Figure 4 represents the spatial distribution of the SES index in Mexicali, showing social vulnerability polarization. We identified the hot spots of AGEBs with high social vulnerability and with high levels of PM_{10}. The AGEBs with high SES are located in the Northeast region of the city, whereas a higher number of AGEBs with lower SES are located in the Northwest region (Figure 4a). Significant spatial clusters (hotspots) of a socially vulnerable population (Figure 4b) were mainly located in the Northwest and Southeast regions of the city. The distribution from the bivariate local Moran's Index showed significant spatial clusters of higher vulnerability where higher levels of PM_{10} existed (Figure 4c). Results of the global Moran's Index were statistically significant (z-score: 18.09 and p-value: 0.001). They confirmed that the spatial distribution of high–high follows specific clustering patterns that included 57 AGEBs in the Northwest region of Mexicali. We identified another relevant cluster (five AGEBs) located in the Southeast region with a high level of social vulnerability and an intermediate level of exposure to PM_{10}.



(**a**) (**b**)

Figure 4. *Cont.*



(**c**)

Figure 4. (**a**) Spatial distribution of the socioeconomic status (SES) index. The values in parentheses represent the range by standard deviation and the number of AGEBs for each category. (**b**) Local spatial autocorrelation for the socially vulnerable population. Data from 2010 Census. (**c**) Bivariate local Moran's Index for spatial autocorrelation between PM_{10} exposure and social vulnerability (SV).

3.4. Descriptive Statistics and Spatial Distribution of Air Quality Perception

3.4.1. Description of Individual Responses by Air Quality Perceived

We assessed how the perception of the air quality (city-wide and at the place of residence) diverged by socioeconomic attributes, health status, knowledge of health effects, pollution sources, and the changes perceived in the last four years. Throughout the city, the current air quality was perceived as "regular," by 32% of the respondents, whereas 46% perceived it as "poor," and 22% perceived it as "very poor" More than 76% of the respondents perceived that the air quality worsened, whilst 17% considered no change, and 7% perceived that the air quality had improved. We found less consensus at the local level, and some residents even perceived good air quality (around 8%). When the survey was conducted in January 2019, the average concentration of PM_{10} was 87.5 μg/m^3, and the average annual concentration for that year was 76.75 μg/m^3, a very close value to the estimated value for 2015. However, we did not use data from 2019, since only one station in the center of the city was monitoring $PM_{10.}$ The responses obtained from 199 individuals are in Figure 5. Most respondents were in an age range between 18 and 31 years (31%), and the majority were women (63%) (Figure 5a,b). The highest percentage reported a monthly household income that was less than the II decile of the average nationwide household income [71]. Among the different income levels, the most common perception of air quality was regular or poor, with a perception that it became worse in recent years. The perception of regular or poor air quality had a similar distribution among age groups, while the perception of improved air quality predominated in the young population and women. Similar perceptions occurred at different education levels with a noticeable higher perception of inferior air quality in those individuals with higher education levels (Figure 5c,d). Concerning the way respondents learned about air quality, many of them (60%) reported media such as the Internet, followed by newspapers and TV. A considerable percentage reported only relying on their senses (odors and poor visibility) (40%). This distribution was the same among those who perceived regular or poor air quality. In the case of perceived improvements over time, a higher proportion of respondents learned from the media (Figure 5e). Fifty-six percent of the respondents pointed to stationary sources (manufacturing and generating plants) as the primary sources of air pollution; 23% considered mobile sources; 18% identified area sources (burning of household waste, burning grassland, and unpaved roads); and 3% of respondents considered natural sources such as dust storms (Figure 5f). This distribution did not change in the different air quality categories. However, when exploring the participating sources related to improved air quality over time, a higher proportion of participants identified mobile sources. When inquiring about health concerns and air pollution, 86% mentioned respiratory illness (cough, cold, asthma, allergies), and 14% associated air pollution with chronic diseases, neurological or metabolic conditions. Frequent respiratory symptoms in at least one member in the household was answered by 55% of the respondents (Figure 5g,h). The highest percentage of individuals that perceived air quality worsening over time also reported an association between severe health effects and frequent respiratory symptoms with air pollution. We present the frequencies and percentages associated with each category of perceived air quality at the local level and perceived changes over time in Table S3 of the Supplementary Material.

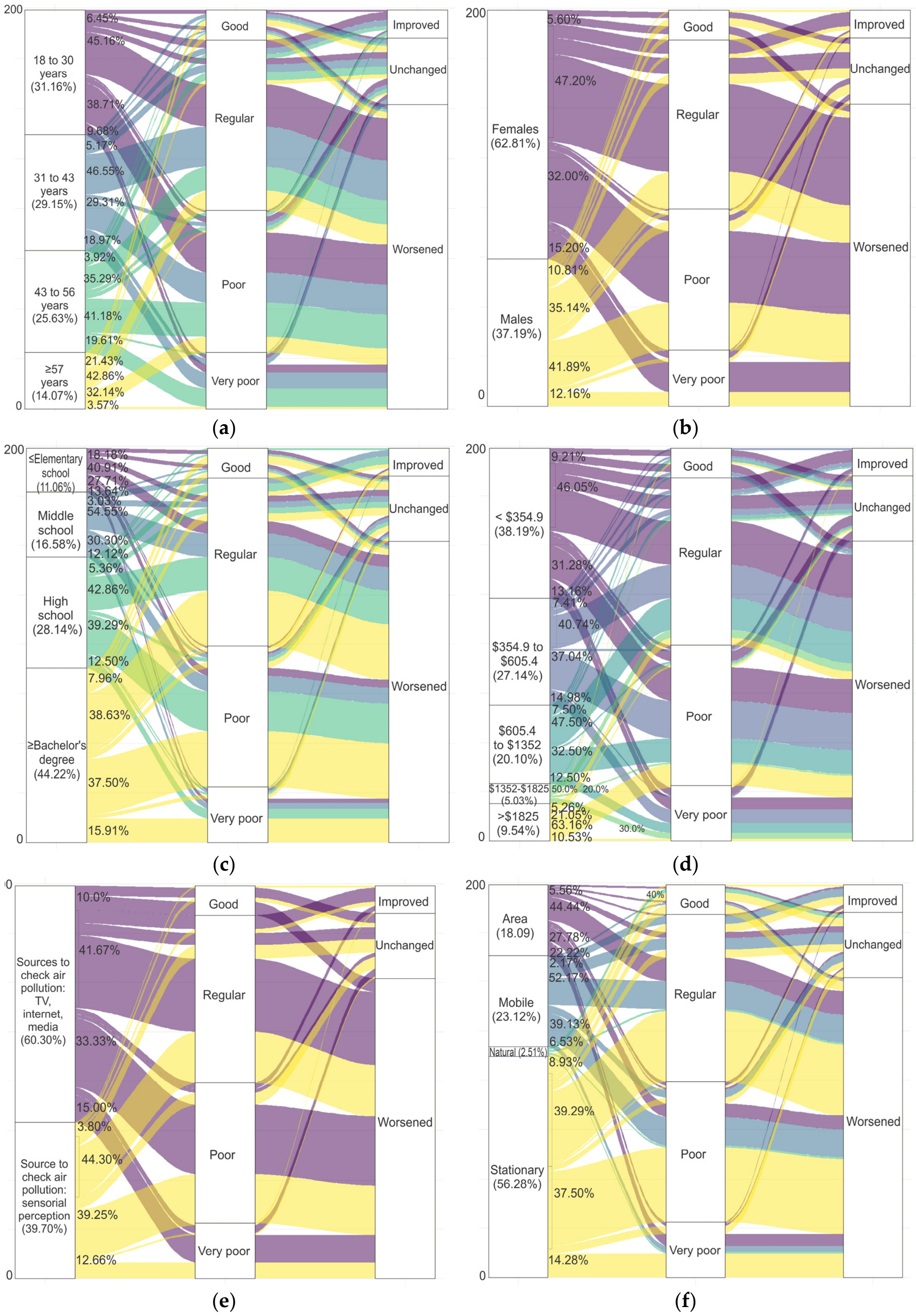
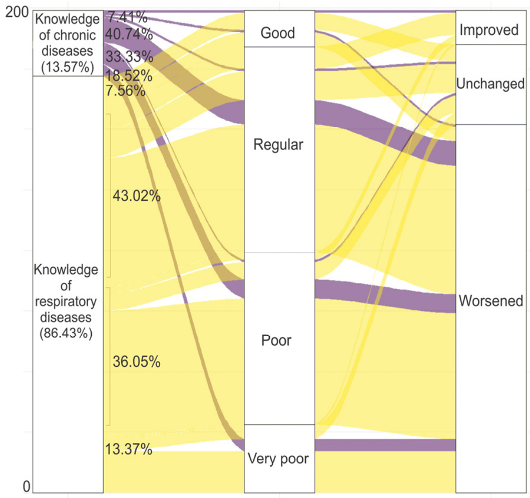
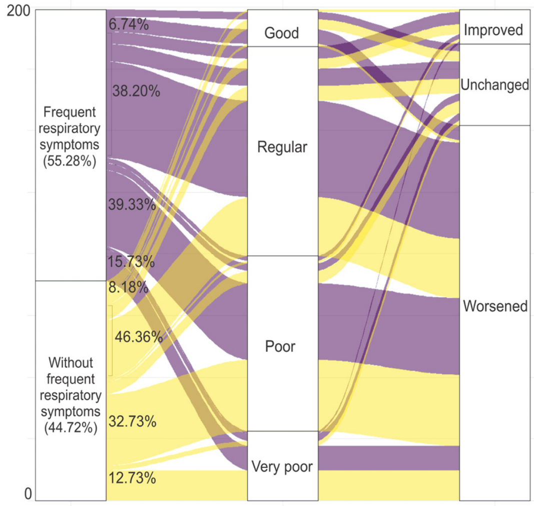


Figure 5. *Cont.*



(g)



(h)

Figure 5. Distribution of perceived air quality at the local level and the perceived changes in the air quality over time by (**a**) age range; (**b**) sex; (**c**) education level; (**d**) average monthly household income (2019 USD); (**e**) sources to check air quality; (**f**) the presence of frequent respiratory symptoms in at least one household member; (**g**) knowledge of the diseases related to air pollution (respiratory or other such as chronic diseases, cancer, neurological and metabolic diseases); and (**h**) the type of pollution sources perceived as more polluting. The colors are related to the number of categories in the first column of each figure. The numbers located next to the first column correspond to the associated percentages of air quality perception at the local level within each category of the first column.

The perceptions of air quality according to the estimated levels of PM_{10} indicated that those respondents in the higher PM_{10} exposure regions perceived, in higher proportions, that the air quality was "poor" or "regular." In moderately exposed areas, slightly higher proportions perceived the air quality as very poor, and even a small fraction considered it "good." In general, we identified a limited knowledge of air pollution-related health effects, other than respiratory conditions. A lower proportion of knowledgeable individuals existed in areas of very high exposure. Regarding pollution sources, the stationary sources were the most frequently reported in high exposure areas. Area sources such as agricultural areas, trash burning, and fireworks, particularly in the winter, were frequently identified in those areas with moderate exposure. Figure 6 presents the proportions of responses related to air quality perception, air pollution sources, and the knowledge of air pollution-related health effects in each one of the estimated categories of exposure.

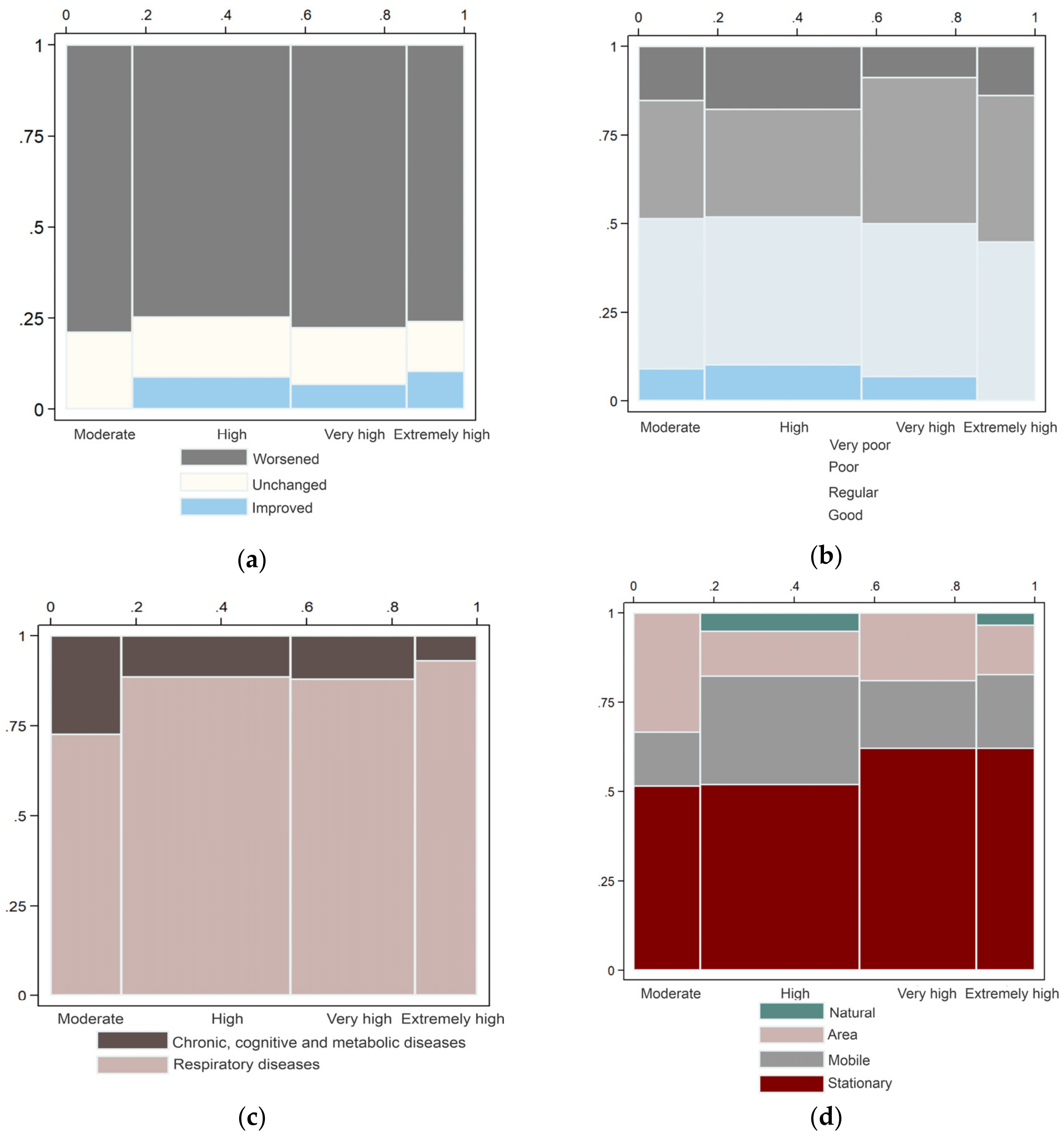


Figure 6. Responses to the perception of air quality by the estimated categories of exposure to PM_{10}. (**a**) Fractions of the perceived changes in the air quality on time (last four years); (**b**) fractions of the perceived air quality at a local level; (**c**) fraction of the responses about the knowledge of health effects related to air pollution; and (**d**) fractions of the perceived primary sources of air pollution.

3.4.2. Spatial Distribution of Air Quality Perception, Estimated Exposure to PM_{10} and Stationary Sources of Pollution

The geographic distribution of the responses related to perceived air pollution, estimated categories of exposure, and the location of stationary sources of pollution are presented in Figure 7. The perception responses do not show apparent differences among the estimated categories of PM_{10} exposure. A global Moran's Index for spatial autocorrelation between these two variables does not show a significant association (I: −0.0172, z-score: −0.249, and p-value: 0.39). The perception of good air quality was infrequent across the exposure zones. In extremely high exposure zones, we did not find responses of perceived good air quality. However, in the same areas, the perception of very poor air quality was less frequent than the perception categories of "poor" or "regular" air quality. A similar tendency regarding a frequent perception of intermediate categories "regular" and "poor" persists in the remaining exposure level areas. The percentages of responses by the estimated categories of exposure are in

Figure S4 (Supplementary Material). Additionally, the geographic distribution of the responses of perceived changes in air quality over time showed a consensus on the perception that the air quality has "worsened" throughout the city (Figure S5, Supplementary Material). Regarding the location of stationary sources of pollution, they are predominantly located at the periphery of the city, mainly in the Southeast region. The western region, which was estimated with high exposure to PM_{10}, has electric power generation industries, meat products industries, and metal product manufacturing, which were perceived as very polluting by the residents of these areas. The distribution of responses shows that the proximity to industries was linked to a perception of "very poor" air quality in areas with lower occurrences of PM_{10} exceeding days. The Moran's Index identified a small cluster where the perception of poor air quality was associated with the high presence of industries near to the respondent's residence in Southeast Mexicali (I: −0.144, p-value: 0.013) (Figure S6, supplementary material).

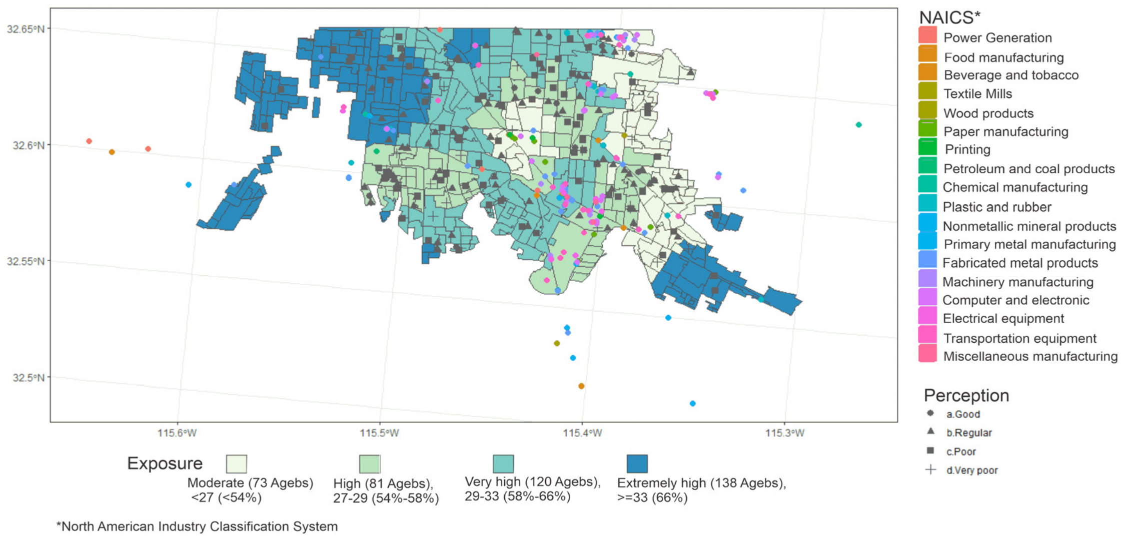


Figure 7. Spatial distribution of the responses about the perception of the current state of air quality, the location of stationary sources of pollution and the estimated categories of exposure to PM_{10} (PM_{10} concentration from the data of monitoring sites from 2015); localized industries correspond to those with more than 30 employees, and that belong to subsectors 221, 311–313, 321–327, 331–336 and 339 according to the North American Industry Classification System.

3.5. Statistical Model for the Association between Perceived Air Quality, Socioeconomic Attributes, and Estimated Exposure to PM_{10}

Results of the Kruskal–Wallis H test showed significant differences between the categories of average monthly household income and the perceived changes in the air quality of the city. We included the results of the estimated exposure areas at the AGEBs level and the knowledge of health effects related to air pollution in the ordered logistic model as confounding variables based on previous studies [29,65,66]. The estimated coefficients are in Table 2. Results show that income and air quality perception in the place of residence have a significant effect on the perceived air quality changes over time in Mexicali. Respondents who reported low household income had lower odds of perceiving that the air pollution has improved versus the perception of "unchanged" or "worsened" air quality. Respondents who reported that there is "regular poor air quality" in their neighborhood are not likely to report that the air quality has improved in the city. Categories of estimated exposure and social vulnerability included at the AGEBs level did not have a significant effect on the perceived changes. The knowledge on the severity of the health effects related to air pollution does not significantly influence the perception. The small number of respondents who know about the severe health effects may have influenced the coefficients obtained.

Table 2. Estimates for the perceived changes in air quality (worsened, unchanged, improved) on time.

Variable	Description	Odds Ratio	95% CI
Average monthly household income (2019 USD) [1]	<US $354.9 (Ref)		
	From US $354.9 to US $605.4	0.36 **	[0.15–0.90]
	From US $605.4 to US $1352	0.30 **	[0.11–0.86]
	From US $1352 to US $1825	0.42	[0.08–2.20]
	>US $1825	0.48	[0.11–2.02]
Knowledge of health effects related to air pollution [2]	No (Ref)		
	Yes	0.51	[0.13–1.96]
Perception of air quality in the location of the individual's residence [3]	Good (Ref)		
	Regular	0.41	[0.14–1.21]
	Poor	0.21 ***	[0.07–0.69]
	Very poor	0.32 *	[0.08–1.21]
Exposure areas by exceedance days of PM_{10} concentrations [4]	Moderate (Ref)		
	High	1.22	[0.44–3.39]
	Very high	1.27	[0.43–3.78]
	Extremely high	1.58	[0.42–5.91]
Social vulnerability (categories by SES index) [5]	Medium-high SES index (Ref)		
	Low SES index	0.58	[0.24–1.38]
N = 199 Log-likelihood = −127.54			
Equality coefficient test through the response Chi2(12) = 2.37 Categories [6] Pseudo R^2 = 0.78			

[1] The exchange rate for when the survey was conducted was 1USD = 19.16 Mexican pesos. World Bank's collection of development indicators [72]; [2] "Yes" if the respondents relate chronic diseases such as cancer, neurological or metabolic diseases with air pollution. [3] The place of residence was assigned based on the reference streets or ZIP code. [4] The categories of days with exceedances are based on the WHO guideline (50 µg/m^3). [5] The social vulnerability was categorized as very high when the socioeconomic status (SES) index was less than or equal to the 75th centile. [6] The result indicates that the proportional odds assumption was not violated. *** for $p < 0.001$, ** $p < 0.05$, * $p < 0.01$.

Demographic variables such as age, sex, and education level did not have a significant effect on the perceived changes through the ordinal logistic regression model (Table S4, Supplementary Material).

4. Discussion

4.1. Linking Air Pollution and Social Vulnerability

In this analysis, we assessed social vulnerability, the estimated exposure to PM_{10}, measured the public perception of air quality, and evaluated the spatial distribution and the relationships among them. We focused on the importance of the evidence of these links when considering air quality management in the context of sustainable development goals. The estimated PM_{10} levels suggested a high exposure to PM_{10} across the city. We found spatial patterns of higher exposure in AGEBs located in the periphery of the city, specifically in the Northwest and Southeast areas. These areas are near to the sources of PM_{10} emissions and adjacent to agricultural areas, areas with reduced vegetation cover, unpaved roads, and affected by the periodic burning of waste and frequent dust storms [73]. Industry and geothermal plants are contributing to deteriorating the air quality in these areas [74]. When assessing social vulnerability, we found clusters of AGEBs with lower SES located in the same peripheral areas. The SES index indicates that a higher amount of people without post-basic education, with unemployment, and no health insurance reside mainly in the Northwest area, near the

Mexico–USA border, and South of Mexicali, where socio-spatial environmental and health inequalities have been reported [36,75,76].

In those peripheral regions, we found clusters (hot spots) of significant spatial autocorrelation between high social vulnerability and high exposure to PM_{10}. Therefore, people in these areas have reduced adaptive capacity and have a higher susceptibility to face the risks associated with air pollution [21]; for instance, people with low education levels often access lower-wage jobs. Additionally, in poor working conditions, low-income individuals are often unable to locate homes in places with better environmental conditions or to cover expenses to protect themselves. In Mexico, the "Agenda 2030" for sustainable development [77], particularly Goal 11, proposed that all the public policies require the consideration of the vulnerability to climatic change, especially in disadvantaged populations. However, until now, public policies attending the social vulnerability to the risk associated with air pollution, have not received enough impulse. Evidence of the relationship between socioeconomic drivers and particulate matter pollution comes from other developing countries [78,79]. In those studies, they found relevant links with land use, infrastructure, and energy consumption, that if contemplated, could result in effective policies to reduce socioeconomic disparities [80]. Concerning PM_{10} exposure in Mexicali, we found that the socially deprived population was highly exposed. Urban development programs have been insufficient to reduce potential PM_{10} sources such as unpaved streets or unsustainable agricultural practices. Therefore, the results suggest that it is necessary to align the strategies in the PM_{10} pollution control in Mexicali, as well as urban planning, with social factors in order to promote sustainable development in this region.

4.2. The Association of Air Pollution, Socioeconomic Attributes and Air Quality Perception

The spatial distribution of the answers shows that the overall perception is not associated with the modeled exposure to PM_{10}. Strong association occurred only in areas with very high exposure. In those areas, air quality perception relies on the individual senses (odors and the visible manifestation of smog and dust). In agreement with previous studies [27,81], we found that perceived changes in air quality occur in areas where people are exposed to the visible manifestation of pollution, such as extremely high concentrations of PM_{10}. For instance, a previous analysis of the spatial dimension of environmental and social hazards related to the public perception in Mexicali, Ley-García et al. [82] showed that only 23% of their sample showed congruence between exposure and perception. In those instances, where the perception was higher than the exposure, the proximity to potential sources of pollution played a role. We identified this issue in areas with moderate exposure to PM_{10}, where some respondents reported very poor air quality when industries were in the proximity. On the other hand, the sense of attenuation mentioned in [82] is manifested here as well, since only 14% of the respondents living in extremely high exposure areas perceived very poor air quality. This sense of attenuation, in some cases, is related to the order of priorities that people have. Especially in border cities, the violence associated with drugs, immigration, economic and health disparities is part of them. In a similar manner, Mexicali's industrial growth as a result of a considerable number of manufacturing industries attracted by incentives like cheap labor and the access to a local source of electricity is perceived by the residents as a critical factor of risk. Most of these industries, the settlements where people belonging to lower SES, and air pollutants represent an environmental hazard are concentrated in the peripheral areas of the city. Air quality perception in those areas has an essential role in engaging self-protect actions as well as promoting collective actions to improve environmental conditions.

Our findings from the statistical analysis of low-income level affecting pollution perception (including variables at the individual and community level), agreed with recent studies conducted in the United States, South Korea, and China [29,66]. In our case, when people perceived the surroundings as polluted, they were less likely to consider that the overall air quality in the city improved. The other studies [29,66] reported a similar tendency; lower-income inhabitants had higher odds of considering that the air quality had not improved. These findings also agree with the ones by Schmitz et al. [66], indicating that the concern for pollution, in immediate surroundings, negatively influences the perception of air quality at the city level. Other authors [29,65] postulated that when studying the built environment, individual-level socioeconomic factors are more affordable predictors of air quality perception than objective measurements from monitoring stations. Usually, air quality data is not widely disseminated, and it is not straightforward to interpret [83]. In this regard, the sensitization to engage the population around air pollution problems is necessary to promote behavioral changes towards the air quality control strategies and the self-protection attitudes [34]. Knowledge about the long-term risk of exposure to air pollutants can influence behavioral changes [84]. We found a lack of knowledge about the impact of air pollution on health. Only 7% of the respondents in areas of extremely high exposure were aware of the severity of health effects related to air pollution, particularly in low socioeconomic groups. The knowledge about respiratory diseases, reported by most respondents, is limited to asthma, allergies, cough, and the flu. Other diseases, such as pulmonary cancer and cognitive effects, were not recognized by the respondents. Although existing knowledge of health effects and self-reported diseases related to air pollution have shown a significant association with perceived air quality [63,66], in our study, no statistical significance was obtained. Similar results to ours were obtained in a study conducted in Seoul with a larger sample [29]. A possible reason for this difference is that the population with high social vulnerability and a very high exposure to PM_{10} may be affected by other social problems, limiting their attention to environmental risks such as air pollution [27,80]. Therefore, beyond generating data, governments should provide appropriate communication channels and prioritize actions in the disadvantaged population. Some strategies involve providing understandable information. This goal can be accomplished through media, interventions based on volunteer monitoring and participation with observations, implementing workshops, and using low-cost air quality sensors in low-SES areas. Actions like sustainable agricultural practices, modernizing the supply of conventional energy to clean energy sources, and promoting the planting trees could contribute to increase the wellbeing of this population. Moreover, local governments need to promote source-oriented actions that reduce the emissions of particulate matter from an inclusive perspective. For instance, it is necessary to guarantee the paving of streets in neighborhoods on the periphery where the population is most exposed and lacks the economic resources to do so in a particular way. In Mexico, unpaved streets continue to be a challenge in urban planning; local governments have limited budgets in this area. Hence, it is necessary to show the importance of this issue in cities like Mexicali, which has social, health and mobility implications and the need for prioritized actions.

The objective is to generate an understanding in the population and local officer managers, with a sense of inclusion.

4.3. Limitations

Our study's limitations are related to the temporary differences among the air quality data obtained for 2015 and the socioeconomic variables from the 2010 Census. These differences may be biased since we used retrospective social vulnerability data; it is not possible to ensure that the individuals remained in the specified AGEBs for the year the exposure was estimated. However, we chose information from 2015 to achieve a higher statistical sufficiency in the air quality records and recent information on socioeconomic characteristics at the AGEB level.

These temporal differences also were also a limitation in the information at the individual level; however, in 2019, only one monitoring site was regularly measuring PM_{10}; therefore, it was not possible to estimate exposure at the AGEB level in areas with no functioning monitoring stations. The estimated average annual concentration for 2019 was similar to the one obtained for 2015. In this sense, we considered, as selection criteria, to retain the information, only residents with more than four years living in Mexicali. Although the air quality perception may not adequately reflect the tendencies in air quality if the changes are small, concerning PM_{10}, considerable changes may be more noticeable through the senses. Another limitation is related to the small sample size, which may result in un-coverage bias. However, a good spatial coverage was achieved. The sample corresponds to people who visit open spaces with more frequency, and only cover urban areas (see Table S5 in the

Supplementary Material to compare population characteristics with the Census data). In this sense, further studies could consider a house-by-house survey.

Despite the technical limitations regarding the availability and coverage of air quality data, our study has an essential contribution in the scarce evidence about the linkages between air pollution, socioeconomic status, and air quality perception in Latin American countries. The findings can serve as a base for further research. Besides, our effort to obtain information in addition to requests from other researchers can put pressure on the consistent generation of data on air quality.

5. Conclusions

The results of this study show the existence of spatial patterns of the socially vulnerable population significantly associated with high exposure to PM_{10} in Mexicali. Spatial distribution and statistical analysis indicate that air quality perception at a local level is affecting the lack of perception in air quality changes over time. Considerable agreement between the perception and data from monitoring stations occurred in the areas with a higher exposure to PM_{10}; in many cases, the perception of poor or very poor air quality was related to nearby industries. The estimates of PM_{10} exposure and socioeconomic characteristics aggregated at the AGEBs level do not influence the perception in air pollution changes over time. Individual socioeconomic factors such as income have a relevant adverse effect on perceived changes. The knowledge of health effects related to air pollution is scarce in the city, and is not significantly linked to the level of air quality perception. Clusters of the socially vulnerable population living in areas of high exposure to PM_{10} are mostly unaware of the severe health effects associated with air pollution. Therefore, more attention should be directed towards these areas, both in the control of PM_{10}-emitting sources and social programs to improve the resilience and adaptive capacity of the residents. Additionally, there is a need for a local risk communication strategy related to the concentrations and the health effects in this part of the city.

The findings of our research contribute to broadening the knowledge about the social factors that affect the exposure and perception of air quality in developing countries. These results may serve as evidence for policymakers to conduct air pollution abatement policies, not only based on technical information but also focused on socioeconomic and cultural factors.

Supplementary Materials: The following are available online at http://www.mdpi.com/1660-4601/17/13/4616/s1, Figure S1: Geographic location of monitoring stations, centroids of each AGEB and buffers used for the IDW method, Figure S2: Principal components analysis scree plot as selection criteria, Figure S3: Circular buffers to assess proximity to industries and perception of air quality. 1-mile radius buffers were centered at the respondent's place of residence. The number of industries within each buffer was calculated. We use the "queen" proximity matrix, Figure S4: Responses of perceived air quality by exposure areas, Figure S5: Perceived changes on air quality in the last four years in Mexicali. Survey 2019, Figure S6: Bivariate local Moran's Index for spatial autocorrelation between the presence of industries nearby the residence's place and perception of air quality. Localized industries correspond to those with more than 30 employees, and that belong to subsectors 221, 311–313, 321–327, 331–336 and 339 according to the North American Industry Classification System, Table S1: Results of the Kaiser-Meyer-Olkin (KMO) for measuring adequacy sampling, Table S2: Results of the Kruskal-Wallis H test for individual and AGEB level variables with responses of air quality perception. Consist of the chi-square test statistic with ties (X2), the degrees of freedom (df) and the significance level (p-value), Table S3: Socioeconomic characteristics, health concerns and knowledge of health effects by the perceived air quality, Mexicali, 2019. Percentages of responses in parenthesis, Table S4: Estimates for perceived changes in air quality (worsened, unchanged, improved), Table S5: Demographic characteristics of the sample and information from the 2015 Census for the municipality of Mexicali.

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Consideraciones para el Capítulo IV

Los resultados de la investigación realizada en el Capítulo III respecto a la importancia de las variables socioeconómicas y la percepción de la calidad del aire en cuanto a la exposición de PM_{10} en Mexicali son relevantes para indagar de que manera influyen como determinantes en la disposición a participar en estrategias para mejorar la calidad del aire y la valoración que se da a la calidad del aire en la ciudad.

Un hallazgo relevante se asoció con el poco conocimiento de los efectos de salud y la importancia del entorno construido en el lugar donde residen las personas sobre su percepción de la calidad del aire, cuya relación fue más directa que aquella asociada a las mediciones de las redes de monitoreo. En este sentido se postuló la sensibilización y diseminación de información a nivel local en poblaciones socialmente vulnerables como punto de partida en la priorización de acciones para reducir la exposición de las personas que residen estas áreas.

En el capítulo IV la percepción de la calidad del aire se retoma para evaluar su influencia en una política de forestación urbana con especies nativas para mitigar las altas concentraciones de PM_{10} en la zona urbana de Mexicali.

Los datos obtenidos acerca de la percepción nos permiten también comparar la perspectiva de los habitantes con la de actores claves entrevistados en esta ciudad y encontrar aspectos a fortalecer.

CAPITULO IV

BENEFICIOS ESTABLECIDOS HACIA UN PROGRAMA DE FORESTACIÓN URBANA PARA MEJORAR LA CALIDAD DEL AIRE EN MEXICALI: UN ESTUDIO DE VALORACIÓN CONTINGENTE.

Muñoz-Pizza, D. M., Villada-Canela, M., Rivera-Castañeda, P. Reyna, M.A., Osornio-Vargas, A., Martinez-Cruz, A. L. (2020). Stated benefits from urban afforestation to improve air quality in an arid city: A contingent valuation in Mexicali, Baja California, Mexico. Urban Forestry & Urban Greening. Under-review.

Resumen.

Las zonas áridas alrededor del mundo están experimentando severos problemas asociados con el incremento de la urbanización y cambio climático. La contaminación por PM_{10}, erosión del suelo y escases de agua son importantes retos ambientales. Las peligrosas concentraciones de material particulado en las ciudades áridas ha sido planteada en la evidencia científica. Bajo este contexto y promoviendo estrategias de desarrollo sustentable se plantean los arboles urbanos como estrategia de mitigación. Los árboles urbanos son reconocidos por proveer servicio de filtrar el aire y mejorar la salud pública. Sin embargo, estos servicios son poco reconocidos en la gestión local de la calidad del aire.

Simulando un mercado no existente, este estudio documenta la disposición a pagar (DAP) por mitigar la contaminación por PM_{10} a través de un escenario de forestación urbana con especies nativas en Mexicali, una ciudad árida localizada en el noreste de México, en la frontera México – Estados Unidos. Nuestro protocolo de valoración contingente de elección binaria con respuesta de seguimiento condujo a una DAP promedio de 88 dólares anuales por hogar. Variaciones en la DAP se asociaron con la percepción de la calidad del aire y la presencia de síntomas respiratorios en algún miembro del hogar. La DAP más baja fue de 75 dólares, reportada para los encuestados que percibieron una mala calidad del aire en su vecindario y sin miembros del hogar afectos por síntomas respiratorios frecuentes. En contraste, los encuestados que percibieron una buena calidad del aire y con al menos un miembro del hogar encarando síntomas respiratorios frecuentes, reportaron una DAP de 99

dólares. El promedio de beneficios establecidos por los encuestados representa alrededor del 0.8% del ingreso medio anual de los hogares.

Los resultados subrayan el rol crítico de la percepción de la calidad del aire y la conciencia ecológica sobre los beneficios de los arboles urbanos como factores necesarios para promover un mayor compromiso de la comunidad y tomadores de decisiones.

Palabras clave: calidad del aire; PM_{10}; forestación urbana, especies nativas, valoración contingente, ciudades áridas, síntomas respiratorios, Mexicali.

Stated benefits from air quality improvement through urban afforestation in an arid city –A contingent valuation in Mexicali, Baja California, Mexico (Revisado y reenviado a Urban Forestry & Urban Greening)

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Abstract

Cities in drylands are expected to experience increasing challenges when it comes to air pollution. Currently, concentrations of particulate matter in these cities frequently reach dangerous levels. Urban afforestation represents an alternative to increase human health in arid cities via air-filtering and dry deposition. By simulating a non-existing market through a contingent valuation protocol, this study estimates the willingness to contribute monetarily to an urban afforestation scenario in Mexicali –an arid city located at the US-Mexico border. We estimate an average annual willingness to pay (WTP) of (2019) USD 88 per household. Variations in WTP are associated with the respondent's perception of air quality and the presence of respiratory symptoms in the respondent's household. The smallest WTP (USD 75) is reported by those perceiving poor air quality in their neighborhood and with no household members affected by respiratory symptoms. Respondents perceiving good air quality and with at least one household member facing respiratory symptoms report a WTP of USD 99. The highest WTP represents around 0.8% of the annual household income. This WTP, when extrapolated to and aggregated over the total number of households in Mexicali, justifies the implementation of an urban afforestation program supplying 30 thousand tree seedlings annually.

Keywords: Air quality; urban afforestation; contingent valuation; arid cities; respiratory symptoms, Mexicali.

1. Introduction

Air pollution is a problem affecting human health in arid and semiarid cities. The concentrations of PM_{10} in these cities frequently surpass the World Health Organization's recommended thresholds of 20 μg/m^3 annual mean, and 50 μg/m^3 24-hour mean (UNEP et al., 2016). These concentrations are partially due to meteorological events common in drylands and favor the accumulation of atmospheric pollutants –i.e. extreme temperatures, low precipitation, frequent dust storms, and wind erosion processes (Ozer et al., 2006; Li et al., 2008). Anthropogenic factors behind high concentrations of atmospheric pollutants include reduced vegetation, agricultural waste, road traffic, and manufacturing industries (Massey et al., 2013; Radaideh, 2017). Severe cases of PM_{10} in arid and semiarid cities are associated with effects to human health, including morbidity and mortality due to respiratory diseases (asthma, acute bronchitis, pneumonia, influenza, pulmonary function) and cardiovascular affections (De Longueville et al., 2010; Maleki et al., 2016; Wang et al., 2019; Yunesian et al., 2019).

Urban green infrastructure mitigates air pollution and improves humans' health (Jayasooriya et al., 2017). Notably, urban trees improve air quality through air-filtering and dry deposition processes –trees remove air pollution by intercepting particulate matter on plant surfaces and absorbing gaseous pollutants through the leaf stomata (Terzaghi et al., 2013; Janhäll, 2015; Nowak et al., 2018). Reductions in PM_{10} associated to an increase in tree coverage have been reported in arid and semiarid regions, including Denver, Tucson, Northern Negev, Mediterranean cities, central Chile and north Mexico (Nowak et al., 2014; Uni and Katra, 2017; Manes et al., 2016; Escobedo and Nowak, 2009; Baumgardner et al., 2012). Consequent positive impacts from urban trees on human health have also been documented (Nowak et al., 2018; Jones and Goodking, 2019).

However, urban afforestation has been overlooked as a strategy to combat PM_{10} pollution in arid and semiarid cities of emerging economies. The arid city of Mexicali, located at the Mexico-US border, is an illustrative case of how an urban afforestation program has received little attention from both policy makers and the general public. Mexicali has been ranked among the cities with the highest concentration of PM_{10} worldwide (WHO, 2016). Despite this situation, an urban afforestation program launched by the State administration has lacked a strong communication campaign which, in turn, has deterred residents from becoming beneficiaries of this program –which delivers tree seedlings and tree-planting assistance to citizens who request so (SPA, 2018; SPA, 2019). The overlooking of urban trees as instruments to decrease PM_{10} pollution is partly due to stakeholders' lack of awareness about how ecosystem services from urban trees contribute to the functionality of a city (Escobedo et al., 2011). For instance, in explaining the State's urban afforestation program's goal, policy makers highlight urban trees' contribution to water capture and store and reduction of CO_2 emissions but overlook air-filtering services that contribute to controlling PM_{10} concentrations (SPA ,2017).

In this context, it does not come as a surprise that there is no previous information on the value that residents of arid cities in emerging economics assign to afforestation efforts in their cities. By taking Mexicali as a case study, this paper carries out a contingent valuation exercise to estimate the stated benefits from improvements in air quality derived from urban afforestation. Following previous contingent valuation studies (see section 2), we have also explored how this monetary value varies with the respondent's air quality perception at the neighborhood level and the presence of respiratory symptoms in the respondent's household.

Results from this study are useful not only for Mexicali but also for other cities located in drylands. For instance, around 65% of Mexico's territory is dryland and hosts 30% of its population (Becerril-Piña et al., 2015). Drylands cover approximately 41% of Earth's surface and host more than 38% of human population (Reynolds et al., 2007). Severe droughts are expected to increase their coverage worldwide –across Africa, southwestern Asia, northwestern India, southwestern USA, northern and central Mexico, western South America, and Australia (Gamo et al., 2013; Yao et al., 2020). Adding population growth to the equation, cities in drylands will experience increasingly difficult challenges when it comes to water scarcity and air pollution (Buharg and Urdal, 2013).

2. Previous contingent valuation studies inferring benefits from air quality improvements

Contingent valuation (CV) is extensively used in environmental impact assessments and cost-benefit analysis to estimate benefits provided by goods that are not traded in a market (Mitchell and Carson, 1989). Our CV survey simulates a non-existing market in which respondents trade money and air quality changes generated through an urban afforestation scenario. In general, CV would yield willingness to contribute monetarily (or willingness to pay, WTP) to air quality improvements; and it CV would deliver willingness to take a monetary compensation (or willingness to accept, WTA) when a scenario implies a deterioration in air quality (see Carson et al., 2001). As responses are elicited under a hypothetical market, CV yields stated preferences –as opposed to preferences revealed in a real market. Consequently, estimates resulting from a CV survey can be interpreted as the self-reported monetary value of the benefits that respondents perceive they receive from the changes presented in the CV scenario –i.e. stated benefits from, in this case, an urban afforestation scenario.

Discrete choice experiments (DCE) and hedonic prices method (HPM) represent two alternative methods to CV. Both methods have been implemented in similar context than ours (e.g. Anthon et al. (2005); Sagebiel et al. (2017)). We have deemed CV as the most useful method in our context due to two main reasons. First, we are not aware of available data on house prices that can be linked to afforestation variation in Mexicali –i.e. as a revealed preferences method, HPM relies on market data not available in Mexicali. Second, while an afforestation scenario can be decomposed in attributes and presented in the format of a DCE, this decomposition may imply unrealistic scenarios. In our specific context, we have chosen to describe the good under valuation (i.e. an urban afforestation scenario) as a bundled good to keep it as similar as possible to the afforestation program in place at the State level.

CV has previously been used to estimate benefits from improvements in air quality. Table 1 presents a list of these CV studies.[1] The first column reports authors and year of the study. The second column reports the country or city under study. The third column describes the improved air quality scenario under valuation. The fourth column reports control variables other than the conventional respondents' socioeconomics used in modeling the willingness to pay (WTP). The last column reports estimated annual WTP (in 2019 USD).

Table 1. Studies implementing a contingent valuation protocol to estimate the willingness to pay for improvements of air quality.

[1] Studies in table 1 represent a non-comprehensive list of CV studies that have focused on estimating the benefits from improvements in air quality. Closely related literatures include i) CV studies focusing on the benefits from biodiversity conservation strategies in urban contexts (Amirnejad et al., 2006; Madureira et al., 2011; Chu et al., 2020); ii) CV studies estimating the benefits from recreational and cultural amenities in urban contexts (Lo and Jim, 2010; Sirina et al., 2017; Chen and Qi, 2018); iii) CV studies estimating the benefits from mitigation of climate change and heat island effects (Le Tran et al., 2017; Zhang et al., 2019); and iv) CV studies estimating WTP for green areas in terms of coverage and distance from respondent's houses (Sabyrbekov et al., 2020).

Authors (year)	City/ Country	Improved air quality scenario	Control variables in addition to socioeconomic ones*	Annual WTP (2019 USD)**
Wang et al. (2020)	Xingtai, Guiyang (China)	Vehicular restrictions, regulatory and technological measures to industries. Clean energy.	Air quality perception, exposure time to pollution, filter installed in their households, believe that air pollution is caused by enterprises and distrust in government.	49.1 per person
Guo et al. (2020)	Zhengzhou, Pingdingshan, Zhumadian (China)	Improvements in air quality to meet the air quality guideline set by the World Health Organization.	Average air quality index (AQI) from ground-level monitoring stations associated to each survey location.	11.5 per person
Pu et al. (2019)	31 provinces (China)	Program to reduce heavy air pollution days by 50%. The measures include industrial energy-saving.	Risk perception and attitude: perceived risk of air pollution, environmental awareness of protecting air quality, knowledge of air pollution and related health effects, government control trust.	23.3 per person
Zahedi et al. (2019)	Catalonia, (Spain)	Technological measurements, biofuel production, investment in public transport.	Pro-environment attitude, subjective norms, perceived behavioral control, environmental concern.	100.57 to 200.9 per household
Ouyang et al. (2019)	Shanghai, (China)	Regulatory and economic measures. Higher electricity prices and fuel costs to reduce the use of coal and oil.	Concern about haze, subjective perception of haze, respiratory diseases, social trust in haze data published by the government, household expenditure on preventive respiratory diseases, expenditure on haze mitigation	343.3 per household
Zhang et al. (2019)	Beijing, (China)	Regulatory and economic measures. Sand and dust weather mitigation.	Family members will support respondent`s pro-environment behavior, health conditions of the respondents.	48.58 per household
Dong and Zeng (2018)	Beijing, (China)	Regulatory measures to decrease smog by 30%, 45% and 60%	Respondent's knowledge about smog, risk perception of smog, satisfaction in policy, trust in information.	158 per household
Ardakani et al. (2017)	Shahr-e-Ray, Shoosh, Haft-e-Tir and Tajrish, (Tehran)	Control and reduction in pollution	Geographic region of residence	9 per person
Wei and Wu (2017)	JingJinJi Region, (China)	Regulatory measures to reduce 80% of severe $PM_{2.5}$ polluting days	Knowledge about health effects related to air pollution, whether respondent believes that the government should take action to control air pollution, member of communist party.	149 per household
Akhtar et al. (2017)	Lahore, (Pakistan)	50% reduction of pollution through	Respondent's subjective view about air quality, suffering from respiratory illness	135 per household

		technological and regulatory measures.		
Sun et al. (2016)	30 provinces (China)	Mitigate smog crisis through clean energy generation systems	Indoors or outdoors job, life expectancy, sources of smog, household energy expenditure	172 per household
Filippini and Martínez-Cruz (2016)	Mexico City, (Mexico)	Air quality improvement through regulatory and technological measures.	Whether a household's member suffers a respiratory illness, concern about economic and environmental issues	92 per household
Yu et al. (2015)	Yangtze River Delta (China)	Reduction in number of days that air pollution and poor visibility occurs (above 349 AQI), through regulatory measures	Objective visibility (through monitoring of sites), respondent's perception of atmospheric visibility, and attitudes towards environment	Not specified
Yang et al. (2014)	Suzhou, China	Reductions of 20%, 30%, 40%, and 45% in CO_2 emissions through regulatory measures	Perceived risk from increases in greenhouse gas emissions, and attitudes toward government's management practices	56 per person
Wang et al. (2009)	Ji'nan, China	Improve air quality going from Class 3 to Class 2 in national standards through technological and regulatory masures.	Whether a household member suffers a respiratory illness, and expenditure on the treatment of respiratory illness	15 per person
Carlsson and Johansson-Stenman (2000)	Sweden	50% Reduction of harmful substances through regulatory measures	Respondent's location (large city versus smaller city), whether respondent suffers a respiratory illness, and respondent's awareness of actual levels of pollution	47 per person

*Socioeconomic variables include respondent's and respondent household's characteristics such as income, education, age, gender, household size, whether house is rented or owned, etc.
** The reported WTP has been converted to 2019 USD based on exchange rates published by the World Bank's collection of development indicators (WDI, 2019).

The list in Table 1 illustrates three features we wish to highlight. First, previous CV studies have focused on scenarios that improve air quality via regulatory and/or technological measures. Urban afforestation scenarios have yet to be on the radar of contingent valuation studies that estimate benefits from air quality improvements. To the best of our knowledge, only Zhang et al. (2020) have previously discussed the relevance of air filtering services from urban trees. They have investigated the WTP for small green infrastructure based on trees' ecosystem services that people value the most. Respondents ranked air-filtering at the top of their preferences –from among air-filtering, sound barrier, temperature regulation, protection from flood events, and biodiversity conservation.

A second feature illustrated in Table 1 is that particulate matter as received little attention as the pollutant of interest –CO_2 is the pollutant that has received the most attention so far. Consequently, we believe that the focus on PM_{10} is also a novelty in this CV study. The third highlight is that, when modeling respondent's WTP, previous CV studies control for whether a member in the household suffers a respiratory illness and, with less frequency, for the respondent's air quality perception. We follow suit these studies and control for both factors.

3. Study area and methods

3.1 Study area

Located at the Mexico-US border (Fig 1.a), Mexicali hosts 752.6 thousand inhabitants (COPLADE, 2018). Its climate is arid, with winter rainfall (around 75mm annually), average high temperatures in summer (around 42.2ºC), and average high temperatures in winter (21.1ºC) (Cueto et al., 2013). Air pollution in Mexicali is associated with natural sources, emissions from the transportation sector, electric power generation, industry, and unpaved streets (Rojas-Caldelas et al., 2013). Also, mineral dust resuspension and long-range transport (Choi et al., 2006; Carmona et al., 2015) are important sources of emissions.

The annual average concentration of PM_{10} in Mexicali has been reported as 80% higher than the national regulation (50 µg m^{-3}) (Zuk et al., 2007). The most recent national official report of air quality lists Mexicali with the highest annual PM_{10} concentrations (95 µg m^{-3}), and with the second with the highest 24-hour average PM_{10} concentrations (274 µg/m^3) (INECC, 2018). Particulate matter in Mexicali includes elements of soil mixed with metallic and non-metallic minerals which have been associated with hemolytic and pro-inflammatory effects, cardiopulmonary diseases, and reduced lung function (Osornio-Vargas et al., 2011; Reyna et al., 2018).

Green areas per resident in Mexicali –including recreation, sport, and other public services and functional green areas-roads— are estimated at 7.77 m^2 (Peña-Salmon et al., 2014). This number does not reach the minimum of 9 m^2/inhabitant suggested by the World Health Organization (Russo and Cirella, 2018). Most of these green areas (parks and other areas with recreational use) are shown in Fig 1.b.

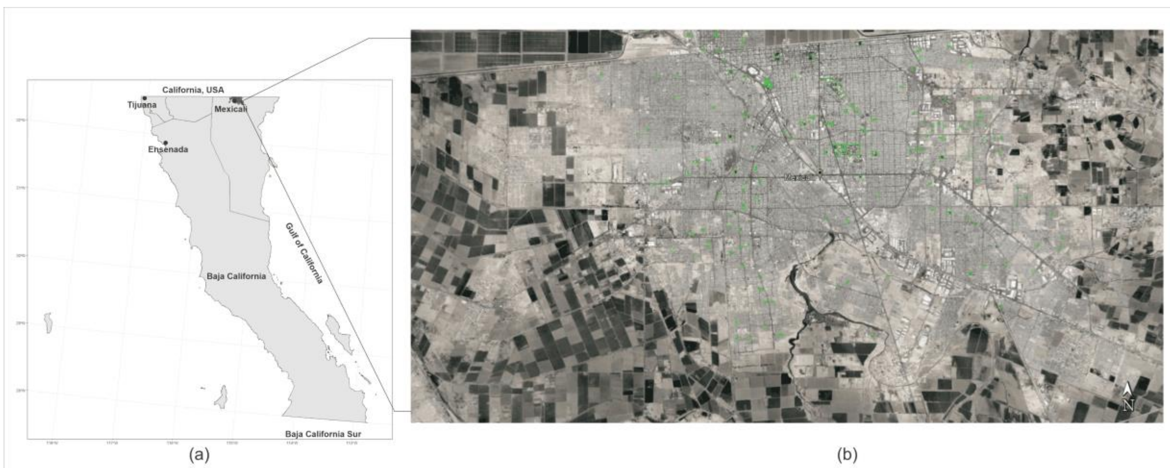

Fig 1. Location of Mexicali, Baja California, Mexico (32.55º N, 115.47º W) (a). Functional green areas and for recreational uses (polygons in green) in urban area of Mexicali downloaded from Google Earth Pro 2020 (b).

The State Urban Afforestation Program of Baja California[2] aims to increase afforestation and reforestation in schools and public parks, and to increase urban green areas across the State

[2] Programa Estatal de Forestación Social y Urbano.

to decrease greenhouse gas emissions (SPA, 2017). In 2017, the program reported an annual production of 200,000 tree seedlings of native and introduced plants per year in four nurseries. The program provides tree seedlings and tree-planting support to citizens who request so and commit to taking care of the planted trees.

This urban afforestation program, however, lacks a strong communication campaign. For instance, no webpage has been set up to inform specificities about the program. Also, official information about its operation is not readily available online –it is not clear when the program was launched, or its operations costs, among other relevant information. Given the reliance of this program on citizens' self-motivation, the lack of easy access to information has arguably been a deterrent to reach as many beneficiaries as possible.

3.2 Questionnaire design and data collection

The design of our questionnaire has accounted for the recommendations from the National Oceanic and Atmospheric Administration (NOOA) Panel (Arrow et al., 1993). In particular, adopting a face-to-face interview, pretesting, a referendum question when gathering the respondents' WTP a thorough description of the contingent valuation scenario (including photographs). Also, some recommendations were adapted to developing countries' contexts to deal with possible sources of bias. The interviewer bias was treated with training and a prior explanation of each question to the interviewers, who have a background in environmental issues, which is relevant to provide explanation when the surveys are implemented face-to-face. Partial response bias was treated locating possible sensible questions such as income and education level after the WTP question. Other possible sources of bias pointed out by Riera et al. (2016) in developing countries are non-neutrality and complacency due to respondents' perceptions about potential political usage of the data. This bias was addressed, assuring the respondent that the purpose of the exercise was entirely academic, and no political organization was supporting its implementation.

Data were gathered during January 2019. The protocol was piloted on 30 respondents to define the bids presented through the double-bounded format and to polish the questions. The final instrument is composed of 36 questions. Respondents spent around 20 minutes answering it. A total of 270 face-to-face surveys were conducted in open spaces (e.g. malls, parks, etc.) to 18 years old or older individuals. This sample size allows for representability at the household level in Mexicali –with an error type I of 5%[3]. From the 270 surveys, 240 were fully responded, and 223 include the geographical references (neighborhood, ZIP code) of the respondent's house. The sites and geographical coverage achieved in the final sample are presented in Fig 2.

[3] In research where the variable of interest is qualitative, an alpha value is usually assumed at 0.05. The sample size formula for categorical data when the total of observational units (inhabited particular homes) are known $is\ n = N(Z)^2 * (p)(q)/(d)^2(N-1) + (Z)^2(p)(q)$, where $Z =$ value for selected alpha level in each tail, in this case, 1.96, $(p)(q) =$estimate of variance, maximum possible proportion (0.5)*1- maximum possible proportion (.5) produces maximum possible sample size. $d =$acceptable margin of error (error researcher is willing to accept), 0.05. N=291763 inhabited particular homes, Census 2015 (INEGI, 2015). (Bartlett et al., 2001)

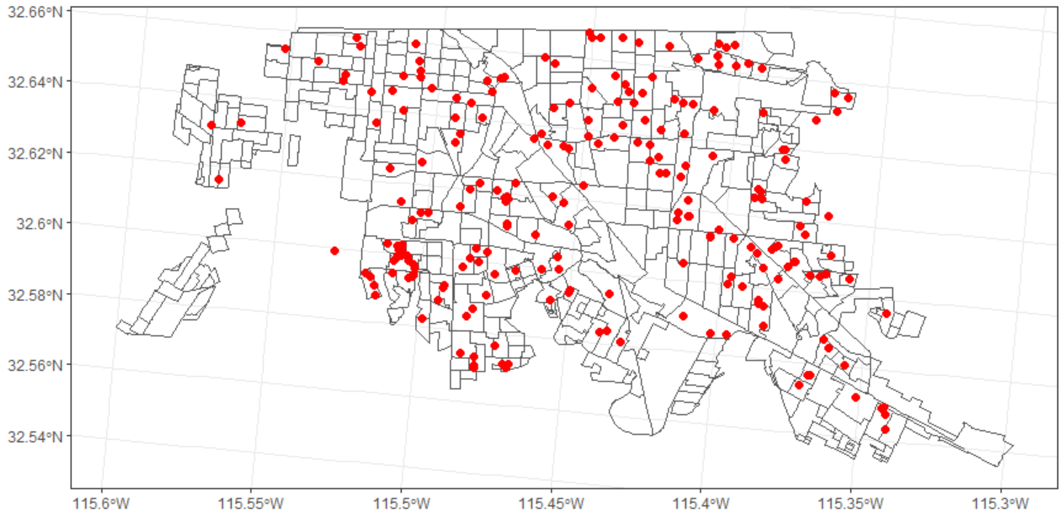

Fig. 2 Survey coverage. Red dots represent respondents' place of residence.

The questionnaire is composed of five sections.[4] The first section introduces the respondent to the air pollution issue in general and describes the conditions in Mexicali. We first present the respondent to a Likert-scaled question that measures awareness of environmental issues in Mexicali. Then, we explain what particulate matter is and its effects on human health. We present graphical information about the number of days in a year that PM_{10} concentrations surpass the national regulation in Mexicali [see Fig. S1. in Supplementary Material]. Then, urban trees are described as providing air-filtering services that can decrease PM_{10} concentrations and consequently improve human health.

The second section of the survey presents the contingent valuation scenario. It is described as an urban afforestation program that would mitigate air pollution by planting native species[5] —*Prosopis glandulosa* (mesquite dulce), *Prosopis juliflora* (mesquite), *Acacia farnesiana* (huisache) and *Parkinsonia aculeate* (palo verde). The potential to reduce the PM_{10}

[4] The questionnaire is available from the corresponding author upon request.
[5] Native tree species have adapted to the local high temperatures and limited precipitation, and require less water than non-native species. These species are considered ecologically relevant for arid and semi-arid environments of northern Mexico (Herrera-Arreola et al., 2007; Prasad and Tewari, 2016).

concentration associated with this strategy is described as a decrease between 10% to 20% in PM_{10} concentration —these numbers are based on results reported by studies focusing on air-filtering services from canopy species in arid and semi-arid environments (McDonald et al., 2016; Manes et al., 2016; Uni and Katra, 2017).

Before being faced to the DBDCV question, respondents were asked the following:

> *considering what we have previously described to you, would you be willing to contribute monetarily for the afforestation program with native trees to be maintained and expanded? The contribution is on a household and monthly basis for two years.*

When the respondent answers no to this question, a follow-up question was presented to identify protest zeros.

If the respondent was willing to contribute with a monetary contribution, then he/she was asked:

> *Would you be willing to contribute B_j^I Mexican pesos? Keep in mind that this contribution is on household and monthly basis for two years.*

If the respondent answered yes to B_j^I, the initial bid, then a follow-up question presented B_j^H, where $B_j^H > B_j^I$,

> *Would you be willing to contribute B_j^HMexican pesos? Keep in mind that this contribution is on household and monthly basis for two years.*

If the respondent answered no to B_j^I, the initial bid, then a follow-up question presented B_j^L, where $B_j^L < B_j^I$, *Would you be willing to contribute B_j^L Mexican pesos? Keep in mind that this contribution is on household and monthly basis for two years.*

The definition of a vehicle payment in Mexico is particularly complicated. For instance, suggesting an increase in taxes is unrealistic and unpopular. Thus, based on what we observed in focus groups, we allowed respondents to choose their preferred vehicle payment from three alternatives –through an environmental fund administered by an NGO, water bill, or electricity bill.

The third section gathers demographic and socioeconomic information at the individual and household levels –such as age, sex, education, household size and residence (zip code, neighborhood, and street).

The fourth section gathers the respondent's air quality perception and health concerns. The perception of air quality is associated with the proximity to environmental risks and varies by the unit of aggregation, i.e., the perception at the neighborhood level is usually different than at the city level (Bickerstaff and Walker, 2001). To address this issue, respondents answer a five-point Likert-scaled question: "very good," "good," "regular," "poor," and "very poor" air quality both at the neighborhood level and at the city level. Health concern includes the knowledge of health effects and the presence of frequent respiratory symptoms in household members.

The fifth section gathers indicators of civic engagement. Civic engagement involves individual and community attitudes and behaviors related to community and political involvement, through formal (neighborhood associations) or informal (participate in walks, tree planting) relationships to address issues of public concern (Adler and Goggin, 2005).

Participation in community activities such as neighborhood meetings was measured as the ability to work for a common purpose (Paldam, 2000). On the other hand, the variable "visits to public park" on a Likert scale (frequently, occasionally, rarely, very rarely, never) was included because the use of green spaces promotes the maintenance and appropriation of these areas. The two variables can lead to generating awareness and influence pro-environmental behaviors.

3.3 Estimation of WTP via a double-bounded dichotomous contingent valuation question

This study gathers stated preference data by implementing a double-bounded dichotomous contingent valuation (DBDCV) protocol. In a contingent valuation protocol, once the air improving scenario is described to the respondent, the respondent is asked whether he/she would be willing to contribute monetarily to implement the described scenario. The DBDCV protocol presents respondent j to a randomly assigned bid (B_j^I) to which the respondent can answer yes or no. If his/her initial answer is yes, then a follow-up question presents the respondent to a bid (B_j^H) that is higher than the initial one ($B_j^H > B_j^I$). If his/her initial answer is no, then the follow-up question presents the respondent to a bid (B_j^L) that is lower than the initial one ($B_j^L < B_j^I$).

Consequently, respondents provide one of the following sequences of responses: i) both answers are yes (*y*,*y*); ii) both answers are no (*n*,*n*); iii) the initial answer is yes and the subsequent is no (*y*,*n*); and iv) the initial answer is no and the subsequent is yes (*n*,*y*).

Assuming that WTP is normally distributed, then an empirical distribution can be inferred by maximizing an interval-regression likelihood function (see Hanemann et al. (1991) and Lopez-Feldman (2012) for details); i.e.

$$\sum_{j=1}^{J}\left[d_j^{yy} ln\left(\Phi\left(x_j'\frac{\beta}{\sigma}-\frac{B_j^H}{\sigma}\right)\right)+d_j^{nn} ln\left(1-\Phi\left(x_j'\frac{\beta}{\sigma}-\frac{B_j^L}{\sigma}\right)\right)+\ d_j^{yn} ln\left(\Phi\left(x_j'\frac{\beta}{\sigma}-\frac{B_j^I}{\sigma}\right)-\Phi\left(x_j'\frac{\beta}{\sigma}-\frac{B_j^H}{\sigma}\right)\right)\right.$$
$$\left.+\,d_j^{ny} ln\left(\Phi\left(x_j'\frac{\beta}{\sigma}-\frac{B_j^L}{\sigma}\right)-\Phi\left(x_j'\frac{\beta}{\sigma}-\frac{B_j^I}{\sigma}\right)\right)\right]$$

where $d_j^{yy}, d_j^{nn}, d_j^{yn}$ and d_j^{ny} are indicators variables defining which sequence of answers where provided by respondent j; x_j is a vector of control variables; and σ is the standard deviation of the normal distribution.

The DBDCV question sets out to increase the statistical efficiency of the single-bounded dichotomous contingent valuation (SBDCV) question (Hanemman et al., 1991). This increase in efficiency implies smaller sample sizes in comparison to the SBDCV protocol. However, the DBDCV is not free of criticism. Besides the usual issues when it comes to contingent valuation protocols –e.g. warm glow effect, anchoring, sensitivity to scope, and hypothetical bias (Carson et al. 2001; Carson 2012;)—, there is space for inconsistent answers to the follow-up question (Cooper et al., 2002).

Finally, we use the estimated coefficients from the DBDCV through the maximum likelihood estimation in Stata, as implemented by Lopez-Feldman (2012), to estimate the WTP under different scenarios. The maximum likelihood estimation begins with a linear function for a dichotomous choice model and estimates the linear function:

$$WTP_i(x_i, u_i) = x_i\beta + u_i$$

where x_i corresponds to the control variables: socioeconomic characteristics, air quality perception, health concerns and civic engagement, β are the estimated parameters and u_i is the error term.

4. Results

4.1 Description of respondents' characteristics

Table 2 reports descriptive statistics of respondents' characteristics and perceptions. As 51 out the 240 respondents (21%) reported a zero WTP,[6] statistics are reported for both the entire sample (n=240) and the non-zero WTP subsample (n=189). Fisher's exact tests are reported to explore whether the relative frequencies differ systematically across the entire sample and the non-zero WTP subsample. Nonparametric Kruskal-Wallis H tests are also presented to compare if the included variables significantly differ between zero and non-zero responses within the categories of each variable.[7]

In general, the results of the Kruskal-Wallis H test for differences among zero response and non-zero response for all the variables do not show statistically significant differences. Also, maintaining the assumption of normality, Fisher's exact tests suggest that non-zero WTP respondents are reasonably similar to respondents in the entire sample. The exceptions are age and perception of air quality at the neighborhood level. For the case of age, the non-zero

[6] The percentage of zero responses in our sample (21%) falls in the lower bound of values reported in previous studies –from 20% to 30% (Carlsson and Johansson-Stenman, 2000; Wang et al., 2015; Sun et al., 2016; Ardakani et al., 2017; Dong and Zeng, 2018).

[7] The Fischer's exact test allows testing whether there is an association between two categorical variables, under the hypothesis that the row and column effects are independent in an r ×c contingency table. This test is considered more accurate when the entries in each cell are small (Mehta and Patel, 1983). Kruskal Wallis H test,based on ranks rather than the trait values themselves and relaxes the assumption of normality (Vargha and Delaney, 1998).

WTP sample is composed of 55% of people older than 38, which is the median age in the entire sample. For the perception of air quality, the non-zero WTP sample is comprises of 52% of people perceiving poor or very poor air quality at the neighborhood level –versus 48% in the entire sample. A slightly higher percentage of non-zero WTP respondents are older and have poor or very poor perceptions about air quality at the neighborhood level.

Otherwise, the non-zero WTP subsample closely replicates the relative frequencies of the entire sample when it comes to i) percentage of female respondents (61%); ii) percentage of respondents within category of education –3% *(no school attendance), 9% (elementary school), 18% (middle school), 26% (high school), 35% (bachelor), and 9% (graduate); iii) percentage of respondents within self-reported monthly income range –9% (< USD 136), 30% (between USD 136 and USD 355), 27% (between USD 355 and USD 605), 20% (between USD 605 and USD 1,352), 5% (between USD 1,352 and USD 1,826), 6% (between USD 1,826 and USD 2,347), and 3% (> USD 2,347); iv) percentage of households that own their house (70%); v) percentage of households with more than 3 members (50%); vi) percentage of household with at least one household member suffering respiratory symptoms (45%); vii) percentage of respondents perceiving air quality at city level as poor or very poor (70%); viii) percentage of respondents participating in neighborhood meetings (25%); and ix) percentage of respondents visiting public parks (73%).

Table 2. Descriptive statistics of respondents' characteristics on entire sample (n=240) and on sample with non-zero WTP responses (n=189). Fisher's exact tests are reported to test for systematic differences. Results of the Kruskal-Wallis H test for statistically significant differences among zero response and non-zero response groups. Consist of the chi-square test with ties (χ^2), the degrees of freedom (df), and the significance level (p-value).

Variables	Categories	Entire sample n=240	Non-zero WTP sample n=189	Kruskal-Wallis test

		No.	Percentage (%)	No.	Percentage (%)	
Age Median: 38 years	Above the median	122	50	86	45	X^2=0.74 df=1 p-value=0.388
	Below the median	118	50	103	55	
	Fisher's exact: 0.02					
Gender	Male	93	39	70	37	X^2=0.014 df=1 p-value=0.906
	Female	147	61	119	63	
	Fisher's exact: 0.332					
Education	No school attendance	7	3	5	3	X^2=0.118 df=1 p-value=0.732
	Elementary school	21	9	15	8	
	Middle school	44	18	35	19	
	High school	63	26	50	26	
	Bachelor	84	35	68	36	
	Graduate	21	9	16	8	
	Fisher's exact test: 0.894					
Monthly household income (2019 US dollars)	< USD 135.7	22	9	17	9	X^2=1.339 df=6 p-value=0.969
	USD 135.7 to USD 354.9	73	30	57	30	
	USD 354.9 to USD 605.4	64	27	47	25	
	USD 605.4 to USD 1,352	47	20	42	22	
	UD 1,352 to USD 1,826	12	5	9	5	
	USD 1,826 to USD 2,347	15	6	11	6	
	> USD 2,347	7	3	6	3	
	Fisher's exact test: 0.494					
House ownership	Yes	168	70	127	67	X^2=0.409 df=1 p-value=0.523
	No	72	30	62	33	
	Fisher's exact test:0.085					
Household size Median: 3 members	Above the median	120	50	94	50	X^2=1.520 df=1 p-value=0.210
	Below or equal than the median	120	50	95	50	
	Fisher's exact test: 0.500					
Frequent respiratory symptoms[a]	Yes	108	45	87	46	X^2=0.343 df=1 p-value=0.558
	No	132	55	102	54	
	Fisher's exact: 0.635					
Air quality perception at neighborhood level[b]	Regular-good	124	52	91	48	X^2=0.052 df=1 p-value=0.820
	Poor- very poor	116	48	98	52	
	Fisher's exact: 0.041					
Air quality perception at city level[b]	Regular-good	71	30	53	28	X^2=0.377 df=1 p-value=0.539
	Poor- very poor	169	70	136	72	
	Fisher's exact: 0.387					
Participation in neighborhood committees' meetings	Yes	59	25	47	25	X^2=2.254 df=1 p-value=0.133
	No	181	75	142	75	
	Fisher's exact: 0.999					
	Yes	176	73	138	73	X^2=1.202

Visits to public parks[c]	No	64	27	51	27	df=1 p-value=0.273
	Fisher's exact:0.999					

[a] Cough, phlegm, and difficulties of sleeping caused by coughing or wheezing mainly in children or a household member.
[b] Variables of air quality perception were dichotomized due to small observations in extreme categories.
[c] Yes, if respondent visits public parks frequently or rarely; no if respondent never visits public parks. The variable was reduced to two categories due to small number of responses in the middle categories.

4.2 Description of zero responses

Table 3 reports reasons for zero WTP by category of perception of air quality at neighborhood level. The general message from table 3 is that the majority (69%) of zero responses are protest responses. Reasons for a protest response include lack of trust on institutions (29%); the belief that those that pollute should be charged (16%); that clean air is a human right (14%),and the opinion that more green areas are not necessary for Mexicali (4%).

Table 3. Reasons for zero WTP and perception of air quality at neighborhood level, N=51

Reasons for zero WTP	Poor and very Poor	Regular and good	Frequency	%
Insufficient income	11	5	16	31
Lack of trust on institutions	11	4	15	29
Those who pollute should be charged	4	4	8	16
Clean air is a human right	5	2	7	14
Other reason	1	2	3	6
More green areas are not necessary	1	1	2	4
Total	33	18	51	100

4.3 Description of answers to bids

As illustrated in Fig. 3, three bid ranges were randomly presented to respondents –covering the range from US 2.1 to US 10.4 (2019 US dollars). The first range includes US 2.1, US 3.6, and US 5.2; the second, US 4.9, US 5.2, and US 8.1; and the third, US 7.1, US 8.1, and 10.4.

We would expect that for each range, the percentage of yes responses monotonically decreases when the bid increases. This pattern is observed for the first and third ranges –with around 100% of yes to US 2.1, 80% to US 3.6, and 50% to US 5.2; and 80% to US 7.1, 70% to US 8.1, and around 25% to US 10.4. Answers to the second bid follow a non-monotonic decreasing pattern –with 70% yes to US 4.9 and 20% to US 8.1 but around 80% to US 5.2.

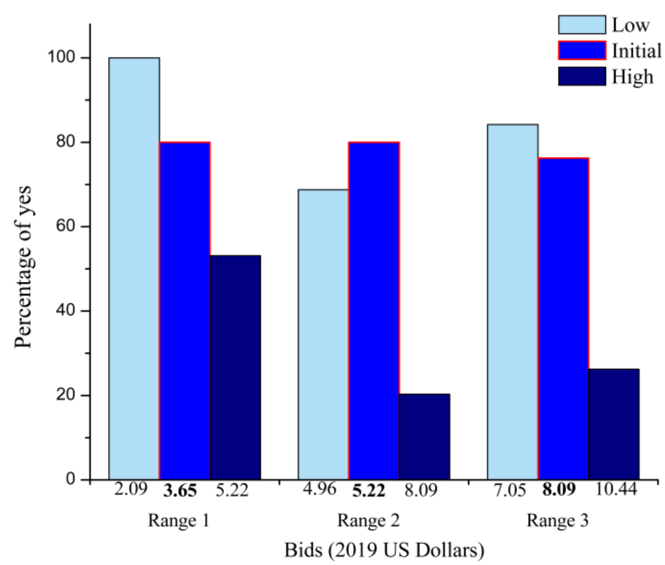

Fig 3. Percentage of yes responses to bids presented to respondents

Fig. 4 reports the relative frequencies of the preferred vehicle payment by range of bids presented to the respondents and also for the entire non-zero subsample. When focused on the entire subsample, around 20% of the respondents prefer to contribute through a fund created and labeled as only for afforestation purposes; around 38% of respondents prefer to contribute to funds administered by a NGO; around 26% prefer to pay via their water bill,and 15% prefer to pay via their electricity bill. Fig. 4 illustrates that these percentages remain relatively similar across the ranges of bids presented to respondents.

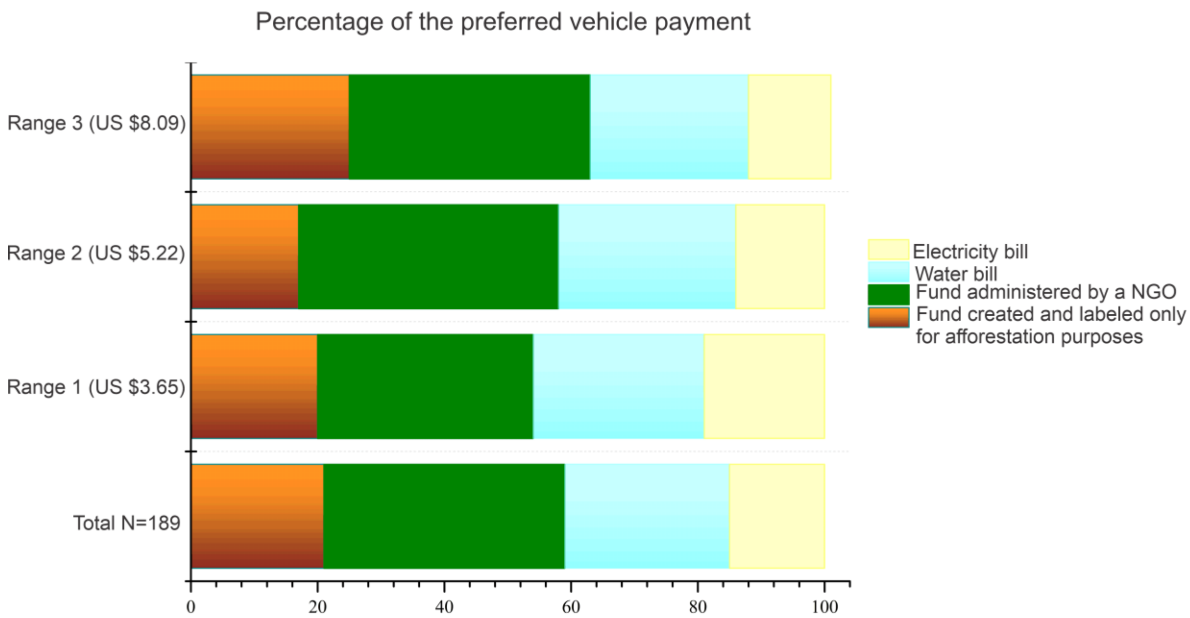

Fig 4. Relative frequencies of the preferred vehicles of payment for non-zero responses.

4.4 Econometric estimations

Table 4 reports coefficients obtained via six different specifications of our double-bounded dichotomous choice (DBDC) model on the subsample of non-zero WTP respondents (n=189) –we deem this appropriate as excluding the zero WTP respondents does not substantially change the composition of the sample. Specification (I) only includes the intercept, which is the (unconditional on control variables) average monthly household's WTP estimated at USD 7.44 (2019 USD)[3]. Specification (II) controls for respondents' socioeconomic variables, such as age, gender, education, and whether respondent's house is owned by the household.[8] The coefficient associated with the respondent's age is statistically significant and negative. Given that this variable is dichotomous and identifies 38 years old respondents (the sample median)

[8]. Income is not included in our final specification due to three reasons: i) due to missing values in reported income; ii) the potential collinearity with education, and iii) income yielded insignificant coefficients when included as a control variable. We report in Table 1.A (see Supplementary Material) specifications including income –DBDC, bivariate probit, and logit specifications. In these specifications, income remains insignificant, and the coefficient associated with the bidding amount remains significant and with a negative sign.

or older, the estimated value of its coefficient implies that respondents of 38 years old or older report a WTP that is USD 0.92 lower than respondents younger than 38. Education is not statistically significant in our specifications.[9]

Specification (III) in Table 4 builds upon the second model by adding variables capturing family concerns. These variables include a dichotomous variable identifying the households with more than three members which is the sample median, and a dummy identifier of the households affected by frequent respiratory symptoms such as cough, phlegm, or sleeping problems due to respiratory complications. Specification (III) yields no significant coefficients associated with the household size. However, the self-report of the households with members experiencing respiratory symptoms yields a significant coefficient. The significance of these variables remains in specifications (IV) to (VI), with coefficients around 0.86, 0.87, and 1.03, respectively.

Specification (IV) builds upon specification (III) by controlling for the respondent's air quality perception at the neighborhood and city levels. The variables controlling perception take different values. If the respondent perceives a poor or very poor air quality at the neighborhood level, his/her WTP is smaller by around USD 0.88 (2019 USD).

Specification (V) in Table 4 adds civic engagement proxies –a dichotomous variable identifying the respondents that visited public parks (the year previous to the survey) and a

[9] Previous authors have documented a lack of statistical significance for the coefficient associated with education (e.g. Wang et al., 2009; Achtnich, 2012). An explanation is that a high formal education does not necessarily imply greater environmental awareness. Torgler and Garcia-Valiñas (2007) postulated the relevance of non-formal education. The inclusion in the formal programs and diffusion of topics with orientation in the care of the environment, air pollution, and health effects can have a more considerable influence.

dichotomous variable identifying those participating in neighborhood meetings. Both variables yield insignificant coefficients.

Specification (VI) keeps the variables that are significant in the previous specifications and the gender variable –which is kept because, in logit and bivariate probit specifications that check for robustness, gender yields statistically significant coefficients (see Table 2.A and Table 3.A in Supplementary Material). Given that statistical significance and magnitude of coefficients remain similar than in the previous five specifications, specification (VI) is our preferred one based on its overall statistical performance, as measured by the Akaike Information Criterion (AIC) –which is the smallest for specification (VI) at 518 versus values ranging 524 to 528 for the other.

The estimated intercept remains fairly similar across the six specifications reported in Table 4, which we interpret as evidence that the estimated average of WTP is robust. We have also carried out an alternative specification to check the robustness of the relationship between the dichotomous responses and the bids presented to the respondents. These specifications include logit models (that only model the latest response of the double-bounded dichotomous answers) and biprobit models (that model both dichotomous responses as dichotomous variables whose errors terms are correlated). The results of these models are reported in Table 2.A and Table 3.A (Supplementary Material), respectively. In general, our respondents are found to be responsive to the bids presented to them and the WTP estimates resulting from these alternative models fall within the range reported in Figure 5.

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Table 4. Double bounded dichotomous choice models on respondents with non-zero WTP (n=189)

Variables	**Intercept (I)**	**Socioeconomics attributes (II)**	**Family concerns (III)**	**Air quality perception (IV)**	**Civic engagement (V)**	**Significant variables (VI)**
Socioeconomic variables						
38 or older[a]		-0.921 (0.443) **	-0.903 (0.447) **	-0.871 (0.445) **	-0.843 (0.445) *	-0.999 (0.418) **
Male[b]		0.446 (0.442)	0.415 (0.433)	0.488 (0.431)	0.478 (0.430)	0.485 (0.430)
High education level[c]		0.030 (0.451)	0.157 (0.446)	0.295 (0.445)	0.265 (0.453)	
House ownership[d]		0.238 (0.479)	0.122 (0.471)	0.022 (0.467)	0.044 (0.468)	
Family concerns						
Household with more than three members[e]			0.625 (0.442)	0.538 (0.439)	0.528 (0.440)	
Household with members experiencing frequent respiratory symptoms[f]			0.801 (0.442) *	0.865 (0.439) **	0.874 (0.438) **	1.032 (0.420) **
Air quality perception by geographical context[g]						
Poor or very poor air quality at the neighbourhood level				-0.888 (0.456) *	-0.902 (0.419) **	-0.931 (0.415) **
Poor or very poor air quality at the city level				-0.060 (0.504)		
Proxies of civic engagement						
Visits to public parks[h]					0.140 (0.470)	
Participation in neighbourhood meetings[i]					-0.231 (0.476)	
Intercept	7.444 (0.217) ***	7.535 (0.445) ***	6.877 (0.509) ***	7.363 (0.634) ***	7.272 (0.648) ***	7.740 (0.407) ***
Sigma	2.640 (0.179) ***	2.607 (0.178) ***	2.543 (0.173) ***	2.509 (0.171) ***	2.507 (0.171) ***	2.527 (0.172) ***
LR chi2		5.26 0.261	12.73 0.047	17.56 0.025	17.87 (0.037)	15.60 (0.003)
Log-likelihood	-260.809	-258.176	-254.518	-252.162	-252.011	-253.062
AIC	525.617	528.352	525.036	524.325	526.022	518.12

Standard errors in parenthesis; *** p<0.01, **p<0.05, *p<0.1

[a] 1 if the respondent is older than 38 (which is the sample median); 0, otherwise

[b] 1 if the respondent is male; 0, female

[c] 1 if respondent attended high school or equivalent; 0, otherwise

[d] 1 if the respondent has his/her own house; 0, otherwise

[e] 1 if respondent's household has more than three members (which is the sample median); 0, otherwise

[f] Cough, phlegm and difficulties of sleeping caused by coughing or wheezing mainly in children or some household member
[g] if respondent perceives that air quality is poor or very poor; 0, if respondent perceives good that air quality is good or regular.
[h] 1 if respondent visits public parks frequently or rarely; 0 if respondent never visits public parks
[i] 1 if respondent participates in neighborhood meetings; 0 if respondent has never participated in neighborhood meetings.

4.5 Estimation of the WTP

In order to compare different scenarios, WTP was estimated based on specification (VI) and significant coefficients, including air quality perception variable and the variable of households with members frequently affected by respiratory symptoms. Fig 4. presents the WTP to improve air quality through urban afforestation under eight scenarios and take as base the estimated WTP without control variables (approximately USD 7.44). As we seek to estimate variations due to perception and health concerns, the other variables were maintained in their reference values.

Results in Fig 5 illustrate how point WTP estimates vary depending on air quality perception. Keep in mind that the unconditional WTP is represented with the dotted line in Fig. 4. In all scenarios, a larger WTP prevails for the respondents who perceive air quality between good and regular in their neighborhood. Among the respondents who reported at least one member with frequent respiratory symptoms related to allergies and respiratory diseases, the estimated WTP was higher, USD 7.79. At the same time, WTP decreases to USD 6.69 if the respondent reports that no household member has frequent respiratory symptoms. On the other hand, both variables lead to the higher WTP among the respondents who perceived good air quality and a household member affected by frequent respiratory symptoms (USD 8.26). In contrast, the lower WTP corresponded to respondents without household members affected by frequent respiratory symptoms and who perceived poor air quality USD 6.29, as shown by line 1 and line 4 in the bottom box in Fig 4. Estimated WTP and 95% confidence intervals are presented in Table 5. These scenarios suggest the importance of air quality perception in the knowledge of health effects for the design of strategies to improve air quality. The aggregate annual value is calculated for these significant variables in the proposed scenarios in Table 5.

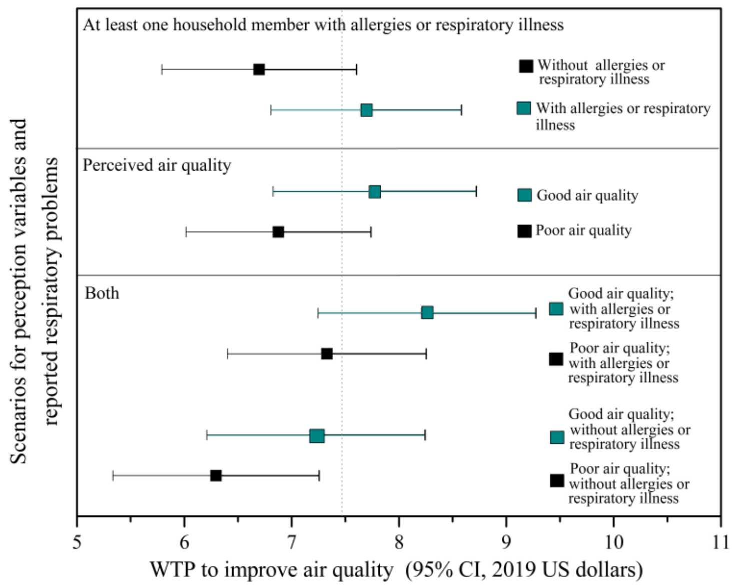

Fig 5. Estimated monthly WTP (in 2019 USD) to improve air quality by air quality perception and household members with reported respiratory problems. The dotted line corresponds to the WTP without control variables (7.44 in 2019 USD). Green color refers to the categories with a positive effect on the WTP (Good air quality perceived and household members with reported allergies or respiratory illness). Black color relates to the perception of poor air quality.

Table 5. Monthly and annual WTP per household (2019 USD) for scenarios considering perception of air quality at the neighborhood level, and respiratory symptoms in the household.

Specification		Monthly WTP per household (in 2019 USD)	95% Confidence Interval	Annual WTP (in 2019 USD)
I. At least one household member with frequently respiratory symptoms related to allergies or respiratory diseases	1.With frequently respiratory symptoms	7.69	6.81 – 8.58	92.28
	2. Without frequently respiratory symptoms	6.69	5.79 – 7.60	80.28
II. Perceived air quality	1. Good air quality	7.77	6.83 – 8.72	93.24
	2. Poor air quality	6.88	6.02 – 7.74	82.56
II. Perceived air quality and at least one household member with frequently respiratory symptoms	1. Good air quality; with frequent respiratory symptoms	8.26	7.24 – 9.27	99.12
	2. Poor air quality; with frequent respiratory symptoms	7.33	6.40 – 8.25	87.96
III. Perceived air quality and without a household member with frequently respiratory symptoms	1. Good air quality; without frequently respiratory symptoms	7.23	6.21 - 8.24	86.76
	2. Poor air quality; without frequently respiratory symptoms	6.29	5.33 – 7.26	75.48

Table 5 reports an average annual WTP per household of USD 87.96. We can interpret this number as the average stated benefits derived from the air-filtering service that trees would provide in Mexicali –particularly concerning PM_{10}. Heterogeneity in the WTP is associated with perceptions of air quality and respiratory symptoms at home. Respondents that perceive poor air quality in their neighborhood and without household members affected by frequent respiratory symptoms report USD 75.48. In contrast, those perceiving good air quality and with household members with frequent respiratory symptoms report USD 99.12.

5. Discussion and policy implications

5.1 Determinants of the willingness to pay

Results in section 4 imply that residents of Mexicali are willing to contribute monetarily to an urban afforestation program. This WTP varies with age –younger respondents report a higher WTP than older respondents. This direction in the effect from age has also been documented by Carlsson and Johansson-Stenman (2000), Wang and Zhang (2009), Yu et al. (2015), Wei and Yan (2017), Pu et al. (2019) and Zahedi et al. (2019).

A respondent in a household with someone suffering frequent respiratory symptoms reports higher WTP than those whose household have no members suffering from respiratory symptoms. This positive effect is in line with results reported by Filippini and Martinez-Cruz (2016) for Mexico City. Also, Zhang et al. (2019), Wang et al. (2015), and Akhtar et al. (2017) documented a positive and significant effect in Shanghai (China) and Lahore (Pakistan) for the willingness to pay to improve air quality. We suggest that this higher WTP is due to that the respondents in a household with a member suffering respiratory symptoms are more aware of the private costs of air pollution, and they are more altruistic towards those members suffering such symptoms.

A third component relevant to our results is air quality perception. We document a negative effect on WTP from poor air quality perception at the neighborhood level. The direction of this effect has been previously documented by Yu et al. (2015) and Sun et al. (2016) in China for the WTP to reduce the days when air pollution and poor visibility occurs. Bickerstaff (2004) associated this effect with a disconnection determined by people's perception of their ability to act, their attachment to the place, and their commitment to neighborhood problems.

5.2 This paper's estimates in comparison to estimates from previous studies

The estimated maximum annual WTP to improve air quality through native trees in Mexicali is (2019) USD 99, with a 95% confidence interval between USD 86 and USD 111. This amount is consistent with previous contingent studies applied to air quality improvements in Mexico. In Mexico City, the study of Filippini and Martínez-Cruz (2016) proposed regulatory and technological measures to improve air quality, and the estimated annual average WTP per household was (2019) USD 92.14. Blackman et al. (2018), also focusing on Mexico City, reported an annual WTP of (2019) USD 108.7 to be exempted from a regulation imposing one day without driving weekly. Estimates from Blackman et al. (2018) can be interpreted as reflecting costs that the regulation imposes on car drivers, and our USD 99 can be seen as reflecting a lower bound to private costs due to respiratory symptoms.

Fig 6 presents the annual WTP as a percentage of annual average household income from studies using both stated preferences and revealed preference methods in Mexico. In Baja California, the annual average household income is (2019) USD 12,685 (INEGI, 2019), and therefore our highest annual WTP estimate (USD 99) represents 0.78% of the annual average household income. The upper part of Fig 5 shows that our estimates fall within those reported by Filippini and Martínez-Cruz (2016) and Blackman et al. (2018) –0.58% and 1.00%, respectively. Studies based on hedonic price functions report a higher WTP as a percentage of annual average household income. Rodríguez-Sánchez (2014) reports a WTP of around 1.4% of annual household income. Chakraborti et al. (2019) reported a WTP equivalent to 2.44% of annual household income. Fontenla et al. (2019) documents that an average household is compensated with 2.8% of their income for an increase of $1\mu g/m^3$ in PM_{10}.

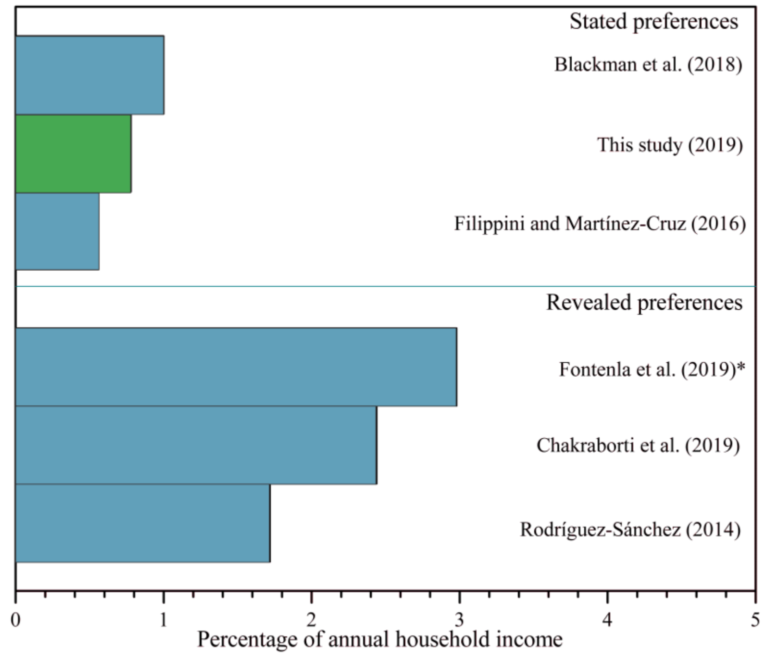

Fig 6. Willingness to pay estimates as a percentage of annual household income to improve air quality in Mexico. * Fontela et al. (2019) reports willingness to accept estimates.

5.3 Policy implications

Our results imply that Mexicali's residents are willing to contribute monetarily to an urban afforestation program on the grounds that it would improve air quality –PM_{10} concentrations in particular. Around 80% of our respondents have reported a positive WTP. While there is heterogeneity in the WTP, the point estimates suggest a relatively small range of annual values per household –with a minimum of around (2019) USD 75 and a maximum of around (2019) USD 99. Extrapolating the 21% that reports the highest annual WTP to the 61 thousand households in Mexicali, we estimate aggregated benefits from urban afforestation in Mexicali at (2019) USD 6.04 million.

To put our estimated benefits in context, it is useful to estimate the costs of providing a tree seedling in Mexicali. We have estimated these costs at USD 186.74 per seeding.[10] This number refers to a two-meter mesquite tree seedling, and results from adding three categories of costs –i) market price of a tree seedling; ii) planting costs; and iii) per tree seedling administrative costs. The market price of a two-meter mesquite tree seedling is USD 104.38 in Mexicali –-this paper's main author has personally verified this value in nurseries located in Mexicali. Planting a tree seedling implies preparation of the location, renting of planting equipment, and labor costs. All together, these costs amount to USD 78.29 per tree seedling.[11] We have estimated administrative costs per tree seedling at USD 4.07. This number results from dividing the budget allocated to running an afforestation program in Baja California by the number of tree seedlings planned to be provided. Total annual budget is obtained by adding annual budget for nurseries and germplasm bank operating in Mexicali (USD 377,143.29) and the costs of georeferencing of sites where afforestation is carried out to monitor, and coordination meetings between NGOs and government (USD 29,702.71).[12] Thus administrative costs amount to USD 406,845.98. Nurseries are expected to provide 100,000 tree seedlings per year. Thus 406,845.98/100,000=4.07 is our estimation for per tree seedling administrative costs.

[10] The per tree cost may vary because planting costs can be reduced if multiple tree seedlings are planted at once. In addition, these costs are subject to the conditions of the soil, the location, and the size of the tree.
[11] This information has kindly been provided by Maite Cortés García Lozano, executive director of Colectivo Ecologista Jalisco, A. C., via personal communications. Colectivo Ecologista Jalisco is a civil society's organization that defends public interest in matters of environmental and social sustainability (http://www.cej.org.mx/).
[12] These numbers have kindly been provided by officials of the Environment Protection Agency of the State of Baja California, via personal communications, and complemented by consulting the Official Newspaper of the State.

Thus our estimates of annual WTP per household, when extrapolated to and aggregated over the total number of households in Mexicali, suggest that benefits from afforestation justify the implementation of an urban afforestation program supplying 30 thousand tree seedlings per year.

We have motivated this study by highlighting that there is an urban afforestation program at the state level that Mexicali's residents could benefit from. However, there is a lack of awareness about the program due to a poor communication campaign –there is no readily information about it with the exception of a couple of news on internet that report the number of trees planted by the program at the state level and a short paragraph on how citizens can apply to become beneficiaries of the program.

The lack of a communication campaign is, arguably, a deterrent to afforestation in Mexicali and the State of Baja California. Thus a low-hanging fruit action is to increase the information available to citizens. Also, administrators of the afforestation program may want to consider citizens' donations as an additional source to finance afforestation. Indeed, reaching out for donations implies an increase in the transparency on how resources are managed and the progress of the program. Administering donations via a government-NGO partnership is an option that may be well-received by residents of Mexicali –recall that around 40% of those willing to contribute responded that they would trust an NGO in administering the contributions.

5.4 Limitations and further considerations

A concern may arise from excluding zero responses when implementing the double bounded dichotomous specifications. We have deemed appropriate to base our estimates on only non-zero respondents because the sample that excludes zero respondents looks similar to the entire sample. Despite this similarity, zero respondents may be genuinely not willing to contribute monetarily; if this was the case, then our exercise might overestimate the benefits from the afforestation scenario.

In responding to such concern, we highlight two features of our results. On one hand, around 70% of our zero respondents can be classified as protest respondents –these respondents likely have a positive WTP but find the scenario either unrealistic or unreliable. Indeed, the 30% of zero respondents that cannot be classified as protest zeros may truly be willing to pay zero, and the potential for overestimation remains. To explore for the possibility of overestimation, we have compared our results with previous contingent valuation studies that have obtained benefits from improvements in air quality in the Mexican context (see section 5.2). Estimates from previous studies work as a baseline against which our estimates can be judged. To make the comparison stricter, we have compared the highest WTP estimated in this study against the average WTP estimates reported in Filippini and Martínez-Cruz (2016) and Blackman et al. (2018). These comparisons have been carried out in terms of WTP as a percentage of a household's annual income. Our highest estimates are equivalent to around 0.8% which falls between the average values reported by Filippini and Martínez-Cruz (2016) (0.58%) and Blackman et al. (2018) (1.00%). Thus we believe that our estimates fall within a reasonable range despite arising from only non-zero answers.

A relevant issue that we have not considered in our afforestation scenario is that trees may also produce disservices associated with the potential allergenic, biogenic volatile organic compound emissions (Escobedo et al., 2011) and the water requirements (Vijayaraghan, 2016; Azeñas et al., 2019). We leave an exploration of this issue to future research.

6. Conclusions

This study contributes to a nascent literature of contingent valuation studies valuing afforestation strategies to improve air quality in urban contexts –and, to the best of our knowledge, it represents the first attempt to do so in an arid city of an emerging economy. The scenario under analysis is an urban afforestation program with native trees in Mexicali, Baja California, Mexico. The estimated mean monthly WTP per household falls within the range of (2019) USD 6.29 and USD 8.26. The highest annual WTP estimated in this study is USD 99 and represents around 0.8% of the annual household income. Residents' perception about air quality is an important determinant of their willingness to contribute monetarily to urban afforestation –with respondents perceiving poor air quality at their neighborhood reporting smaller willingness to contribute. Also, respondents with household members suffering frequent respiratory symptoms report a higher willingness to contribute monetarily.

The WTP estimates in this study suggest that the benefits from an urban afforestation program in Mexicali justifies the provision of at least 30 thousand mesquite trees at around (2019) USD 186 per two-meter tree seedling. Our results motivate the suggestion that policymakers in Mexicali and Baja California are missing out on two opportunities. On the one hand, they can initiate a communication campaign informing citizens about how to become beneficiaries of the State Urban Afforestation Program. On the other hand, they may want to consider a government-NGO partnership to administer potential citizens' contributions to the program.

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Zuk, M., Tzintzun-Cervantes, M.G., Rojas Bracho, L., 2007. Tercer almanaque de datos y tendencias de la calidad del aire en nueve ciudades mexicanas. Secretaría de Medio Ambiente y Recursos Naturales. Instituto Nacional de Ecología. México. 46-61. ISBN 978-968-817

Consideraciones para el Capítulo V

Los resultados del capítulo IV muestran de manera generalizada preocupación por la calidad del aire en Mexicali. Se encontró que la percepción de la calidad del aire y la afectación personal o familiar por síntomas respiratorios que pueden estar asociados a la contaminación del aire juegan un rol determinante en la disposición a contribuir por mejorar la calidad del aire.

Estos hallazgos indican que la percepción de la calidad del aire en el entorno inmediato y la sensibilización hacia los efectos de salud asociados, no solo influyen en los cambios observados en la calidad del aire en el tiempo, también tiene un rol significativo en la implementación de estrategias que debe ser considerado en la gestión.

En el capítulo V se incluyen dos preguntas a actores clave en la gestión para comparar la percepción que tienen de la calidad del aire en la ciudad respecto a la de los ciudadanos y la manera en que los temas de vulnerabilidad social y la percepción abordados en los capítulos previos son incluidos dentro del diseño de programas de política pública.

CAPITULO V

ANÁLISIS DE POLÍTICA BASADA EN EVIDENCIA EN LA GESTIÓN DE LA CALIDAD DEL AIRE EN MÉXICO DESDE LA PERSPECTIVA DE LOS ACTORES CLAVE.

Estudio por ser sometido a Environmental Science & Policy.

Resumen.

La contaminación del aire es un problema de salud pública relevante alrededor del mundo. La evidencia presentada en los estudios previos incluidos en esta tesis señaló la relación significativa de los factores socioeconómicos en la exposición a contaminantes atmosféricos, direccionando un caso local, también mostró como estos factores inciden en un riesgo incrementado de sufrir efectos de salud asociados a la contaminación del aire en estudios conducidos en diferentes países. Además, se encontró un rol significativo de la percepción de la calidad del aire en la disposición a participar en estrategias de política pública para mejorar la calidad del aire.

Importantes iniciativas a nivel internacional han conjuntado científicos y tomadores de decisiones para proponer estrategias de control para este riesgo ambiental. Sin embargo, existen controversias en el establecimiento de estándares y en el planteamiento de políticas públicas para mitigarlo. La política basada en evidencia constituye un marco ideal para la adecuada toma de decisiones en políticas ambientales, pero existen diversas barreras para su implementación en la gestión local de la calidad del aire. Este estudio tiene el propósito de identificar las barreras y oportunidades para mejorar el rol de la evidencia en el diseño de programas para mejorar la calidad del aire e indagar como se incorpora la evidencia en términos sociales, en especial la vulnerabilidad social dentro del proceso de toma de decisiones. El análisis se conduce a través del método de teoría fundamentada aplicado al análisis de las perspectivas de actores clave involucrados en la gestión de la calidad del aire en México. Se aplicaron entrevistas a funcionarios, científicos y representantes de organizaciones no gubernamentales (ONGs) ubicados en siete áreas metropolitanas. Los resultados muestran diferencias importantes en la capacidad técnica y científica para producir

evidencia entre las ciudades y semejanzas en barreras relacionadas con la limitada capacidad institucional, presión de los grupos de interés, brechas en el sistema legal y limitada transferencia del conocimiento. Las oportunidades para incrementar la incidencia de la evidencia en las políticas para mitigar la contaminación del aire requieren dar seguimiento a los programas, garantizar fondos para la investigación, contextualizar la investigación como problema público, impulsar la participación de traductores del conocimiento y de organizaciones no gubernamentales como importantes puentes entre los tomadores de decisiones y los científicos. La política basada en evidencia debe considerar factores económicos y políticos para su implementación orientados a lograr un mayor impacto social.

Palabras clave: política basada en evidencia, gestión de la calidad del aire, actores clave, barreras, facilitadores, México.

Analysis of evidence-based policy in air quality management in Mexico: a stakeholder's perspective

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Abstract

Air pollution is a significant concern worldwide. Decision-makers and scientists have brought together essential initiatives to propose strategies to control this environmental risk in different parts of the world. However, there is still a controversy to establish standard and public policies to mitigate it. Evidence-based policy is an ideal framework for adequate decision-making on environmental policies, but there are significant barriers to its implementation in air quality management. This paper aims to identify barriers and opportunities to improve the role of evidence in designing programs to improve air quality from different stakeholders involve in air quality in Mexico. We applied a grounded theory method to conduct and analyze interviews of office managers, scientists, and members of non-governmental organizations involved with official programs to improve air quality in seven different cities with official programs to improve air quality. Results show important differences in the technical capacity to produce evidence among cities and similar barriers to use the evidence, mainly institutional capacity, interest groups, legal frameworks, and limited knowledge transfer. Opportunities to increase evidence in air pollution mitigation policies involve follow-up programs, guaranteed research funding, contextualizing of research as a public problem, and assigning a central role role to knowledge brokering and non-governmental organizations as critical links between decision-makers and scientists. Effective evidence-based policy implementation must also consider economic and political factors for their implementation to achieve a broader social impact.

Keywords: evidence-based policy; air quality management; stakeholder's interaction, barriers, facilitators, Mexico

1. Introduction

Air pollution remains a global concern, putting the health of their populations at risk and having enormous economic consequences (Gou et al., 2013; OECD 2016). The understanding of air pollution and its impacts on health requires sound scientific evidence for real-life policy and decision-making processes (Pleijel and Lidskog, 2011; Rose et al., 2017). Robust evidence on air pollutants-induced damage has been the basis for public policies and global agreements, as the Paris Agreement on Climate Change (Caplin et al., 2019) and the Convention on Long-Range Transboundary Air Pollution (CLRTAP). Those actions emphasized the recognition of scientific support by decision-makers and the role of scientists in environmental governance. Likewise, global organizations such as The Climate and Clean Air Coalition (CCAC) and the World Health Organization (WHO), have coordinated efforts to reduce air pollution (Schmale et al., 2014) with extensive scientific support.

Scientific evidence has been a guide for the advances in air pollution control policies and regulations. Sullivan et al. (2018) highlighted the importance of long-term research and monitoring as examples of how science has contributed to the Clean Air Act's policies and regulations. Many strategies around the world have been implemented to reduce air pollution. However, air quality standards and restrictions on primary sources of pollution are often questioned. Political will, interests' groups, and the disagreement between the scientific community seem to influence such decisions (Tollefson, 2019). Despite these questions, it is clear that the advancement of air quality control requires science to assess risk and exposure and to evaluate the impacts of policies (Goldman and Domini, 2019) to protect the health of the population and the environment.

Researchers in Mexico have collected a significant body of evidence on health outcomes such as respiratory diseases, premature mortality, preterm birth, abnormal lung function and cognitive pathologies related to air pollution (Calderón-Garcidueñas et al., 2000; O'Neill et al., 2008; Barraza-Villareal et al., 2008; Escamilla-Nuñez 2008, Osornio-Vargas et al., 2011; Sarnat et al., 2012; O'Neill et al., 2013; Calderón-Garcidueñas et al., 2015). In these studies, Mexico City and the metropolitan cities of Mexicali and Monterrey represented case studies. These cities have some of the worst air quality related to PM_{10}, $PM_{2.5}$ levels in the Americas (WHO, 2018). Mexico is a point of reference for planning policies to mitigate air pollution, mainly through vehicle restrictions in Mexico City (Davis, 2017).

In Mexico City, policies have been enacted since the late 1980s and early 1990s, these are mainly focused in the relocation of industries, fuels improvement, modernization of the vehicle fleet, vehicular restrictions, and improvements in public transport (Molina, L., and Molina, M. J, 2002; Fernandez-Bremauntz, 2008). Although these policies contributed to reducing the level of air pollutants (Lacasaña-Navarro et al., 1999), particulate matter $PM_{2.5}$ and PM_{10}, and gaseous pollutants (NO_x and O_3) still exceed the Mexican regulation (INECC, 2018) and several cities lack air quality monitoring systems as well.

The science-policy interface in Mexico has developed grually. The main advances in evidence-based policy (EBP) related to air quality management centers in Mexico City. In 2004 the creation of the National Center for Environmental Research and Training (CENICA) strengthened the capacity to carry out studies on the health effects and exposure to air pollutants and the benefits associated with the reduction of pollution levels, contributing to the formulation of public policy programs (Fernández-Bremauntz, 2008). Moreover, the highly specialized advisory councils in the Mexican Federal government have increased their role, mainly in the design and assessment of environmental and social public policies (Flamand, 2017).

Currently, the National Strategy of Air Quality (ENCA for its acronym in Spanish) (SEMARNAT, 2017) is the principal management tool to coordinate actions between different governmental areas to control, mitigate, and prevent emission and high levels of air pollutants. This strategy recognizes the importance of research and monitoring and promotes EBP as a critical subject. At the local level, the instruments that integrate the ENCA are the Management Programs to Improve Air Quality (ProAire). Recognized institutions and research centers like the National Institute of Ecology and Climate Change (INECC for its acronym in Spanish), the National Institute of Public Health (INSP for its acronym in

Spanish), Atmospheric Science Center "CCA-UNAM", and the Mario Molina Center, have participated in the air quality decision-making process as part of committees and forums. A shared vision was achieved through research groups (Lankao, 2007), which contributed to incorporating the air quality in the local agenda; however, the push of an effective policy program is still limited. Changes in the energy and fuel sector are a clear example of this limited incidence (Flamand and Rojas-Bracho, 2015).

To get a deeper understanding of the factors limit or strengthen the use of evidence in the design of air pollution control policies, we conduct 38 semi-structured interviews with key actors (environmental and health officers, scientists, and representatives of Non-governmental organizations (NGOs)). The selected actors participated in the design of ProAire or air quality standard updates. We analyze the context perceived by the stakeholder and the determinants of the use of evidence in the policy process. While this study considers Mexico's specific case, the challenges and perspectives identified apply to other cities in developing countries.

In the following sections, we describe the theoretical framework, the data collection and the method used to analyze the interviews, followed by a section of results. The results integrate 1) the context of air quality management in different cities of Mexico, 2) the evidence within the science-policy interface as a process (production-knowledge transfer-use-coproduction, including values and interests of the stakeholders), 3) the determinants of the policymaking; 4) the barriers and opportunities to improve the role of evidence in air quality management in Mexico. The paper ends with a discussion of the findings, policy recommendations, and some important conclusions.

2. Theoretical framework

The concept of Evidence-Based Policy (EBP) has as precedent on the concept of Evidence-Based Medicine (EBM). The EBM was described as formal doctrine in the 1990s, highlighting the relevance of evidence from clinical research and randomized control trials in medicine (Sackett et al., 1996). Later the concept was applied to incorporate the best available evidence in the decision-making of public health (Brownson et al., 2018). First, the concept of evidence was addressed only to scientific evidence. However, more recent approaches expanded into any information/knowledge generated through quantitative and qualitative methods, including ‘hard’ data that involve stories and testimonies from beneficiaries and affected individuals, and the knowledge from the policy sphere (Brownson et al., 2009; Ansell and Geyer, 2017) for proper decision-making.

The EBP is considered a standard for adequate decision making (Becker and Bryman, 2004), but complex to put in practiced. Producing scientific knowledge does not imply its translation to practice (Fazey et al., 2014) and even more in environmental problems like air pollution. Research in environmental problems is considered a “wicked” problem involving behavioral changes, and cross-sector collaboration (Barret et al., 2005) and dealing with high-power group`s interests.

The analysis of the literature pointed out the factors influencing the decision-making processes. In some cases, there is a lack of information about the environmental problem, such as the state of the system, causes, consequences, pressure forces, or possible solutions (Villada-Canela, 2013). In other, the language or format represents a barrier in its utilization. Its applicability for societal goals is also a factor (Archie et al., 2014; Cairney et al., 2016). Characteristics such as credibility, relevance, legitimacy, timing, and accessibility have an important role in the use of evidence (Dunn and Laing, 2017). Additionally, institutional arrangements, regulatory frameworks, and the lack of a supportive culture are relevant factors with inference in the use of evidence (Milton et al., 2007; Aro, et al. 2015; Morton, 2018).

All these barriers or enablers were classified through an in-deep literature review of the EBP by Olivier et al. (2014), which characterized them in “contact and collaboration,” “research and researcher characteristics,” “policy-maker characteristics,” and “policy characteristics.” Specifically, in environmental issues, Walsh et al. (2019) included some other categories, like the nature of evidence, research-practice links, and the influence of the community in the use of science. We considered all these characteristics when analyzing our data to identify barriers and facilitators.

3. Materials and Methods

In this study, barriers, facilitators, and social, economic, and political determinants were identified from stakeholder interviews conducted during 2018 and 2020. The interviews were systematized using Atlas.ti Software 8 (Scientific Software Development GmbH, Berlin, Germany) and the analysis of interviews used a Grounded Theory Approach (Glaser and Strauss, 2006). See the description of the actors interviewed, and the method below.

3.1 Data collection and analysis

To identify the actors involved in air quality management in the country and obtain relevant information on their expertise and functions, we reviewed: 1) The scientific literature linking air pollution and health, air quality management, economic valuations linked to air quality and air quality perception, 2) the participants in the design of official local or regional programs to improve air quality. After that, snowball sampling technique were used and the attendance to the 2nd meeting of the thematic network of atmospheric pollution and mitigation of climate change "Redcam" 2018. A forum where researchers and decision-makers on the subject participated to discuss actions to reduce polluting emission and their impacts on human health (Páramo-Figueroa, 2018).

Additional to the relevant actors from Mexico City, we considered stakeholders from other cities, which according to measurements of monitoring networks, have problems with air pollution (mainly by Ozone, PM_{10}, and $PM_{2.5}$) (INECC, 2016), These cities are Ciudad Juárez, Jalisco, Mexicali, Monterrey, Guanajuato, and Puebla. They share the following characteristics: 1) are densely populated urban areas, and 2) have a management program "ProAire" to improve the air quality at a regional or local level.

We conducted semi-structured interviews following a guide to answer the following reseach questions: How stakeholders perceive the air pollution and the air quality management concerning public health protection? What is the opinion of the stakeholders regarding the EBP? What are the factors that limit or promote the use of evidence in policy-making? Which research perspectives can contribute to improving decision-making?

The interviews were conducted between May to October 2018 and April 2020. These periods were considered to cover prospects after government changes. At the national level, which took place in late 2018 and at the municipal level in the course of 2019. We conducted a total of 38 semi-structured interviews. 14 to scientists from academic institutions, 17 to decision-makers, covering public sector officers in environmental and public health at the federal and local levels. Six to representatives of non-governmental organizations (NGOs) (see Table 1). In most cases, the interviews were conducted face to face and when it was not possible due to geographical location or agenda-settings, by phone. In general, each interview took between 30 and 40 min. Participants provided informed consent before the interview; the interviews were tape-recorded and transcribed afterward.

Table 1. List of stakeholders (type of actor, institution, role/expertise)

Stakeholder[1] Group	Institution/Expertise	Number of interviewees	Code
Ministry of Environment (State level)	Air quality management	12	E2, E3, E7, E8, E13, E19, E22, E24, E33, E34, E35, E37
Ministry of health (Federal and state level)	Protection against risk and environmental health	4	H11, H27, H32, H36
Federal office of environmental protection	Environmental hazards	1	E21
Medical researchers	Epidemiology and environmental health	2	S1, S20
Physicochemical researchers	Atmospheric science	3	S14, S15, S23
Urban planning researchers	Air quality in urban planning	3	S10, S25, S26
Environmental economic and social science researchers	Economic valuation applied to air pollution mitigation. Environmental policies and air quality perception	6	S6, S17, S12, S16, S18, S28
Non-governmental organizations	Environmental law, air pollution mitigation	7	O4, O5, O9, O29, O30, O31 O38

[1] The groups of actors interviewed have participated in the design of programs and/or regulations to improve air quality carried out in different states of Mexico.

The analysis of the information was done under the Grounded Theory framework considering the proposed elements by Corbin J. (2015). These elements include categories about perspectives, attributes (dimensions and properties), context (conditions), and action/process (consequence). The first stage of encoding was carried out according to categories reported in the reviewed literature. Secondly, we conducted axial codification in the transcribed interviews, matching categories to subcategories according to their properties and dimensions (Mertens, 2017), as found in the transcriptions. This process was carried out through open codification. The Qualitative Data Analysis Software ATLAS.ti assisted an open coding procedure.

We validated the research through investigator triangulation. A subset of seven interviews was coded by the first and fifth authors of this paper to review agreements and differences between the codes. The remaining interviews were encoded jointly. Preliminary results of the triangulation were shared with the rest of the others authors for feedback, according to Farmer et al. (2006). We use excerpts of interviews and translate them into English as evidence of the critical issues. Additionally, we used the Statistical Software R version 3.5.2 (to visualize the frequencies of some codes by stakeholder's group).

4. Results

We extracted 72 codes, and matched to the categories identified in the literature and the analysis of the interviews. The categories are: “Production of evidence”, “Actors characteristics”, “Knowledge exchange”, “Political determinants of decision-making” (Figure 1). The codes grouped in these categories represent relevant elements of the use of evidence in the cycle of formulation of public policies, from the design of the research project to the moment in which the public policy program is formalized. These categories are related, and depending on whether the relationship between them is bidirectional or one-way can lead to different results about the use of evidence. When the generation of evidence considers the characteristics of the actors, political determinants, and decision-makers promote the exchange and generation of evidence, it can lead to co-production processes. Nevertheless, there are cases where the relationship is a single direction is presented, and the research products are presented without the exchange of ideas, known as a "practical model."

The analysis also identified a set of interrelated barriers (B) and facilitators (F) related to the challenges of integrating and increasing the role of evidence in air quality management.

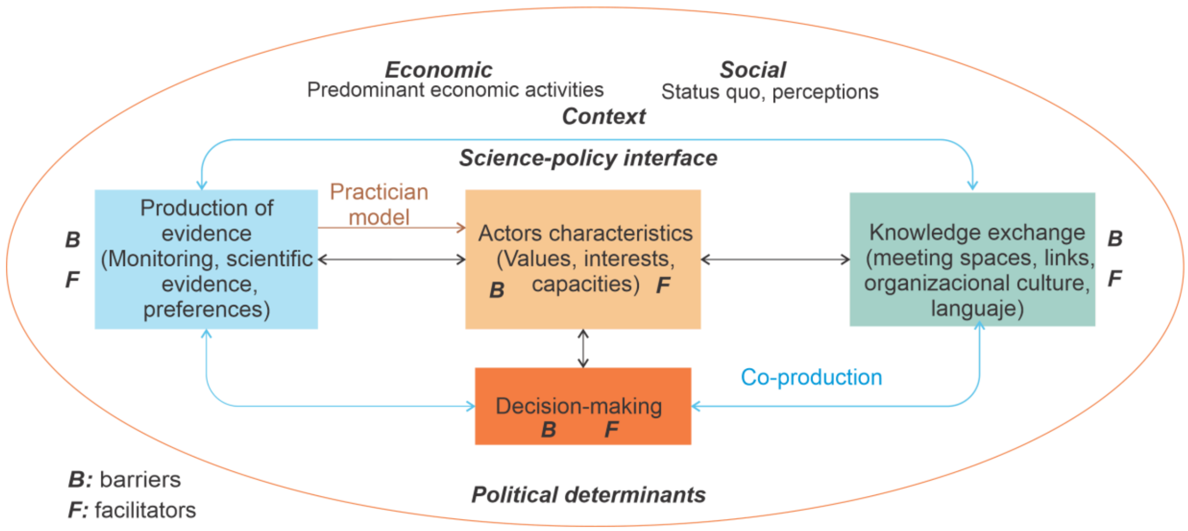

Figure 1. Categories to analyze the factors influencing the Evidence-based Policy in air quality management. the bold text represents the major categories to analyze. The direction of the arrow indicates whether it is a two-way relationship or a one-way relationship. The black lines indicate the relationships within the political science interface. The blue lines represent a feedback process that can lead to co-production and the brown line a one-way relationship of communication of the evidence.

4.1. The perceived context

Here we analyzed the stakeholders' general perception about air quality in the country and the implemented strategies to combat air pollution. The stakeholders agreed that air quality is deteriorating in most cities. In the case of Mexico City, where gradual improvements were achieved with strategies implemented since the ´90s, there is a concern because not enough progress has been achieved. Also, a perception of non-compliance with environmental regulations to protect public health occurs in most of the cities with atmospheric monitoring.

"On the one hand, we have great political measures, such as the implementation of the "no driving car" program, (HNC for its acronyms in Spanich) around 1989; after the part of unleaded gasoline was made, when the catalytic converters were installed, there was a significant decrease. Now it is getting more complicated, the measures tend to be much less effective, but that is because the major interventions with significant impact have already been implemented. Now everything is left to small measures to achieve small decreases" (H36)

"In Monterrey, we have been working since the ´90s, and unfortunately, reduced actions are taken, but we have not attacked the most important ones, such as we lose ourselves looking for solutions that help us but do not solve the problem" (S10)

Participants from the three sectors (authorities, academy, NGOs) used Mexico City as an example in the air pollution control policies. They recognized that among the strategies implemented, mainly technological solutions to improve fuel and programs to modernize the vehicle fleet received attention. Urban planning solutions, such as the relocation of industries and public transport improvements, were considered the most effective in protecting public health. Problems underlying the social and economic context were considered limiting in the implementation of these strategies. Accurately, in the maintenance program for passenger vehicle "VVO," problems as corruption was identified. Concerning more stringent control policies over emission from stationary sources, was highlighted high dependence on economic interests. Additionally, social perception about risk health and the little perceived utility of the proposed strategies are signed as obstacles within the social context.

Also, authorities highly involved in decision-making and adequate academic training, identified a managerial problem related to a lack of legal frameworks for ensuring air quality and establishing responsibilities. They also saw limitations on the implementation of the measures proposed in the “ProAire” due to the lack of a more stringent regulatory system of emission sources. In this sense, interviews noted that:

“There is an inconsistency because I, as an authority, I have to see the fulfillment of the air quality norm, but we do not have any mechanism for those who generate the pollution. We have a loop problem, with a regulation that is not enough because there are not conditions to demand more" (E8)

“We as air quality authorities, we have no powers so that the most polluting sectors stop polluting, what we do, sometimes we are normative, sometimes we are managers” (E38)

Some differences were found between the perceptions that the key actors have on the strategies implemented in each city. Some actors think that other cities are following the example of Mexico City without adapting to the local context. However, we found that the authorities considered crucial, having knowledge of the primary sources of pollution for the design of strategies. In cities such as Mexicali, measures have focused on the sustainable management of the waste generated by the agricultural fields, or the case of brick factories in Jalisco and Ciudad Juárez. Despite this, there is a good agreement in which the management must adapt to the each city’s specific context, and it requires local evidence.

“The way to carry out the “ProAire” has stuck. I saw that almost none of the proposals are based on experimental studies in the field, where the particles come from sectors where the VOCs come from, and those investigations are crucial to orient the direction of the strategies; as these studies have not original data, many of them are copy and paste from other “ProAires”, sometimes for good and sometimes for bad." (E13)

4.2. The science-policy interface

4.2.1 Production and preferences in evidence

Air quality management requires extensive technical support and scientific evidence. This premise was apparent to all stakeholders. However, access to the required evidence or information for air quality management, in most cases, is not available to them. Figure 2 shows the main factors that positively or negatively influence the production of evidence mentioned by each stakeholder group. In the three groups, access to evidence and information systems, especially on air quality and health effects data were the factors more frequently recognized as influencing the support in the decision-making process. Critical issues identified in these codes include insufficient coverage of monitoring stations, lack of monitoring in many cities, limited epidemiological surveillance at the local level, and the fact that data is not updated or had difficulty in accessing it.

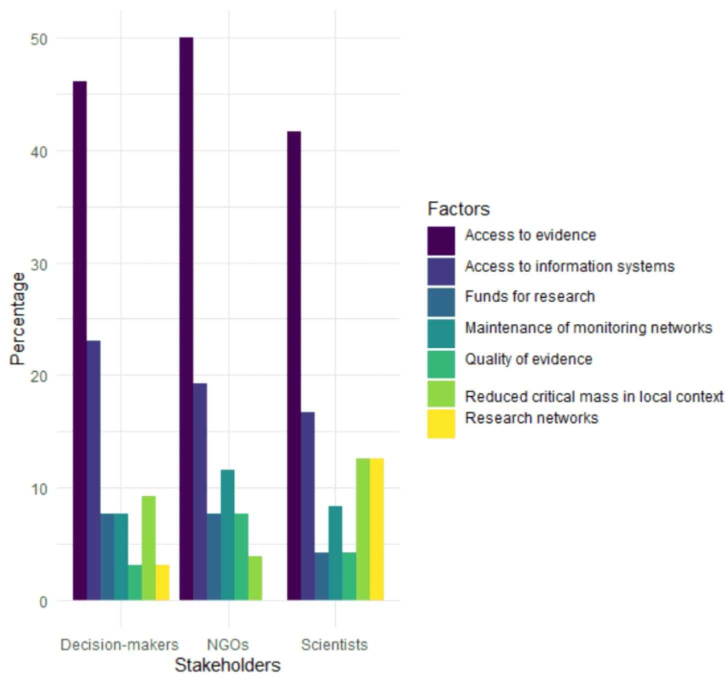

Figure 2. Factors linked to the production of evidence in air quality management

Concerning these factors, the stakeholders expressed that:

"It must be taken into account that monitoring systems do not work 100% for all the country's cities. There are times when we ask how the air quality problem is in someplace, and we do not know; the monitoring equipment does not work 100%, knowledge is deficient due to lack of data" (O38)

"*I can assure you that emission inventories are not being updated as often as required and do not have the level of specificity needed to be able to direct adequate public policy*" (E37)

The quality of the evidence is not identified as a problem by the actors. However, both scientists and decision-makers consider areas of opportunity to increase the number of researchers working on the topic or the formation of research networks. Differences and similarities identified between Mexico City and the other cities considered in the study are presented in Table 2.

Table 2. Differences and similarities in the generation of evidence between Mexico City and other cities in Mexico

Production of evidence	
Mexico City	Monterrey, Mexicali, Ciudad Juárez, Guadalajara
Robust monitoring network with extensive coverage	Little or no coverage by the atmospheric monitoring networks
Deficiencies in the systematization, updating and homologation of the emissions inventory	Deficiencies in the systematization, updating, and homologation of the emissions inventory
Financing sources to ensure equipment maintenance and operation	Lack of resources to monitor the air, ensure the maintenance and operation of the equipment.
Relevant critical mass with expertise and sufficient technical staff	Reduced technical staff and expertise.
Relevant participation of advisory councils (INECC, INSP) to generate evidence	Relevant participation of advisory councils (INECC, INSP) to generate evidence
Solid scientific collaboration networks	Networks of scientific collaboration in the formation
Limited resources for scientific research and lack of incentives for researchers to participate in decision-making.	Limited resources for scientific research and a lack of incentives for researchers to participate in decision-making.

The actors revealed the importance of investing in infrastructure and research, fostering increased technical capacities, and forming multidisciplinary research networks.

"Only a few states have worried about knowing the air pollutions levels in some of their cities. It is indeed needed to invest in infrastructure, research, and formation of high-training human resources in the air quality topic." (O30)

Other important topics that were evidenced relate to the preferences regarding the sources of evidence. The information generated by the advisory councils is widely valued by decision-makers, followed by refereed academic publications, especially those developed at the local level. In the absence of local information, decision-makers point to evidence at the international level, reports from the World Health Organization, and technical reports from consultants. On the other hand, scientists and NGOs consider that publications that have already undergone a peer review and are made without obeying particular predefine interests should have a more significant role. Some actors in these two groups mentioned the following:

"We consult official sources of information, for example, INEGI regarding demographics, urban facilities and INECC as the technical support of the Ministry of the Environment. We also do the review of scientific articles and information from the monitoring network" (E2)

"First we consult articles, because we assume that an article is the result of a scientific investigation; the article gives us an added value that was subjected to peer review" (S15)

The relevance of the issues addressed in the investigation is also an aspect to consider. Air quality management gives priority to the technical support from monitoring sites and emission factors of potential sources of air pollution. However, other issues related to implementation are beginning to be recognized as necessary in the generation of evidence, especially economic impacts, cost-effectiveness analysis, and social and psychological factors related to mobility were mentioned. Excepting for Mexico City, the stakeholders highlighted the evidence of the strategies implemented have on public health as urgently required evidence, in addition to social and economic evaluations.

"The trend continues to present the topics of environmental monitoring, the impacts on health, but they are merely technical issues of risk, and there were no presentations that should be present as social evaluations of risk communication programs" (S17)

4.2.2 The stakeholders and their characteristics

Attitudes, skills, and interests play a crucial role, limiting or pushing the use of evidence in air quality management. Figure 3 presents the codes associated with the characteristics of the actors. The reciprocity when listening to opinions, making proposals and contextualizing them within the political sphere are essential characteristics to facilitate the use of evidence. To achieve this openness, those designed as decision-makers must have sufficient professional training in the area in charge. Also, an academic initiative in several cities, coupled with NGOs perseverance, has contributed to establishing new standards in some criteria pollutants, whose negotiation processes are time-consuming.

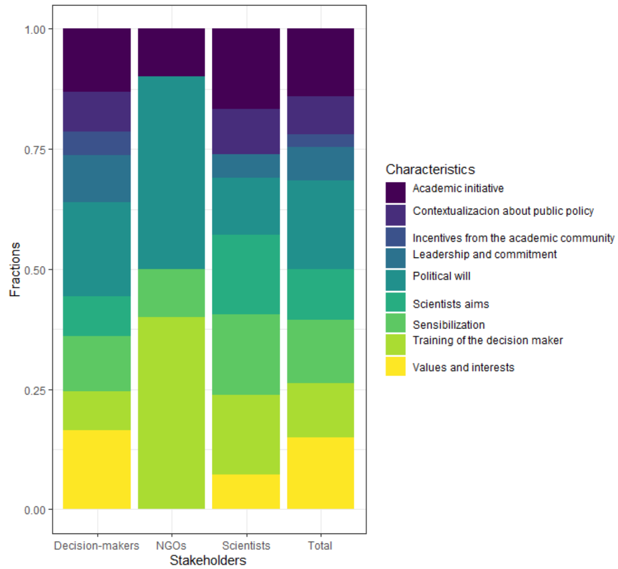

Figure 3. Relevant characteristics of the behavior and attitudes of the actors in the EBP

There was a consensus between the stakeholders that a lack of political will is the main obstacle to achieving a higher incidence of evidence. Another critical barrier has to do with values and interests. For instance, actors pointed out that air pollution control seems not to be part of the decision-makers' priorities since it is an issue that involves many interests and whose strategies to control or mitigate involve a high political cost and, in some cases, loss of acceptance among citizens. At the same time, the obstacles attributed to the scientist's characteristics are related to the researcher's purposes, to focus only on contributing to knowledge rather than influencing the political sphere. In many academic institutions in the country, the actors mentioned that there are few incentives for researchers to exercise active participation, which requires a lot of time and commitment. Concerning these factors, the actors commented:

"Decision-makers have political interests that make these issues temporary for them, not issues to address them in the long term, so they will listen to you as the issue is of political utility or fits their agendas, but it is not a commitment that they will carry" (O4)

"The researcher is generally oriented to generate knowledge and to seek to report such research in those journals that have a high level of quality because that generates long-term remuneration for the researcher and rarely pay attention to the relevance of their research concerning the needs to solve a social problem" (D7)

"I think there are agreements at other levels, by professionals from other multilateral organizations, internal pressure groups. There is much information, but anybody cares. For example, the Ministry of Finance is not interested in anything about the environment. As long as the environment is not considered a development problem that costs the country, nothing happens" (S17)

4.2.3 The knowledge exchange

The relationships and communication channels among decision-makers, scientists, and the community are crucial elements in the incidence of evidence in air quality management. The interviews showed six principal codes associated with the exchange of knowledge, among them: 1) meeting spaces, 2) dissemination of information to the community, 3) research models towards co-production with feedback processes, 4) links between decision-makers and scientists, 5) links between scientists and NGOs, and 6) the organizational culture. Also, multi-stakeholders' meetings, and digital media were identified as enabler in the use of evidence, while the scientific language were identified a negative factor. Figure 4 shows the percentages of cites associated with these codes according to the stakeholder's group.

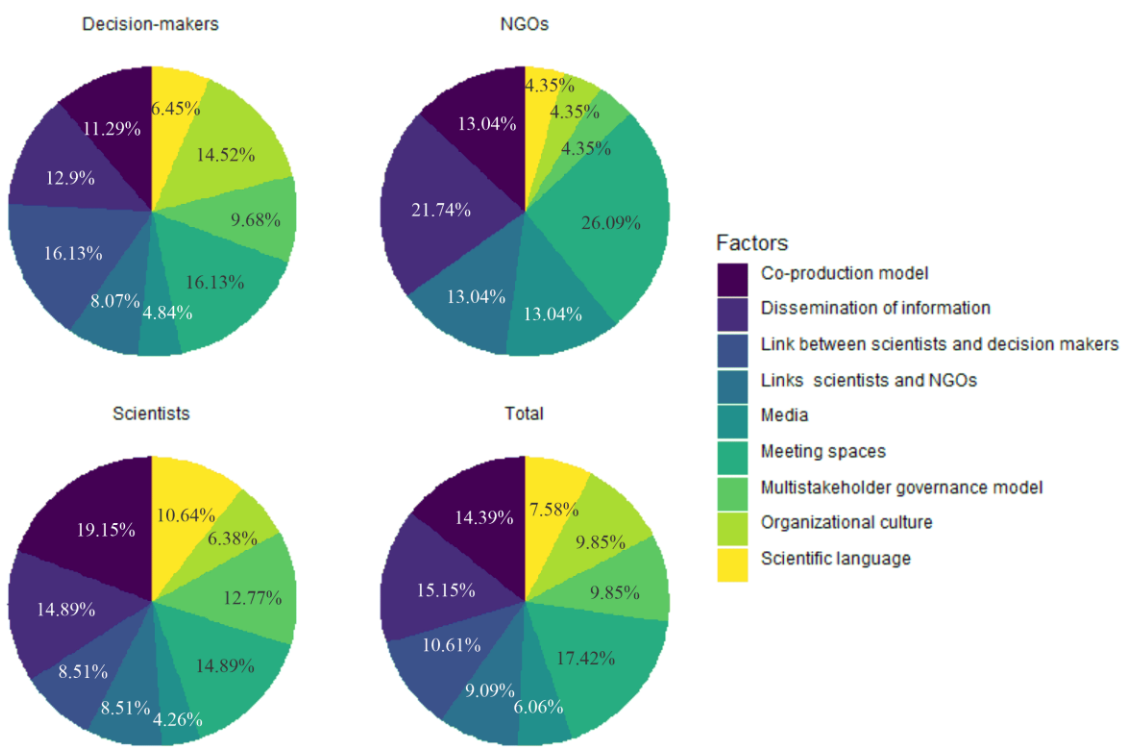

Figure 4. Relevant factors in the knowledge exchange on the air quality management

The actors from Mexico City, Guadalajara, and Monterrey pointed out that a supportive organizational culture is being promoted in their respective places, where the exchange of knowledge is being encouraged through medium differences. Regarding air quality, the actors emphasize the importance of forums as meeting spaces to discover the information generated from academic and polity spheres and establish relationships. Also, generating think-thank or potentiate advocacy to complex issues in air quality management. Besides, an area of opportunity is the use of digital media to disseminate scientific information to the community in two ways, to generate pressure on groups with broad power and to provide the population with a better understanding of the reasons behind the implementations. Obstacles were associated with the lack of these meeting spaces in some cities, the involvement of a few groups of actors in the meetings to propose strategies and difficulties associated with scientific language. Some actors mentioned the relevance of the information format, using executive summaries or support in knowledge brokers. Table 3 presents excerpts from the interviews associated with the principal codes seen as facilitators or limitations on the use of evidence.

Table 3. Stakeholder's perspectives about knowledge exchange

Factors	Facilitators	Limitations
Meeting spaces	"We try to participate in meetings and workshops to explain best what the results of the research work means" (D11)	"It seems that what we lack participation schemes that could be accessible to interested groups" (O38)
	"We have held press conferences, held workshops, and given a conference to establish relationships with decision-makers" (O4)	"There is a lack of available spaces for this support from the academy to the government sector" (D2)
Dissemination of information	"As long as the information is available to citizens, citizens can demand that authorities and those who intervene or have an involvement in air quality do things better" (D21)	"One of the limitations to trigger more far-reaching measures in terms of air quality is how to inform the population" (O5)
Link scientists and decision-makers	"Entailment agreements are the formal mechanism that the university has to engage with the public, private sector, and civil society groups. The non-formal is the one that I would promote is that each researcher must have their relations with the three sectors" (S26)	
	"We constantly have agreements so that based on the information we can provide or allowing them to help us operate certain very specific equipment to carry out research, their research will feedback into public policy" (D37)	

Link scientists and NGOs	"NGOs have been a very important link for the government to pay attention to certain investigations" (S1)	
	"The NGOs have followed up on how things are being done. If people do not move or researchers don't move, nothing moves, you have to apply pressure" (S26)	
Organizational culture	"There has been the best of attitudes by the CDMX government to listen to us. They were the ones who looked for us" (S20)	"The university became a manager to bring the academy closer to public servants, it was not always successful, but at least that level of dialogue existed, it is something in which we are very little developed" (S1)

4.3 Determinants of the decision making process

The analysis revealed how certain factors inherent to the political system act as barriers or facilitators in the incidence of evidence on the decision process and how these factors predominate in the design of public policies beyond the evidence. The interviewees indicated that decision-making largely depends on institutional capacity, agenda settings, agreements at the inter-institutional level, financial resources, and the follow-up given to the programs. Concerning this, the authors mentioned the following:

"For decision-makers, sometimes this information can become a threat to their particular agendas; making changes that result in improving air quality can have high political costs, although the scientific evidence is conclusive". (O4)

"To make decisions, not everything depends on scientific evidence, if not political capacity to mobilize resources of power of all kinds, economic and political. Decisions are no longer made with scientific evidence" (S12)

Some actors also mentioned that as authorities in the air quality area, they have a limited capacity to make decisions involving sectors with broader economic power. Besides, their agendas must be adjusted in two ways. One, prioritizing short-term issues, to which the media devotes more attention than the air quality and, also, following international trends, so that strategies focused on air quality often do not appear in the priorities of the public agenda in many country's cities.

At the organizational level, relevant obstacles related to the lack of interinstitutional coordination and bureaucratic structures, limiting the participation of relevant sectors on air quality, imposing obstacles to addressing economic resources towards the generation of scientific evidence, and strengthening atmospheric monitoring. In this sense, stakeholders point out that factors such as the programs' follow-up, despite changes of government or political party, have contributed to overcoming these obstacles in Mexico City. In contrast, in other metropolitan cities such as Mexicali, government changes have made it challenging to continue with some strategies and slow down the learning curves of officers involved in air quality management.

"At the national level we have a very strong challenge in terms of monitoring, their position is fragile because they do not have enough personnel and insufficient resources and at any time of change of administration these systems go down" (D26)

"At the federal level, it is expected that the state "ProAire" will continue. However, activities have stagnated in recent months" (D34)

Between the scientist's groups, an essential issue is the political time frame. Although there is the willingness of decision-makers to listen to the information that scientists produce, a significant barrier is time. Investigations require a long process while in the political sphere, decisions are made in a quickly, following a reactive approach.

"Decision-makers want the solutions in the moment, and that cannot always be had from the academy" (S23)

These were the political determinants that ultimately defined the degree of influence that scientific evidence has on management implementations.

4.4 Facilitators, barriers, and their interrelationships in the incidence of evidence in decision- making.

The interviews' analysis showed the facilitators and barriers in the use of evidence in air quality management. Figure 5 presents an overview of the codes identified as barriers or facilitators and described in the previous sections. Regarding the use of scientific evidence, stakeholders perceive it mainly as an argument to position the issue on the public agenda and to achieve a better understanding of the problem. Also, there is broad recognition of roles associated with supporting, legitimizing, or justifying strategies that affect various sectors and seek acceptance from civil society.

A critical gap existed in the role of evidence in the final phases of the policy cycle. Only the case of Mexico City showed consistency and sufficiency of data to assess the public health impact of the implemented policies, which was considered a relevant input in decision-making. In other cities, such as Ciudad Juarez and Mexicali, the evaluation issue took place at a slower pace due to multiple barriers generating evidence. As a consensus, the political and economic determinants constitute the main groups of barriers interrelated with the production and exchange of knowledge. For instance, obstacles that appear to generate scientific evidence from a technical point of view were strongly associated with important political determinants such as institutional capacity, organizational structure, and administration changes.

The interviewees mentioned essential areas of opportunity when moving towards a multi-stakeholder management model and changing the system to manage atmospheric monitoring. Concerning the monitoring network, one strategy mentioned was involved sectors representing relevant emission sources, such as the transport or industrial sectors, to ensure the needed financial resources. Another crucial element mentioned by actors as an area of opportunity was the formation of research networks instead of isolated efforts, increasing the mechanisms for the exchange of ideas, and establishing collaborative relationships.

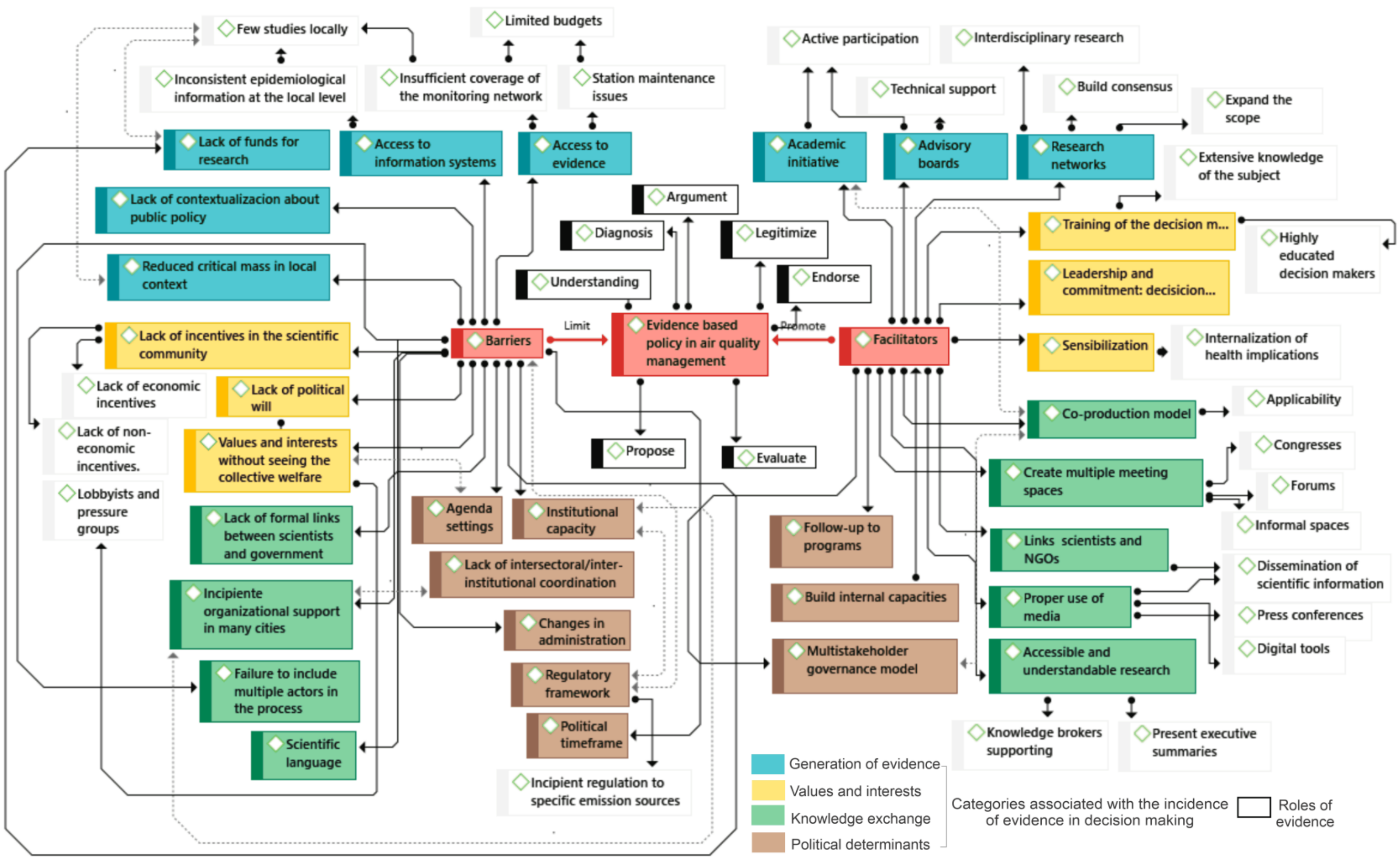

Figure 5. Scheme of barriers and facilitators that influence the use of evidence in the management of air quality. The boxes with a black outline represent the identified roles of the evidence. The upper black boxes show the most frequently reported, the boxes at the bottom are recognized with less frequency. The main barriers and facilitators are grouped in categories: the generation of evidence (blue boxes), values and interests (yellow boxes), knowledge exchange (green boxes), and political determinants (brown boxes).

4. Discussion and policy recommendations

4.1 Discussion

This study analyzed the stakeholders' perspectives concerning the air quality management and the use of evidence, as well as, the barriers and facilitators necessary to achieving a higher impact of evidence through decision making. Five main categories and 72 codes were collected from the interviews of researchers, government officers, and NGO's representatives in the field of air quality management. The identified main categories of barriers and facilitators agreed with those reported in previous studies (Oliver et al., 2014; van de Goor et al., 2017; Brownson et al., 2018; Walsh et al., 2019). All these authors identified as main barriers the access to relevant and applicable evidence, values and interests of the actors and factors related to the decision making processes. Among the aspects to be promoted, we also found the need to develop a co-production model and develop mechanisms for knowledge exchange.

We found that air quality management requires addressing aspects such as creating research networks, creating formal and informal links among decision-makers and scientists, and introducing modifications to the monitoring processes. Changes could start by including more sectors to secure resources and expand coverage and make it more participatory to achieve greater dissemination of information.

Concerning to policy determinants that influence the role of evidence, Weible et al., 2008, distinguishes them through unitary, collaborative and adversary political subsystem where the use of evidence depends on the degree of agreement and coalition between decision-makers and stakeholders. Previous studies in Mexico have found that EBP, in the air quality control policies, has been restrained by factors such as political convenience, in the case of the incorporation of unleaded fuels. Bravo and Torres (2000), discussed that this decision was taken for political convenience, without evidence of the economic and social factors involved in such implementation. Another similar example is the vehicular restriction program, “Hoy no circula.” Davis (2008) discussed that the first results of this program did not show the expected success and pointed out that the increase in demand for automobiles and the circulation volume could have been anticipated if the evidence on behavioral responses had been taken into account.

In this sense, even if the scientific evidence is present, previous studies have signed the lack of resources and interest of local authorities (Fernandez-Bremauntz, 2008), and bureaucratic and institutional capacity (Lankao P, 2007) as the significant obstacles for the use of evidence in the air quality management in Mexico. Velasco and Retama (2017) pointed out that authorities do not listen to the recommendations of the experts, making again reference of the particular "Hoy No Circula" case, when the country's Supreme Court evaded regulartory restrictions on the age of the cars, because it was an anti-popular policy. These aspects were also relevant to our findings. The stakeholders recognized many gaps and lack of stringent lineament in the regulatory system regarding emission sources as limiting to the margin of action of policies supported by evidence and the lack in disseminating the information that influences the acceptance of specific strategies among the community.

A relevant issue concerning the dissemination of information is to generate evidence about the results of the implementations. In a recent report, Dockery et al. (2018), associated the reduction in premature mortality and increase in life expectancy to the strategies of public policy such as “Hoy No Circula” and inspection and maintenance programs for passenger vehicles (Programa de Verificación Vehicular Obligatoria, PVVO) and some measures included in the air quality management program in Mexico City. They pointed out the importance of working on strategies based on scientific evidence. However, our results show, except Mexico City, that most cities in the country do not have sufficient technical capacity, nor a follow up on the programs to generate evidence on the strategies' results and carry out a feedback process.

Our results are in agreement with those from Franco et al. (2019), concerning the technical and data analysis capacities to conduct strategies to improve air quality in Mexico City. However, different from this study, they found that Mexico City has an excellent institutional interaction across sectors, sufficiency in the staff involved in the air quality management, and established mechanisms of command and control. According to our analysis of the interviews, these factors are considered the main obstacles in the evidence-base air quality management in other parts of the country.

We also identified areas of opportunity in the relevance and applicability of evidence in air quality management and some recommendations to increase the use of evidence in the process, presented in the following section.

4.2 Policy recommendations

The semi-structured interviews allowed us to inquire about the needs of research among the different stakeholders. As a consensus, they identified the need to strengthen the monitoring network, the emission inventories, and the epidemiological information system. Steps necessary to provide researchers and policymakers with the capacity to generate evidence at the local level, essential to support proposition and evaluations of prevention strategies or regulatory measures (Thurston et al., 2009; Molina et al., 2019)

The context of EBP at the national and local level may differ. Brunt et al., (2018), addressed this aspect of air quality management in the UK, integrating national policy measures and statutory effects-based local air quality management process, and considering that pollution sources are best managed at a local level. In this sense, increasing the local capacity to share knowledge and expertise, as well as, developing legal and regulatory frameworks to increase the institutional capacity regarding the most polluters sectors can contribute to greater stakeholder engagement, and deal with the barriers associated with power roles and interest groups (Thaler and Levin, 2015).

Few had explored the issue of evidence and implementation of air quality management from the perspective of vulnerable populations. In Mexico, the air quality index addresses alerts to protect public health. It mainly reports limiting, suspending, or continuing outdoor activities, considering physiologically vulnerable groups (children, the elderly population, or those with pre-existing asthma, cardiovascular conditions), but without mentioning specific actions to be taken by those individuals. On the other hand, considering people most exposed due to social conditions seem to be a matter of argument. Although there is evidence of increased risks of health effects related to air pollution and increased exposure to air pollutants in groups of low socioeconomic status (Benmarhnia et al., 2014; Arceo et al., 2016) calling for attention to this matter, it still is not reflected in better-oriented strategies to protect those individuals. Although local management of air pollutants in socially vulnerable communities is a complex issue, a recommended evidence-based start is disseminating timely forecasts, alerts, and practical advice (Lam et al., 2019) to take self-protection actions.

Advances in the science-policy interplay oriented to EBP have been partially due to the formation of epistemic communities (Greer et al., 2018). These communities, function as a network that shares normative beliefs, validate the evidence and share a joint political enterprise. In Mexico City, there are reliable research groups that have been heard by decision-makers. However, in other cities of the country, it is necessary to increase and encourage more researchers working on the subject, for which the creation of formal agreements and funds for research is essential. In this sense, the thematic network projects are a mechanism that could be used as a link between researchers, policymakers, civil organizations, and where some funds can also be managed (Totlandsdal et al., 2007) to create meeting spaces. The thematic network of atmospheric pollution and mitigation of climate change "Redcam" in Mexico City has made significant efforts to communicate research results. It creates links between the actors that must be transferred to other parts of the country.

The way of bringing the evidence to the political sphere has been pictured in two models, transfer of knowledge and interaction knowledge. The first one assumes scientist's independence, and the second points towards coproduction (Knaggård et al., 2019), where the interaction with the stakeholders is a facilitator to produce evidence. The feedback process between research and policy is essential to move consistently between the policies project and happens in reality (Fuller and Font, 2019). In Mexico's case, it is necessary to promote a more receptive and committed organizational culture to attend to the expert's recommendations regardless of the model of knowledge exchange, while developing incentives from both sides for more significant interaction.

5. Conclusion

This study presents an analysis of the perceived context of the air quality management in Mexico and described the barriers and facilitators to use the scientific evidence in air quality management in Mexico from the stakeholder's perspective. Consistent and small scale technical aspects like atmospheric monitoring, emissions inventories, and health-related data constitute a significant challenge in the country. There are significant differences between cities regarding the production of evidence and knowledge exchange. Political determinants such as institutional capacity, gaps in the regulatory system, and lack of multisector management are obstacles to expanding the role of scientific evidence. Essential areas of opportunity must be addressed, such as creating formal and informal spaces to promote coproduction, build internal capacities, generate incentives to make use, and evaluate the use of the evidence. Public policies on air quality, and the evidence supporting them, require moving towards a comprehensive vision of the problem. The involvement of the public health and economic sectors with the highest incidence on air quality, and researchers from more significant number of disciplines that may document economic, social, health, and behavioral change impacts associated with the strategies. A change in the way the monitoring system operates to participatory schemes and involve a greater number of sectors in decision-making are desired.

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Consideraciones del capítulo V para el contexto de Mexicali.

Los estudios realizados del capítulo II al IV puntualizan hacia la necesidad de dar mayor peso al componente social en la gestión, desde una perspectiva de bienestar y de promover estrategias integrales para mejorar la calidad del aire a nivel local. En el capítulo V algunos aspectos no incluidos dentro del cuerpo principal, fueron direccionados para el caso específico de Mexicali. Por un lado, se busca comparar la percepción de los ciudadanos sobre la calidad del aire con la percepción que tienen los actores clave y por otro indagar como son manejados estos temas en la gestión de la calidad del aire.

De los actores clave entrevistados, siete actores pertenecen a la ciudad de Mexicali, los cuales han estado directamente participando en el diseño de programas para mejorar la calidad del aire. La percepción de los actores es que la calidad del aire es mala en Mexicali, aún sigue siendo un problema ambiental relevante, con elevadas concentraciones principalmente en invierno. Si bien ellos reconocen que se mantiene la mayor parte de los días del año como regular, de acuerdo a la regulación nacional, 68% de los ciudadanos entrevistados la perciben como mala y muy mala. Aunque los actores clave no manifestaron claramente que haya empeorado, el 76% de los encuestados expresaron que esta ha empeorado y en acuerdo con los actores clave 70% de los encuestado considera que episodios de mayor concentración de contaminantes ocurre en inverno. Evidentemente es necesario mejorar la diseminación de información que llega a los ciudadanos, para sensibilizar y mantenerlos mejor informados sobre qué medidas individuales pueden tomar y del porqué de ciertas estrategias que buscan implementarse a nivel gubernamental.

Para conseguir esto es necesario proponer estrategias de soporte financiero y científico que permite tener la información suficiente para documentar los cambios en la calidad del aire de manera oportuna y las repercusiones en salud pública. Algunos fragmentos relevantes al caso de Mexicali, no incluidos en el Capítulo V, expresan lo siguiente:

"Hoy por hoy la calidad del aire en Mexicali está muy comprometida, en cuanto a que las concentraciones de gases y partículas contaminantes que se presentan en la cuenca. En concreto la calidad del aire tiende a ser de regular a mala en una buena cantidad de días al año y tiene impacto sobre la salud pública.

“Apenas empieza el sector salud a darse cuenta que el factor calidad del aire, es un factor fundamental para el cuidado de la salud en Mexicali, están ya empezándose los primeros estudios de correlación entre las enfermedades cardiopulmonares, respiratorias agudas, episodios de asma con días en los que la calidad del aire es sumamente mala o cae en alguna escala que está por encima de la NOM de calidad del aire.

Los actores reconocen las limitantes para generar información de manera consistente que les permita realizar evaluaciones sobre los programas implementados. La comparación entre las percepciones deja ver que se requieren esfuerzos importantes de comunicación del riesgo y efectos de salud asociados a la población en general y sobre todo a la más vulnerable, cuyo conocimiento en los efectos relacionados a la contaminación del aire es muy reducido.

El tema de vulnerabilidad social como los resultados documentados en los previos capítulos, se consideran relevantes en el diseño de los programas, sin embargo, no aparece documentado en la evidencia que sustenta los “ProAire”. Solo en el ProAire mas reciente se empieza a incluir esta perspectiva. Hay barreras significativas para dar un mayor peso a la priorización de acciones en estos grupos socialmente vulnerables, la capacidad institucional fue señalada como una de las principales barreras. Al respecto se señaló lo siguiente:

“Ha habido quejas, en especial una planta Zahorí, incluso he percibido el efecto, ellos están cumpliendo con su Cedula de Operación Anual COA y todos los documentos que exige la Secretaria, no se les puede cerrar por ese lado. Lo que sería pertinente en ese caso sería que la gente se organizara como comunidad a través de propuestas mancomunadas para que de esa forma se presione a la Secretaria y a las partes correspondientes para que actúen.”

“Asumen muchas responsabilidades del problema al municipio que solo se encarga de las emisiones comerciales al aire, restaurantes, pollerías, por ese lado el municipio si tiene un control, pero es más grande de lo que pueden supervisar. Es un punto en el que no se ha podido avanzar más, de lo que los recursos les permiten hacer”.

“Las gestiones que se realizan para prevenir, disminuir o evitar la contaminación, no están limitadas a algún área o grupo social, ya que si se elimina el beneficio es para todos”

Estos hallazgos señalan que la gestión de la calidad del aire se sigue manejando como algo aislado a los objetivos de desarrollo sustentable, al momento los actores no mencionaron que se estén planteando acciones en este sentido, con acciones específicas que busquen proteger a la población más vulnerable por edad, condiciones de salud y estatus socioeconómico.

La percepción pública de la calidad del aire es algo que debe monitorearse constantemente, y ser parte del diseño de los programas como un indicio importante de los esfuerzos en comunicación del riesgo, de la aceptación que están teniendo las estrategias y de los grupos donde es necesario priorizar acciones.

CAPITULO VI
CONCLUSIONES Y RECOMENDACIONES

En esta tesis se planteó la relevancia de los factores socioeconómicos y de la percepción respecto a la exposición, valoración económica de la calidad del aire e inclusión del tema dentro del proceso de toma de decisiones. Se abordaron 4 objetivos específicos: 1) indagar si los factores socioeconómicos tienen un rol de efecto modificador en la relación contaminación del aire y salud, 2) mostrar evidencia a nivel local de la asociación espacial entre vulnerabilidad social y exposición a PM_{10} en Mexicali, 3) realizar una valoración monetaria de la calidad del aire por los ciudadanos de Mexicali, profundizando en el rol de los factores sociales y de percepción en dicha valoración y 4) analizar la perspectiva de los actores clave sobre la inclusión de estos temas dentro del diseño de programas para mejorar la calidad del aire. A continuación, se describen las conclusiones obtenidas de direccionar estos objetivos

VI. 1 Conclusiones particulares

En el capítulo II se concluye que existe un efecto modificador en el riesgo de tener problemas respiratorios en la población infantil, asociado a las condiciones socioeconómicas en las que viven. Existen importantes aspectos a direccionar sobre la forma en que es evaluado el estatus socioeconómico, variables individuales e índices compuestos, todos ellos en general a partir de información obtenida de censos o encuestas aplicadas a los padres. El ingreso, el nivel educativo y el estatus de seguro médico resultan ser variables relevantes en el análisis, sin embargo, no se ha logrado un mayor acercamiento a indicadores que reflejen más adecuadamente la situación de vulnerabilidad social de la población infantil. Para ello, es esencial direccionar investigaciones interdisciplinarias o transdisciplinarias que permitan tener un mayor acercamiento a los factores, sociales, económicos, y psicológicos y las propias dinámicas familiares, que ponen en mayor riesgo de sufrir efectos de salud asociados a la contaminación del aire.

El capítulo III concluye que en la zona urbana de Mexicali existe una asociación espacial significativa entre la población que vive en alto grado de vulnerabilidad social y una alta exposición a PM_{10}. En dichas áreas, no existe un consenso en la percepción de la población sobre encontrarse en una zona de muy alta exposición. La percepción de una muy mala calidad del aire se asocia generalmente a la presencia de una fuente fija. Los problemas sociales y económicos de estas zonas vulnerables generan una mayor preocupación. Esta población, además, tiene escasos conocimientos de los efectos severos que puede ocasionar la contaminación del aire, lo cual incide en las acciones de autoprotección. Las estrategias a implementarse deben encaminarse en dos sentidos, planificación urbana con una visión de promover el bienestar en estas áreas prioritarias y una efectiva comunicación del riesgo.

En el capítulo IV de esta tesis se concluye que los residentes del área urbana de Mexicali reconocen la contaminación del aire como un problema ambiental importante para su ciudad y están dispuestos a participar en estrategias para mitigarlo. Aunque el ingreso es una limitante para acceder a participar monetariamente; la falta de confianza en las instituciones jugó un rol importante en la aceptación del programa de forestación propuesto. Los beneficios que otorgaron 21% de los encuestados por mitigar las altas concentraciones de PM_{10} se estimaron en 0.8% del ingreso medio anual de los hogares, que al compararse con los costos del programa durante un año resulta ser costo efectivo. El rol de la percepción de la calidad del aire y conciencia de los efectos de salud en la disposición a pagar mostraron la importancia de crear sensibilización ante este riesgo. Los hallazgos de este trabajo no buscan promover una mayor carga impositiva a la población, sino generar conciencia de la valoración que dan los ciudadanos a la calidad del aire.

En el capítulo V de la tesis se concluye que el tema de vulnerabilidad social es ampliamente usado como discurso en el argumento y fases iniciales del diseño de estrategias para controlar la contaminación del aire, sin embargo, su inclusión no permea hacia la implementación. Las estrategias que se manejan para proteger la salud de la población a nivel general, carecen de un enfoque de priorización a los grupos que fisiológicamente o por condiciones socio económicas son más vulnerables. Los actores clave plantean la existencia de otros problemas sociales y económicos que requieren una mayor atención. En este sentido, pensar en las políticas de contaminación del aire desde una perspectiva de bienestar, contribuye también a mejorar las condiciones de vida de población, por ejemplo, el tema de movilidad sustentable en zonas de la periferia, pavimentación y vialidades para promover otros medios de transporte o de tamaño adecuado para realizar caminatas, el arbolado urbano, y el cuidado del entorno donde confluyen poblaciones fisiológicamente y socialmente más vulnerables. Por otro lado, se concluyó que la evidencia en términos económicos se maneja como una condición necesaria y valorada por los actores clave en la toma de decisiones.

A pesar de las diferencias en la capacidad técnica entre diversas ciudades del país para monitorear la calidad del aire, existen factores comunes que obstaculizan la incidencia de la evidencia en la toma de decisiones, entre ellas, la limitada capacidad institucional, los grupos de presión con amplio poder económico, la falta de recursos destinados a la investigación para hacer transferencia hacia las instituciones gubernamentales y brechas en el sistema regulatorio. Factores clave deben ser promovidos entre ellos formar grupos de investigación sólidos e interdisciplinarios, que de manera colectiva estén dispuestos a participar y empujar el seguimiento a los programas, crear incentivos por parte de las agencias gubernamentales y académicas para promover esta participación, promover una cultura organizacional con mayor apertura a los espacios formales e informales que den pie a procesos de coproducción.

VI. 2 Conclusiones generales

La evidencia generada a partir de los cuatros manuscritos que integran esta tesis señalan la importancia de considerar los factores socioeconómicos y la percepción de la calidad del aire en la evaluación de la exposición a contaminantes atmosféricos y en el diseño de programas para mejorar la calidad del aire.

Los hallazgos del capítulo I, mostraron evidencia de que los factores socioeconómicos inciden en la exposición y en el riesgo. El efecto del estatus socioeconómico puntualiza a un mayor riesgo en grupos de bajo estatus socioeconómico. En términos de modelación y comunicación de resultados se encontraron importantes ventajas en el uso de índices compuestos cuando estos se manejan al mismo nivel de agregación que la estimación de la exposición. Este conocimiento fue aplicado en el caso de estudio, la zona urbana de Mexicali donde fue posible identificar clústeres de mayor vulnerabilidad social en zonas de alta exposición a material particulado PM_{10} en la región Noroeste y Sureste.

En cuanto al análisis de percepción de la calidad del aire en la ciudad, la secuencia de los estudios realizados nos permitió comprobar que la percepción, no solo es un factor relevante en la exposición ante la falta de una asociación directa con las mediciones de los sitios de monitoreo, lo que se puede ver reflejado en escasos comportamientos de autoprotección. También evidenció que dicho factor es relevante en el soporte público hacia programas de política públicas para mejorar la calidad del aire.

La percepción además de tener un componente importante derivado de lo que apreciamos con los sentidos, está ligada con experiencias relacionadas con el problema, tales como padecer o tener familiares que experimenten frecuentemente síntomas respiratorios o efectos asociados a la contaminación, con el acceso a información del estado de la calidad del aire y con lo que observa del entorno inmediato, las condiciones de donde se reside, entre ellas, el acceso a áreas verdes, calles no pavimentadas, el tener industrias cerca. Todos estos factores pueden actuar creando un distanciamiento hacia el problema y sentimiento de incapacidad a aportar en las soluciones, mediado a su vez por las condiciones socioeconómicas que indicen en las prioridades que tiene cada persona. Dichos factores fueron relevantes en los resultados arrojados en los capítulos II al IV, subrayando la importancia de incluir estas perspectivas en el diseño de estrategias para mejorar la calidad del aire.

En el capítulo V se contrasto la percepción de los actores clave con la de los ciudadanos de Mexicali. Se encontró acuerdo en que la calidad del aire es mala, sin embargo, se mostró que es necesario promover la generación de datos de manera consistente y oportuna para evaluar los cambios en el tiempo y los efectos que han tenido las estrategias en la salud pública. La perspectiva de factores socioeconómicos y de la percepción pública que se encontraron como relevantes en los capítulos previos constituye una brecha importante en el diseño de estrategias para mejorar la calidad del aire, su incorporación no logra trascender a las propuestas, implementación y evaluación. Existen esfuerzos importantes para comunicar los niveles de concentración de varios contaminantes criterio en redes sociales y otros medios, pero no son accesibles para toda la población y no se ha creado conciencia de las repercusiones en la salud.

El uso de métodos mixtos permitió tener un mayor entendimiento del problema, comprobar, comparar y ampliar el conocimiento generado en cada estudio al tener resultados de las fases previas. El acercamiento con la población y con los actores clave permitió contextualizar los resultados de la investigación, direccionando algunos elementos de la complejidad que engloba la gestión de la calidad del aire, entre ellos, diferentes percepciones, valores e intereses de los involucrados, y diferencias distribucionales en la exposición. La aplicación de métodos mixtos contribuye además con evidencia acerca de las necesidades y barreras que pueden existir por parte de la población, así como barreras en la esfera política, que dificultan la puesta en marcha de intervenciones con mayor impacto social. Finalmente, el uso de métodos mixtos implica tener una mayor apertura para adecuarse al desarrollo de la investigación, valorar las aportaciones que los datos duros y juicios subjetivos proporcionan en cada fase del proceso.

VI.3 Limitaciones

De manera general, este proyecto de investigación evidencía la complejidad del tema de la calidad del aire desde una perspectiva social, incluyendo conocimientos y herramientas usadas en epidemiologia, salud ambiental y economía ambiental. Cada capítulo presenta limitaciones propias asociadas con las fuentes de datos y supuestos de cada modelo utilizados en las estimaciones, las cuales fueron especificadas en cada estudio. En términos generales las limitaciones se engloban en los siguientes aspectos:

- La estimación de la exposición encierra en sí misma una gran complejidad, que requiere el uso de otras disciplinas, como la química atmosférica. Aspectos relacionados con la temperatura, el viento y eventos como tormentas de arena son de gran relevancia en la concentración de contaminantes en Mexicali y serán considerados en futuras investigaciones. En la evaluación de exposición solo se consideró PM_{10} como un problema persistente en Mexicali. La alta concentración de maquiladoras en la ciudad y plantas generados de energía eléctrica son una importante fuente de emisión a ser considerada en estudios posteriores.

- En el capítulo II, la revisión de literatura tomó criterios de selección muy específicos en los que no fue posible encontrar estudios para América Latina en las bases de datos consultadas. Los estudios evaluados consideraron el reporte de diferentes efectos de salud y rango de edades dificultando la realización de una revisión sistemática.
- En el Capítulo III la disponibilidad de datos fue una de las principales limitaciones, en Mexicali se cuenta con una poca cobertura de sitios de monitoreo y pocos se encuentran en operación de manera regular. La suficiencia estadística en las mediciones y el número de estaciones funcionando fueron determinantes para seleccionar el periodo de análisis de exposición, que al no coincidir con los datos obtenidos del censo de población a nivel de AGEB puede conducir a un sesgo por las diferencias temporales. En este sentido se cuidó la consistencia del nivel de agregación.
- Respecto a la información para evaluar efectos en salud, ninguna instancia local o a nivel estatal nos permitió acceder a información a nivel de código postal que permitiera tener congruencia con los datos de exposición y de vulnerabilidad social. La información epidemiológica disponible se encuentra a nivel municipal perdiendo un gran nivel de detalle para evaluaciones a nivel local.
- Para los capítulos III y IV la información individual recabada a través de encuestas realizadas cara a cara, corresponden a personas mayores de 18 años que fueron seleccionadas aleatoriamente en lugares públicos (centros comerciales, parques, locales comerciales pequeños, calles), se debe tener presente estas características de la muestra en los resultados del estudio. Aunque se trató de capturar la población socialmente vulnerable realizando las encuestas en diferentes puntos de la ciudad, esta variable no estaba bajo nuestro control, al tratarse de encuestas dirigidas aleatoriamente.
- Respecto al índice de vulnerabilidad social, los datos provienen del censo de población y vivienda, muchas variables que son componentes importantes de la vulnerabilidad social, como la infraestructura alrededor como el acceso a áreas verdes, o variables de capital social no son direccionadas en los censos. Sin embargo,

las variables que utilizamos en la construcción del índice han mostrado tener un importante valor explicativo en estudios de salud ambiental en la literatura revisada.

VI.4 Significancia del estudio e implicaciones para la toma de decisiones.

Esta investigación contribuye como el primer estudio en Baja California y México que evalúa la asociación entre factores socioeconómicos y de percepción pública en la exposición a PM_{10} y dentro del diseño de políticas públicas a nivel local.

Los resultados de la revisión de literatura son relevantes para estudios en epidemiologia social y salud ambiental, al identificar brechas de investigación y aspectos que deben ser considerados al evaluar el SES y su efecto en el riesgo por exposición a contaminantes atmosféricos.

El capítulo III contribuye con evidencia a nivel local y sentando bases para el desarrollo de investigaciones que direccionen los factores socioeconómicos y de la percepción de la calidad del aire en el contexto de países en desarrollo.

Los resultados del capítulo IV aportan a la literatura internacional naciente sobre el papel de la infraestructura verde como estrategia para mitigar la concentración de contaminantes atmosféricos y direcciona aspectos importantes de sustentabilidad que se pueden adecuar al contexto de ciudades áridas en otras regiones del mundo, sobre todo por la tendencia en estas regiones a enfrentar una mayor aridez y concentración de población en las ciudades. Además, los resultados de este estudio contribuyen en la identificación de variables relevantes para la valoración de servicios ecosistémicos.

El capítulo V contribuye a la escasa evidencia científica sobre la identificación de barreras y facilitadores para impulsar el uso de la evidencia en la gestión de la calidad del aire en el contexto de países en desarrollo.

Los resultados obtenidos en esta tesis tienen importantes connotaciones para la toma de decisiones en Mexicali y también a nivel nacional. La relación del estatus socioeconómico en la exposición a contaminantes atmosféricos no es algo que debe darse por sentado, en los estudios direccionados se mostró que tiene una asociación significativa con la exposición.

Los tomadores de decisiones deberían consideran realizar esfuerzos que prioricen acciones en estas áreas, mejorando el entorno construido, con acciones como la pavimentación de calles, infraestructura vial adecuada para realizar caminatas, acceso a áreas verdes, acceso a movilidad sustentable. Estas acciones a su vez pueden motivar a llevar a cabo comportamientos proactivos, para mejorar las condiciones ambientales del entorno.

Los resultados de esta tesis también subrayaron la poca incidencia que tiene el tema de vulnerabilidad social en el diseño de los ProAire, y en los índices que alertan situaciones de contingencia. Es necesario direccionar estrategias oportunas limitando las actividades que generan mayores emisiones, informando y evitando en lo posible la realización de trabajos en exteriores, así mismo dar alertas tempranas a las instituciones de educación básica y preescolar para limitar las actividades al aire libre.

Los hallazgos sobre el rol de la percepción para contribuir en los programas de política pública, indican que es necesario avanzar en estrategias de comunicación del riesgo, brindando información sobre los efectos de salud relacionados a la contaminación del aire. Estas estrategias de comunicación deben direccionar diferentes medios de comunicación como: redes sociales, televisión, periódico, campañas y talleres para crear una mayor sensibilización con el tema. El monitoreo participativo que se está llevando a cabo en Mexicali, es una iniciativa importante que debe ser fortalecida con la participación de diferentes actores.

Un tema importante que se evidenció en esta investigación fue que se carece en muchos lugares del acceso a los datos y evidencia que permita evaluar el impacto de las estrategias para mejorar la calidad del aire. Es necesario invertir en la generación de información consistente, en la medición de contaminantes y también en términos de vigilancia epidemiológica donde existe un gran rezago.

La trazabilidad y seguimiento a los programas es un aspecto que deber ser promovido ampliamente, así como la creación de vínculos con el sector académico que de manera formal permitan tener un proceso de retroalimentación a través de todas las fases del ciclo de diseño de la política pública.

VI.5 Perspectivas de investigación

Los resultados de la investigación y limitaciones encontradas revelaron diferentes puntos a fortalecer y nuevos aspectos a indagar en futuros estudios, entre ellos:

1. Estimación de exposición considerando factores meteorológicos creando una línea base para su posterior evaluación al margen de alguna estrategia implementada.

2. Direccionar aspectos de vulnerabilidad diferenciada en los niños y respecto al estatus socioeconómico, tomando en cuenta nutrición, tiempo que permanece fuera de casa, actividades que realiza, comportamientos, persona a cargo de su cuidado. Recabando información en una muestra representativa, en un diseño de largo plazo.

3. Explorar efectos en salud con alta incidencia en Mexicali, además de los respiratorios y evaluar su posible asociación con la exposición a contaminantes atmosféricos. Diferenciando composición del material particulado por zonas de diferente estatus socioeconómico.

4. Evaluar la valoración de la calidad del aire en una muestra más amplia de la población, plateando diversos escenarios de política pública que formen parte de los programas estatales y dando oportunidad al planteamiento de escenarios por parte de los ciudadanos.

5. Desarrollar y validar un índice que permita evaluar el uso de la evidencia científica en el diseño de los programas de gestión para mejorar la calidad del aire.