An ecosystem service perspective on urban nature, physical activity, and health

Roy P. Remme[a,b,1], Howard Frumkin[c], Anne D. Guerry[a,d], Abby C. King[e,f], Lisa Mandle[a], Chethan Sarabu[g], Gregory N. Bratman[d], Billie Giles-Corti[h], Perrine Hamel[a,i], Baolong Han[j], Jennifer L. Hicks[k], Peter James[l,m], Joshua J. Lawler[d], Therese Lindahl[n,o], Hongxiao Liu[p], Yi Lu[q], Bram Oosterbroek[r], Bibek Paudel[s], James F. Sallis[t,u], Jasper Schipperijn[v], Rok Sosič[w], Sjerp de Vries[x], Benedict W. Wheeler[y], Spencer A. Wood[d], Tong Wu[j], and Gretchen C. Daily[a,z]

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Nature underpins human well-being in critical ways, especially in health. Nature provides pollination of nutritious crops, purification of drinking water, protection from floods, and climate security, among other well-studied health benefits. A crucial, yet challenging, research frontier is clarifying how nature promotes physical activity for its many mental and physical health benefits, particularly in densely populated cities with scarce and dwindling access to nature. Here we frame this frontier by conceptually developing a spatial decision-support tool that shows where, how, and for whom urban nature promotes physical activity, to inform urban greening efforts and broader health assessments. We synthesize what is known, present a model framework, and detail the model steps and data needs that can yield generalizable spatial models and an effective tool for assessing the urban nature–physical activity relationship. Current knowledge supports an initial model that can distinguish broad trends and enrich urban planning, spatial policy, and public health decisions. New, iterative research and application will reveal the importance of different types of urban nature, the different subpopulations who will benefit from it, and nature's potential contribution to creating more equitable, green, livable cities with active inhabitants.

decision-support tools | equity in access | green space | public health | urban sustainability

The use of public space for outdoor physical activity (PA) is recognized to be essential, especially in cities, as highlighted by responses to the COVID-19 pandemic (1). While issuing stay-at-home orders, many governments allowed residents to go outside for exercise to promote health and well-being. Yet,

[a]Natural Capital Project, Stanford University, Stanford, CA 94305; [b]Institute of Environmental Sciences, Leiden University, 2333 CC Leiden, The Netherlands; [c]Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, WA 98195; [d]School of Environmental and Forest Sciences, University of Washington, Seattle, WA 98195; [e]Department of Epidemiology & Population Health, Stanford University School of Medicine, Stanford, CA 94305; [f]Stanford Prevention Research Center, Department of Medicine, Stanford University School of Medicine, Stanford, CA 94305; [g]Department of Pediatrics, Stanford University School of Medicine, Stanford, CA 94305; [h]Healthy Liveable Cities Group, Centre for Urban Research, Royal Melbourne Institute of Technology University, 3000 Melbourne, Australia; [i]Asian School of the Environment, Nanyang Technological University, 639798 Singapore; [j]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 100875 Beijing, China; [k]Department of Bioengineering, Stanford University, Stanford, CA 94305; [l]Department of Population Medicine, Harvard Medical School and Harvard Pilgrim Health Care Institute, Boston, MA 02215; [m]Department of Environmental Health, Harvard T. H. Chan School of Public Health, Boston, MA 02215; [n]Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, 104 05 Stockholm, Sweden; [o]Stockholm Resilience Centre, Stockholm University, 106 91 Stockholm, Sweden; [p]Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, 510650 Guangzhou, China; [q]Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong; [r]Maastricht Sustainability Institute, Maastricht University, 6200 MD Maastricht, The Netherlands; [s]Sean N. Parker Center for Allergy & Asthma Research, Stanford University School of Medicine, Stanford, CA 94305; [t]Herbert Wertheim School of Public Health and Human Longevity Science, University of California San Diego, La Jolla, CA 92093-0631; [u]Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, VIC 3000, Australia; [v]Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, DK-5230 Odense M, Denmark; [w]Department of Computer Science, Stanford University, Stanford, CA 94305; [x]Cultural Geography/Wageningen Environmental Research, Wageningen University & Research, 6700 AA Wageningen, The Netherlands; [y]European Centre for Environment & Human Health, University of Exeter Medical School, Knowledge Spa, Royal Cornwall Hospital, TR1 3HD Truro, United Kingdom; and [z]Department of Biological Sciences, Woods Institute for the Environment, Stanford University, Stanford, CA 94305

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[1]To whom correspondence may be addressed. Email: r.p.remme@cml.leidenuniv.nl.

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many millions of people live in urban neighborhoods lacking sufficient accessible space that is safe and conducive to exercise for all its residents.

Insufficient PA is a leading risk factor for morbidity and premature mortality globally. Physical inactivity is responsible for at least 6% of global premature mortality, with 1.4 billion adults at risk for developing or exacerbating inactivity-related diseases (2, 3). Conversely, regular PA reduces risks of more than 20 chronic health conditions, ranging from diabetes, hypertension, and cardiovascular diseases to many types of cancer (4, 5). As motorized and technology-centric urban lifestyles contribute significantly to decreased activity (4), there is an urgent need to identify a broader set of available approaches to stimulate PA and to inform policies meant to promote it by enhancing access to and programming in (e.g., events or tours) urban nature (6–9).

Nature positively affects human health through several pathways, of which providing opportunities for PA is a widely recognized one (6, 10). Recent research demonstrates that urban nature can provide increased opportunities for PA, with both the quantity and quality of natural elements playing a role (11–14) (Box 1). For example, people may be more likely to jog recreationally if there are nearby trails in attractive parks (15), and more likely to cycle to work if the routes are treed (16). Similar findings hold over a wide range of geographies and urban contexts (11), age groups (17, 18), and PA levels and types (19, 20) (Box 1). Although PA is associated with the built environment [e.g., walkability, traffic speed and density, and availability of recreational facilities (21–23)], there is also a vigorous research frontier focused on quantifying the benefits of nature-based approaches to enhancing PA in cities (24, 25). Urban nature can contribute to healthier, more equitable, and more sustainable cities in many ways (24, 26, 27), with the provision of opportunities for PA as one pathway.

New research is needed to inform where, how, and how much to invest in improving urban nature to enhance not only PA, but also the multitude of other benefits provided by urban nature (28). These include urban cooling, flood control, air quality, water quality, protecting and enhancing biodiversity, and livability through aesthetics and recreational opportunities (24, 26), many of which contribute to public health.

It is important to note that urban nature does not provide unalloyed good. Economic, psycho-social, and physical risks can be associated with urban green spaces. For example, "green gentrification" that may follow provision of amenities, such as parks and trails, can increase property values and lead to the displacement of established low-income communities (29, 30). Here the harm comes not from nature access or contact itself, but from systemic policies and practices that fail to protect the vulnerable. Controlling gentrification requires carefully executed social and economic policies, such as community land trusts, rent control, and ample housing construction (31, 32). Similarly, physical violence or perceived threat of violence (e.g., driven by prejudice and discrimination from fellow humans) in urban nature can make people feel or be unsafe or unwelcome, and therefore eclipse other potential benefits of time in nature (33, 34). As with green gentrification, these harms come not from nature contact itself, but from personal factors (e.g., gender, age, or past experiences) and the interaction of societal dynamics and hierarchies, low-occupancy, and other factors. Finally, urban nature brings physical risks—and fears of risks—such as allergic reactions, vector- and water-borne diseases, excessive sunlight exposure, and injuries. These natural physical risks are generally far smaller in magnitude than the benefits of nature contact, and can be effectively mitigated with appropriate precautions (35, 36). In this report, we focus primarily on positive impacts of greenspace, reflecting on the potential harms as moderators of the urban nature–PA relationship.

Interest in leveraging nature for positive health outcomes is growing, particularly for preventive measures, including solutions, such as prescriptions for spending time in parks, because of rising costs of chronic disease (37, 38). Yet, to what extent planners take increased PA or health outcomes into account as one of the many cobenefits when making decisions regarding urban nature remains unclear (39). The diffuseness of knowledge connecting urban nature to improved health through increases in PA, and its limited accessibility, hinders its use in decision making.

We aim to integrate the science relating nature in and around cities, PA, and health with an ecosystem services approach to inform policy-making, planning, and management through the lens of multifunctionality of urban nature (40, 41). We focus specifically on PA as a pathway between nature and health, as this has received little attention in ecosystem service literature. While the connection between nature, PA, and health also holds outside urban contexts, we focus specifically on cities because of their relatively high population densities and low access to nature compared to rural settings. An ecosystem service approach describes how nature contributes to human well-being (42). While review studies have framed the nature–PA–health connection within a general ecosystem service context, none have thoroughly conceptualized the relationship in a stepwise ecosystem service approach (10, 25, 43). Such an approach facilitates its integration into broader assessments of nature's benefits.

We use the following general ecosystem service framework to describe the flow of services from nature to society in roughly four components: the ecosystem (ecological conditions and processes creating potential services), ecosystem service supply (the processes and interactions through which nature and people realize benefits), the benefit (the change in human well-being accrued from making use of the service), and value (the importance that individuals or groups attach to the benefit) (42, 44). In this framing (Fig. 1), nature in the urban system represents the ecosystem. The ecosystem service supply is the exposure to urban nature for PA, which requires contributions by nature (an attractive or conducive environment) and people (accessing urban nature and choosing to use it for PA) (45). Improved PA (in both quantity and quality) constitutes the benefit, subsequently leading to the benefit of improved health, which also can be valued in both nonmonetary and monetary terms.

Ecosystem service assessments often use spatial modeling approaches to show the impacts of past or future changes in ecosystems on human well-being (46, 47). Such models reveal how changes in ecosystems can influence flows and values of services to beneficiaries across a landscape (46, 48). Understanding the impacts on different beneficiaries is key, also in relation to understanding inequity, exclusion, and systemic racism (49). The results of such assessments can be presented in actionable ways for key end-users, including governments, the healthcare sector, and urban planners. In addition, when relating nature and health, such spatial analyses can inform broader health assessment frameworks, such as health impact assessments (50), on changes in PA and health benefits from urban greening.

While spatial models have been available for multiple ecosystem services for many years, and have been applied for several nature–health connections (e.g., water-quality regulation or urban heat mitigation), only a few examples exist that directly relate

Box 1. Definitions.

"Urban nature" refers to outdoor spaces that retain noticeable elements of nature to which residents can be exposed, in and around the city (104).

"Elements of urban nature" range from street trees to urban parks and from riverbanks, beaches, and lakeshores to peri-urban forests, arrayed with varying size, type, composition, and configuration (97).

"Nature exposure" refers to the amount of contact that an individual or population has with nature (97).

"Access to urban nature" is defined as the opportunity people have, or perceive to have, to be exposed to urban nature. Access is a function of distance and physical barriers (93), but also of capabilities and socioeconomic factors (104), including but not limited to discrimination, legal rights, mobility, safety, financial costs, opportunity costs, and availability of amenities (15, 25).

"The choice to use" urban nature for PA is a component of exposure that turns the opportunity (i.e., a person's access) into the supply of the ecosystem service (i.e., human–nature interaction leading to a human benefit): exposure to urban nature for PA. The choice to use urban nature for PA is a function of personal characteristics, as well as social, economic, and environmental factors.

"Physical activity" is bodily movement that is initiated by skeletal muscles and results in energy expenditure. It encompasses a wide range of characteristics, from light intensity (e.g., leisurely walking, fishing) to medium and vigorous intensity PA (e.g., brisk walking, jogging, cycling, sports), and from recreational to utilitarian (e.g., active commuting) (4) domains or purposes.

"Health" is "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity" (105).

"Mediators" address pathways through which X affects Y (106). For example, nature exposure is a mediator of the relationship between urban nature and PA, and PA is a mediator of the relationship between urban nature and health.

"Moderators" specify factors that may alter the association between X and Y (106). They can be socioeconomic, demographic, environmental, or behavioral factors that determine the strength of the effect of urban nature on, for example, PA.

"Control variables" to adjust analyses for possible confounding are generally applied in studies on the relationship between urban nature, PA, and health. Studies commonly use the following area-level and individual-level control variables to adjust their models: socio-demographic variables (age, gender, education, income, ethnicity, race, marital status, employment status, and family size) and personal characteristics (e.g., dog ownership, smoking, alcohol consumption) (57). In this report, control variables are not listed for individual examples unless relevant.

urban nature to PA, and PA modeling studies rarely take into account other urban ecosystem services (51, 52). Existing reviews provide excellent overviews of the state of knowledge (6, 8, 10, 15, 53), but do not address the implications of the findings for guiding urban planning decisions and tools that support such processes.

We develop a broadly applicable model framework to support decision-making, both to contribute to the assessment of multifunctionality of urban nature and to feed spatially explicit nature-related health outcomes into broader health assessment frameworks. The framework treats PA benefits derived from urban nature as an ecosystem service. We ground our analysis in the literature linking nature exposure and PA, illuminate pathways between nature and health (Fig. 1) (6, 8, 10, 53), and synthesize key findings that guide model development. This culminates in a model framework for urban nature, PA, and health to support a diverse set of decision-making contexts in cities around the world.

The Current State of Knowledge

We build on evidence, now extensively reviewed, that characterizes and assesses associations among nature, PA, and health. This section covers key points distilled from this evidence base that directly impact the development of a model framework, which are the outcome of an expert workshop.

1. PA has Positive Impacts on Health. There is strong and growing scientific evidence that PA contributes to good health through prevention of many chronic diseases and conditions, such as cardio-metabolic diseases, cancers, osteoarthritis, bone health, and mental health (4, 5) (no. 1 in Fig. 1). The positive health effect of PA has been shown across many PA intensities and types (4). In the remainder of the report, we focus less on health outcomes in the overall relationship between urban nature, PA, and health under the well-grounded conclusion that urban nature will positively contribute to improved public health if it stimulates increased PA.

2. Exposure to Nature is often Associated with PA. Since the mid-2000s, multiple systematic reviews have addressed nature and PA, regarding both the association between nature and the amount of PA, and the level of benefit delivered per unit of PA (15, 20, 54) (no. 2 in Fig. 1). Calls for metaanalyses (8, 53) have been answered to date with limited-scope metaanalyses (e.g., focusing on children or older adults), which thus far have had limited success in quantifying associations (18, 55). In general, reviews of this literature indicate a positive, yet weak, association between nature and PA, with no evidence for causality (8, 14). This is likely due to heterogeneity in assessing both nature and PA variables, along with nature being but one component of the urban system that affects PA practices (Fig. 1). Further clarity on the relationship between nature and PA can be gained by identifying critical factors in terms of the components of this relationship (see next four subsections) and data and research methodologies (points 3 and 4). Such information will improve understanding of these relationships and allow for better deployment of the ecosystem services approach in the creation of actionable information and tools

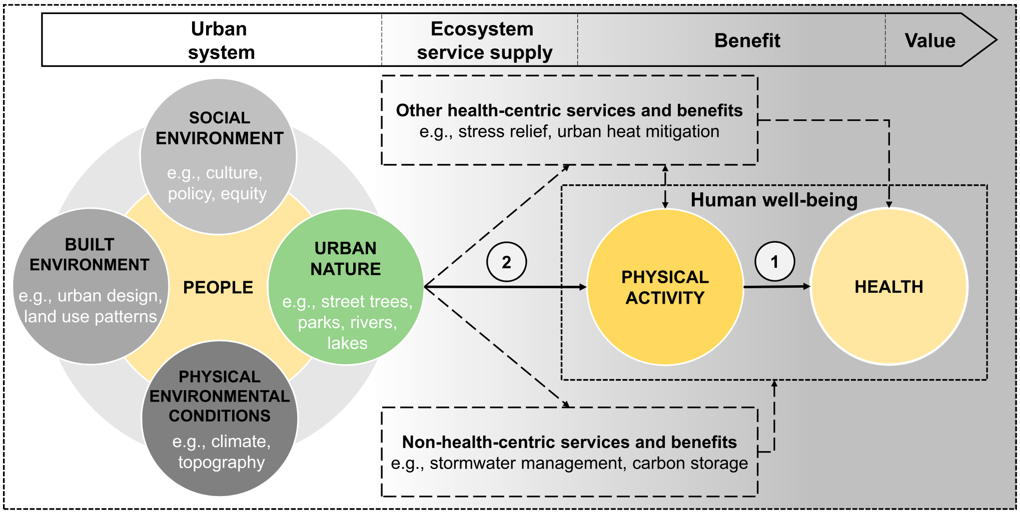

Fig. 1. Conceptual model of the relationships among urban nature (as part of the urban system), PA (quantity and quality), and health, aligned with an ecosystem service approach. Numbers correspond with *The Current State of Knowledge* points 1 and 2.

for decision-makers interested in using urban nature to improve health.

2a. The strength of the association between nature and increased PA may vary across different intensities and types of PA. Urban nature affects different PA intensities (i.e., light versus moderate-to-vigorous PA) differently within people's neighborhoods, as exemplified for The Netherlands (56). However, the majority of studies have not distinguished between intensities and address a single PA outcome, such as total PA or walking (56). This approach hinders understanding of how and when urban nature contributes to different intensities. In addition to different intensities, different PA domains, such as recreational (e.g., various sports) and utilitarian activities (e.g., active transport), are associated with urban nature in different ways (10, 18).

2b. Different elements of nature are likely to differ in the strength of their associations with PA and domains and intensity of PA. Elements of nature may promote PA in a specific setting, and do so more strongly than other elements, but this relationship may be context-dependent. Evidence on how specific urban nature types interact with PA is still limited, with the largest body of literature focusing on aggregate indicators for urban nature (e.g., green space or greenness) that combine all vegetation types, using satellite-derived vegetation indices, land-cover maps, or street-level greenness (57, 58). Urban parks, aggregating elements of nature and the built environment, have also been studied widely (15, 54), yet there is still a need to further understand the importance of different park features, characteristics, and qualities (59, 60). The same is true for other urban nature settings, with a call to assess which elements of nature and combination of elements, as well as their quality [i.e., attributes that encourage or discourage visitation and use (61)], contribute to PA in different contexts (62).

2c. The strength of the association between nature and increased PA varies by population characteristics and social pressures. Some studies find that age, gender, ethnicity, and race moderate the relationship between contact with urban nature and PA, especially in parks (15, 63). However, there are few studies analyzing how relationships may differ across population groups (10, 64). Such comparisons are specifically relevant to understand differences that may be connected to social inequity, systemic racism, and exclusion (65, 66). More research has been done for specific subgroups, including children and adolescents (17, 55), adults (67, 68), older people (18, 69), women (70, 71), and disadvantaged populations (72). For many of these groups, the referenced reviews show some evidence of a positive association between urban nature types and PA.

2d. PA in nature may provide additional health benefits, compared with PA indoors and in the built environment. Multiple studies have found that PA in nature may be better for mental health and improved affect as well as lead to higher enjoyment than PA indoors or in built environments (73–75). Relatedly, PA in nature may be positively associated with attention restoration and stress reduction, as found in studies in the United Kingdom and Iceland (76, 77). In addition, there is evidence that people are physically active for longer time periods and at higher intensities during outdoor activities, compared to indoor activities (75). However, the current evidence base is limited and inconclusive with respect to potential additional benefits associated with this "green exercise" (75).

3. Methodological Constraints, Including Research Design, Confounding, Measurement Error, and Bias, Limit Current Understanding. The vast majority of studies linking urban nature to PA stem from the fields of epidemiology and public health and have applied cross-sectional designs, limiting the possibility of addressing causality (8, 53). There is a strong call for more studies with rigorous longitudinal, experimental, and quasiexperimental designs to better understand and ultimately generalize the association (8, 15). There is also a strong call for consistency in measuring the association between urban nature and PA. Many empirical studies control for confounding variables at individual and area levels (Box 1) (57, 71), although which variables are included can vary widely (78). Cross-sectional studies sometimes rely on a simple means comparison instead of adjusting for confounders (8). A recent review on PA and urban parks calls for more consideration of confounding factors in empirical studies (15). At the same time, researchers should primarily focus on improving the measurement of the primary variables (i.e., urban nature and PA levels) and the main confounders, as these have the most impact on results, rather than aiming to exhaustively capture confounders (53). As is common, there is likely a bias in the literature toward publishing positive associations (8, 54).

4. Novel Data Sources Expand Opportunities to Study, Model, and Predict the Relationships among Nature, PA, and Health Outcomes. Vast datasets are being used to analyze multiple aspects of the urban nature–PA relationship and a growing diversity of data sources are being creatively applied to assess related cultural ecosystem services such as recreation, landscape aesthetics, and spiritual experiences (79). On the ecological side, recent studies have leveraged novel data about urban nature, such as street-view imagery to assess how people experience greenness of their environment at eye level, and results have shown greenness is associated with PA (58, 80). Using data from activity-tracking applications on smartphones, a global study recently quantified inequality in PA at the country level; these data could be used to examine how access to nature is related to objectively measured PA at a large scale (81). Social media provide another rich source of information (82); geolocated Tweets, for example, have helped assess park use in United States cities (83, 84) and, in Birmingham (United Kingdom), to understand seasonal differences in PA (85). As tools and techniques for analyzing large and novel datasets improve, so will our understanding. Yet despite their potential, numerous practical and ethical challenges remain when deploying the technologies and approaches necessary to extract meaning from large datasets (86), ranging from user biases, to limited spatial coverage, or high costs of datasets.

Modeling PA as an Ecosystem Service

Current knowledge about nature's role in PA and human health underpins our model framework. To align with other ecosystem service models, we trace a pathway from the ecosystem to human well-being in order to predict how changes in nature will facilitate PA and health (Fig. 1). We further operationalize the pathway (the ecosystem service) between the ecosystem (urban nature) and PA (the benefit) using a more detailed conceptual model (Fig. 2). We illustrate the steps in this model for different urban nature types in *SI Appendix*, Fig. S1.

We suggest four model-building steps to translate the conceptual model into an actionable model that enables scenario analysis to inform policy processes. Step 1 is to identify "elements of urban nature." Step 2 is to characterize "exposure" to nature as a mediator that facilitates PA. Step 3 is to quantify the effects of nature exposure on PA in the vein of a "dose–response relationship." Step 4 is to quantify health benefits resulting from PA in urban nature. We aim, at this stage of knowledge, to address population-level effects and, eventually, with increasing knowledge, to increase specificity to the level of subgroups (e.g., gender and age categories) and at-risk subpopulations (e.g., people with obesity or cardiovascular disease). From a spatial perspective, the combination of high-resolution urban nature data and different levels of population data should enable subcity-level analyses (e.g., neighborhood or project level). A full-fledged model would enable the assessment of impacts on PA of changes in urban nature from a specific project for different demographic groups. Below, we describe the steps of our model framework and required data in more detail.

We illustrate the model framework's steps, its use for scenario analysis, and applications at the population level and subgroup level with a hypothetical case for Amsterdam, The Netherlands (Fig. 3). Amsterdam is implementing a new green infrastructure plan, with one key strategy being to improve existing parks and develop additional parks (87). We adopt this strategy as the planning scenario and compare it to the current situation to illustrate how the model framework can be used to analyze the impact on PA and health of the population.

Step 1: Characterizing Urban Nature. This first step characterizes the elements of nature within cities that potentially influence PA. It includes their location (e.g., relative to the location of a population that can engage in PA), size (total area), spatial configuration (e.g., level of fragmentation and connectivity between urban nature elements), composition (proportions of different types of nature elements, and species within them), and quality (how well maintained, attractive). This step connects elements of nature to the aspects of the built environment that are most important for PA, such as connected street networks, availability of sidewalks, the mix of land uses, available amenities (e.g., playgrounds, benches, or restrooms), and recreational facilities (7, 89). For this step, spatial data are needed for both the elements of nature and of the built environment. This step enables quantitative comparisons between scenarios if spatially explicit data on urban nature of both the current situation and potential futures are available (Fig. 3).

Three general data types have been used to quantify urban nature: land use/land cover, vegetation indices (e.g., normalized vegetation difference index), and to a lesser extent, street-view imagery for eye-level greenness. Although these aspects often produce different estimates of urban nature, and quality and coverage vary between places (53, 57), each method has merits and could yield a core dataset for a model. Different data types can be combined to provide a more detailed characterization and quantification of urban nature. This is the case in our illustration of Amsterdam, where land-cover data are combined with high-resolution vegetation cover data from aerial photographs to create detailed urban vegetation maps (87) (Fig. 3). Increasingly, cities and crowd-sourced platforms, such as Open Street Map, are maintaining highly accurate, detailed georeferenced databases on urban nature (e.g., street trees, parks, trails) (90).

Step 2: Determining Exposure to Urban Nature. The presence of urban nature does not imply that people become physically active; people need to have contact with and exposure to it (91). In step 2, we establish the pathway between urban nature and PA, determined by both an overarching mediator (i.e., exposure) and multiple moderators, as indicated by arrow 2 in Fig. 1 and expanded in Fig. 2, both for the baseline situation and changes in exposure under different scenarios. Nature exposure mediates the association between urban nature and PA and is determined by two factors: a broad definition of "access" and the "choice to use" nature for PA (Fig. 2 and Box 1). Studies show that access to urban nature influences whether people choose to use it, thereby influencing PA among adults (51, 92).

Key moderators differ by urban nature type, as do levels of accessibility, use, and the PA domains (*SI Appendix*, Fig. S1). For example, green streetscapes are generally accessible and are both utilitarian and recreational in their use-profile (i.e., used for active transport and leisure walks), while peri-urban nature has much higher access barriers (e.g., transport, costs, time), and is predominantly used for recreation and not for active transport by city dwellers. In many, often low-middle income, countries, peri-urban areas consist largely of nonaccessible lands (e.g., farmland or industrial sites) that limit access by urban populations.

To model exposure, data on both access and equity of access to nature are needed. Moderators that define equity of access

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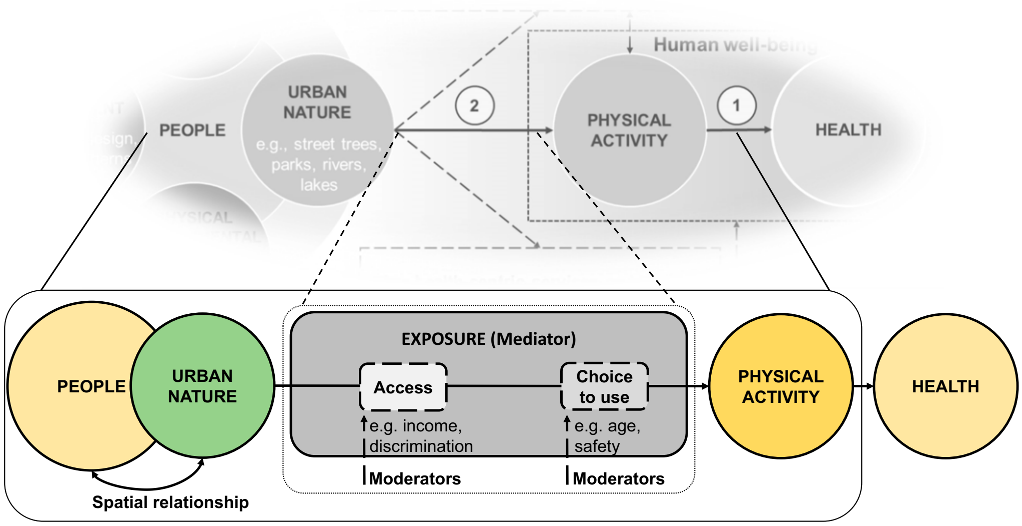

Fig. 2. Detailed conceptual model of relationship between urban nature and PA where exposure to nature and the two factors determining it (access and choice to use) mediate the role of urban nature in stimulating PA, modified by external moderators.

can include physical distance to or availability of nature (93), ownership (public/private), and sociodemographic variables, such as age, socioeconomic status, cultural identity and associated practices, and gender (26). They should also include crucial aspects, such as safety, discrimination, and inclusivity for all users. Data for such moderators could include census block data or, for example, historical redlining boundaries that relate to racist mortgage practices and that perpetuate inequity in modern-day cities, especially in North America (94). Including such data makes it possible to target specific population groups, which is important for steps 3 and 4 of the model framework. For many developed countries, statistical data on most of these moderators are available at neighborhood (e.g., census tract) level. In Amsterdam, for example, data on a wide variety of population characteristics are available at a neighborhood level (Fig. 3).

Addressing choices for the use of nature for PA requires understanding what drives choices for different types of users or user groups. Data on choice patterns around use are less readily available but could be collected systematically through observational studies or surveys.

Step 3: Quantifying PA. The third step is to quantify the PA related to this exposure. In this model framework, PA is the response variable that changes if the dose of urban nature and exposure to nature changes, for example after an intervention (9). We note that PA in nature may make up a small proportion of an individual's total PA, but could be highly important for PA and health at the population scale, if improvements in urban nature target groups with poor access to nature, high risk for chronic diseases, or low PA.

The model framework allows for assessing changes in PA with multiple metrics, relevant in different decision contexts. An applied model would ideally quantify both light and moderate-to-vigorous PA. These two intensity levels have different impacts on health at the population scale. Thus, in addition to increases in total PA at the population scale, the number of inactive people who are stimulated to engage in even a light form of PA is a key output of a nature–PA model. This is especially important, given the expanding evidence base supporting its health-enhancing and quality-of-life effects, particularly among inactive and older populations (4).

The model framework allows for differentiation between recreational and utilitarian PA. While changes in recreational PA may be more easily targeted by modifications to urban nature (e.g., developing a new urban park that includes a bike trail), changes in utilitarian PA may lead to larger gains at the population level, as active commuting to work or school may be routine and frequent. A model should provide outputs in quantitative metrics, such as additional PA in minutes per week, additional steps taken, or additional metabolic equivalent task hours [a measure of the intensity and duration PA (4)]. Data for different metrics can be distilled from current literature or potentially from crowd-sourced datasets related to activity tracking apps.

In Fig. 3 we show that analyses could be done at population level, using data from the literature (e.g., ref. 11), or using targeted empirical information on group responses (e.g., how different age groups' amount of PA changes with additional neighborhood parks). This step produces the first important outputs (e.g., maps and indicators), indicating differences in PA levels between the initial situation and applied scenarios.

Step 4: Quantifying Health Benefits. The final step is the quantification of health benefits. For some health risks, such as type 2 diabetes and cardiovascular events, dose–response curves have been developed between PA and the disease risk (4), which can be integrated into this step of the model framework, as exemplified in Fig. 3. In the Amsterdam case, we relate the risk of all-cause mortality to the amount of PA at the population level obtained from step 3, and the relative risk of mortality from cardiovascular disease based on a group's weekly activity levels and average daily hours of sedentary behavior (4). This step results in an additional set of outputs for both the initial situation and the scenarios. Ideally, a broader range of health aspects would be included, covering diseases and conditions, such as cancer, hypertension, osteoarthritis, and mental health disorders (5). This final step could apply aggregated health metrics to quantify the benefits of PA [e.g., the WHO HEAT tool (95)], or apply metrics such as disability adjusted life years, which can subsequently be translated to monetary values. Alternatively, other methods of

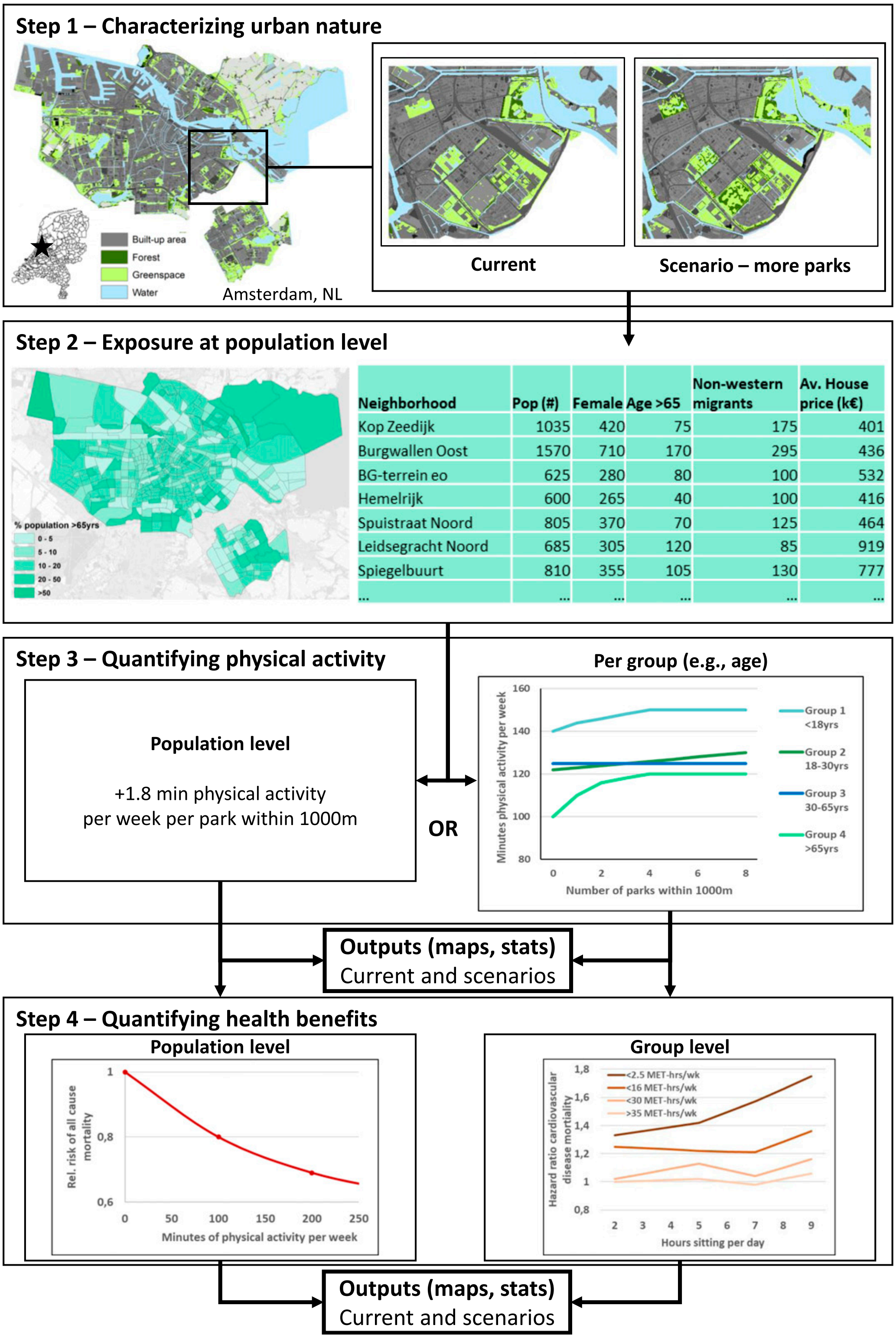

Fig. 3. An illustration of a hypothetical model application for Amsterdam, The Netherlands based on the presented model framework. Step 1 shows urban nature data for the current situation and a scenario with increased and improved city parks (see ref. 87 for details). Step 2 shows neighborhood-level data that moderates exposure to nature, assumed to remain constant between the two scenarios (88). Step 3 applies the relationship between park availability and PA to quantify the change in physically active time between scenarios at the population level (11), or for individual groups (hypothetical). Step 4 uses the relationship between PA and health outcomes to quantify health benefits at population level or for groups, with examples for relative risk of all-cause mortality and hazard ratio of cardiovascular disease mortality based on metabolic-equivalent task-hours per week and hours of sitting per day (4). The arrows show how data from each step feed into the next step and the model output. Sets of output maps for the initial situation and the applied scenarios result from step 3 (PA output) and step 4 (health benefits output).

monetary valuation, such as avoided treatment costs or productivity loss, could be applied as well to assess benefit–expenditure ratios of urban planning projects (96).

Key Research Needs and Opportunities

Innovations in science, data, and technology can accelerate development of decision-support tools for urban nature and health. An urban nature–PA decision-support model will complement existing nature–health approaches and tools (97, 98), provide input for broader health assessments (e.g., health impact assessments), and can be integrated with urban nature models that quantify urban ecosystem services (26, 28).

Workshop attendees identified four highly promising research frontiers for further advancing an urban nature–PA model, some of which have been recently reviewed (8, 53, 57, 80, 99).

First, when using the presented model framework, flexibility is key, given the complexities and advances in the science and ongoing shifts in PA patterns (100). Insights into different subpopulations and regional differences in PA will improve, so anticipating moving from aggregated population data to data on subpopulations is important. Elements from the model framework need to be tailored to local contexts, regarding socio-ecological–technical characteristics of a city (26), to address multiple decision contexts, decision-makers, and actor groups.

Second, how can greening cities be planned and implemented in an integrative way that considers the increase in attractiveness of a neighborhood but also provides important instruments to avoid potential adverse outcomes, such as increase in rents that could displace poorer populations (i.e., gentrification) (101)? Equity and justice are an essential pillar for improving health and well-being in cities (43, 102), including through interactional justice (i.e., quality of interpersonal interactions in public space), recognitional justice (i.e., consideration of different sociocultural values), procedural justice (i.e., inclusiveness in decision-making), and distributional justice (i.e., equitable access to resources) (102, 103).

Third, empirical research advances are essential to strengthening an urban nature–PA model. The essential advances have been meticulously outlined in key reviews (8, 53, 57), and were addressed in point 3 of *The Current State of Knowledge*. A key point is to improve understanding of how societal, behavioral, and environmental factors moderate the relationship between different urban nature settings and PA types, and which moderators are most important in different contexts. In addition, more research from across the world is especially needed; to date, research has focused heavily on developed Western nations and to some extent on China and Southeast Asia (15, 57, 78). Understanding from much of the world remains weak. Improving this understanding is crucial, as most of the world's urban population will reside in low- and middle-income countries in the near future.

Finally, new sources of data on the quantity and quality of urban nature and PA have the potential to advance spatial models if used carefully, ranging from increasingly rich sources of land-use data, and street-view data to spatially explicit activity tracking platforms.

Conclusion

Urban residents have a clear need for accessible and attractive outdoor spaces with different elements of nature to support active lifestyles. Simultaneously, the public health community and city planners are aiming to improve people's health through the promotion of PA. This combination of needs and goals provides a clear incentive for producing decision-support tools that can bring insight into how green city planning can lead to increased PA and contribute to healthy cities. The wider environmental and social impacts of these decisions must also be recognized. Integration of a nature-based PA model into ecosystem service assessment tools can help better take into account the multiple values of protecting and improving urban nature.

Here we have proposed a framework for developing a spatial model that can help determine where, for whom, and by how much changes in urban nature can increase PA and improve health, addressed through an ecosystem service lens. Such a model can be used in decision-making to guide and inform multiple stakeholder groups and allows tailored city-specific approaches. Current scientific knowledge supports an initial model that can distinguish broad trends and enrich debates on real-world urban planning and public health decisions. At this point the model remains in a conceptual phase, because data for different steps in the modeling approach are not readily available and accessible to apply broadly. Therefore, both insights from new research and an iterative process of application are needed to build and refine models based on the presented framework. Such efforts will help improve the level of detail of modeling outputs, including understanding the importance of different types of urban nature, different subgroups of the population that will benefit, and different domains and intensities of PA that will change.

There is ample opportunity to leverage new technologies and data sources to expand and strengthen research on the urban nature–PA relationship and provide valuable input for a broadly applicable model. The growing possibilities can be crucial to determine in which contexts urban nature types can be beneficial for PA and the health of different population groups. That knowledge, in combination with an actionable model, will help to provide a broad range of decision-makers the information to identify and remove barriers for disadvantaged populations, and to make choices that support the equitable provision of these critical opportunities for maintaining and improving health.

Data Availability. There are no data underlying this work.

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