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AIR POLLUTION AND HEALTH (S ADAR AND B HOFFMANN, SECTION EDITORS)

Urban Form, Air Pollution, and Health

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Abstract

Purpose of Review Urban form can impact air pollution and public health. We reviewed health-related articles that assessed (1) the relationships among urban form, air pollution, and health as well as (2) aspects of the urban environment (i.e., green space, noise, physical activity) that may modify those relationships.

Recent Findings Simulation and empirical studies demonstrate an association between compact growth, improved regional air quality, and health. Most studies are cross-sectional and focus on connections between transportation emissions and land use. The physical and mental health impacts of green space, public spaces that promote physical activity, and noise are well-studied aspects of the urban environment and there is evidence that these factors may modify the relationship between air pollution and health.

Summary Urban form can support efforts to design clean, health-promoting cities. More work is needed to operationalize specific strategies and to elucidate the causal pathways connecting various aspects of health.

Keywords Urban planning · Built environment · Sprawl · Walkability

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Introduction

Urban form can impact various aspects of human interactions with the built environment including via transportation systems [1, 2]; environmental systems (e.g., air quality, land consumption [3, 4]); social capital (e.g., community engagement, political participation [5]); and health [6, 7]. Williams [8] provided a useful definition of urban form: “physical characteristics that make up built-up areas, including shape, size, density and configuration of settlements … considered at different scales: from regional, to urban, neighborhood, block and street.” Measuring urban form is an evolving effort [9, 10]. Cities and local government are increasingly focusing on how planning decisions that affect urban form may impact human health and the environment [11–13]. Here, we consider relationships among urban form, air quality, and health, and we explore other aspects of the urban environment (i.e., green space, noise, and physical activity) that may modify the relationship between air pollution and health [14, 15].

Connections between air quality and health are well established [16–18]. Health impacts associated with within-city differences in pollutant concentrations are comparable to between-city differences [19]. Urban form-related policies may improve urban energy efficiency [20], carbon emissions [15, 21], and human exposure to air pollution [22, 23]. Ongoing research aims to identify promising strategies for modifying urban form to improve various outcomes (e.g., air quality) and generate co-benefits among those outcomes.

The objectives of this review are to summarize recent findings from the literature on (1) relationships among urban form, air pollution, and health (e.g., diseases of the body and mind) and (2) the potential for synergistic impacts, confounding, and/or effect modification of air pollution and health associations by three additional aspects of the urban environment: green space, noise, and physical activity. Consistent with the goals of this journal, we focus on literature from the past ~5 years.

Literature Review Methods

We performed systematic searches in the PubMed and Web of Science databases. We combined search terms to describe urban form ("urban form," "built environment," "sprawl," "walkability") with "air pollution" and "health." Then, we replaced the term "health" with one of the following terms: "physical activity," "physical inactivity," "exercise," "noise," "mental health," "green space," or "park." In general, the search term "built environment" returned the most articles among the urban form terms; "health" and "physical activity" returned the most articles by health term.

The searches returned 215 unique articles. Each article's abstract was screened for relevance to this review, resulting in 60 articles for inclusion. We scanned reference lists and used the "cited by" function in Google Scholar for key articles to supplement our database and to search forward in time; these steps provided an additional 46 articles. Among the 106 articles, most were published within the past 5 years (75 articles were published 0–5 years ago, 23 articles 5–10 years ago, and 8 articles more than 10 years ago). (Thirty-one additional articles are cited for context and to highlight other related review articles.) Table 1 gives a summary of search terms and results for each search.

Because of space constraints, several important topics related to our core area (urban form, air pollution, and health) are not included in this review, e.g., relationships with environmental justice and environmental equality; more-recently studied pollutants such as ultrafine particles; relationships in low- vs. high-income countries and communities; neighborhood-level SES; the changing nature of transportation (e.g., car-sharing, autonomous vehicles); and differences by age, sex, and other demographic attributes. We leave those and other important topics for future reviews.

Results

Our review is focused on urban development and land use patterns that influence air quality as well as other factors of the urban environment that may modify that relationship. For related topics not covered here, we point readers to review articles on the built environment and health [24, 25], land use regression [4], small-scale passive barriers [26], near-roadway gradients [27], and the relationship between the built environment, walking, and biking [28–31].

Connections among Urban Form, Air Pollution, and Health

Simulation Studies: Regional Air Quality

Simulation or modeling studies to assess the impact of urban form on air quality and exposure are designed in a number of ways; for example, by using idealized representations of urban expansion [32] or by evaluating city-specific future development scenarios by coupling transportation (e.g., travel demand) and air quality (e.g., dispersion) models [33–37]. While most studies develop models for a single city, a limited number of studies assessed national- or regional-scale impacts of compact vs. sprawl development on criteria pollutants using land use, transportation, and air quality models [38]. (Literature on urban form and greenhouse gas emissions [39, 40] is not our focus here.) Modeling studies typically explore various potential future land use scenarios (e.g., increasing or maintaining density vs. sprawl development) and generally find that compact development improves regional air quality; for example, one study [38] found that a 10% increase in population density would result in a 3.5% decrease in household vehicle travel and emissions. However, these studies report mixed effects on health impacts associated with the scenarios and highlight concerns regarding exacerbation of concentration hotspots. A case study of alternative development patterns of North Carolina's Raleigh-Durham-Chapel area found that compact growth would decrease regional fine particulate matter ($PM_{2.5}$) concentrations (-0.2%; sprawl would increase concentrations by 1%); however, attributable mortality would increase by 39% owing to spatial co-location of concentrations and population centers [36].

Multiple studies aim to assess the impact of changes in vehicle fleet composition or travel behavior in conjunction with urban form; for example, shifting trips to bicycle transport [41, 42•] or electrification of the vehicle fleet [43]. A useful extension of past simulation studies would be to evaluate specific policies rather than regional development patterns. A ground-breaking study by Macmillan et al. [42•] evaluated specific policy goals and estimated impacts on public health using system dynamics modeling; for various interventions related to increasing bicycle mode share, they report that benefits outweigh risks by a factor between 6 and 24. Some studies evaluated how travel activity patterns affect exposure [44, 45] and health [46]. (Further discussion of the tradeoffs between physical activity and air pollution is in the section titled "Physical Activity").

A general finding from these studies is that land use changes will likely need to be coupled with improvements in vehicle efficiency and fuels to realize health benefits from improved air quality. For example, modeling for Austin, TX, suggests that compact growth alone does not improve ozone (O_3) concentrations (a 14-ppb reduction in O_3 was only realized when

Table 1 Summary of search terms and results for this review

Search terms			PubMed[a]	Web of Science[a]
Urban form	Air pollution	Health	6	19
Built environment			69	138
Sprawl			8	24
Walkability			9	15
Urban form	Air pollution	Physical activity/physical inactivity/exercise	0/0/0	9/2/5
Built environment			15/3/4	72/6/5
Sprawl			2/0/1	5/0/2
Walkability			5/1/3	13/1/2
Urban form	Air pollution	Green space/park	1/0	1/0
Built environment			4/6	10/6
Sprawl			1/0	2/0
Walkability			0/1	0/1
Urban form	Air pollution	Noise	1	5
Built environment			8	19
Sprawl			1	9
Walkability			2	4
Urban form	Air pollution	Mental health	0	1
Built environment			8	16
Sprawl			1	1
Walkability			1	1

[a] The values in this table represent search results: 215 unique articles were identified among all searches; 60 articles were retained after review of abstracts based on whether the article included both an air quality and urban form component; 46 additional articles supplemented the database from article reference lists and using the "cited by" function for key articles. In general, some articles exist in both databases, some in only a single database; therefore, the values in this table represent the relative frequency terms appear in the literature rather than the absolute number of articles.

improvements in vehicle efficiency were coupled with land use strategies [33]); similarly, in a study of Raleigh, NC, reductions in vehicle emissions may be necessary to protect against elevated exposures in dense neighborhoods [36]. The bulk of these studies investigate the land use and transportation connection with a focus on vehicular travel. Future studies could explore connections between land use and other modes of transport (e.g., transit-oriented development) or include other emission sources associated with urban development (e.g., household-level emissions).

Empirical Studies: Regional Air Quality

Most empirical studies of urban form and air quality are exploratory and cross-sectional (i.e., between-city). Many studies employ city- or county-level urban sprawl indices to evaluate impacts on transportation patterns and energy use [1, 21], O_3 exceedances [47], and environmental justice [48]. More recent articles employ city-level characteristics such as more urban contiguity (e.g., a 4% increase in urban contiguity could offset projected increases in NO_2 concentration associated with 10% increase in population [49]), high population centrality (e.g., a 1 interquartile range [IQR] increase in centrality results in a 5–10% decrease in concentrations for $PM_{2.5}$ and O_3 [50]), and high quality transit service (e.g., an IQR increase in centrality results in a ~ 4% decrease in $PM_{2.5}$ concentrations [50]). These studies report that those metrics are associated with lower levels of air pollution in the USA [50], China [51], and globally [49, 52]. Bereitschaft et al. [53] tested five sprawl indices across 86 US cities; they report 3–10% increases in $PM_{2.5}$ and O_3 concentrations per 1 standard deviation change in each index. In general, these studies found that urban form may have modest but important effects on meeting air quality standards for criteria pollutants (especially when multiple changes to urban form are implemented simultaneously [52]). Few studies evaluate a wide range of measures of urban form. The pollutant assessed varies by study. Many of these studies evaluate one or a small number of urban form variables hindering comparisons across studies and identification of specific land use policies that have repeatedly been successful in reducing concentrations.

Recent studies advance previous work by using longitudinal (instead of cross-sectional) data and by adding new urban form metrics and pollutants. We identified two relevant studies that used longitudinal datasets [54•, 55•]; they corroborate findings from the cross-sectional studies in US and Chinese cities, namely, that sprawl-type development (as measured by impervious surface, low centrality, low density, or limited land use mixing [54•, 55•]) is generally correlated with increased concentrations. Recent studies have also explored how air quality varies with walkability [56], using landscape metrics (e.g., fragmentation of urban patches was associated with poor air quality [57]) and greenness (e.g., mixing of urban forest was associated with improved air quality [57]) as additional urban form metrics [53, 57], and assessing exposure to specific sources such as traffic [58]. A strength of empirical studies is that they are based on measured concentrations and thus rely on direct observations to estimate the relationship between urban form and air quality. However, empirical studies struggle to provide projections for future policy or land use changes. In addition to using longitudinal data and exploring additional urban form variables, future empirical studies could also explore using finer spatial scales (i.e., neighborhood-level measures) to simultaneously explore between- and within-city impacts of urban form; to date, most studies focus on city-level measures of urban form.

Empirical Studies: City-, Neighborhood-, or Route-Level Air Quality

In addition to large-scale between-city analyses of urban form and air quality, multiple studies explore smaller-scale, within-city patterns. Exploratory studies have assessed walkability and air quality and reported that poor air quality is often located in high walkability areas [59–61]. For example, 2–4% (4–7%) of neighborhoods are sweet- (sour-) spots [22, 59, 61]; furthermore, a significant portion of walking and biking (e.g., 20–44% in Minneapolis, MN [22]) may occur in neighborhoods with poor air quality. ("Sweet-spots" here refers to low-pollution, high walkability neighborhoods; "sour-spots" refers to high-pollution, low-walkability.) Other studies have measured health outcomes (e.g., C-reactive protein) [62] or estimated exposure across land use types [63, 64]. These studies found that components of walkability may have apparently competing effects, for example, high residential density neighborhoods are generally associated with poor air quality [62, 63] yet features such as increased land use mix may decrease concentrations [62]. That result highlights a complicating issue of using composite indices such as walkability or sprawl; underlying components of the index (e.g., residential density and land use mix) may have competing effects.

There are many studies that identify the impacts of time activity patterns and mode of travel on exposure and intake [65–68]. An emerging area of work focuses on identifying small-scale influences of the built environment on exposure; for example, the impact of traffic and road geometry [69–71], route choice [72, 73], and type of bicycle facility [69, 70, 74]. Most of these studies found that small-scale differences in the built environment can impact personal exposure. For example, choosing a route in low vs. high traffic density [70, 72, 75] could reduce during-commute exposure to particulates, NO_x, and CO by ~20%; similarly, building bicycle facilities with separation from traffic could reduce exposure to particulates by ~10% [71, 73]. One study makes a distinction between exposure impacts at the individual vs. population level [22].

A weakness of these studies is that they are often carried out in a single city, neighborhood, or transport corridor, potentially limiting the generalizability of the findings; as mentioned above, studies with larger sample sizes are often cross-sectional rather than using time-series data. A barrier to expanding these studies to larger scales is that land use data with sufficient specificity is frequently unavailable or inconsistent across cities. Additional work to assemble land use data at fine spatial scales across large (e.g., continental) geographies would allow for simultaneous exploration of city- and neighborhood-level impacts of urban form on air quality and exposure.

Urban Form, Air Pollution, and Mental Health

Most research on relationships among urban form, air pollution, and health (including the majority of the studies listed in the previous sections) focus on either exposure or estimate health effects by extrapolating findings from studies that assess the health effects of air pollution on diseases of the body (e.g., cardiovascular or respiratory disease). However, urban form measured on the city- or neighborhood-level may also impact mental health [76]. Many of the studies that report associations between urban form and mental health explore similar factors as studies of urban form and air pollution, e.g., increased cognitive function in the presence of green space (see further discussion in the section titled "Green Space") [77•, 78–80], more social cohesion in walkable areas [5, 81], and better mood during active travel [82, 83]. Although there is a significant body of literature on mental health in urban settings [76], the number of studies that assess the impact of urban form on the relationship between air pollution and mental health is small which makes it difficult to generalize findings or posit causal pathways. A small number of studies reported that diagnosed depression and anxiety are higher in high walkability areas; that correlation might be attributed to environmental stressors such as air pollution or noise [84•, 85], but more work is needed to shed light on causes. One study [86] found that high road noise exposure increased the association between air pollution and cognitive function (see further discussion in the section titled "Noise"). More refined techniques to assess mood or mental health may usefully contribute to future studies [87]. Most of these studies rely on cross-sectional or convenience samples; studies with more robust approaches and using panel data may improve the strength of evidence regarding urban form, mental health, and interactions with air quality. Improving measurement of this relationship would help researchers to assess interactions among various health outcomes as well as their association with urban form. Table 2 summarizes key articles from this section.

Urban Form, Air Pollution, and Interplay with Other Aspects of the Urban Environment

Various aspects of the urban environment, that themselves are health determinants, may modify the relationships among urban form, air pollution, and health. Here, we summarize recent findings from three such factors: green space, noise, and public spaces that promote physical activity. In general, there is a need to assess causal pathways among these factors in the urban environment.

Green Space

Proximity to green space (e.g., parks, tree cover, or open space) is an aspect of the built environment that may provide health benefits by increasing physical activity [88] or reducing exposure to air pollution [77•, 89] among other pathways [90]. Distinguishing among causal pathways remains challenging. Recent research that aims to characterize the health benefits of green space has explored the classification of greenness [91], methodologies to assess exposure to green space [92], and aspects of environmental justice [93, 94]. Studies have demonstrated an association between higher greenness and beneficial birth outcomes (e.g., a 1 IQR increase in normalized difference vegetation index (NDVI) was associated with 4 to 21 g higher birth weight among studies [95–97]), reduced rates of prostate cancer (e.g., an odds ratio of 0.82 for a 1 IQR increase in NDVI [98]), reduced mortality (e.g., a rate ratio of 0.95 for a 1 IQR increase in NDVI [99•, 100]), and enhanced cognitive function (e.g., a 1 IQR increase in NDVI was associated with a 5–6% increase in working memory [77•, 78, 101]). However, a small number of studies did not find a protective effect [102, 103]. A limited number of studies have included air quality as a covariate and noted attenuated effects for green space when accounting for exposure to ambient air pollution [77•, 99•] suggesting that some of the impact of green space on health may be attributable to lower air pollutant concentrations. For example, one study [77•] found that elemental carbon accounted for 20–65% of the association between school greenness and cognitive function. These findings suggest there are potentially important interactions between green space, air pollution, and health; utilizing green space for individual and societal benefits is a widely studied topic [80, 104, 105].

While the studies cited above suggest that green space may be overall health-promoting, in part through the reduction of air pollution, more work is needed to assess causal pathways [106]. Furthermore, work to understand how to operationalize these findings would be beneficial, e.g., what type of green space (well-designed parks vs. vacant lots; NDVI does not distinguish among design components of vegetated areas) is most health-promoting, what policies best take advantage of these findings, and the most beneficial locations within an urban area for urban green space.

Noise

Traffic noise has been observed as a health risk factor [89], and noise is correlated with land use and urban form [107, 108]. Noise and air pollution have some shared but some differences in spatial patterns [109–111]. Noise is associated with disruption of sleep patterns (e.g., living in high traffic areas increased the odds of short sleep by 24% [112]) and birth outcomes (e.g., a 6 dB(A) increase in noise decreased birth weight by 19 g [113]). Studies have assessed confounding between ambient noise and air pollution as correlated exposure variables and found that each exposure may be an independent risk factor (e.g., the study cited above on noise and birth weight did not find different effects when adjusting for air pollution [90, 113]). Another study found that road traffic noise may exacerbate the association between air pollution and cognitive function (i.e., a stronger relationship between air pollution and cognitive function was observed in areas with high traffic noise [86]). As with the other factors discussed in this section, there is a need to assess causal pathways among factors. Further reporting on noise and health can be found in this review article [114].

Physical Activity

Physical activity plays many roles in the urban environment, e.g., an outcome of urban form (via design of public spaces), an effect modifier for exposure-outcome relationships, and a determinant of air pollution and noise (via active travel). Many studies compare various aspects of the impact urban form has on air quality, physical activity, and health with the goal of estimating aggregate health outcomes. We focus on recent findings in this literature; additional information is available in a separate review article [115].

A number of studies employ health impact assessments (HIA) to explore tradeoffs between physical activity and exposure to air pollution in urban environments that support or impede participating in physical activity [116–119]. These

Table 2 Summary of key findings from select studies on urban form, air pollution, and health[a,b]

Study	Year	Location	Simulation or empirical	Spatial scale	Health or exposure measure	Pollutant	Key findings
Stone et al. [38]	2007	USA (11 cities)	Simulation	Multi-city	Emissions in census tract	CO, NO_x, $PM_{2.5}$, VOC	• 10% increase in population density associated with 3.5% reduction in vehicle travel and emissions • Densification in urban areas twice as effective as suburban zones
Mansfield et al. [36]	2015	Raleigh, USA	Simulation	Single city	Mean regional concentration; population-attributable mortality	$PM_{2.5}$	• Compact development scenario reduced (-0.2%) $PM_{2.5}$ concentrations but increased (39%) $PM_{2.5}$-attributable mortality • Concentration hotspots within cities are important for health
Macmillan et al. [42•]	2014	Auckland, New Zealand	Simulation	Single city	Air pollution: population-attributable mortality; Other: mortality from injury and physical inactivity	PM_{10}, CO, CO_2	• Assessed five policy scenarios related to active transport and health (injury, physical inactivity, air pollution, and carbon emissions) • Best practices for adding separated bicycle facilities on major roads (and speed reduction on local roads) yields health benefits 10–25 times greater than costs
Bechle et al. [49]	2011	Global (83 cities)	Empirical (cross-sectional)	Multi-city	Mean urban concentration (satellite measurement)	NO_2	• More populous cities associated with higher concentrations • 4% increase in urban contiguity could offset a 10% population increase
Bereitschaft et al. [53]	2013	USA (86 cities)	Empirical (cross-sectional)	Multi-city	Mean urban concentration (EPA monitor measurement)	NO_x, VOCs, $PM_{2.5}$, O_3, CO_2	• Tested 5 sprawl indices in regression models controlling for land area and population • 3–10% increase in $PM_{2.5}$ and O_3 concentrations per 1 standard deviation change in each sprawl index
Larkin et al. [55•]	2016	China (830 cities)	Empirical (longitudinal)	Multi-city	Mean urban concentration (satellite measurement)	NO_2, $PM_{2.5}$	• Change in lights at night (a proxy for development) associated with changes in NO_2 and $PM_{2.5}$ • Urban area expansion was strongly associated with NO_2 but not $PM_{2.5}$
Hankey et al. [22]	2016	Minneapolis, USA	Empirical (cross-sectional)	Single city	Particulate concentration; rates of walking and cycling	UFPs, BC, $PM_{2.5}$	• Most active travel (20–42%) is spatially co-located with high concentrations • About 20% of local roads could be utilized to shift active travel away from high traffic corridors (reducing exposure by 15%)
James et al. [56]	2015	USA (nationwide cohort)	Empirical (cross-sectional)	Multi-city	$PM_{2.5}$; walkability	$PM_{2.5}$	• Highest tertile of walkability associated with a 1.6 $\mu g/m^3$ increase in $PM_{2.5}$ • The pollution-walkability relationship varied by region
Hatzopoulou et al. [71]	2013	Montreal, Canada	Empirical (cross-sectional)	Single city	Roadway concentration	UFP, BC, $PM_{2.5}$, CO	• Cycling on off-street trails was associated with lower concentrations of BC (-12%), UFPs (-1.3%), and CO (-5.6%) • No significant change in exposure for on-street bike lanes

[a] This table includes select recent studies that illustrate work on various dimensions of urban form, air pollution, and health. Additional studies are discussed in the text.

[b] *UFP* Ultrafine Particles, *BC* Black Carbon, *VOC* Volatile Organic Compound

studies found that health benefits from shifting to more active modes of travel or lifestyles outweigh the risk of increased air pollution exposure (through an activity-related increased minute ventilation) and accidents. For example, one study [116] found that (in terms of life-years) the lifetime benefits of increased physical activity were much larger (on average, 3–14 months gained) than the cost from air pollution dose (0.8–40 days lost) or traffic accidents (5–9 days lost). HIA has also been used at the population level to assess tipping points between risk factors (i.e., physical inactivity vs. exposure to air pollution) [120], population-level exposure to air quality under different urban form or travel scenarios [121], and travel reduction strategies [122]. These studies generally find that strategies to encourage active travel can have significant benefits to the entire population via reduced ambient concentrations [121] and benefits to the individual via increased physical activity. However, similar to the simulation and modeling studies of regional air quality discussed in previous sections, HIA studies are generally based on hypothetical shifts in behavior associated with changes in urban form and have mostly focused on changes in transportation emissions. Furthermore, they are dependent on a specific set of assumptions about changes in travel behavior (i.e., shifts to more active modes) that may not be supported by urban infrastructure in some parts of the world [46, 120, 123].

Multiple studies have used retrospective data and found spatial correlation among levels of physical inactivity and ambient air quality [124, 125] or obesity and proximity to traffic [126]. Re-analysis of cohort studies in Denmark and China (originally used for air pollution health effects studies) have reinforced the finding that physical activity benefits outweigh risks of air pollution exposure [127, 128•, 129]; although for some pollutants and activities that effect may be attenuated (e.g., in the Danish cohort, interaction terms were significant for respiratory disease from NO_2 while gardening or cycling [128•]). One cohort study of children in California, USA, found that strenuous exercise in communities with high O_3 concentrations was a predictor of being diagnosed with asthma (relative risk of 3.3 for children playing three or more sports vs. no sports) [130]. Questions remain about how shifts in urban form may impact overall exposure and aggregate population-level health benefits [56, 60]. Most of the cohort studies were not designed to assess tradeoffs between physical activity and air pollution exposure; future studies could focus on this question during study design.

To address limitations of the existing HIA and cohort studies, researchers have performed controlled experiments to assess health indicators when exercising in clean vs. polluted environments. Multiple studies have used cycling as the mode of exercise in these experiments and measured changes in brain plasticity [131], heart rate variability [132], blood pressure [133, 134], and respiratory and inflammatory responses [135–138]. In general, findings are mixed from these studies. While some studies observed differences in health indicators between clean and polluted environments (three studies; $n = 38–42$ participants per study), other studies found minimal or no effect (four studies; $n = 12–28$ participants per study); significant effects were reported for brain plasticity (i.e., brain-derived neurotrophic factor (BDNF) increased [14.4%; $p = 0.02$] when cycling in an air-filtered room but did not increase [0.5%; $p = 0.42$] when on a busy road [131]), heart rate variability (i.e., elevated concentrations of O_3, ultrafines, and black carbon along high traffic routes were associated with changes in heart rate variability [132]), and inflammation (i.e., percentage of blood neutrophils increased more after exercise near a road [3.9%; $p = 0.003$] vs. in a clean room [0.2%; $p = 0.83$] [136]). Although these controlled experiments are often not directly related to differences in urban form, they inform how changes in transportation mode (potentially induced by changes in urban form) may impact individual exposure and health responses. Table 3 summarizes key findings from select studies on the three aspects of the urban environment discussed in this section.

Summary and Conclusions

Simulation and empirical articles report that compact growth has the potential to improve regional air quality. However, the magnitude of impact varied among studies. Land use strategies will likely need to be coupled with emission reduction strategies including promotion of active transportation (i.e., vehicles, fuels, vehicle miles traveled) to realize exposure reductions across the entire population. To date, most empirical studies use city-level measures of compact growth owing to lack of availability of detailed land use data across jurisdictions; among the studies, lower urban sprawl indices, higher levels of transit service, and higher population centrality were most commonly associated with improved air quality. Assembling detailed neighborhood-level variables (e.g., land use mix, street connectivity, land use classification) at the continental scale would allow for analyses of both between- and within-city effects of urban form. Additionally, moving from cross-sectional analyses to longitudinal empirical studies might help uncover land use policies with the most potential for success in reducing concentrations. Most of the simulation studies focus on connections between land use and transportation, with a particular focus on vehicular travel; few studies explore impacts of urban form on other emission sources. Modeling of future conditions depends on assumptions about, e.g., elasticities between transport and land use as well as projections of future vehicle efficiency and fuels.

We reviewed additional aspects of the urban environment that may modify the relationships among urban form, air pollution, and health (i.e., green space, noise, and public spaces that promote physical activity). Among these factors, tradeoffs

Table 3 Summary of key findings from select studies on three aspects of the urban environment (green space, noise, physical activity) that may modify the relationships among urban form, air pollution, and health[a,b]

Study	Year	Location	Additional aspect of urban environment	Spatial scale	Health or exposure measure	Pollutant	Key findings
Dadvand et al. [77•]	2015	Barcelona, Spain	Green space	Single city	Cognitive function (working memory)	Elemental Carbon	• IQR increase in NDVI associated with 5–6% increase in working memory • 20–65% of effect was explained by elemental carbon concentration
Hystad et al. [95]	2014	Vancouver, Canada	Green space	Single city	Birth weight; preterm birth	NO, NO_2, $PM_{2.5}$, BC	• IQR increase in NDVI associated with higher term birth weight (20.6 g) • Findings robust to models adjusted for air pollution and noise
Tzivian et al. [86]	2017	Germany (3 cities)	Noise	Multi-city	Cognitive function (5 neuropsychological subtests)	PM_{10}, $PM_{2.5}$, NO_x, NO_2	• Increase in $PM_{2.5}$ associated with decrease in cognitive function in areas with high road noise • Air pollution and road noise may act synergistically on cognitive function in adults
Gehring et al. [113]	2014	Vancouver, Canada	Noise	Single city	Birth weight; preterm birth	NO, NO_2, $PM_{2.5}$, PM_{10}, BC, CO, SO_2	• Noise negatively associated with birth weight (-19 g per 6 dB(A)) • Associations between noise and birth weight largely unchanged in joint air pollution-noise models
de Hartog et al. [116]	2010	Netherlands (entire country)	Physical activity	Multi-city	Life-years gained or lost	$PM_{2.5}$, Black Smoke	• Benefits of increased physical activity were much larger (3–14 months gained) than the cost from air pollution dose (0.8–40 days lost) or traffic accidents (5–9 days lost) • Study limited by assumptions about human behavior
Andersen et al. [128•]	2015	Aarhus and Copenhagen, Denmark	Physical activity	Multi-city	Mortality	NO_2	• For most causes of mortality, exposure to NO_2 did not modify health benefits from physical activity • For respiratory mortality associated with cycling and gardening, benefits from physical activity may be attenuated by air pollution
Bos et al. [131]	2011	Antwerp, Belgium	Physical activity	Single city	Brain plasticity (Serum BDNF)	UFP, $PM_{2.5}$, PM_{10}	• BDNF increased (14.4%; $p = 0.02$) when cycling in an air filtered room; no increase (0.5%; $p = 0.42$) on a busy road • Benefits to brain plasticity from physical activity could be attenuated by exposure to air pollution
Jacobs et al. [136]	2010	Antwerp, Belgium	Physical activity	Single city	Exhaled NO; blood cell counts; platelet function	UFP, $PM_{2.5}$, PM_{10}	• Percentage of blood neutrophils increased more after exercise during a road test (3.9%; $p < 0.01$) than in a clean room (0.2%; $p = 0.83$) • Cycling in a polluted environment was associated with a small increase in inflammatory blood cells

[a] This table includes select recent studies that illustrate work on various dimensions of the urban environment, air pollution, and health. Additional studies are discussed in the text.

[b] *UFP* Ultrafine Particles, *BC* Black Carbon, *BDNF* Brain-Derived Neurotrophic Factor

between physical activity and exposure to air pollution was the most widely studied topic. Health impact assessments generally find that benefits from increased physical activity outweigh risks from air pollution exposure. These studies are estimates, not observations; in addition, they rely on specific assumptions, e.g., significant changes in behavior. Cohort studies generally reinforce this finding but also show that health benefits from physical activity may be attenuated by exposure to air pollution in certain cases. Green space may be an effective health-promoting aspect of the built environment. Multiple studies report beneficial birth outcomes and cognitive function associated with greenness; however, more work is needed to evaluate causal pathways (e.g., increased physical activity vs. reduced exposure to air pollution). Since green space has the potential to be health-promoting in multiple dimensions (e.g., increasing physical activity, decreasing exposure to air pollution, and improving mental health), it may be a particularly attractive strategy to design health-promoting public space in the urban environment. Traffic noise is associated with disruption of sleep and low birthweight; studies have assessed confounding among noise, air pollution, and health and suggest noise may be an additional risk factor in urban environments. More work is needed to identify causal pathways among these factors and how they interact with relationships among urban form, air pollution, and health. In general, there is an important need for work that focuses on specific policy objectives and interventions that would help planners and policy makers to operationalize findings from the literature.

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Compliance with Ethical Standards

Conflict of Interest Steve Hankey and Julian D. Marshall declare that they have no conflict of interest.

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