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ESTIMATING GREENSPACE EXPOSURE AND BENEFITS FOR CUMULATIVE RISK ASSESSMENT APPLICATIONS

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Estimating Greenspace Exposure and Benefits for Cumulative Risk Assessment Applications

National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

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This report highlights the presentations, discussions, and practical suggestions offered by the meeting participants only; this report does not necessarily reflect the views or policies of the U.S. Environmental Protection Agency or any other entity. This report does not present consensus opinions of the meeting participants.

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ABSTRACT

This document provides a summary of the technical meeting on greenspace and cumulative risk assessment (GS-CRA) convened May 4−5, 2015 in Cincinnati, OH, by the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) National Center for Environmental Assessment (NCEA). This report highlights the presentations, discussions, and practical suggestions offered by the meeting participants; however, the report does not present consensus opinions of the meeting participants.

Meeting Objective: Identify and evaluate approaches and appropriate data sources for measuring greenspace and exposure, and examine the distribution of health impacts of greenspace (e.g., across socio-economic status, sensitive populations), including risk reductions, from a cumulative risk assessment perspective, with attention to uncertainty in reporting and measurement.

Approach: The meeting was structured to focus on (1) approaches and tools for estimating greenspace (GS) exposure, and (2) potential risks and benefits of GS exposure for human health and insights for cumulative risk assessment (CRA) applications. Meeting participants shared duties in presenting relevant research on agenda sub-topics and leading group discussions.

Findings: Both GS assessments and CRAs are relatively new approaches for characterizing both the health benefits and risks associated with complex environmental exposures. While existing evidence supports that GS effects are primarily beneficial for human health, GS assessments strongly depend on the factors specific to the places and populations of interest, which can differently influence the duration, frequency, and type of human exposure to various types and quantities of GS. Quantification and qualification of dose-response relationships related to GS exposure is limited for GS assessments, largely due to uncertainty around GS exposure measures and the mechanisms of action between GS engagement and human health outcomes.

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AR	attention restoration
ART	Attention Restoration Theory
ASPPH	Association of Schools and Programs of Public Health
ATSDR	Agency for Toxic Substances and Disease Registry
BE	built environment
CAU	census area unit
CCAAPS	Cincinnati Childhood Allergy and Air Pollution Study
CORINE	Coordination of Information on the Environment
CDC	Centers for Disease Control and Prevention
CRA	cumulative risk assessment
CREAL	Centre for Research in Environmental Epidemiology (Centre de Recerca en Epidemiologia Ambiental)
CRESH	Center for Research on Environment, Society and Health
CVD	cardiovascular disease
DALY	disability-adjusted life year(s) (lost)
EPA	U.S. Environmental Protection Agency
EVI	enhanced vegetative index
FEV	forced expiratory volume
GIS	geographic information system
GLUD	Generalised Land Use Database
GPS	global positioning system
GS	greenspace
GS-CRA	technical meeting on greenspace and cumulative risk assessment
ICD	International Classification of Diseases
LAI	leaf area index
LiDAR	light detection and ranging
MODIS	moderate resolution imaging spectroradiometer
NCEA	National Center for Environmental Assessment (EPA ORD)
NDVI	normalized difference vegetation index
NHEERL	National Health and Environmental Effects Research Laboratory
OKI	Ohio-Kentucky-Indiana Regional Council of Governments
ORD	Office of Research and Development (EPA)
PA	physical activity
PM	particulate matter
$PM_{2.5}$	fine particulate matter (with an aerodynamic diameter of a nominal ≤2.5 microns)
PUFA	polyunsaturated fatty acid(s)
SES	socioeconomic status
TRAP	traffic-related air pollution
UGSI	urban greenspace index
UI-UC	University of Illinois, Urbana-Champaign
USFS	U.S. Forest Service
UTC	urban tree cover
VOC	volatile organic compound(s)
WHO	World Health Organization

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Cover drawing courtesy of Chelsey Mitchell.

EXECUTIVE SUMMARY

ES.1. MEETING PURPOSE AND SCOPE

The Cincinnati Office of the EPA National Center for Environmental Assessment (Cincinnati) convened a technical meeting to explore how methods and measures used to assess greenspace (GS) could contribute to cumulative risk assessments (CRAs) and vice versa. GS was broadly defined as open land that is at least partly vegetated, located in or adjacent to urban or suburban areas. A key consideration is the use and effectiveness of GS as an ecosystem service and potential risk management practice to benefit human health. The purpose of the meeting was to inform methods and measures for assessing environmental health benefits and risks of GS and to consider how to incorporate these factors into cumulative risk analyses.

ES.2. OBJECTIVES AND APPROACH

The main objectives of the meeting were to (1) identify how GS is being described and its impacts assessed and (2) gain insights from GS assessments for CRA applications. To realize these objectives, the EPA NCEA organizers brought together a group of GS experts and practitioners from multiple disciplines to participate in joint presentations and facilitated discussions. The presentations and discussions were topically organized by exposure and health, and framed by conceptual models and driving questions developed by the organizers.

ES.3. KEY FINDINGS AND SUGGESTIONS

Evaluating GS effects on public health is a new and growing field of research. Published studies show that assessments of impacts can be influenced by the measures used to describe various attributes of the GS. Few confirming examples exist to determine whether it is valid to apply the measures used in one study to assess GS effects for another, or to extend them more broadly. Measures of GS exposures and related effects continue to evolve, but fully quantitative GS health assessments are not yet available. Instead, a mixture of qualitative and quantitative methods is used to define dose-response relationships. A number of study results show promise for better understanding GS impacts. Researchers categorized the strength of causal relationships (as high, medium, low) linking GS to health effects, and many paths toward improved research have been identified. The technical work group found several areas of consensus regarding GS impacts. In most analytical frameworks, the benefits of GS outweigh the risks. There are benefits of GS by itself (e.g., a direct impact that reduces physiological and psychological stress) and perhaps more often there are indirect benefits whereby GS reduces the magnitude or effect of other exposures to stressors, lessening adverse outcomes. Common examples of indirect impacts that may be related to stress reduction include lower risk of respiratory and cardiovascular disease and improved birth outcomes. Negative impacts of GS include well-characterized exposures to environmental irritants such as pollen or mold for which causal mechanisms are fairly well understood. For other impacts, both negative and positive, more research is needed to understand the mechanisms and magnitudes of GS exposures and related health outcomes. Finally, the addition of expertise in environmental psychology and microbiomics could enrich suggested approaches and metrics for assessing GS exposures and effects in the context of CRAs.

Five joint findings for GS assessments and CRAs can be distilled from the discussions:

1. *GS effects are mainly beneficial.*
   Current evidence suggests that GS supports public health directly by providing a dynamic space for exercise, social interactions, and other behaviors that are thought to lower psychological stress and improve mood. Additional benefits of exposure to GS appear to include improved cognition, attention restoration, and improved immune function. Although data are limited, GS might mitigate or attenuate health outcomes brought on by psychological stress (e.g., cardiovascular disease). A few adverse effects from GS exposure also occur—notably respiratory and dermal irritation related to allergens.

2. *Both GS assessments and CRAs are spatially dependent.*
   Both assessments can be conducted at different levels of spatial extent, with resolutions ranging from rough to highly refined. However, unlike conventional CRAs, the meaningful attributes of a GS—beyond those associated with objectively spatial measurements—are not well characterized.

3. *Both GS assessments and CRAs strongly depend on location and population characteristics.*
   Part of the planning phase of any risk assessment is to identify the scope of the effect(s) and characterize affected population(s); CRA and GS analyses incorporate these two factors in different ways. The scope of a CRA is often defined to increase the tractability of the multiple stressors being addressed. Simplification can involve placing limits on the number of chemicals, exposure pathways, or health effects to include. With GS evaluations, the scope of the analysis generally relates to the physical boundaries (e.g., the definition of the type and boundaries of the GS, or the amount of GS within a defined buffer), although the set of potential health endpoints in the nearby population is often considered in the assessment scope. The relative absence of GS characteristics (e.g., ecological features like biodiversity, landscape structure, and behavioral prompts like paths and overlooks) from GS assessment is a significant shortcoming. GS assessments also exhibit a strong dependence on the population under consideration that mirrors the way in which activity profiles of a population (or individuals) is used when assessing exposures to chemicals in a CRA.

4. *Quantification and qualification of dose-response relationships related to GS exposure is limited for GS assessments. The same is true for complex chemical mixtures typically assessed in CRAs.*
   A mathematical dose-response relationship linking GS exposure with any specific health outcome(s) does not yet exist. Uncertainties in the characterization of exposure and causality for GS are similar to the methodological limitations of environmental chemical exposure assessment, lacking even the cursory causality information that is available for a subset of chemicals studied in controlled animal experiments.

5. *Both GS assessments and CRAs are relatively new approaches for characterizing complex environmental exposures. Considerable uncertainty underlies GS exposure measures used to assess various health outcomes*.
   Uncertainties remain in the best available methods for quantifying and qualifying GS exposure as well as characterizing the etiology of various health endpoints, potentially limiting the usefulness of CRA analysis that incorporate GS. A lack of understanding regarding the mechanism or mechanisms through which GS might affect these health outcomes underlies many of the uncertainties in the exposure measures. Further research and exposure classification is needed, but full incorporation of all dimensions of GS exposure into a CRA model is unlikely.

1. INTRODUCTION

1.1. MEETING PURPOSE AND SCOPE

The Cincinnati Office of the U.S. Environmental Protection Agency (EPA) National Center for Environmental Assessment (NCEA)—Cincinnati hosted a technical meeting to evaluate the effect of greenspace (GS) on human health from a cumulative risk assessment (CRA) perspective. The group broadly defined GS as open land that is at least partly vegetated and located in or adjacent to urban or suburban areas. Access and exposure to GS have been reported to influence human health. The meeting explored how these influences can be explicitly considered in GS assessments and CRAs.

The multiple pathways or roles through which GS potentially affects human health and the different measures of GS used by researchers across different studies complicates existing analyses. The mechanisms or causal pathways that best explain associations between GS and health outcomes are uncertain. While some of the uncertainty is related to the newness of the field and the relatively limited number of studies, some of the uncertainty also due to the diversity of GS measures used (e.g., areal extent or plant density) and the range of causal pathways explored (e.g., reduced air pollution via filtering, improved psychological well-being from exposure to nature). Because GS can potentially act as either a nonchemical stressor or an exposure modifier, it appears to be a good candidate for examination in a cumulative risk context to help evaluate its application and effectiveness as an ecosystem service and potential risk management practice.

The experts assembled to evaluate GS for insights into CRA (and vice versa) were asked to review existing GS exposure measures, methods, and health effects being considered across different fields of study, focusing on which measures are useful for assessing different health outcomes and which are candidates for extending GS insights to CRA applications. The meeting discussions highlighted in this report are intended to inform methods for evaluating environmental health risks and benefits associated with GS.

1.2. OBJECTIVES AND APPROACH

The two main objectives of the meeting were to identify (1) how to characterize GS and assess its impacts and (2) to present insights from GS assessments for CRA applications. The approach for realizing these objectives involved identifying experts from multiple disciplines, as outlined in the meeting agenda (see Appendix B). Sets of participants then jointly developed and delivered presentations. A facilitated group discussion of GS measures and roles followed the presentations. Further topics of interest were captured for discussion as time allowed. The EPA organizers also developed a set of driving questions to guide the presentation materials and group discussions of GS toward identifying insights for CRA:

- How can existing cumulative risk assessment frameworks consider GS as it relates to exposure assessment for human health?
- How is GS conceptualized across disciplines?
- What health outcomes are relevant to GS prevalence and access?
- Which evidence-based measures of GS provide the most applicable, reliable, and replicable estimates for GS exposure in urban settings?
- What are the specific mechanisms for certain health benefits, and can this information be used to inform biologic plausibility of reported associations with GS?

Twice during the month prior to the meeting, the organizers and invited participants convened by teleconference to outline the working agenda. From the outset, participants identified the importance of defining how key terms would be used. Reflecting collective inputs at the meeting, GS is defined in this report as open land that is at least partly vegetated and located in or adjacent to urban or suburban areas. Note that water also can be an important part of what are called natural areas. Commonly referred to as blue space, water areas are not usually included when measuring the size and shape of GS, and they are not included in GS as it has been defined for this report.

1.3. PARTICIPANTS

The meeting participants, their affiliations, and key areas of expertise are identified in Table 1-1.

1.4. REPORT ORGANIZATION

This meeting report on the technical meeting on GS and CRA is organized as follows:

- Chapter 2 provides overview information about GS and CRA.
- Chapter 3 summarizes the exposure presentations and synthesizes key discussion points.
- Chapter 4 summarizes the health effect presentations and synthesizes key discussion points.

- Chapter 5 highlights core elements of the combined GS exposure and effect discussions and provides context for considering GS in CRA.
- Chapter 6 offers insights for cumulative risk applications.
- Chapter 7 lists the references cited in this report and additional relevant publications.
- Appendix A presents the biosketches of meeting participants.
- Appendix B provides the meeting agenda and the technical presentations.
- Appendix C presents the draft glossary distributed at the technical meeting.

Table 1-1. Meeting participants

Name	Organization	Key expertise
Invited GS experts		
Julia Africa	Harvard T.H. Chan School of Public Health	Ecological infrastructure, biophilic design, and restorative landscapes
Geoffrey Donovan	U.S. Forest Service (USFS), Pacific Northwest	Environmental economics, urban tree benefits, safety, and public health
J. Aaron Hipp	North Carolina State University	Built environment (BE) and health behaviors, physical activity
Perry Hystad	Oregon State University	Environmental epidemiology, greenness, and chronic health effects
Laura Jackson	U.S. EPA National Health and Environmental Effects Research Laboratory (NHEERL)	Ecosystem services, urban ecosystems
Michelle Kondo	USFS, Philadelphia	Environment, public health, and safety; urban stabilization/sustainability
Yvonne Michael	Drexel University School of Public Health	Epidemiology, psychosocial factors in health, healthy aging, women's health
Richard Mitchell	University of Glasgow	Influence of physical and social environments on population health
Mark Nieuwenhuijsen	Centre for Research in Environmental Epidemiology (CREAL), Barcelona	Environmental exposure and health impact assessment, epidemiology
Patrick Ryan	University of Cincinnati (Cincinnati Children's Hospital and Medical Center)	Environmental epidemiology, air pollution
William Sullivan	University of Illinois at Urbana-Champaign	Greenspace and healthy, sustainable communities; attention restoration
Matilda Annerstedt van den Bosch	Swedish Agricultural University	Behavioral medicine, epidemiology, natural environments, and public health
EPA Cincinnati GS-CRA team		
Glennon Beresin	Association of Schools and Programs of Public Health	Greenspace and public health
Amanda Evans	Oak Ridge Institute for Science and Education	Cumulative exposure and risk, mixtures
Rebecca Gernes	Association of Schools and Programs of Public Health	Greenspace and public health
Glenn Rice	EPA ORD NCEA	Cumulative exposure and risk, mixtures

Table 1-1. Meeting participants (continued)

Name	Organization	Key expertise
EPA Cincinnati GS-CRA team (continued)		
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Argonne CRA collaborators		
Richard Hertzberg	Argonne National Laboratory	Cumulative exposure and risk, mixtures
Margaret MacDonell	Argonne National Laboratory	Cumulative exposure and risk, mixtures
Technical expert-facilitator		
Travis Miller	Ohio-Kentucky-Indiana (OKI) Regional Council of Governments	Land use planning

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2. FRAMING CONTEXT FOR CUMULATIVE RISK AND GREENSPACE (GS) ASSESSMENTS

To examine how GS analyses could inform CRA practices and potentially be incorporated into future CRAs, the technical experts prepared presentations describing how GS exposures are assessed and how GS can affect human health. Basic concepts underlying a CRA and GS assessment are presented in Sections 2.1 and 2.2, respectively. Section 2.3 describes the development of conceptual models as a way to organize key information and communicate elements of an assessment to interested parties; an overarching conceptual model illustrating features of greenspace (GS) exposures and health effects is also presented.

2.1. CUMULATIVE RISK ASSESSMENTS

CRA is a relatively recent and evolving field of risk analysis. CRAs are designed to characterize and quantify, to the extent possible, the combined risks to human health or the environment from exposures to multiple stressors, including chemical, physical, biological, and psychosocial stressors (U.S. EPA, 2003; U.S. EPA, 2007; NAS, 2009). CRAs that focus on human health risks are typically evaluated from a population perspective. Such CRAs consider the given population's vulnerabilities to potentially harmful stressors (e.g., a genetic predisposition to harm from exposures to a certain mix of stressors). The U.S. EPA (2003) Framework identifies key elements of CRAs and observes that approaches for conducting a CRA can range from qualitative to quantitative, depending on available data and resources. Some CRAs have focused on communities that are more burdened than others, as part of environmental justice evaluations. Other CRAs focus on diseases, which are multifactorial, so applying a CRA approach helps assure that multiple factors are considered and reduces the potential for missing a key factor.

CRAs in particular, and risk assessments in general, are conducted to help risk managers make decisions. Ideally, CRAs should be conducted in a decision-relevant context and used to convey to a risk manager what is known about the risks and benefits associated with the exposure conditions for the population group of interest by considering the multiple stressors and buffers to which the population might be exposed and associated health effects. A buffer (sometimes referred to as a mediator) mitigates an adverse exposure or effect; in epidemiologic studies, buffers may modify exposures, modify effect measures, or be identified as confounders. As an example, some people consider polyunsaturated fatty acids (PUFAs) in fish to be a buffer because some studies show decreased risk of cardiovascular disease (CVD) among people who eat fish, and these decreases have been attributed to the PUFAs (Cohen et al., 2005a, 2005b).

We note that decision makers generally have concerns beyond health risks; these can include cost, feasibility, and social acceptance among other factors.

A CRA for environmental health differs from a classical chemical- or source-based risk assessment in several important ways. First, a CRA typically focuses on a specific population instead of on a pollutant source (e.g., emissions from a facility stack or effluent discharge pipe). Consequently, the focus is on a population's health risks, reflecting all relevant sources contributing to their exposures and other factors that influence exposure−disease relationships.

Second, in CRAs, those "exposures" are extended to include influential environmental and population-specific conditions, and they can be quite complex—involving not only multiple chemicals but also nonchemical stressors and other factors that directly impact public health, and they could render some populations more vulnerable to environmental exposures.

Third, CRAs potentially can evaluate multiple health effects. This feature reflects the complex nature of the exposures as well as joint toxicity, with the potential for toxicological interactions.

Fourth, the complexity often requires using simplifying methods in CRAs. For example, a risk assessor could group chemicals by similarities in health (toxicity) endpoints, in timing of different exposures, or in their occurrence via specific pathways or environmental media.

Fifth, because of the higher dimensionality and potentially large number of interactions, information needed to quantify risk across all key elements is typically incomplete. Thus, conducting an uncertainty analysis is an essential aspect of a CRA. Much of the information characterizing exposures and effects in a CRA may be qualitative; consequently, the uncertainty analysis could lack statistical descriptors such as confidence intervals. Instead, uncertainty analyses for CRAs tend to contain descriptions and rankings of factors judged to be most influential.

2.2. GREENSPACE (GS) ASSESSMENTS

The evaluation of GS in terms of environmental health risks and benefits has many of the same features as a CRA. First, the population is key to understanding potential GS impacts. Second, one of the primary complexities associated with GS assessments are the multiple ways to describe and measure GS as well as the various ways humans interact with GS and are exposed to features within GSs (e.g., released pollen). Third, GS has been reported to affect multiple aspects of human health through various suggested mechanisms. Fourth, GS exposure measures commonly used in health assessments are considered simplifications or proxy measures (e.g., there are few studies of health effects that examine how people actually engage with GS).

Most GS effects appear to be strongly determined by (1) the manner and extent of interaction with the GS by nearby individuals or the community and (2) the innate aspects of the GS. Similarly, cumulative chemical risks can be influenced by the exposure characteristics of route, concentration, and extent of exposure (represented by exposure time, frequency, and duration), taking into consideration overlaps of timing of exposures and effects across multiple stressors. Finally, GS analyses have substantial uncertainty given the many ways in which GS could affect health.

There are some important differences between GS analyses and CRAs. Whereas a CRA is an evaluation process that may or may not focus on a specific physical location, a GS assessment focuses on a physical entity with geographic descriptors. In trying to understand the causal mechanisms through which GS influences public health, it might be easier to conceptualize a GS as representing a collection of nonchemical stressors and buffers, as well as exposure or effect modifiers. Then the GS evaluation would be similar to a CRA that addresses multiple stressors and impacts on a specific population (or individual).

Multiple-stressor exposures for a GS assessment need to be more fully defined than they have been for CRAs. For example, instead of defining exposure as contact with chemical, physical, or biological stressors, the GS exposure measures might include characteristics that suggest or indicate specific types of population interactions with the GS.

The general measures most commonly used are quantity (how large is the GS area), quality (detailed characteristics including on-site attractions such as playgrounds or flower gardens), and function (likely effects on environmental quality parameters or population use). Metrics for function can include measures of environmental effects (e.g., pollen concentrations affecting air quality) as well as the specific functions and opportunities the GS provides for the population. Actual population use, such as frequency of physical activity (PA) within the GS boundaries, would also be measured when possible.

2.3. CONCEPTUAL MODELS

Conceptual models are representations, usually graphical, of the assumed relationships between sources and effects (Suter, 1999). For chemical risk assessments, many conceptual models are easy to interpret because they show actual material flows from emission sources to an exposed population. For more complex cases, including CRAs (perhaps including CRAs that would evaluate GSs), the connections shown in the model could depict direct and indirect effects of stressors and buffers on multiple endpoints. Models can also reflect complex processes and activities that include physical, psychosocial, and biological effects.

Conceptual models could serve three important purposes in CRAs: (1) they help analysts thoughtfully examine and clarify their assumptions concerning the potential relationships among the stressors, buffers, and health outcomes assessed; (2) they can facilitate communication among risk analysts, risk managers, and stakeholders; and (3) they can help identify important information gaps and research needs. Conceptual models can also help organize the data collection, analysis, and reporting of a CRA (Suter, 1999). One goal of this technical meeting was to develop a clear, overarching conceptual model as a way to broadly illustrate the complex relationships between GS and human health outcomes, potentially increasing the application of conceptual models in GS analyses.

Conceptual models for GS could range from simple schematics to highly complex flow charts (Hartig et al., 2014; Tzoulas et al., 2007; Lachowycz and Jones, 2013). Because GS can alter stressors (e.g., shade can reduce overall heat), stressors can influence GS (e.g., heat alters GS health), and GS can be a source of stressors (e.g., tree and grass pollen). It is not surprising that conceptual models depicting GS effects can potentially include several double-ended arrows and multiple connections. Because some of these relationships are not well understood, the conceptual models may be incomplete or the depicted relationships could be speculative.

One recommended approach that has been successfully applied in ecological risk analysis is to create modular component models (e.g., for activities, sites, and populations that can be recombined as needed for different settings) (U.S.EPA, 1998). Another useful approach is to employ hierarchical models, beginning with the simplest portrayal of the most important elements and connections. The example conceptual model in Figure 2-1 illustrates a broad overview of relationships among GSs, different types of stressors, and human health.

This conceptual model illustrates the occurrence of and interactions among four different types of stressors commonly considered as part of a CRA: chemical, biological, physical, and psychosocial. These stressors are linked to the physical location and context of a specific area. Context includes not only physical factors such as climate and seasonal trends and physical proximity to GS, but also the characteristics of an area (e.g., socioeconomic status, community identity, and local infrastructure and policy), as well as individual characteristics related to person-environment interaction.

Individuals exhibit their own intrinsic characteristics (e.g., age, gender), as well as modifiable characteristics such as perceptions of safety. The model shows that the occurrence of and exposures to these four different types of stressors can be influenced by the quality, quantity, and specific environmental and sociobehavioral functions associated with GS. These characteristics and functions, which serve as the basis for GS metric development and assessment, are further illustrated in Figure 2-2. The interactions subsequently influence environmental quality and physiological, psychological, and social pathways; collectively, these affect human health outcomes. Note that this model is meant to convey an overarching view of how GS can interact with both stressors in the environment and populations; it is not intended to be exhaustive.

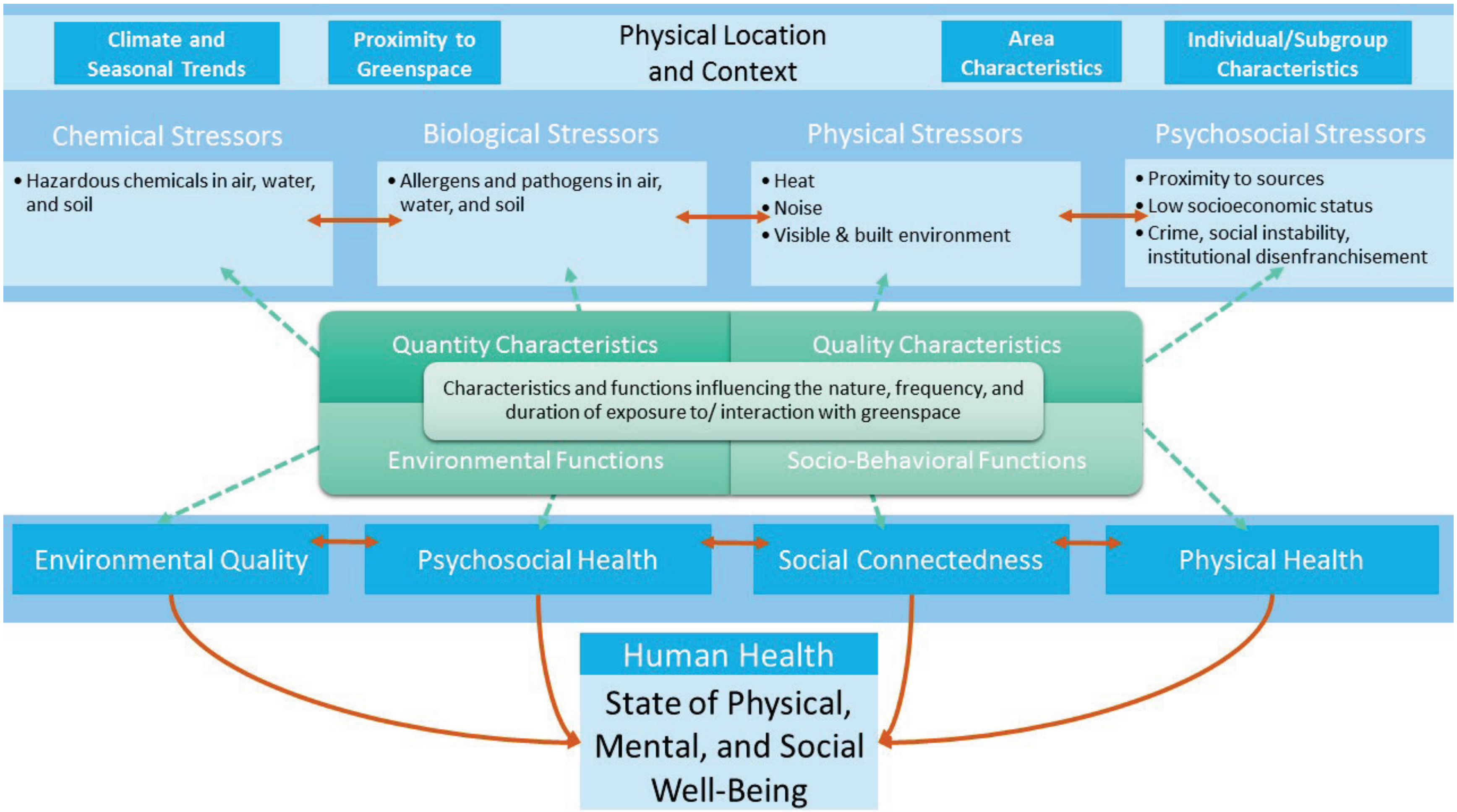

Figure 2-1. Overarching conceptual model illustrating features of greenspace (GS) exposures and health effects.

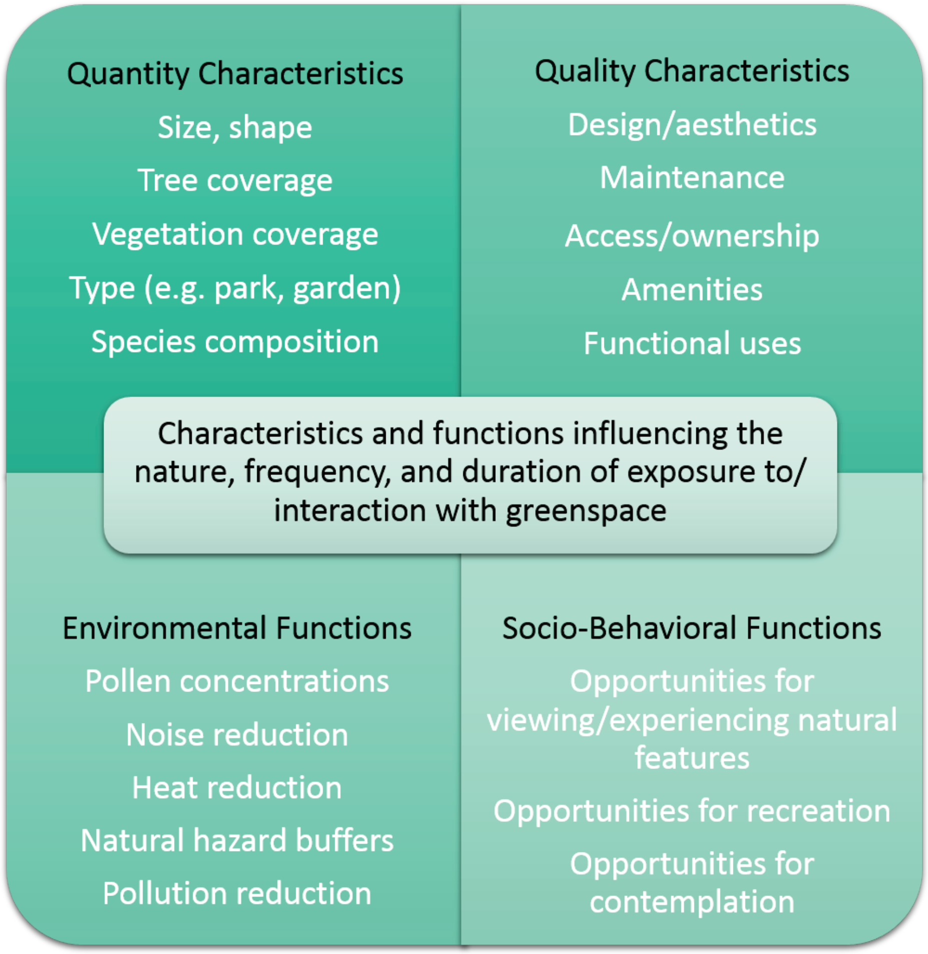

Figure 2-2. Greenspace (GS) characteristics and functions that influence exposures and interactions.

Although GS research is growing rapidly, the uncertainty regarding mechanisms of action for the variety of outcomes is a fundamental barrier to developing accurate estimates of risks or benefits to health from GS. Greater use of conceptual models to depict specific relationships between GS and human health could help further strengthen ongoing advances in GS analyses. For example, conceptual models could help illustrate known and hypothesized mechanisms between GS exposure and specific health endpoints (e.g., CVD or ragweed allergy) and potential combinations of GS exposures with various chemical and nonchemical stressors. In many cases, multiple features of the same GS might offer a different profile of benefits or risks for different groups of people. Further, detailed conceptual models could also help delineate differential exposures and effects, as well as key assumptions and uncertainties, for specific subgroups such as age, gender, socioeconomic status, or urban and rural populations (Suter, 1998).

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3. GREENSPACE (GS) EXPOSURE ASSESSMENTS AND METRICS

Highlights of the work group presentations on GS exposure metrics and assessments are presented in Section 3.1 and Table 3-1. The full sets of slides that accompanied these presentations are provided in Appendix B, in the same order as the list of participants in Appendix A. Key exposure considerations from these presentations and the accompanying discussions are highlighted in Section 3.2. Approaches and metrics for GS exposure assessments are described in Section 3.3.

3.1. TECHNICAL PRESENTATIONS

Multiple experts within the topical areas identified in the agenda led the presentations on assessing GS exposures. Key points from each presentation are highlighted below.

3.1.1. Exposure Assessment Approaches

Laura Jackson (*EPA National Health and Environmental Effects Research Laboratory [NHEERL]*)
Mark Nieuwenhuijsen (Centre for Research in Environmental Epidemiology *[CREAL]*)
Matilda Annerstedt van den Bosch (*Swedish Agricultural University*)

Three distinct approaches to GS exposure assessment were described from ongoing programs in the United States and Europe. In the United States, the EPA (2015) EnviroAtlas (http://enviroatlas.epa.gov/enviroatlas/) is a publicly available data resource for mapping and evaluating ecosystem services supply, demand, and drivers of change. EnviroAtlas conceptualizes GS as providing three categories of services that benefit human health: (1) buffers against natural and anthropogenic hazards, (2) opportunities for healthful behaviors such as active transport (e.g., bicycling or jogging) and social interaction, and (3) supporting environmental functions such as carbon sequestration and wildlife habitats. This resource does not include potential negative consequences for human health, such as from pollen exposures. Environmental data on GS are available at the watershed level (hydrologic unit code [HUC] 12) for the contiguous United States and at fine-scale resolution for selected communities.

Estimates of GS derive mainly from 30-m (roughly 100-ft) satellite imagery and aerial photography. EnviroAtlas also provides health-related metrics such as tree cover along roads and streams, temperature and pollution reduction by tree cover, and walking distance to parks, schools, and day-care centers with surrounding GS. Sociodemographic variables are included to assess distribution and estimate the potential for improvements in population health through GS interventions.

Table 3-1. Presentation highlights: greenspace (GS) metrics and exposure

No.	Topic	Scope notes	Presenters	Key points
1	Exposure assessment approaches	Overview of how GS is determined, illustrated by EnviroAtlas, PHENOTYPE, and World Health Organization (WHO) GS indicator	Laura Jackson (*EPA*) Mark Nieuwenhuijsen (*CREAL*) Matilda Annerstedt van den Bosch (*Swedish Agricultural University*)	• Definitions of GS and potential health and ecosystem services • Different levels of measurement for indicators of interest (e.g., level 1, 2, 3 for PHENOTYPE) • Policy indicators developed broadly for universal application and comparability • Overview of specific metrics at various scales
2	Tree cover measurements	Normalized difference vegetation index (NDVI), regional to local urban tree cover (UTC)	Geoffrey Donovan (*U.S. Forest Service [USFS]*) Perry Hystad (*Oregon State University*)	• NDVI commonly used in epidemiological studies; it is unclear what it actually captured • NDVI is potentially useful for validating finer scale measures • Comparison of several tree cover estimates and epidemiological applications
3	Access to greenness		Richard Mitchell (*University of Glasgow*) Michelle Kondo (*USFS*) Matilda Annerstedt van den Bosch (*Swedish Agricultural University*)	• Comparison of coarse- and fine-scale measurements in the United Kingdom • Measures of residential greenness vs. access and use of GS • Overview of vacant lots as potential stressors or ecosystem services • No standard scientific measure of access

Table 3-1. Presentation highlights: GS metrics and exposure (continued)

No.	Topic	Scope notes	Presenters	Key points
4	Built environment (BE)		Perry Hystad (*Oregon State University*) Yvonne Michael (*Drexel University*)	• Objective vs. qualitative measures for BE • Natural experiments are currently the main approach for assessing GS and BE together • Variables and relationships differ at different scales • Discussion of potential data sources for BE-GS assessment
5	Design, environmental psychology	Includes canopy shape, way-finding strategy, attention/ cognition restoration	Julia Africa (*Harvard*) William Sullivan (*University of Illinois, Urbana-Champaign [UI-UC]*) Richard Mitchell (*University of Glasgow*)	• Underlying: psychoevolutionary theory and Attention Restoration Theory (ART) • Biophilic design, viewable GS and insights for CRA • Exposure duration (defined as time per event), frequency, concentration of GS, mode of delivery • Cultural differences in definition and value of GS
6	Specific populations, exposure	Includes aging, lower socioeconomic status (SES)	Yvonne Michael (*Drexel University*) Richard Mitchell (*University of Glasgow*) J. Aaron Hipp (*North Carolina State University*)	• Exposure differences by subgroup • Gender, race, socioeconomic position, age • Sequence of exposure over the life course • Intersections with accessibility
7	Exposure metrics, links to health	Illustrated by attention restoration effect	William Sullivan (*UI-UC*) Yvonne Michael (*Drexel University*)	• GS exposure elements include frequency, duration, and nature of interaction with GS • Experimental approaches for estimating GS exposure • Beyond physical contact; GS views linked to reduced stress and improved performance • Estimating exposure (dose)-response

Specific metrics to estimate GS exposure and related health impacts from land cover composition were described and categorized as indicators of healthful exposures and/or indicators of effect measure modifiers. For example, the amount of visible tree cover from a residence is estimated with a 50-m buffer around the residence, and this 50-m buffer estimate is applied as an indicator for both potential engagement with natural features (healthful exposure) and for potential protection against heat, air pollution, and night light (effect modification) (U.S. EPA, 2015).

In Europe, the European Union has established a project to investigate the interconnections between exposure to natural outdoor environments (in both rural and urban settings) and better human health and well-being. Referred to as the Positive Health Effects of the Natural and Outdoor environment in Typical Populations in different regions in Europe (PHENOTYPE, http://www.phenotype.eu/), thist project is coordinated by the CREAL in Barcelona, Spain. The PHENOTYPE program assesses the natural environment via a multilevel approach using quantitative, qualitative, and in-field assessments to estimate GS exposures and associated health effects. The approach has three levels of analysis. The first consists of quantitative assessments that involve objective measures of natural environments, such as large-scale vegetative coverage, and that evaluate effects with secondary health data from epidemiological studies. The second involves assessments that use detailed secondary data to estimate the quality of the natural environments for smaller areas, such as data on the specific attributes of municipal parks (e.g., whether a play area is available for children, or whether there are hiking trails). The third approach is at the most localized scale, involving primary data collected through environmental audits and used to measure environmental quality.

These three levels provide different opportunities for GS exposure assessments. At the broadest scale, measures such as the normalized difference vegetation index (NDVI) are useful for estimating generalized availability of GS within an area and provide the opportunity to compare different regions and cities. However, these measures do not provide the level of detail necessary to estimate access to greenness, which can only be obtained under the second and third levels of analysis. GS quality can be assessed across several categories, including ownership, size and shape, functional uses, location, management and perception of management, community identity, and climate factors.

The second featured European program focuses on the World Health Organization (WHO, 2001) indicator, which was developed in response to the 2010 Parma Commitments that aim to provide each child with access to urban GSs for play and physical activity by 2020. As part of specific planning toward and monitoring of this goal, a measure was developed to define GSs and appropriate spatial metrics for evaluation. The methodology for this measure was designed for easy and widespread practical use with publicly available data, with an emphasis on screening and on comparability among regions over performance in statistical or spatial modeling. The measure uses population distribution and geographic information system (GIS) data to calculate and provide the ratio of people within a designated buffer area of a GS to the city's total population, as an implicit environmental health indicator.

GSs were defined spatially as green-covered areas that are a minimum of 1 ha in size (roughly 2.5 acres), providing a recreational use (such as a park, public garden, or zoo), including suburban areas managed as parks and green areas adjacent to urban areas, per the definition of urban GSs from Urban Atlas (http://www.eea.europa.eu/data-and-maps/data/urban-atlas). In a case study of Malmo, Sweden, a Euclidian buffer distance of 300 m (roughly 1,000 ft) around GSs was chosen to represent accessibility for the city. While intended for use in assessing the public health endpoints of physical activity and stress, the measure does not include estimates of quality or actual walking distances to GSs. The measure is to be validated in relation to health data and tested in further case studies in Europe.

3.1.2. Tree Cover Measurements

Geoffrey Donovan (*U.S. Forest Service [USFS]*)
Perry Hystad (*Oregon State University*)

Several data sources and methods were described for determining tree cover for large areas. The NDVI is derived from satellite imagery of chlorophyll and is the measure most widely applied in epidemiological studies of surrounding greenness and health. Several studies use GIS to derive the mean NDVI value for the determined buffer distance(s) around the point of interest (e.g., a residence or a school) as a measure of surrounding greenness (Agay-Shay et al., 2014; Amoly et al., 2014; Dadvand et al., 2014; Hystad et al., 2014). Recently, the standard deviation of NDVI rather than the mean value has been used as a measure of variation in greenness, which could differentiate areas with both green and built features (Periera et al., 2012).

Other satellite-derived imagery sources include the moderate resolution imaging spectroradiometer (MODIS) NDVI, enhanced vegetative index (EVI), U.S. Forest Change Assessment Viewer (ForWarn), and the MODIS leaf area index (LAI). These sources can provide more detail on the type of greenness and phenology, but they are not frequently used in GS exposure assessment because of lower resolution imagery. Land cover classification is another measurement of large-scale greenness. Land cover classifies imagery along several categories, which can range from basic classifications (e.g., tree canopy, water, buildings) to more explicit categories for land use and vegetation cover (e.g., parkland, roadways, industrial areas). Available at different scales and resolutions, land cover data sets are particularly useful in measuring change in greenness over time. Light detection and ranging (LiDAR) is another sensing method measuring elevations on Earth using a pulsed laser (by illuminating a target and analyzing the reflected light to estimate distance). This method can detect vegetation cover and land use in three dimensions and at high resolution. However, data are more difficult to interpret from this method so it is not used as frequently as NDVI and other measures of land cover.

At a smaller scale of analysis, data on urban tree cover (UTC) and land use are increasingly available at the municipal level. These can provide information on more specific attributes such as tree species composition, tree removal and loss (e.g., due to emerald ash borer infestation or to widen streets), and individual park features and access points. With the variety of measures available, the emphasis is on determining exposure metrics relevant to the health outcome of interest, the population, and area characteristics. Much is yet to be learned about specific patterns of GS use that are difficult to ascertain from measurements based on imagery. There is a growing emphasis—especially for health data—on integrating large-scale objective measures such as those that can be collected with NDVI, with individual data like those gathered from global positioning satellites (GPS) and more subjective data obtained from surveys and environmental audits. Additionally, measurements of GS from a street-level perspective rather than bird's eye imagery may be useful in assessing visible greenness. With a consensus neither sought nor reached, the following topics were also discussed at the meeting:

- NDVI as predictor of health effects: What exactly does NDVI measure? Is analysis of mechanisms possible using only NDVI?
- Residential greenness, passive proximity versus active engagement for access and use: What are the health outcomes most associated with each, and what is their potential joint influence on various outcomes?
- What are the best methods to consider temporality, such as seasonal variation in both GS and health effects, and acute versus chronic exposures?
- Is there a threshold for exposure? Consider floor versus ceiling for visible effects of GS.

3.1.3. Access to Greenness

Richard Mitchell (*University of Glasgow*)
Michelle Kondo (*USFS*)
Matilda Annerstedt van den Bosch (*Swedish Agricultural University*)

Different definitions of GS were discussed, as were other natural features that could be included (e.g., water bodies/features, or “blue space”), acknowledging that no single consensus definition exists for what constitutes GS. Research highlights were shared from the Center for Research on Environment, Society and Health (CRESH, http://cresh.org.uk/), which examines GS using land cover data at multiple resolutions. Scotland’s map compiles GS data from all 32 Scottish council areas, a political subdivision unit, and classifies 23 unique spaces using primary and secondary codes to capture spaces with multiple functions, such as woodland areas within parks. Using GIS, a buffer analysis can produce a measure of the proportion of green land cover within an area, as well as the population within a certain distance to GS. Different data sets can produce different results using this method. Differences can be illustrated by comparing the percentage of GS based on three different GS data sets. These data sets include (1) the Coordination of Information on the Environment (CORINE, http://www.eea.europa.eu/publications/COR0-landcover) data set, derived from satellite imagery; (2) the Ordnance Survey MasterMap (the United Kingdom’s most detailed vector-based data: https://www.ordnancesurvey.co.uk/business-and-government/products/mastermap-products.html); and (3) CRESH’s own model-based estimates of the percentage of GS land cover.

Two key considerations for assessing access and exposure to greenness are: (1) the scale of analysis (e.g., neighborhood, municipality, or regional) and (2) the assumption of accessibility through measures of proximity and coverage. A short distance to objectively measured GS does not necessarily mean that GS is accessible (e.g., it could be a private park). Similarly, a measure of GS coverage in an area does not provide information on the frequency, duration, and nature of use for populations of interest. Other challenges in measuring access were discussed such as visible greenness, exposure in indoor spaces, and individual time spent in a GS. Monitoring devices using GPS sensors are one method used to inform GS exposure estimates with time and location data, although these tend to be used only in relatively small studies.

Vacant lot greening efforts in Philadelphia provide a valuable opportunity for considering a natural experiment design and for conducting GS access research. Findings are inconsistent for the potential health benefits and risks of greened vacant lots. Using GS audits and resident focus groups and interviews, a recent study (Heckert and Kondo, under review) examined the potential impact of vacant lot greening on residential perception and access. Results indicate that many residents did not notice when a lot had been greened, and they were unsure how to interact with the space in this new condition, but continued negative perceptions were reported around remaining vacant lots.

This overview led to a renewed group discussion of GS definitions with specific attention to perceptions of quality or design that might influence associated health effects. For example, while an overgrown vacant lot could contribute to an NDVI-based measure of GS, it might actually have adverse effects for nearby residents. Additionally, factors such as design and community involvement around projects such as vacant lot greening could substantially influence perceptions and ultimate community impacts of newly greened spaces. The effect of participatory design and accessibility (e.g., perceived access, perceived safety, perceived function) regarding green interventions is an area needing further research.

3.1.4. Built Environment

Perry Hystad (*Oregon State University*)
Yvonne Michael (*Drexel University*)

Key aspects of GS accessible or implemented through changes in the built environment were identified. Defined as the human-made spaces in which people work, live, and play, the built environment is often determined locally, through land use planning, zoning ordinances, and design guidelines. Parks, trails, green roofs, community gardens, and green stormwater infrastructure are all examples of planned GSs in the built environment. Increasing access to GS is an emerging policy priority in many urban areas for its potential ecological and social benefits, and the evaluation and validation of such interventions are developing areas of research.

Natural experiments provide an opportunity to evaluate the influence of GS while minimizing some of the confounding inherent in observational studies and improving the causal inference available from cross-sectional studies. Addressing the definition of GS as part of urban open space, the impacts of transforming blighted vacant land into GS from a study in Philadelphia were discussed, including reductions in gun assaults, vandalism, and self-reported improvements in stress and exercise (Kondo et al., 2015; South et al., 2015).

In studies of the built environment, the measurement of GS includes objective measurements such as land use and NDVI, residential proximity to parks, and street-level audits using Google Earth. Subjective measures such as qualitative GS audits and residential surveys are also used. It is important to control for other built environment factors when evaluating the effect of GS because that can be highly correlated with other variables. A study of GS and reproductive outcomes indicated a lower risk for several birth outcomes in higher NDVI areas after controlling for air pollution, park proximity, walkability, and noise (Hystad et al., 2014). Further, qualitative assessments of microenvironments have been found to impact social functioning and could modify the effect of GS exposure (Brown et al., 2008). Finally, crowdsourcing studies are another avenue of analyzing visible GS, with some finding subjective classifications of "happy," "beautiful," and "quiet" in images with greenery compared to images with no greenery (see Mappiness, http://www.mappiness.org.uk/).

3.1.5. Design and Environment Psychology

Julia Africa (*Harvard T.H. Chan School of Public Health*)
William Sullivan (*University of Illinois at Urbana-Champaign*)
Richard Mitchell (*University of Glasgow*)

Design features can affect exposures to GS. Considering connections between humans and nature from a psychoevolutionary perspective relative to human history, the built environment can be viewed as a novel living space for humans compared to natural surroundings. Current research tends to create a false dichotomy between psychological and physiological responses to GS; we know less about how strong the relationships are between individuals and landscape characteristics that support observed health effects. Some research supports a link between nature and human health regardless of the type of exposure, finding reduced cortisol levels for both those who viewed a forested area and those who walked through it (Park et al., 2010). Meanwhile, the potential for adverse impacts of GS also exists, as illustrated by increased crime, air pollution (e.g., pollen), or an individual's fear of certain natural features (e.g., dark areas or poison ivy). GS in rural environments is also a growing area of research that presents many questions, considering the different perspectives and experiences of rural populations with nature and associated impacts.

Theoretical background and experimental evidence of Attention Restoration Theory (ART), which hypothesizes that mental concentration improves after exposure to nature, builds on the early work by Kaplan and Kaplan (1982, 1989) and Kaplan (1995). The ART researchers assert that attention takes one of two forms in the brain: involuntary or directed. Involuntary attention requires little effort and produces little mental fatigue. Items, ideas, or places that are fascinating draw on involuntary attention. Conversely, directed attention requires a high degree of effort and focus and is used for tasks such as learning, problem solving, and planning. The focused effort required for directed attention fatigues mental processing more easily than involuntary attention. Mental fatigue can lead to inattentiveness, irritability, and impulsive decision making. According to ART, brief exposure to natural settings and scenes activates involuntary attention, which allows for rest and recovery of the ability to focus attention. Interrupting directed attention with restorative stimuli could lead to improvements in memory and performance. In the two experimental studies of ART discussed, the performance of participants was measured in response to different exposures to GS. Measures of attentional performance before and after the GS exposure indicate that exposure to greenness is associated with improvements in cognition and memory.

It is worth noting that ART is one of several theories used by environmental psychologists to describe observed effects of nature on human consciousness, well-being, and health. Other notable contributions include the biophilia hypothesis (Wilson, 1984; Kellert and Wilson, 1993), the savanna hypothesis (Orians and Heerwagen, 1992), the habitat theory, and prospect-refuge theory (Appleton, 1975). A more recent contribution by Heerwagen (2006) described a framework for "features and attributes of buildings linked to well-being needs and experiences" (e.g., views of outdoor nature, natural lighting, interior plantings), reflecting the relationship between nature and health in anthropocentric terms. Cramer and Browning (2008) consolidated these observations in three broad experiential categories describing human-nature relationships: nature in the space, natural analogs, or nature of the space (see Ryan et al., 2014).

Further discussion focused on the contribution of specific natural design features to observed responses. In a classical exposure-response model, design features influence positive or negative appraisal of an individual's adaptive capacities, with a negative appraisal increasing the likelihood of psychological and physiological stress responses such as elevated cortisol, blood pressure, and heart rate (Cohen et al., 1995). All current psychoevolutionary theories described above suggest that natural environments are more likely to soothe or positively stimulate our neurobiology as compared with most features of the built environment. Notably, Edward O. Wilson created the term "biophilia" to describe the "innate tendency [in human beings] to focus on life and lifelike processes," suggesting that these responses are cross-cultural and ahistorical.

Design features that echo the movement, variability, and periodicity found in nature through stimulation of the five senses can influence physiological and psychological responses. Examples of natural design elements include the use of fractal and Fibonacci sequences found in babbling brooks, dappled sunlight, or flower petal structures; the use of natural fibers and materials like stone in built environment settings; and the elevation of natural "soundscapes" like birds singing as a component of GS. Exposure was discussed in terms of frequency, duration, and intensity of immersion over various intervals; the interplay between indoor exposure to natural design elements, and a potential "priming" effect for outdoor exposures was briefly discussed as an area warranting future research.

The government of Singapore has incorporated periodic exposure to GS as part of its Nature Pyramid, a food and healthy living guide patterned after the U.S. Food and Drug Administration's food pyramid. Singapore's example illustrates the potential for integrating GS exposure into the urban fabric (Beatley, 2012). The Nature Pyramids model has inspired the Biophilic Cities Network (http://www.biophiliccities.com), a group of urban planners, landscape architects, and public health clinicians that seeks to transform our urban model to support our innate affinity for and exposure to nature.

3.1.6. Specific Populations: Exposure

Yvonne Michael (*Drexel University*)
Richard Mitchell (*University of Glasgow*)
J. Aaron Hipp (*North Carolina State University*)

The potential for differential exposure to GS for specific population subgroups involves considering differences across factors such as life stages, gender, and socioeconomic variables. The need to address specific populations stems from the multiple functions of GS and multiple pathways of GS exposure. GS can be considered as having both salutogenic (beneficial to health) and pathogenic (detrimental to health) effects, and as such, has the potential to increase or decrease inequalities in health through public health interventions (e.g., path creation and health walk promotion). Population subgroups are described in relation to both differential exposure and susceptibility. To illustrate the exposure aspect, proximity or access to GS could be a function of environmental justice or cultural and behavioral factors determining frequency, perceptions, and type of activities occurring in the GS. Gender differences reported for GS and health relationships emphasize the importance of capturing quality as well as quantity of greenspace and not assuming uniform health benefits of GS for all population subgroups (Richardson and Mitchell, 2010). In a recent analysis, women were found to be likely to use GS at lower levels than men, although women reported using GS for similar purposes (Miller et al., 2014). Considering susceptible populations, certain subgroups might have particularly positive or adverse responses to a certain GS. For example, an asthmatic child could be more at risk of an asthma attack in areas with high tree pollen, and that potential could be magnified in the presence of other common urban irritants such as diesel exhaust from heavily trafficked corridors.

In addition to particular health conditions, attention to subgroups with different social, cultural, and environmental norms and expectations was discussed as influential when estimating exposure. Specific grouping categories include gender, socioeconomic status, race, ethnicity, and life course. While some data suggest that the quality of a GS is more important to women, the evidence is mixed regarding differences in use among the men and women who do access GS. Whether and how this affects the estimates of GS exposure is an area needing further research to assess whether the pathways affecting access or use could differ between men and women.

Studies of GS often examine socioeconomics variables such as income and level of education. In general, results indicate that access to quality GS decreases with socioeconomic position and among minority race communities (Wolch et al., 2014), and there is evidence that GS use is lower among lower-income and minority groups even when GS is available (Jones et al., 2009; Hipp et al., 2013a). After controlling for socioeconomic position, Suminski et al. (2012) found that nonwhite Midwestern communities had the least access to GS and the number of amenities within GS/parks. Others have shown that for GSs that are used, minority races and those of Hispanic ethnicity are more active in the GSs compared to whites (Floyd et al., 2008); this result was associated with amenities within the spaces, such as sport facilities. Perceptions of GSs are also important in determining access, and evidence suggests that different groups perceive spaces differently. Considering exposure, it was suggested that assuming access via proximity alone is insufficient for understanding the complex relationship between proximity, access, and use among different groups.

Finally, considerations for exposure were discussed from a life-course perspective, which examines the changes in certain influential factors for different age groups. Risk and exposure were again discussed in terms of access and susceptibility at certain stages of development and life. For example, children might have limited access to GS depending on their proximity, mobility, and the rules of their household. Older adults may also have limited access, but for other reasons than children do. Sensitivity to allergens and chronic conditions can also vary by age. Evidence was presented that adults are more likely to access parks than either children or older adults, whereas teens are more likely to access parks within a mile of their homes (Cohen et al., 2006). The discussion centered around the need to consider differences in exposure and susceptibility in further research studies, which have rarely considered data based on actual visits and activities in GSs.

3.1.7. Exposure Metrics, Links to Health

William Sullivan (*University of Illinois at Urbana-Champaign*)
Yvonne Michael (*Drexel University*)

A number of metrics can be used to assess exposure and response related to GS. Frequency, duration, and the type of the interaction with the given GS were discussed as central components of the exposure evaluation. Exposure is not limited to physical contact with nature; research studies indicate that having a view of GS is associated with improvements in mental performance and stress reduction (Kuo and Sullivan, 2001; Ulrich et al., 1991). Although specific metrics can differ across studies, most research includes a measure of canopy cover or canopy density as an initial environmental exposure, with qualitative and individual information on use added as available or feasible. Controlled experimental studies have implemented canopy density as a “dose” of GS, with participants exposed to varying amounts of green imagery (Jiang et al., 2015).

Biomarkers such as cortisol levels and skin conductance have been used to measure stress responses across different GS exposure settings. With the ability to control short-term exposures to greenness, studies such as these are building evidence of acute exposure and health response (Jiang et al., 2014a, 2014b). Additional research is needed to develop measures of long-term exposures and effects. Note that canopies are not the only GS metric warranting further examination; beyond blue space, a number of vegetation types can be identified that are not related to trees. In addition, surface features that are not vegetation (and are simply colored green) are captured in certain measures of GS. Therefore, a clear understanding of each GS measure is important to their relevant applications and potential combinations and extrapolations across studies.

3.2. KEY EXPOSURE CONSIDERATIONS

The technical meeting discussions identified several essential considerations for assessing exposure to GS and natural environments. The exposure measures evaluated are commonly guided by the health outcome of interest. Coverage and distance measures are widely used in ecological studies of various health and other population-level outcomes, including reproductive and respiratory outcomes, mortality, and housing values (Mitchell and Popham, 2008; Dadvand et al., 2012a, 2012b; Hystad et al., 2014; Li et al., 2015). Measuring exposure to assess health outcomes such as psychological stress or attention restoration (AR) requires different, often more complex accounts of the nature, duration, and frequency of an individual's interaction with GSs.

Location is another essential component of exposure assessment, not only to estimate coverage and proximity to vegetation but to account for the local contexts shaping the nature of and interactions with GS in a specific area. These contexts can include physical features of the GS like topography, land use, ownership patterns, and other cultural and sociodemographic norms (Lachowycz and Jones, 2013; Berland et al., 2015).

After establishing the health effect or effects of interest and the context of the GS, the exposure assessment commonly considers qualitative and quantitative features of the actual GSs. Quantitative measures are largely objective and address elements such as size, shape, distribution, and distance to the GS(s) in an area. Quality estimates relate to the nature of the space and the types of activity or engagement it can provide; amenities, maintenance, public accessibility, and functional uses are common qualitative measures (Nieuwenhuijsen et al., 2014). Examples of common measures are discussed in Section 3.3 and summarized in Table 5-1.

To the extent possible, exposure assessments should also consider the reasons for and nature of the populations' engagement with the GS (e.g., for physical activity, to attend a social event, to fish for leisure), as well as the frequency and duration of the interaction; this includes potentially different impacts of short-term versus long-term engagement with natural spaces. Such assessments should allow for multiple types of engagement, perhaps even within a single trip. The report authors acknowledged that this level of detail is not often feasible for large ecological studies. Finally, the frequency, duration, and nature of the interaction with GSs often vary across different populations (Rosso et al., 2011; Ord et al., 2013; Sullivan et al., 2014).

In addition to accounting for the proximity and nature of engagement with the GSs themselves, assessments should evaluate potential exposure to other environmental and social stressors and the implications for susceptible populations. Such exposures can occur within, adjacent to, or outside the GS setting or interaction area; for example, trees in a park may filter some pollutants in the air, but overall exposure to air pollution may increase if the park is near a major highway or intersection. Engagement with GS can also have adverse effects for certain subgroups, namely those susceptible to aeroallergens or asthma triggers (Tzoulas et al., 2007, Lovasi et al., 2013).

Several factors in the social environment, from local policies and cultural norms to traffic, noise, or crime rates, can inform attitudes and engagement with GS. Community and individual perceptions of safety, function, and accessibility may differ across subgroups and can affect the nature and duration of activity within and around GSs (Mitchell et al., 2015). These complex, place-based factors can influence the use of GS as well as present additional stressors that can mediate or otherwise intersect with the benefits or risks associated with GS engagement.

3.3. ASSESSMENT APPROACHES AND METRICS

A tiered approach is generally applied to assess GS exposures, with the level of detail depending on the population and health outcome of interest, available metrics, and time and other resources available to those conducting the assessment. Considerations of scale, data accessibility, and comparability across different areas have led many researchers to rely on large-scale spatial estimates of GS, while questions of access and quality are determined at smaller units of analysis. At the largest scale, satellite-derived imagery can produce estimates of world-wide vegetation cover at various resolutions.

One of the most widely used metrics is the NDVI, which is based on the natural infrared light-reflective properties of chlorophyll. The methodology and interpretation of the NDVI are detailed elsewhere (Weier and Herring, 2011); the index ranges from −1 to 1, with lower values indicating little to no greenness. Daily NDVI values are available from 1972 to present at a 30-m resolution, the smallest available for global satellite imagery. While different types of earth image data such as LiDAR and MODIS are available, NDVI is a widely applied measurement due to its availability, relative ease of interpretation, and comparability across studies.

A second resource for large-scale GS measurement is land cover data. These data provide information on different types of land use and vegetation. Large-scale land cover databases such as CORINE in Europe and the National Land Cover Database in the United States are widely used for GS quantification (Richardson and Mitchell, 2010; Annerstedt et al., 2012). Land cover data can distinguish among different types of GS, where NDVI cannot. Such a metric is useful for tracking greenness over time, both for research purposes and for policy development goals, including those identified in the WHO/Europe Parma Commitments (Annerstedt van den Bosch et al., 2014a, 2014b).

At smaller spatial scales, land use and ownership information is available for many municipalities and counties across the United States and Europe, often at an individual parcel or lot level. These types of data provide more contexts for GS within the built environment, for example, allowing the user to distinguish a public park from a private cemetery, determine access points, or observe the types of features (roads, parking lots, buildings) that surround the GSs. Assessments at this level have much more detail than available from satellite imagery and are mostly used for studies at the municipal or neighborhood scale. Created and managed locally, land use data sets are more difficult to compare across studies, as classification and resolution may vary (Nieuwenhuijsen et al., 2014).

Information can also be analyzed with area demographics, such as those collected by the U. S. census or the American Community Survey, which are available at census block levels and higher. For more qualitative spatial assessments, open-source resources such as OpenStreetMap can be used to identify specific GS features, such as parks, trails, or playgrounds (Agay-Shay et al., 2014).

Data from large-scale surveys are also used to measure access to and use of GS. These data cover a larger extent than many field-based measures, but they are distinct from land cover and GIS-based measures of exposure. In such surveys, respondents are asked to report their access to and/or use of GS. Sometimes these are relatively crude measures. In the European Quality of Life surveys, for example, respondents are asked to rate their ease of access to recreational//green areas, and whether they use them. However, sometimes the measures are sophisticated, with environment type, visit purpose, and activity carefully captured. The English Monitoring Engagement with the Natural Environment survey is an example. In general, the more sophisticated the capture of exposure to and use of natural environments, the less sophisticated any accompanying health metrics tend to be. Self-reported general health, for example, might be recorded for use as a predictor of contact with nature, rather than as a consequence. Yet, larger surveys capturing exposure to and/or use of GS in less detail often also capture useful self-reported health metrics such as mental well-being. Where fine-scale geographic identifiers are available, the measures of natural environment captured in all these kinds of survey can also be compared to surrounding GS (Grigsby-Toussaint et al., 2015).

The most detailed methods used in GS exposure analysis occur in the field; GS audits, questionnaires, or monitoring data from participants can provide a full picture of perceptions, lifestyle decisions, and actual engagement with GS (Kondo et al., 2015). GS and street audits are conducted either in person or by using street imagery, such as Google Street View, and they assess physical features as well as real-time population counts.

Questionnaires can provide information such as self-reported physical activity, stress levels, and perceptions of nearby GS availability, safety, and self-reported engagement (Nieuwenhuijsen et al., 2014; Kondo et al., 2014). Although many researchers obtain biomarker data in clinical settings, monitors worn by participants can also record several types of behavior and exposure, including real-time location and movement, environmental exposures, heart rate, and accelerometry (Almanza et al., 2012; Adlakha et al., 2014; Ryan et al., 2015).

Studies are beginning to investigate responses to GS exposures in experimental settings (Jiang et al., 2014a, 2015; South et al., 2015). Online methods such as crowdsourced image analysis are also being used to assess built environment quality (Hipp et al., 2013b; also see Mappiness, http://www.mappiness.org.uk/). While these methods can produce a more complete picture of individual exposure, they require significant human and technological resources. Often, research that uses monitoring or in-person audits is applied for specific places or projects, such as a neighborhood block, school, or a planned event or intervention. Studies using smaller sample sizes or specific geographical areas commonly face limitations to external validity and the ability to compare among different populations and areas.

There is emerging consensus that GS exposure assessments should consider more detailed exposures related to duration and frequency, population subgroup, and the specific design and communication attributes of the GSs being studied. Temporal variation in both GS and human engagement can affect exposure over short-term periods, but also by season and across the life course (Rosso et al., 2011). Additional research is needed to identify the appropriate distances and times at which to evaluate GS, and whether these may vary across different pathways (U.S. EPA, 2015).

Hunter et al. (2015) present evidence that specific features of a space, such as design of amenities and species composition, can affect perceptions and usage of GSs. However, communication and local context is important to understand how GSs are integrated with a specific area and how to optimize engagement surrounding an intervention to improve public health (e.g., activity programming for a new multi-use path) (Nieuwenhuijsen et al., 2014; Hunter et al., 2015). Developing and validating metrics to account for these issues is an ongoing effort in GS exposure assessment research.

4. GREENSPACE (GS) AND HEALTH

The technical presentations on health effects of GS are summarized in Section 4.1, and key points are highlighted in Table 4-1. Key health considerations identified from these presentations and the subsequent group discussions are highlighted in Section 4.2. Approaches and measures for GS health assessments are described in Section 4.3.

4.1. TECHNICAL PRESENTATIONS

Multiple experts led the presentations on assessing health effects of GS within the topical areas identified in the agenda. Key points from each are highlighted below. While the state of research on each of these outcomes differs substantially, this section aims to present the current established and hypothesized pathways for GS exposure and the mechanisms through which it may impact specific populations and health outcomes.

4.1.1. Respiratory Effects

Patrick Ryan (*University of Cincinnati*)
Geoffrey Donovan (*USFS*)

An evaluation of studies of allergic reactions that focused on respiratory conditions such as asthma indicated that some chronic effects are linked to repeat occurrences of acute effects, such as chronic inflammatory airway disorder associated with repeated asthma attacks. Mechanisms are well understood for respiratory effects from pollen, air pollution, and specific indoor allergens (e.g., dust mites, cockroaches, and pets). Less understood are how these factors might interact with conditions in the physical or social environment to influence asthma (i.e., environmental conditions that can exacerbate or moderate the frequency and severity of asthma attacks). Some are related to GS (e.g., pollen and physical activity), while others are related to community or physical attributes (e.g., crime rate, weather, and community resources). Sociobehavioral benefits from GS are well established. Benefits include crime reduction, stress reduction, and an increase in people's physical activity.

Environmental benefits are less pronounced and somewhat dependent on the metrics used, but they include reductions in heat, noise, and air and water pollution. Among the deleterious environmental impacts of GS are increased exposure to allergens, certain volatile organic compounds (VOCs), and pesticides/fertilizers (e.g., from GS maintenance).

Table 4-1. Presentation highlights: health effects of greenspace (GS)

No.	Topic	Scope notes	Presenters	Key points
1	Respiratory effects	Includes allergy/ asthma and beneficial effects (e.g., air filtration)	Patrick Ryan (*University Cincinnati*) Geoffrey Donovan (*USFS*)	• Potential benefits of GS exposure and mechanism • Potential risks of GS exposure and mechanism • Exposure characterization issues • Previous findings and preliminary results from asthma/allergy cohort: NDVI more associated than access
2	Reproductive effects		Geoffrey Donovan (*USFS*) Perry Hystad (*Oregon State University*) Yvonne Michael (*Drexel University*)	• Consistent findings for improved birthweight with higher GS exposure • Small signals but potentially significant at population and economic scale • Discussion of birthweight as outcome—"blunt" measure, could be refined to other markers • NDVI more associated than access, more evidence needed to establish mechanistic pathways
3	Obesity and physical activity		Matilda Annerstedt van den Bosch (*Swedish Agricultural University*) J. Aaron Hipp (*NC State University*)	• Evidence of urban parks as settings for health benefits related to physical activity • Uncertainties around proximity vs. activity in parks • Use of big data: crowdsourcing, monitors, and mobile devices • Policy implications
4	CVD and mortality	Includes cause-specific and all-cause mortality	Perry Hystad (*Oregon State University*) Mark Nieuwenhuijsen (*CREAL*)	• Mortality difficult to relate to GS; requires large sample size • Small reduction in all-cause mortality from GS • Reduced GS via removal of ash borer-infested trees related to increased respiratory and CVD deaths • Moderate/high evidence regarding GS and non-CVD effects

Table 4-1. Presentation highlights: health effects of greenspace (GS) (continued)

No.	Topic	Scope notes	Presenters	Key points
5	Neurologic/ neurodevelop-mental effects		Mark Nieuwenhuijsen (*CREAL*) Patrick Ryan (*University of Cincinnati*)	• Mental health disorders fourth leading cause of disability adjusted life years (lost) (DALYs) • Indirect benefits on child neuro health via noise, mixed re air pollutants • Direct benefits of recovery from fatigue • Reduction in stress and crime • Possible mechanisms of increased physical activity and social interactions
6	Psychosocial effects		Michelle Kondo (*USFS*) Matilda Annerstedt van den Bosch (*Swedish Agricultural University*) Julia Africa (*Harvard TH Chan School of Public Health*)	• Stress biology is multifaceted • Expanding use of mobile technology for "GS exposure" • Some focused research: recently greened vacant lots, use of virtual reality nature scenes and sounds • Mechanisms not always understood (social stressors like racism or perceived inequities diminish resilience and increase the need for stress mitigation activities or resources like GS)
7	Attention restoration/ cognition		J. Aaron Hipp (*NC State University*) Laura Jackson (*EPA*)	• Four mechanisms proposed • Attention restoration related to school performance and elderly cognition • Nature appreciation and social interaction can reduce stress (Note that stress is distinct from mental fatigue, which can result from stressful and delightful experiences, and the underlying physiological and neural pathways differ.)
8	Economic and community benefits	Includes property values, crime/safety	Michelle Kondo (*USFS*) Geoffrey Donovan (*USFS*)	• Perceptions: safety vs. property attractiveness vs. energy savings • Strong influence of community involvement

Table 4-1. Presentation highlights: health effects of greenspace (GS) (continued)

No.	Topic	Scope notes	Presenters	Key points
9	Specific populations and health	Includes age, lower socioeco-nomic status (SES)	Richard Mitchell (*University of Glasgow*) Patrick Ryan (*University of Cincinnati*)	• Mixed benefits per gender • Equigenesis not established yet • More benefits to those in financial difficulty • Differential impacts on population age groups needs info on effect susceptibility vs. age

Highlights of the Cincinnati Childhood Allergy and Air Pollution Study (CCAAPS) that focused on traffic-related air pollution (TRAP) showed that closer proximity to objectively measured GS (NDVI) was associated with a lower probability of asthma, although closer distance to the nearest park was associated with higher probability for asthma for both low- and high-TRAP conditions (Ryan et al., 2015).

4.1.2. Reproductive Effects

Geoffrey Donovan (*USFS*)
Perry Hystad (*Oregon State University*)
Yvonne Michael (*Drexel University*)

A recent evaluation of GS effects on reproductive outcomes identified three possible causal pathways (Kihal-Talantikite et al., 2013). The most plausible biological pathway is the psychosocial pathway where GS affects maternal stress through a psychoneuroendocrine mechanism. Health improvements included promotion of psychological restoration, improvement of attention, and reduction of stress and anxiety.

A physiological pathway where GS affects maternal health has been identified but is only considered hypothetical at this stage. Postulated physiological benefits include changes (improvements per reduced stress) to mental disorders, cardiovascular disease, and metabolic disruptions. The third pathway is the reduction of environmental risk factors, including air pollution, noise, and microclimates (mainly heat). Most studies investigated some relationship to probability of low birth weight (James et al., 2015; Dzhambov et al., 2014). The GS effect on low birth weight was small, with mixed evidence of GS impact on preterm and very preterm births.

4.1.3. Obesity and Physical Activity

Matilda Annerstedt van den Bosch (*Swedish Agricultural University*)
J. Aaron Hipp (*North Carolina State University*)

Evaluations of the benefits of physical activity (PA) have considered both direct impacts and improved activity associated with GS. The direct health benefits are widespread, from reduced early mortality to reduced obesity rates to increased cellular antioxidants. For most endpoints, there is strong causal evidence for the benefits of PA. The exception is urbanized areas with high levels of noise and air pollution, where PA with increased breathing rate results in higher pollutant exposure. Research shows mixed results; in one study, Dadvand et al. (2014) showed a relationship between living close to parks and 60% higher relative prevalence of asthma in children, but found benefits of greenspace for body weight and sedentary behavior. Considering potential effects related to physical activity, biking along high-use roads could potentially reduce the benefits of PA (due to adverse health effects associated with exposure to traffic-related pollutants). While GS size and proximity correlate with PA, the type of activity is influenced by the specific user group; the attributes and facilities (such as fields and trails) also matter, as do communication and programming efforts around GSs (Hunter et al., 2015). Measurement of PA is varied. Actigraph, an accelerometer device, is widely validated in epidemiology studies of PA. New tools include mobile devices and crowdsourcing annotations of outdoor scenes (Adlakha et al., 2014; Hipp et al., 2013b). Results show temperature and seasonal dependence and suggest that winter monitoring should focus on malls and other large indoor walking areas. Several policy weaknesses were identified regarding planning and design of GS, mostly that empirical evidence is rarely used, particularly information on GS quality (Veal, 2012).

4.1.4. Cardiovascular Disease and Mortality

Perry Hystad (*Oregon State University*)
Mark Nieuwenhuijsen (*CREAL*)

Relating mortality to GS is complicated. While mortality is an observable, discrete endpoint, it has multiple causes and is best measured in terms of early mortality (e.g., years of life lost). Mortality studies require large population sizes, and results are often expressed as risk ratios. Most often, GS is represented by its area as percentage of the census area unit (CAU), while some researchers use NDVI at the CAU or a buffer zone. All-cause mortality reduction was small (8%) when comparing highest to lowest GS metrics (Gascon et al., 2016). In a natural experiment, infestation of emerald ash borers was related to increased respiratory and CVD mortality, with a greater effect in counties with higher household income: 6.8 additional respiratory disease deaths per 100,000 adults and 16.7 additional CVD deaths per 100,000 (Donovan et al., 2013). Other composite analyses show GS "greenness" having moderate to high strength of evidence for many health endpoints, but low to moderate strength for CVD (Gascon et al., 20162016; Jonker et al., 2014; Takano et al., 2002; Pereira et al., 2012). CVD studies are often cross-sectional and limited to short-term influences on risk factors (e.g., change in blood pressure) so they may not reflect long-term influences. Preliminary results from the Nurses' Health Study for the period 2000−2010 showed no association between NDVI and CVD (James et al., 2015). GS exposure was most often represented by NDVI.

4.1.5. Neurologic/Neurodevelopmental Effects

Mark Nieuwenhuijsen (*CREAL*)
Patrick Ryan (*University of Cincinnati*)

Mental health and behavioral disorders were reviewed in general and for child development in particular. One condition, unipolar depressive disorders, was the fourth leading cause of disability-adjusted life years, or disability-adjusted life years (lost) (DALYs) (WHO, 2001). One review report of 4 child studies and 24 adult studies found limited causal evidence for surrounding greenness and mental health, with one complication of differences in how exposure assessment was conducted (Gascon et al., 2015). GS can reduce exposures to air pollution, heat, and noise. The impact of heat reduction on neurobehavior/mental health is unknown. Noise is associated with neurobehavior and cognition problems in children. GS (trees and shrubs) can reduce noise by 5−10 decibels. While many air pollutants adversely affect central nervous system conditions, GS reductions of pollutant concentrations were small and some GS can exacerbate pollutant-caused conditions (e.g., increased nitrogen dioxide around street trees in urban canyons where tall buildings affect air circulation or increased pesticide exposures from their use in GS areas).

The Cincinnati Childhood Allergy and Air Pollution Study of TRAP showed a few statistically significant GS benefits, but only for areas with high TRAP and only for a few markers (e.g., hyperactivity at age 7 with GS measured by NDVI). In general, GS improves neurobehavioral conditions and mental health by recovery from fatigue; reduction in stress and crime; and physiological measures, including changes in stress indicators (e.g., salivary cortisol, blood pressure). Possible mechanisms include direct effects from viewing and being near GS and the presumption that GS increases physical activity and social interaction, which contribute to improved mental health, although evidence remains inconsistent, particularly for physical activity (Dadvand et al., 2015; Maas et al., 2008; Ord et al., 2013; Lee and Maheswaran, 2010).

By measuring regional cerebral blood flow, one recent study has shown that GS exposure reduces rumination, which is indicative of depression, as well as neural activity in an area of the brain linked to risk for mental illness (Bratman et al., 2015).

4.1.6. Psychosocial Effects

Michelle Kondo (*USFS*)
Matilda Annerstedt van den Bosch (*Swedish Agricultural University*)
Julia Africa (*Harvard TH Chan School of Public Health*)

An overview of stress biology included the pathways of adaptation, resilience, and pathophysiology. Highlights of mobile measurement technology include wearable monitoring devices such as wristbands, chest straps, and headsets that can capture biomarkers of stress and mood. Results from several studies showed health benefits of various GS elements and measures. The viewing of recently “greened” vacant lots resulted in decreased heart rate (South et al., 2015), and a separate study found improved mental health endpoints for those who moved to greener area compared to those who moved to an area with less urban GS (Alcock et al., 2014). Experimental exposures to virtual nature paired with natural sounds (although not to virtual nature alone) resulted in improved physiological stress recovery (Annerstedt et al., 2013). In some studies, GS was associated with improved social cohesion, noted by increased social contact and sense of belonging to a community (Kuo et al., 1998; Kweon et al., 1998; Maas et al., 2009a). GS characteristics most related to improved social cohesion included safety perceptions, well-maintained GS areas, and GS engagement such as community gardens (Francis et al., 2012; Hartig et al., 2014). Measurement of GS using only NDVI is clearly not adequate for measuring how GS affects social cohesion. Exposure to nature has also been found to increase prosocial behavior (Zhang et al., 2014). Although some results derive from reduced stress, other causal mechanisms (e.g., those based on social cohesion) are not well understood; however, there is strong evidence on social isolation having a significant negative health effect (e.g., decreased cognitive function, CVD) (Boss et al., 2015; Samuel et al., 20142014). Entrenched institutional disenfranchisement in subpopulations based on race, ethnic group, education, or economic status could diminish resilience to the adverse impacts of stress. As a social setting, GS can play a role in supporting adaptive behaviors at both community and individual levels (Waverijn et al., 2014).

4.1.7. Attention Restoration/Cognition

J. Aaron Hipp (*North Carolina State University*)
Laura Jackson (*EPA NHEERL*)

Four prevailing mechanistic theories were presented related to GS impacts on health that involve psychological and mental function. Stress reduction theory (Ulrich et al., 1991) was presented previously at this meeting and suggests that GS exposures result in decreased cortisol (Ward Thompson et al., 2012) and blood pressure (Hartig et al., 2003), with concomitant lessening of other health consequences (e.g., dietary disruptions). Attention restoration theory hypothesizes that GS is linked to improved attention and cognitive function (Hartig et al., 1996), including improved academic performance in children (Taylor et al., 2001). One key aspect of nature appreciation theory is that the presence of GS can lead to general mood improvement as well as changes to mental health for those who are positively predisposed towards nature. Social interaction theory says GS impacts are related to interpersonal interactions and mostly related to reduced stress as measured by improved feelings of well-being, with a postulated link to increased social cohesion.

4.1.8. Economic and Community Benefits

Michelle Kondo (*USFS*)
Geoffrey Donovan (*USFS*)

Other benefits of GS exist in the areas of safety, housing/property values, and energy expenses. A growing number of studies have established a connection between GS and safety perception and crime occurrence (Bogar and Beyer, 2015; Kondo et al., 2015), although with mixed results. Some GS may trigger fear of crime. For example, an open brown area might be perceived as better for personal safety than lush GS because of fewer and smaller hiding places for criminals; similar perceptions were found for taller trees as safer than shrubs and short trees (Fisher and Nasar, 1992; Nasar et al., 1993). GS in a public housing development (Kuo et al., 1998) and introduced GS on vacant lots (Garvin et al., 2012) were linked with increased sense of personal safety. In addition, multiple studies have shown GS is associated with fewer occurrences of crime of multiple types, ranging from narcotics-related crimes (Kondo et al., 2014) to property crimes (Donovan and Prestemon, 2012; Kuo and Sullivan, 2001) and violent crimes (Wolfe and Mennis, 2012; Kuo and Sullivan, 2001; Branas et al., 2011). It may be that maintained GS is having a reverse broken-windows effect, where environments that appear cared-for signal fewer opportunities for would-be criminals. Much of the positive impact of GS on inner city populations is tied to community involvement and connectedness (e.g., a community-initiated garden could be seen as more beneficial than a city-initiated grassy field) (Kondo et al., 2015). The economic benefits of GS on neighborhoods are more difficult to determine. While shade trees can reduce energy consumption for air conditioning units, the cost savings are much less than the increase in the house's value, indicating that GS perception and attractiveness might be more important than energy costs. Street trees were found to increase house value by $7,000, and neighboring houses within 30 m (100 ft) showed value increases (Anderson and Cordell, 1988; Donovan and Butry, 2010; Donovan and Butry, 2011).

4.1.9. Specific Populations: Health

Richard Mitchell (*University of Glasgow*)
Patrick Ryan (*University of Cincinnati*)

Two distinct conditions have motivated the study of whether GS affects specific populations differently. One is inequality, where different socioeconomic status (SES) or other demographic groups have different access to GS or receive different exposures to GS. Evidence so far is mixed regarding gender differences, where some studies show improvement for men (e.g., CVD) but not for women, while others show opposite gender effects (Richardson and Mitchell, 2010; Roe et al., 2013; Astell-Burt et al., 2014). The other condition is equigenesis, where conditions and processes tend to improve health equality. Mental health inequality (related to income) seemed smallest for GS with highest/easiest access. Escaping to nature showed more benefit (per mean life satisfaction) for people in financial difficulty than those living comfortably. It is unknown how the equigenic effect, if real, happens. Perhaps it is because impacts are more readily apparent for people in poorer health (e.g., by GS access) compared to those in good health. Impact of GS is likely to vary across age groups and across specific health endpoints. Understanding age-group susceptibility to each major endpoint is then critically tied to understanding the mechanisms by which GS affects those endpoints.

4.2. KEY EFFECT CONSIDERATIONS

Except for indirect influences of GS, such as reduced psychological stress, the information on causal mechanisms relating to GS health effects is generally scant. Of the various effects studied so far, well-known measurement methods are commonly used for some (e.g., asthma and CVD). The difficulties arise in the various ways to describe (and measure) the GS exposure. Childhood asthma is the most well studied respiratory effect in terms of general etiology regarding certain air pollutants such as ozone and particulate matter (PM), but evidence of relevant mechanisms for GS is mixed. Some effects (with asthma as a notable example) have been shown to reflect toxicological interactions among heat, pollution, and neighborhood violence (Gupta et al., 2010).

For many endpoints, community or personal interaction with the GS is key to the beneficial impacts and sometimes-adverse impacts (e.g., pollen exposures among allergic populations). Some beneficial effects include CVD improvement from increased exercise, which can be enhanced by the presence and use of GS. Some SES characteristics are variable in terms of GS impacts (e.g., using GS as a retreat is more beneficial to those in financial difficulty than those well-off). The health effects studied seem highly influenced by the way GS is measured or described, as well as by multiple other personal and community characteristics, including the type and extent of personal engagement with GS and certain genetic vulnerabilities.

4.2.1. Specific Qualities of Respiratory Studies

Ambient air is not fixed to a specific location. Thus, studies across multiple locations are highly desirable to account for variations of air quality and respiratory disease that are not necessarily related to GS. Respiratory disease affects large population segments, especially children with asthma (and parents coping with affected children) and those of all ages with adverse reactions to allergens. Childhood asthma has been heavily studied because of environmental regulations on ozone and PM. There is much more information on modes of action for asthma than for most outcomes, but little of that data mechanistically relates to GS. Causal pathways linking psychological stress and asthma and pollen to respiratory effects in allergic people have been targets of multiple studies. These studies help evaluate short- and long-term exposure to and engagement with GS.

4.2.2. Specific Qualities of Neurological, Psychosocial, and Attention Studies

Neurological, psychosocial, and attention studies are grouped because they share many features and peculiarities related to effect measures and causal pathways. Many neurological, psychological, and behavioral measures involve combinations of physical and biochemical measurements with judgments about what constitutes an abnormal response. Some outcomes such as those related to mental health status, child neurodevelopment, and child academic performance are of significant public health importance (as described in studies from the United States and Europe), so even small improvements could be deemed socially significant. The subjective nature of the effects characterizations can increase the variability across studies. Some psychosocial effects are linked to community interactions and can then reflect GS engagement by the community, such as cooperative planting of gardens. For the mediating factors or outcomes generally termed psychological stress, biomarkers exist that help evaluate small changes, such as blood pressure and cortisol levels, can help establish causal connections to even short-term GS engagements.

4.2.3. Qualities of Studies of Other Health Outcomes

The interpretation of GS studies of other health outcomes also can be affected by the characteristics of the studies. For example, attributing reductions in CVD mortality to GS exposures may be difficult unless the study population size is quite large. Reductions in obesity seem mostly related to increased physical activity (frequency or quality); thus, the two aspects ideally are measured together. Some measurements are not strictly health outcomes but do contribute to community or personal sense of well-being, potentially affecting health. These can include property value, perceptions of community safety and property attractiveness, and a sense of community involvement.

4.3. ASSESSMENT APPROACHES AND MEASURES

The health effects in the GS studies are generally monitored and measured using standard tools, biomarkers, and protocols. Typical measures and effects include the following:

- Psychological measures: attention restoration, social ties, quality of life, and life satisfaction through questionnaires or surveys, either standardized or study-specific.
- Physiological stress measures: serum cortisol and salivary cortisol as biomarkers that can be used to measure stress level from allostatic load; also see the further measures listed below for CVD.
- CVD measures: blood pressure, heart rate, heart rate variability, T-wave amplitude (e.g., measured via electrocardiogram applications), myocardial infarction, stroke, and cardiovascular-related hospitalizations and mortality.
- Neurobehavioral measures: neuroimaging techniques, such as electroencephalogram, functional magnetic resonance imaging, functional near-infrared spectroscopy, arterial spin labeling, electrode cap, and cognitive/neurobehavioral/attention-repetition tests.
- Reproductive measures: birth weight (notably small for gestational age and preterm delivery); maternal stress and health (both a risk factor itself and an influence on other risk factors).
- Respiratory measures: forced expiratory volume (FEV), forced vital capacity, asthma-allergy morbidity, childhood asthma emergency room visits.
- Mental health/well-being: general health questionnaire, strengths and difficulties questionnaire, neurobehavioral AR tests, and emotional and psychosocial tests.

- Mortality: both all-cause and cause specific (e.g., CVD mortality).
- Other measures and combinations: life expectancy, personal characteristics (e.g., CVD in women), and short-term influences on other risk factors (e.g., blood pressure).

Recent advances in personal monitoring technology have been used to measure physical activity, which is an intermediate factor in several health effects (Almanza et al., 2012; Adlakha et al., 2014). These technologies allow people to measure activity durations and locations. Similarly, recent advances in automated sensors and information technology are producing large quantities of different types of data, including from crowdsourced data gathering, often called "big data." Many of these data are measures of intermediate factors or influences on health outcomes instead of the more common morbidity data. Perhaps the best example thus far is physical activity, which is well linked to improvements in cardiovascular function and reductions in psychological and physiological stress. Physical activity can be one direct indicator of the extent of personal engagement with the GS. Data can now be compiled from crowdsourced images (stills and videos) showing where, when, and for how long individuals are engaged in physical activity. Data from other intermediates similarly tracked by personal monitoring combined with GPS locations include mood and types of interactions with GS. While personal-level data are the gold standard for these types of characteristics, the compilation and integration of such data are currently impractical for most studies. Thus, current data metrics are typically qualitative and include self-reported exercise, time spent outdoors, and perceptions of GS access and safety.

5. DISCUSSION SYNTHESIS AND CONTEXT FOR CUMULATIVE RISK ASSESSMENT (CRA)

Highlights of the meeting discussions are presented in Sections 5.1 through 5.10, together with selected citations. These discussion points and suggestions are not intended to (and do not) represent consensus among participants nor do they reflect official positions of the EPA. An overview of measures, metrics, and data sources that are used to assess GS exposures, and to a lesser extent, applications for health research, is presented in Table 5-1.

5.1. ISSUES COMMON TO GREENSPACE (GS) AND CUMULATIVE RISK ASSESSMENTS

Several issues are common to GS analyses and CRAs (see Table 5-1). Because GS analyses and the assessment of cumulative risk are both relatively new areas of scientific study, the basic terminology used in these two areas is evolving and inconsistent across studies and researchers. The data necessary for a risk assessment to be considered “cumulative” and the physical features that must be present for a space to be considered a GS have not been standardized. The inclusion of nonchemical stressors is common to both CRA and GS research. While vulnerability can be defined differently across disciplines, both CRAs and GS assessments can examine how best to evaluate the influence of intrinsic factors (e.g., genetics) and extrinsic factors (e.g., social support groups and health clinics; see DeFur et al., 2007), as well as how to integrate these sources of vulnerability into an analysis.

Part of the planning phase of any risk assessment is to identify the scope and characterize the affected population(s); CRA and GS analyses incorporate these two factors in different ways. The scope of a CRA is often defined to increase the tractability of the multiple factors being addressed. Simplification can involve placing limits on the number of chemicals, exposure pathways, or health effects to include. With GS evaluations, the scope of the analysis generally relates to the physical boundaries (e.g., the definition of the type and boundaries of the GS), although the list of potentially affected health endpoints in the nearby population is often considered in the assessment scope. While few GS studies have compared results from different definitions of assessment scope, many acknowledge the uncertainty (i.e., results may depend on the chosen scope).

Table 5-1. Greenspace (GS) exposure measures and metrics and health applications[a]

			Spatial scale and resolution			
Greenspace tools and measures	**Information resources *(organization)***	**Metrics**	**Scale**	**Resolution**	**Health applications**	**Selected references**
Vegetation coverage	NDVI: *Also:* *EVI: (MODIS)*	Mean and/or variation in vegetative cover per unit *Saturated greenness*	Global	30 m−250 m *250 m*	Reproductive, respiratory, CVD, all-cause mortality, sleep duration, anxiety and depression, stress response, children's mental health/behavior	Fan et al. (2011) Dadvand et al. (2012a) Dadvand et al. (2012b) Wolfe and Mennis (2012) Agay-Shay et al. (2014) Sarkar et al. (2013) Amoly et al. (2014) Balseviciene et al. (2014) Beyer et al. (2014) Dadvand et al. (2014) Markevych et al. (2014) Grazuleviciene et al. (2015) Li et al. (2015) Triguero-Mas et al. (2015)
Tree coverage	Street trees *Also:* *MODIS* *Landsat tree cover*	Street tree density per unit; crown area *Also:* *LAI:* *Percent tree cover*	Municipal	Varies per application *1,000 m* *30 m*	Respiratory, allergic sensitization (to pollen), economic impact: crime	Donovan et al. (2012) Lovasi et al. (2013) Jiang et al. (2014a) Jiang et al. (2014b) Jiang et al. (2015)

Table 5-1. Greenspace (GS) exposure measures and metrics and health applications[a] (continued)

Greenspace tools and measures	Information resources *(organization)*	Metrics	Spatial scale and resolution		Health applications	Selected references
			Scale	Resolution		
GIS: land cover and use, GS coverage	National Land Cover Database	Land cover diversity: mean number of land cover types per unit, land cover, composition	United States	30 m	All-cause mortality, stress response, mental health and well-being	Fan et al. (2011) Mitchell et al. (2011) White et al. (2013)
	CORINE: *(European Environment Agency)*	Land cover composition and classification, percent GS coverage	Europe	25-ha mapping units	Obesity, mental health, all-cause mortality, and more	Annerstedt et al. (2012)
	Urban Atlas (as an example of country-wide land use data)	Urban land use, thematic classification into mapping units; population within distance to GS	European cities	0.25 ha	Population access, ecosystem services	Annerstedt van den Bosch et al. (2014a, 2014b) Larondelle et al. (2014)
	Ordnance Survey Master Map	Surface features, includes vegetated areas >5 m^2 except domestic gardens, regardless of accessibility (public and private)	Scotland, United Kingdom	5 m^2 (1:1,250 map scale)	CVD, all-cause mortality	Richardson and Mitchell (2010)
	Generalised Land Use Database (GLUD)	Land cover composition, percent GS coverage	United Kingdom	1,000-m low-level super output areas	Mental health, children's mental health/behavior	Alcock et al. (2014) Flouri et al. (2014)

Table 5-1. Greenspace (GS) exposure measures and metrics and health applications[a] (continued)

Greenspace tools and measures	Information resources *(organization)*	Metrics	Spatial scale and resolution		Health applications	Selected references
			Scale	Resolution		
GIS: land cover and use, GS coverage (continued*)*	CORINE/GLUD hybrid *(CRESH*)	Land cover composition, percent GS coverage	Scotland, United Kingdom	Census area statistics ward; small area level	Stress response, well-being	Mitchell and Popham (2008) Richardson and Mitchell (2010) Thompson et al. (2012) Roe et al. (2013)
	National Land Cover Classification Database	Land cover composition, percent GS coverage	Netherlands	25 m	Psychiatric morbidity, anxiety and depression	de Vries et al. (2003) Maas et al. (2009a) Maas et al. (2009b) Van den Berg et al. (2010)
	Land use classification	Percent parkland	Australia	Census collection districts	Sleep duration, physical activity	Astell-Burt et al. (2013) Astell-Burt et al. (2014)
	Land Class Database II/ Conservation Area Boundaries/Land Information New Zealand hybrid	Land cover, percent GS per unit	New Zealand	CAU	Anxiety, mental health	Nutsford et al. (2013) Richardson et al. (2013)

Table 5-1. Greenspace (GS) exposure measures and metrics and health applications[a] (continued)

Greenspace tools and measures	Information resources *(organization)*	Metrics	Spatial scale and resolution		Health applications	Selected references
			Scale	Resolution		
GIS: land cover and use, GS coverage (continued)	UTC	Land cover composition	Municipal	1 m	Reproductive effects, respiratory effects	Nowak et al. (2006) Donovan et al. (2011) Lovasi et al. (2013)
	High resolution land cover	Land cover composition	Municipal	60 cm	Economic impacts: housing prices	Li et al. (2015)
	Also: Landsat forest cover change	*Percent forest cover change*		*30 m*		
	ForWarn (USFS)	*Forest change, seasonal phenology, event-specific changes*		*232 m*		
	Gap analysis	*Land cover diversity and composition, percent protected land*		*30 m*		
	LANDFIRE	*Existing vegetation type, cover, height*		*30 m*		
Urban greenspace	Urban GS index *(WHO)*	Access to GS (within 300 m) of a 1-ha minimum size, excludes private gardens within housing areas, cemeteries, buildings	European region of WHO	Varies per application	Physical activity, stress response	Annerstedt van den Bosch et al. (2014a)

Table 5-1. Greenspace (GS) exposure measures and metrics and health applications[a] (continued)

Greenspace tools and measures	Information resources *(organization)*	Metrics	Spatial scale and resolution		Health applications	Selected references
			Scale	Resolution		
GS proximity, distribution	Land use	Proximity to GS, proximity to GS of a certain area	Community, municipal, regional, state	Varies per application	Reproductive effects, CVD, stress response, children's mental health, all-cause mortality	Dadvand et al. (2012a) Dadvand et al. (2012b) Reklaitiene et al. (2014) Balseviciene et al. (2014) Dadvand et al. (2014) Duncan et al. (2014) Tamosiunas et al. (2014) Grazuleviciene et al. (2015) Triguero-Mas et al. (2015)
	OpenStreetMap	Proximity to GS, proximity to GS of a certain area	Global	Vector	Reproductive effects	Agay-Shay et al. (2014)
	Ecological map of Barcelona	Proximity to GS, proximity to GS of a certain area	Municipal	0.5 m	Anxiety and depression	Amoly et al. (2014) Dadvand et al. (2012a)

Table 5-1. Greenspace (GS) exposure measures and metrics and health applications[a] (continued)

Greenspace tools and measures	Information resources *(organization)*	Metrics	Spatial scale and resolution		Health applications	Selected references
			Scale	Resolution		
Visible greenness, GS quantity	Google Street View	Visible GS from address or street centerlines	Municipal, regional	Varies per application	Physical activity	Brownson et al. (2009)
	EnviroAtlas	Percent GS from walkable street centerlines and school and day-care parcel centroids; percent tree cover from busy road edges and 30-m population estimates; percent GS within 250 m; walking distance to nearest park entrance; percent GS, tree cover, wetlands, and water by census block group and 12-digit HUC	Community, national	Varies per application (1 m−30 m)	Multiple hazard buffering and health promotional ecosystem services (varies per application)	Jackson et al. (2013) Pickard et al. (2015)
	Topography, building footprints, ArcGIS viewshed tool	GS viewshed	Spatially explicit	Varies per application	Stress response, allostatic load	South et al. (2015)
	Aerial photography, Google Earth	Tree counts, crown area	Site-specific; national	Varies per application	Neurobehavioral effects, stress response, economic impacts: housing prices	Kuo and Sullivan (2001) Donovan and Butry (2010) Donovan and Butry (2011)

Table 5-1. Greenspace (GS) exposure measures and metrics and health applications[a] (continued)

Greenspace tools and measures	Information resources *(organization)*	Metrics	Spatial scale and resolution		Health applications	Selected references
			Scale	Resolution		
GS quantity, quality, use	GS audits	Tree counts, tree measurements (e.g., diameter at breast height), species composition, people counts and demographics, activities, GS attributes	Community, municipal, regional, state	Varies per application	Physical activity, anxiety and depression, reproductive effects, economic impacts: housing prices	Weich et al. (2002) Araya et al. (2007) Donovan et al. (2011) Francis et al. (2012) Amoly et al. (2014) Reklaitiene et al. (2014) Tamosiunas et al. (2014)
Perceptions of GS, safety, access, quality GS use	GS questionnaires	Perceived safety, perceived access, perceived use, perceived quality, self-reported use	Community, municipal, regional, state	Varies per application	Physical activity, perceptions of GS	Amoly et al. (2014) Reklaitiene et al. (2014) Sugiyama et al. (2014)
GS proximity, use	GPS/GIS	Proximity to GS, routes through GS, time spent in GS and/or near GS features	Individual	Varies per application	Physical activity	Michael et al. (2010) Lachowycz et al. (2012) Adlakha et al. (2014) Klinker et al. (2014)
GS exposure, activity levels	Personal monitors; MapMyRun, accelerometers	Physical activity levels in/near GS	Individual	Varies per application	Physical activity	James et al. (2014) Klinker et al. (2014)
GS health effects	Controlled GS exposure settings	Cognitive performance, stress measurements	Individual (classroom), streets	Not applicable	Neurobehavioral effects, stress response	Jiang et al. (2014a) Jiang et al. (2014b) Jiang et al. (2015)

[a]The entries are presented in the general order of broadest application to more specific.
The measures, metrics, and resolutions not currently linked with a health application are shown in lighter font and italics, to place more attention on those with existing health applications.
(Note that the references are provided as a group and do not necessarily line up with individual entries that are grouped within the corresponding columns.)

For CRAs, the population characteristics commonly relate to personal factors affecting susceptibility to health effects (e.g., per chemical toxicity), while also considering behaviors that influence exposure pathways, exposure duration and timing of exposures. For GS analyses, the population could include those residing near or using features of the GS. In GS analyses, "population characteristics" often relate more to existing health status (e.g., psychosocial stress) and engagement between the population and the GS. To date, the health effects associated with GS proximity and exposures are usually characterized as protective of or otherwise beneficial to health.

One issue common to both CRA and GS evaluations is the reliance on qualitative and self-reported measures of engagement and behavior. Many GS parameters are indeed quantitative, such as NDVI estimates of GS area; quantitative health correlates include serum or salivary cortisol levels to gauge psychological stress. Many parameters, however, are subjective or ranked, such as responses to surveys about perception (e.g., of dangers or personal stress), and the categorization of GS by population use and level of physical activity.

Cumulative risk evaluations that are primarily qualitative are frequently used to set priorities (e.g., to screen for priority hazards and risks in a community), and some are explicitly described as not providing a true risk estimate (e.g., the Cal/EPAEPA [2014] EnviroScreen Tool). One consensus of the work group is that GS evaluations are insufficiently advanced to allow high confidence in incorporating these analyses into a traditional risk assessment involving chemical exposure or exposure-response relationships.

Issues common to CRA and GS evaluations include:

- Inconsistent definitions
- Multiple factors: stressors, exposures, population groups, effects
- Spatial: place-based
- Temporal: acute, short-term, chronic, intermittent, continuous
- Population characteristics: socioeconomic, cultural and other susceptibility factors
- Limited information regarding accessibility is available for inclusion into the assessment: to GS (GS assessments); to health care, public and social services (CRA assessments)
- Limits of extent, resolution for spatial data sources
- Health effects, exposure-response relationships (knowledge limitations regarding potential pathways, associations versus causal mechanisms [for GS]), interactions

- Indices, proxy or surrogate measures
- Generalizability potentially limited by a lack of understanding of underlying mechanisms
    - Limited generalizability of exposure across geographic locations and settings
    - Limited ability to extrapolate findings across different populations and subgroups
- Often qualitative (limited quantitative estimates); can use for screening, ranking

5.2. EVOLVING FIELD OF GREENSPACE (GS) ANALYSES

GS analyses may continue to improve in several ways that potentially will make it more feasible to generalize from the results of a study of one GS and its affected population to another GS and its population. These improvements will make such assessments more amenable for incorporation into risk assessments.

The metrics used to measure GS will likely continue to improve in both resolution and specificity and could make better data available for exposure assessments in more places than currently exist. Continued evolution is expected toward standard metrics to describe the GS and assess potential exposures. For example, with chemical-based CRAs, "mixture" is used even for exposures that are not coincident in time, as long as the chemicals or their effects overlap within the bodies of the exposed individuals. Metrics are needed to address different components of GS, characterize previous exposure to or interaction with GS, and describe multiple levels and critical time windows for exposure in a population.

Although a few examples exist where causal pathways have been suggested to explain how GS exposure affects a specific health outcome, further progress is expected as additional studies of the health effects associated with GS exposures are conducted. Additionally, studies are being conducted that apply both quantitative and qualitative approaches to evaluate the strength of evidence associated with biological pathways that might link GS exposures with a health outcome. Such weight-of-evidence frameworks are recommended by scientific panels (e.g., NRC, 2009; The Presidential/Congressional Commission on Risk Assessment and Risk Management, 1997). They are used in ecological risk assessments (e.g., Suter and Cormier, 2011), have been proposed for cancer risk assessments of chemicals (U.S. EPA, 2005), and have been used for evaluating toxicological interactions among mixtures (U.S. EPA, 2000; ATSDR, 2004). Strength- and weight-of-evidence approaches, including meta-analysis, can be used to synthesize information from different types of studies as well as those of varying quality.

5.3. APPROACHES TO ADDRESS RANGE OF GREENSPACE (GS) TYPES AND SPATIAL AND TEMPORAL SCALES

As an emerging field, GS exposure assessment has followed existing GS quantification methods used in urban planning and forestry. Proximity of the GS to the nearby population has been shown to depend on the particular metric employed (e.g., linear distance to the border of a park versus walking distance to the entrance of the park). The bounding and areal measures of GS have also been expressed with a few common metrics, such as NDVI and skylight detection, as well as the inclusion of vegetation on personal property and greenery in public areas.

A number of health outcomes have been associated with GS, as described in Chapter 4. For psychological effects, an important distinction has been made between different types of positive changes in psychological stress, for example, between recovery from stress and recovery from attention fatigue, and how these changes may be connected to different health outcomes.

Further studies are needed to better characterize the potential for variations in health outcomes due to seasonal changes in GS. For example, consider that northern and central U.S. climates can exhibit dramatic changes in levels of greenness and time spent outdoors associated with GS depending on the season. Examining the influences of seasonally influenced changes in foliage levels and exposures to these levels on health outcomes would be a valuable area for future research.

5.4. AVAILABLE EXPOSURE METRICS: APPLICATIONS AND LIMITATIONS

The geospatial extent, resolution, and type of exposure metric selected for a given study can influence the conclusions that relate GS to health, as highlighted in Chapter 4. For this reason, replicate studies are important, as is the inclusion of different exposure metrics within a single study. This approach can help indicate the influence of a given metric on the results, and, ultimately, it could help build consensus regarding which metrics are more relevant than others for a given health outcome. Examining the influence of multiple metrics might also provide clues about the biological mechanism underlying the relationship between GS and the outcome studied.

A central challenge for GS exposure assessment is distinguishing measures of proximity from those of accessibility and access, as described in Chapter 3. Exposure is broadly defined for GS, so several factors are often included that vary across applications. Exposure magnitude, duration, and the types of interactions between people and the GS are among the more common factors included in GS assessments. Without validation studies and sensitivity analyses on different exposure metrics, it is difficult to determine how robust some conclusions are when applied to different exposure conditions or scenarios evaluated for the GS assessment and CRA application.

5.5. IMPORTANCE OF ENGAGEMENT

Engagement is defined here as the manner and magnitude by which a person or population interacts with a specific GS. The extent and type of engagement can strongly affect the influence of GS on health. The scope of reported engagement varies considerably across studies, from simple proximity to GS, to awareness of GS, to viewing GS through a window, to walking near or stopping in GS, to actual physical activity in GS. The duration of engagement has been shown to be an important factor for both the extent of exposure and the duration of the consequent health impact. The duration of exposure can be quite complex, involving not only the total time over a relatively long period (e.g., a year or more) but also the frequency and duration of each separate encounter with GS. The timing of engagement might also be important—with exposure to GS sought because of, or coinciding with, episodes of psychological stress or poor health or other types of vulnerability that are potentially more important at that point (for that individual) than at other times. For example, gardens or views of GS could have a different effect on individuals in a hospital setting than the same types of GS elsewhere (Ulrich et al., 1991). Consequently, describing the GS only by its physical characteristics (size, shape, and location) could be inadequate.

The concentration and composition of a GS, designed or not, strongly influence the likelihood and frequency of engagement, which can in turn affect health and behavioral responses. At a basic level, well-placed way-finding features such as marked trails and signs communicate the intended uses and appropriate navigation of the space. Beyond these features, visual and other sensory cues within the GS itself are associated with physiological and psychological effects. A body of literature from both landscape architecture and psychology supports benefits to psychological restoration of natural organizational structure, such as Fibonacci sequences of leaf arrangement in plants (Douady and Couder, 1996) and fractal branching patterns (Kuo and Sullivan, 2001).

Stimuli do not necessarily need to be visual—natural soundscapes, scents (including phytoncides), and sensory cues found in GSGS can elicit healthful responses; additionally, there is a line of research examining the cumulative beneficial effects on stress response. In Japan, the concept of *shinrin-yoku,* or "forest bathing," refers to the unique sensory immersion of walking through a forest and has been associated with a number of psychological and physiological benefits; cultural meanings ascribed to plants or natural features can also function as a psychological cue (Tsunetsugu et al., 2010). Although the perceptions and values of GS vary across places and cultures, the design, or absence of design, can impact the species, vegetation density, and sensory quality of GSs. Design should be considered alongside other contextual factors, such as maintenance patterns or social stressors in the surrounding area.

Because of the benefits of GS to mental well-being, another important factor is social engagement, such as community involvement in design and maintenance of GS (e.g., public gardens). The degree of public accessibility to GS is also a factor, as described both by physical obstacles such as fences and gates as well as public perception regarding ownership and access fees. One study demonstrated that while overall neighborhood vegetation did show direct stress mitigation, this effect was counteracted by its inhibition of social support, suggesting maintained park spaces have a stronger positive effect (Fan et al., 2011). Physical activity is another example of an important type of engagement, whereby activity conducted within GS has shown more benefit to health than similar activity conducted indoors. Beyond providing a setting for social gatherings and physical activity, GS features can contribute additional benefits from engagement with natural attributes (e.g., restorative natural sounds, smells, sights). Research is needed to better characterize the potential combined effects of exposure to GS through multiple and potentially overlapping pathways. GS engagement can influence perceptions directly or indirectly. An example of indirect engagement is the benefit from trees providing shade to reduce temperature. One such finding near Sacramento, CA is that trees on the southwest side are perceived as much more beneficial because they provide shade to residences during the hotter times of the day, even though measurements indicate the energy cost savings are quite small (Simpson, 2002).

5.6. MAINLY BENEFICIAL EFFECTS

Several studies have shown GS to improve public health through the benefits of increased exercise and the direct lowering of psychological stress. Other direct benefits of GS for population health include natural buffers against storm surges, extreme temperatures, and noise (Jackson et al., 2013). Indirect or secondary benefits of reduced stress and attention restoration have also been shown, including improved immune function and test performance (Jiang et al., 2014b). Although the data are presently limited, previously established linkages between psychological stress and specific health effects (e.g., CVD) suggest that GS presence could also lower the risk of those health endpoints. In contrast, a few adverse effects from GSs have been shown too. Among the more obvious is the expected increase in allergic reactions caused by pollen from trees and grasses (but note that not all GS measures include grass). Some tree species (e.g., sweet gum) produce VOCs, which can increase ozone, but such contributions to air pollution likely are minor when compared with anthropogenic sources. Some airflow channeling by trees, for example those bounding streets, has been shown to reduce the dilution of PM, but more studies are needed to quantify the change to see whether the increase in air concentration and health risk is significant. Few studies have examined GS for population subgroups, but limited findings suggest potential differences in access patterns and health outcomes by gender, race, and income (Mitchell et al., 2011, Adlakha et al., 2014), with limited evidence of increased benefits for more susceptible populations.

5.7. LIMITED QUANTIFICATION OF EXPOSURE-RESPONSE RELATIONSHIPS

Among the strongest consensus conclusions of the work group is that an analog of a chemical's mathematical dose-response relationship with a health outcome has not yet been identified for the impacts of GS on health. While some GS-health relationships are supported by multiple studies (e.g., physical activity correlated with reduced obesity), the mathematical functions that would allow estimating a "minimum effective GS exposure" are not yet available. Part of the difficulty with establishing such a function is the lack of consistency in quantifying both the GS entity and public engagement with GS (i.e., quantifying the GS "exposures"). In addition, many diseases for which GS might be preventative or mitigating (notably noncommunicable diseases) have a complex, multifactorial etiology, which makes drawing causal inference from epidemiological analyses alone very challenging. This lack of quantitative relationships is a major impetus for using strength-of-evidence approaches to support decisions about GS and health.

5.8. UNCERTAINTIES ASSOCIATED WITH EXPOSURE AND HEALTH MEASURES USED IN DIFFERENT GREENSPACE (GS) STUDIES

The uncertainties associated with both exposure measures and various health outcomes have impeded the progress of this GS research area. A lack of understanding regarding the mechanism or mechanisms through which GS might affect these health outcomes underlies many of the uncertainties in the exposure measures.

A consensus definition of GS and GS exposure did not emerge from this meeting. However, there was consensus that GS is foremost a geographic entity, land that is at least partly vegetated and located in or adjacent to urban or suburban areas.[1] There was also consensus that GS should be defined by its geographic attributes (location, area, shape), and that human exposures to GS should be estimated through additional attributes such as composition, proximity and accessibility to population(s), perceptions of the GS, and the nature of public engagement with the GS.

A number of quantitative or qualitative measures could be used to characterize most of these attributes. GS can be characterized by its measure of greenness using average or relative

[1]Several studies have found beneficial effects of wilderness experiences for human health (Cole and Hall, 2010; Hartig et al., 1991; Sachs and Miller, 1992; Vella et al., 2013); however, this workshop focused specifically on greenspace and population effects in urban areas.

NDVI, or by other attributes including proportion of coverage and private versus public ownership. Similarly, proximity to the public can be measured by linear distance or walking distance between a residence and a GS. Many individual measures and combinations can be used to describe and evaluate various attributes of GS and assess “exposure.” However, absent knowledge about the underlying mechanism through which GS affects a given health outcome, GS is often treated as a composite measure.

Spatial resolution for GS imagery can be a source of uncertainty around GS variation and specific GS attributes within the unit of analysis. NDVI is a common example of this issue, where results cannot pinpoint the attribute of GS (e.g., tree versus open areas, species, or design) that is linked to an effect. Similarly, measures that rely on land use or other nonphysical data often miss GS attributes that might influence engagement or exposure.

The differences in measures of GS itself are compounded by uncertainties in the type of GS and actual human engagement. For example, GS size alone might not relate as well to the potential for physical activity as other characteristics of the GS are considered (e.g., signage and physical structures, or perceptions of safety that encourage or discourage public access and use). For example, an attractive and well-defined entryway into GS open to the public likely encourages visits to and activities within the GS; conversely, the presence of fences or other indicators that GS is privately owned or off limits generally discourages activities in such areas. Neighborhood characteristics such as crime incidence also affect attitudes, perceptions, and ultimately engagement with GS; if an area is perceived as unsafe, public access and activity is likely to decline. In addition to built environment components, variations in climate, seasonality, and topography can lead to faulty comparisons among GSGS located in different regions unless adjustments are made for such factors in the analysis. While the total area of GSGS may be the same for two locations, the amount accessible for activity may differ substantially, for example, if one area is steep and another is flat. As described by Wheeler et al. (2015), the type, quality, and context of GS should be considered in assessing relationships between GS and human health and well-being.

Many health outcomes evaluated in relation to GS also have multiple descriptors and different levels of sensitivity. Among the more detailed and precisely defined outcomes are respiratory function and CVD, which are usually measured using common physiological measures (e.g., FEV_1, or percentage occlusion from vascular disease) or specific medical data (e.g., International Classification of Diseases [ICD] codes or insurance data). Among the more vaguely described outcomes is the sense of well-being, which is not affected only by personal history but also by whether it represents a snapshot of present conditions or the extent of change from previously undesirable conditions. Although many studies have found a link between GS and positive well-being, measures of well-being vary across studies (e.g., self-reported or independently assessed), which can be a challenge for validation.

Health outcome data can be reported a variety of ways, including at the individual, city, county, or national level. In addition, some health outcomes are known to depend on age, so if the age of the study participant is not reported, then the measured effect of the GS on the health outcome could be biased. Similarly, several health outcomes that have been associated with GS are potentially exacerbated by heightened psychological stress. Thus, if stress is not also evaluated when studying those outcomes, then the reported measures of association between the GS exposure and the outcome might not be independent.

5.9. UNCERTAINTIES ASSOCIATED WITH INNATE DIFFERENCES IN GREENSPACE ASSESSED IN DIFFERENT STUDIES

Inconsistent definitions can contribute to uncertainty across studies. The innate differences between places and GSGS, combined with the challenges of available data, make it difficult to establish a consistent definition of GS exposure that is applicable and comparable across settings.

Study design, population, and scale are challenges for validating and replicating GS studies. Randomized control trials can be challenging for GS assessments that by definition consider GSGS in the physical environment, the effects of which are difficult to isolate among experimental and control groups. Experimental designs that have examined GS typically involve a view of GS, either through a window or photograph, and compare results to a control group with alternate or no views. This has been helpful in identifying effects of short-term exposure (e.g., occasional use of a park) on short-term outcomes such as acute stress and attention, but it is less suitable for longer-term exposures (such as daily walks through a GS) and related health effects. Some of the variation across studies can be addressed by statistical approaches, as long as certain assumptions about errors and missing data can be appropriately made (e.g., for comparing or combining cross-sectional with longitudinal studies).

While most GS assessments have similar approaches, there are no standard measures or approaches for different levels of detail. This limits the ability to cross-validate GS studies among cities or data sets. GS assessment has several temporal limitations: (1) critical windows of exposure are unknown for specific population subgroups and outcomes and (2) natural areas, particularly trees, can grow slowly, making natural-experiment approaches time and resource-intensive for researchers and evaluators. In a sense, 30-m resolution NDVI has become a *de facto* measure of greenness due to its wide availability, and it may enable comparisons of GS across studies and regions. However, measurements differ across studies, and comparisons of total greenness across regions can overlook important factors such as climate when assessing

GS (e.g., it is difficult to compare GS in Arizona to GS in Maine). Furthermore, a 30-m resolution image cannot capture the different types of GS that may be essential to determining relevant mechanisms and pathways for health. Recently, research has begun to consider "relative greenness," which standardizes an NDVI value using the mean of the surrounding area (James et al., 2015). Studies can also incorporate more detailed GS data, where available, and compare results with NDVI to begin to address concerns about accuracy and validity of the exposure data. Meta-analyses of studies using NDVI could be used to determine whether different measures (e.g., buffer distances) are associated with certain health outcomes, which could indicate different mechanisms.

Studies also face challenges in comparing measures of accessibility. While objective measurements of access, such as park entrances or population within a certain distance of GS, are attainable for most studies, these do not provide information on true patterns of use. Measurements of perceived access and/or safety can be obtained through questionnaires, but these are not feasible for many large-scale studies. Moreover, perceptions are not measures of actual engagement, which must be recorded through observations, self-reporting, or monitoring. Measuring actual GS engagement is not feasible for many studies, which thus rely on secondary data.

5.10. FUTURE RESEARCH DIRECTIONS

Considering the evaluation of GS from a risk assessment perspective, uncertainties around mechanisms through which GS affects human health complicate the interpretation of many studies and make it difficult to fully inform risk management decisions. Future research should focus on identifying mechanisms through which GS can affect various health outcomes, which would help refine GS exposure measures and might identify other health benefits. GS studies are also needed to integrate more effectively with CRAs and support policy analyses.

Research to date has identified five ways GS is thought to influence health; the strength of supporting evidence for each of these varies (Hartig et al., 2014):

1. GS can provide opportunities for physical activity. Researchers have identified and evaluated features of GS that encourage physical activity, and levels of activity have been measured in and around GS. Importantly, improvements in both self-reported and physiological health measures have been shown to be greater following physical activity in GS than that conducted indoors or in highly built outdoor settings (Hartig et al., 2003; Lee and Lee, 2013; Mitchell, 2013; Shin et al., 2013). Although existing research appears to support the finding that GS is often used for physical activity among people who are physically active, this finding is not generalizable. Evidence remains

inconclusive on whether GS, or specific features of a GS, can themselves encourage physical activity, or whether the mechanism is more psychological than physiological.

2. Similar to physical activity, research on GS and social cohesion focuses on the opportunities GS affords for social interaction in gathering spaces (e.g., for picnics, performances, or other events). Community gardens and greening projects are also part of this research theme, for which common measures are self-reported social interactions or sense of community. In the absence of individual data, publicly available data such as housing tenure or crime rates can be examined to approximate community cohesion or disorder (Ewart and Suchday, 2002; Miles, 2008). Again, it is unknown where GS fits into this process and through what mechanisms it acts.

3. Stress reduction and cognitive restoration are perhaps the most studied sociobehavioral categories, and researchers have used a number of study designs to examine the impact of GS on mental health, which can in turn influence multiple outcomes (depression/anxiety, social engagement, CVD). Studies employing experimental designs that compare mental health outcomes associated with greened versus nongreened environments are relatively common in the literature, and these studies consistently show linkages between greener spaces and positive outcomes such as improved attention, reduced physiological stress, and faster recovery times (Ulrich et al., 1991; Kuo and Sullivan, 2001; Jiang et al., 2015). Although evidence continues to build in this area, a gap exists in the understanding of long-term variables concerning both GS exposure and mental health outcomes. In addition, mental health is arguably entwined with both physical activity and social cohesion. More research is needed to understand the interplay among environment, psychology, and behavior related to GS.

4. GSGS can also influence environmental quality as part of both natural and built environments. Water filtration and storage by GS are well-established benefits, as are the dissipation of ocean storm energy and phytoremediation of contaminated soils. GS mitigates the urban heat-island effect; tree cover also provides shade and shelter from UV exposure. Results of research on air quality and GS have been mixed. Some studies report improved air quality around GSGS, while others have found evidence of increased airborne allergens (aeroallergens) or concentrated air pollutants near GS, particularly street trees, which could be detrimental to populations more susceptible to allergy or asthma and other chronic respiratory conditions.

5. GS can contribute to biodiversity, which supports ecosystem function and the capacity to provide hazard buffering and health promotional services to society. The biodiversity hypothesis posits that biodiversity within GS influences the human microbiome, possibly contributing to increased immune function and reduced allergies (Hanski et al., 2012; Rook, 2013; Kuo, 2015). There is evidence of a number of benefits of biodiversity for human health, from psychological benefits of viewing wildlife to the medicinal, economic, and cultural value of native species and ecosystems (WHO/CBD, 2015).

Many combinations of GS features and attributes are possible, all of which might act in some way to influence either the environment or social or psychological processes related to health. With an improved understanding of how GS influences each of these basic mechanisms, the characteristics of GS most relevant to certain health outcomes could be identified. One strategy common in GS literature is the use of GS measurements at multiple distances, which can be helpful in identifying the mechanism. To illustrate, trees within 10 m (30 ft) of a school window might affect the attention of students in a classroom, whereas those at a greater distance might present opportunities for physical activity and social engagement. Consideration of measures at multiple distances can help further refine exposure descriptors and focus efforts on targeting the enhancement of those GS elements (or combinations) that are most likely to benefit specific populations (and the environment).

Given the many features and functions possible for GS, characterizing its potential risks and benefits to individual or population health calls for approaches that account for multiple factors and potential combinations of factors, both within and beyond the GS, that could affect a given health outcome. Also needed are approaches that capture salient aspects or characteristics of the individual or population interacting with the GS.

No standard framework exists to evaluate all potential exposures and health effects related to GS, either alone or in combination. An alternative that is sometimes employed by regulatory agencies is to define a small subset of possible characteristics and establish standard protocols for including those in research studies. This approach can help inform reasonable risk management decisions in the near term while compiling valuable case study lessons to guide future improvements.

The selection process is illustrated by approaches that have evolved over time for assessing health risks of chemical mixtures at contaminated sites. Decades ago, the information considered in estimating whether a site contaminated with multiple chemicals posed an unacceptable health risk was relatively simple. Such considerations included the similarity of the critical toxic effect across the chemicals and the duration-averaged environmental concentration of each that a hypothetical person could be exposed to (e.g., via incidental soil ingestion or drinking contaminated groundwater as tap water) (U.S. EPA, 1986, 1989). Since that time, approaches have continued to be refined. Assessments now consider toxicities at exposure levels higher than that associated with the critical (most sensitive) effect, adjustments to account for increased vulnerability to certain effects from early life exposures (notably cancer), and more sophisticated exposure and toxicity groupings that consider modes of toxic action and adverse outcome pathways (U.S. EPA, 2000; 2005; 2007; 2014). The same kind of evolution is expected for the methods and measures used to estimate human exposures to (including interactions with) GS and those used to predict associated health effects.

The explosion of big data—the rapidly increasing volume, variety, and availability of data and information from structured and unstructured sources including mobile technology, sensors, and transaction records—is of increasing interest to researchers and the public. Access to big data has concerns, which range from issues of privacy to data validity, as well as promise. First, regarding the data validity, many data sets rely on voluntary inputs so the participants (or study subjects) are unlikely to be statistically representative, affecting the generalizability of findings. For example, consider a study that analyzes data from a mobile application designed to track exercise. These data would be provided only by people already interested in recording their physical activity. With self-reported data from self-selected participants, it also might be difficult to establish a true control group. Second, while some well-developed bioinformatics approaches apply sophisticated statistical methods to yield reasonably reproducible data, crowdsourced images of GS attributes or human activities in GS analyzed by different people are likely to include errors caused by lack of precision and other factors, including fatigue (considering the sheer number of images being evaluated). Much of the crowdsourced information can be qualitative or subjective, such as self-reported exercise levels (moderate or low) or perceptions of GS access. Large amounts of these data might not significantly reduce inter-rater variability; that is, the population variance of self-reported judgments can be quite high so large amounts of data would improve the estimate of only that single variance. The advantage of crowdsourced information is that it can be used to capture multiple states and conditions, including different time frames, seasonal and weather variations, residential versus commercial differences in GS, and size of the metropolitan area, which can modify how land uses are designed and managed.

GS studies that assess how GS outcomes can be effectively included in CRAs would also be useful to promote better policy analyses and integration in this area. Studies of the same health outcome(s) for GS in different locations can help increase the confidence in generalizing a relationship observed in previous studies (e.g., between GS and a specific health outcome) to extend to other GS types, locations, or populations. Alternatively, new studies might find that results from one GS-health outcome study do not apply to other locations or populations, which might provide insights into underlying mechanisms.

The gold standard is to develop randomized controlled trials designed to evaluate the relationship between specific GS exposures and specific outcomes, as well as to examine specific mechanisms of effect. Conducting experiments in the "real world" can be challenging because of extensive spatial or temporal requirements for an intervention, and potentially detrimental effects on study subjects. Consider even a small trial requiring a random assignment of which locations receive a localized greening treatment and which do not. This type of research opportunity, with the right partnerships and willing participants, is rare (Kondo et al., 2015). Alternatively, studies can examine the impacts of projects or naturally occurring events as natural experiments, and develop measures for evaluating the GS components of the intervention or event compared to surrounding areas. These projects can range from local initiatives such as tree planting or trail development, to large-scale events such as the loss of trees from invasive species or natural disasters. Such initiating events have already informed environmental and health impact analyses. Assessment metrics and evaluation strategies for GS benefits could be incorporated into these efforts also.

A tiered approach to GS assessment could increase comparability across studies. "First tier" GS assessments can include widely available and comparable measurements like the size and shape of GS (from satellite imagery or municipal sources), number of entry points to a park, and public or private ownership information using street network and parcel data where available. While not measures of access per se, these metrics could be useful to determine the likelihood of access based on publicly available data. A "second-tier" approach could use databases such as Google Street View, OpenStreetMap, and crowdsourced data for assessments of GS quality. Crowdsourced or other big data could be strengthened with quality assurance analyses in the form of in-person audits or personal monitoring data checks performed on a subsample. Several validated questionnaires already measure behavioral outcomes such as perceived safety, stress, and physical activity; large-scale cohort studies and surveys could incorporate questions pertaining specifically to GS access, perceived access/safety, and time spent outdoors. GS exposure estimates could then be linked to health and behavior outcomes from national surveys such data from CDC's (Centers for Disease Control and Prevention) National Environmental Public Health Tracking Network and the American Community Survey.

5.11. STRENGTH OF EVIDENCE FOR CAUSALITY, IDENTIFYING MAIN ENDPOINTS

Any assessment involves questions about how to evaluate the evidence, often dealing with different kinds of evidence, as well as questions about how to assess confidence in that evidence. One approach for evaluating uncertainties in relationships among stressors, mediators, and outcomes that has been outlined for CRAs is to apply a structured rating scheme that is based on evaluating both the weight and the strength of evidence (Suter, 1993). Here, the weight of evidence referred to the confidence in either the credibility or relevance of the type of evidence. The term strength of evidence is often used today to reflect overall credibility, extending from a more focused earlier definition that reflected a measure of the degree (e.g., the likelihood based on the reported measure).[2] A recent study considered the phrase "weight of

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[2]Griffin and Tversky (1992) provide an illustrative example regarding an evaluation of a letter of recommendation for a student written by a former teacher. The evaluator may consider "two separate aspects of the evidence: (i) how positive is the letter? and (ii) how credible or knowledgeable is the writer? The first question refers to the strength or extremeness of the evidence, whereas the second question refers to its weight or credence."

evidence" too vague and varied in practice, and thus of little scientific use. For this reason, strength of evidence and evidence integration were preferred (NRC, 2014). Ideally, future approaches can consider diverse types of evidence in a rigorous, systematic, and transparent manner that leads to a scientifically defensible conclusion regarding the nature of the relationship (if any) between an exposure and a health outcome. As the field of GS assessment grows, structured evidence-driven approaches will be useful for mapping causal pathways between GS exposure and health outcomes.

Some strength-of-evidence approaches give a higher rating to observed relationships for which plausible underlying causal pathways or mechanisms have been identified. Observed relationships that lack evidence for an underlying causal pathway would be rated lower. Another characteristic given a higher rating is the consistency of results across several studies. Enacting a rating approach usually requires first evaluating multiple studies to determine where the uncertainties lie (e.g., with the GS description or with the health outcomes reported) or with the basic investigative methodology (e.g., where known modifying factors were not adequately taken into account). The evidence is considered strongest for relationships that are consistently shown and that can be explained by specific causal pathways. Examples of relatively strong relationships that would receive a higher rating are reduced psychological stress and improved reproductive outcomes associated with exposure to GS, for which substantial evidence exists across a range of study designs. Figure 5-1 shows a potential ranking of the strength of evidence for GS and different health outcomes based on workshop findings.

Health effect	Pathways for GS contact	Strength of Evidence
Psychological	stress/anxiety reduction; changes in air quality, temperature	Increased
Attention Restoration	improved cognitive restoration and function; recovery from mental fatigue	
Cardiovascular and Mortality	stress/anxiety reduction; changes in air quality, temperature	
Social Cohesion	stress/anxiety reduction	
Reproductive	stress/anxiety reduction; increased social contacts; increased physical activity; changes in air quality, temperature	
Physical Activity	stress/anxiety reduction	
Respiratory	stress/anxiety reduction; changes in biodiversity; changes in air quality; physical activity	Decreased
Neurodevelopmental	stress/anxiety reduction; changes in air quality	

1. Figure is for illustrative purposes only and not intended to be comprehensive.
2. For cited resources of benefits and risks of GS for health, see EnviroAtlas' EcoHealth Relationship Browser: http://enviroatlas.epa.gov/enviroatlas/Tools/EcoHealth_RelationshipBrowser/index.html.

Figure 5-1. Strength of evidence for selected health effects.

As research on GS exposures and effects continues to evolve, evidence will be evaluated in new ways. The insights gained are anticipated to further inform CRA methods for assessing exposures and effects of nonchemical stressors and mediators. One suggestion for future GS evaluations is to develop weight- or strength-of-evidence rating structures and apply those to existing studies for some of the better-understood health effects. For these structured judgments, key GS terms and exposure scenarios would need to be clearly defined, as would ways to express variations when the definitions are not consistently followed. Once this type of structure has been applied, the communications for risk managers could identify those causal pathways that score high in two areas: (1) they are reasonably well explained by the information available, and (2) they are consistently demonstrated in multiple studies. An alternative is to identify those health outcomes for which multiple studies show GS benefits, even (or especially) when the GS descriptors vary (i.e., GS benefits are robust to the selection of GS measure). The first approach is likely to be used for assessing a specific type of GS, public engagement, and health endpoint. The second approach is more general and can be used to evaluate many types of GS because the likelihood of some sort of net benefit is high.

5.12. SUMMARY FINDINGS

Five joint findings can be distilled from the workshop discussions:

1. *GS effects are mainly beneficial. This contrasts with effects typically assessed in CRAs, which are mainly harmful.*
   Current evidence suggests that GS supports public health directly by providing a dynamic space for exercise, social interactions, and other behaviors that are thought to lower psychological stress and improve mood. Additional benefits of exposure to GS appear to include improved immune function, cognition, and attention restoration. Although data are limited, GS might mitigate or attenuate health outcomes brought on by psychological stress (e.g., cardiovascular disease). A few adverse effects from GS exposure also occur– notably respiratory and dermal irritation related to allergens.

2. *Both GS assessments and CRAs are spatially dependent.*
   Both assessments can be conducted at different levels of spatial extent, with resolutions ranging from rough to highly refined. However, unlike conventional CRAs, the meaningful attributes of a GS—beyond those associated with objectively spatial measurements—are not well characterized.

3. *Both GS assessments and CRAs strongly depend on the characteristics of the population, including engagement with GS; scope considerations can differ.*
   Part of the planning phase of any risk assessment is to identify the scope of the effect(s) and characterize affected population(s); CRA and GS analyses incorporate these two factors in different ways. The scope of a CRA is often defined to increase the tractability of the multiple stressors being addressed. Simplification can involve placing limits on the number of chemicals, exposure pathways, or health effects to include. With GS evaluations, the scope of the analysis generally relates to the physical boundaries (e.g., the definition of the type and boundaries of the GS, or the amount of GS within a defined buffer), although the set of potential health endpoints in the nearby population is often considered in the assessment scope. The relative absence of GS characteristics (e.g., ecological features like biodiversity, landscape structure, and behavioral prompts like paths and overlooks) from GS assessment is a

significant shortcoming. Concentrating on specific components of GS versus other features in the built environment can lead to a false dichotomy between the two. In reality, green and grey features can be closely integrated, both physically and in the effects on behavior and population health. GS assessments also exhibit a strong dependence on the population under consideration, that mirrors the way in which activity profiles of a population (or individuals) is used when assessing exposures to chemicals in a CRA.

4. *Quantification and qualification of dose-response relationships related to GS exposure is limited for GS assessments. The same is true for complex chemical mixtures typically assessed in CRAs.*
   One of the strongest consensus findings of the work group is that a mathematical dose-response relationship linking GS exposure with a health outcome(s) does not yet exist. Uncertainties in the characterization of exposure and causality for GS are similar to the methodological limitations of environmental chemical exposure assessment, lacking even the cursory causality information that is available for a subset of chemicals studied in controlled animal experiments.

5. *Both GS assessments and CRAs are relatively new approaches for characterizing complex environmental exposures. Considerable uncertainty underlies GS exposure measures used to assess various health outcomes*.
   Uncertainties remain in the best available methods for quantifying and qualifying GS exposure as well as characterizing the etiology of various health endpoints, potentially limiting the usefulness of CRA analysis that incorporate GS. A lack of understanding regarding the mechanism or mechanisms through which GS might affect these health outcomes underlies many of the uncertainties in the exposure measures. Although addressing these uncertainties represents a common research area between the two fields, we acknowledge that the range of exposures implicated in salutagenic GS range from botanical bioaerosols, which are easy to sample, to neurobiological and cultural responses to the view of a specific landscape, which can be more challenging. Further research and exposure classification is needed, but full incorporation of all dimensions of GS exposure into a CRA model is unlikely.

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APPENDIX A: PARTICIPANT BIOSKETCHES

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APPENDIX A:
PARTICIPANT BIOSKETCHES

A.1. JULIA AFRICA

Julia Kane Africa leads the ecological infrastructure, biophilic design, and restorative landscape areas of the Nature, Health, and the Built Environment program at the Harvard Center for Health and the Global Environment. In this role, she examines the ways in which nature (parks and greenspaces) and natural design cues (natural features in built environment settings) support psychological and physiological health and resilience. The program produced an illustrative review of greenspace and health found here: www.chgeharvard.org/NEI_Paper. She has completed graduate coursework in environmental health, exposure assessment, and sustainable design at the Harvard T.H. Chan School of Public Health and the Harvard Graduate School of Design (MDesS).

A.2. MATILDA ANNERSTEDT VAN DEN BOSCH

Dr. Matilda Annerstedt van den Bosch is a medical doctor working on interdisciplinary projects to study associations between various natural environments and public health with epidemiological and experimental methods. Her main focus is health opportunities provided by greenspaces to various populations, but she also investigates environmental threats like pollen exposure. She has several publications and is coeditor of the Oxford textbook on Nature and Public Health. Among other tasks, she collaborates with the World Health Organization to develop urban health indicators based on geographical and population distribution data. She is president for the Swedish Society of Behavioural Medicine and directing board member of the International Society of Doctors for the Environment.

A.3. GLENNON BERESIN

Glennon Beresin is an environmental health fellowship participant with the Association of Schools and Programs of Public Health (ASPPH), hosted by EPA Office of Research and Development (ORD) National Center for Environmental Assessment (NCEA) in Cincinnati, OH. She is working in cumulative risk assessment under mentors Drs. Michael Wright and Glenn Rice, with a research focus on health impacts of industrial livestock production. Her work is informed by One Health-oriented environmental health research, which integrates human, animal, and ecosystem health. Ms. Beresin earned her Master of Science (MS) and her Master of Public Health (MPH) degrees within the Tufts Friedman School's Agriculture, Food, and Environment program, and Tufts School of Medicine's Public Health and Professional Degrees program, respectively.

A.4. GEOFFREY DONOVAN

Dr. Geoffrey Donovan is an economist with the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station in Portland, OR. He has quantified a wide range of urban-tree benefits, ranging from intuitive benefits—reduced summertime cooling costs, for example—to less intuitive benefits such as crime reduction. More recently, he has focused on the relationship between trees and public health. He found that mothers with trees around their homes are less likely to have underweight babies, and when trees are killed by an invasive pest, more people die from cardiovascular and lower respiratory disease. He has a number of ongoing projects, including a collaboration with the women's health initiative as well as studies using bio-indicators to quantify human exposure to polycyclic aromatic hydrocarbons and heavy metals.

A.5. REBECCA GERNES

Rebecca Gernes is an environmental health fellowship participant with the ASPPH, hosted at EPA ORD NCEA in Cincinnati, OH. Her research focuses on intersections between the built and natural environment, social and economic development, and human behavior in relation to health. Ms. Gernes is currently working on incorporating greenspace exposure assessment into the Cincinnati Childhood Allergy and Air Pollution Study (CCAAPS) as part of her work on cumulative risk assessment with her mentors Drs. Glenn Rice and Michael Wright. She has a dual Masters in Public Health and Social Work (MPH, MSW) from the Brown School at Washington University in St. Louis.

A.6. RICHARD HERTZBERG

Dr. Richard Hertzberg is an adjunct professor of environmental health at Emory University, special-term appointment at Argonne National Laboratory, and a private consultant. He retired from EPA ORD NCEA in 2006 after 25 years, mostly leading the research on mixture risk methods. He is primary author of the EPA 1986 Guidelines for the Health Risk Assessment of Chemical Mixtures and 2000 Supplementary Guidance for the Health Risk Assessment of Chemical Mixtures. He has served on cumulative risk groups for the EPA Office of Pesticide Programs and Risk Assessment Forum, and external advisory groups on mixture risk for Agency for Toxic Substances and Disease Registry, National Institute for Occupational Safety and Health, and the Dutch Health Council. His current work includes modeling mixture dose-response and interaction effects of pesticide combinations. He received a PhD in biomathematics from the University of Washington and a Bachelor of Science (BS) in mathematics from Harvey Mudd College.

A.7. J. AARON HIPP

Dr. J. Aaron Hipp is an associate professor at North Carolina State University, currently working on a variety of projects investigating the built environment and health behaviors. One of Dr. Hipp's projects uses public, outdoor, online webcams across the United States to measure physical activity across built environments including parks, beaches, plazas, and streets. In addition, he works on several accelerometer and global positioning system (GPS) studies to better understand where populations engage in physical activity. Dr. Hipp instructs courses in geographic information system (GIS) and Built Environments and Community Health, and he serves on the national board of the Open Streets Network of Champions.

A.8. PERRY HYSTAD

Dr. Perry Hystad is an assistant professor within the College of Public Health and Human Sciences at Oregon State University. He is an environmental epidemiologist focused on understanding the health impacts related to place (i.e., where we live, work, and play). A large portion of his research uses spatial exposure assessment methods to determine the chronic health effects associated with exposure to air pollution, including cardiovascular, respiratory, and reproductive outcomes. Recently he conducted analyses of residential greenness and adverse birth outcomes and cardiovascular disease. Given the spatially correlated nature of different environmental (and social) exposures, he is developing methods to incorporate multiple exposures related to place into epidemiological analyses.

A.9. LAURA JACKSON

Dr. Laura Jackson is a biologist with the EPA ORD; she is a principal investigator in the Sustainable and Healthy Communities Research Program. Her work focuses on the hazard buffering and health promotional aspects of urban ecosystems. Current studies explore linkages among physical and mental health metrics, near-road tree cover, and neighborhood greenspace. Past research has explored the landscape ecology of urbanizing areas and the effects of the built environment on ecological and public health. Dr. Jackson has developed and led studies in cross-disciplinary research topics and helped to plan and manage environmental research programs at EPA since 1990.

A.10. MICHELLE KONDO

Dr. Michelle Kondo is a research scientist with the U.S. Forest Service, stationed in Philadelphia, PA. Dr. Kondo's research investigates the relationship between environments, public health, and safety. She has conducted multiple community-based air pollution exposure assessments. Her recent work evaluates the effects of urban sustainability and stabilization initiatives, as well as invasive pests, on human health and crime outcomes. Some of her recent work established a relative reduction in crime (narcotics possession) around green stormwater infrastructure installations in Philadelphia, and larger and more significant reductions in crimes surrounding community-initiated greened vacant lots in comparison to city-run cleaned-and-greened lots in Youngstown, OH. She has also recently published a study which measured stress-response to greened versus blighted vacant spaces using mobile biosensors. She has training in civil engineering, urban planning, spatial epidemiology, and environmental health.

A.11. MARGARET MACDONELL

Dr. Margaret MacDonell is a principal environmental systems engineer in Argonne National Laboratory's Environmental Science Division and adjunct professor at Northwestern University. She conducts risk analyses for federal agencies with a focus on cumulative risk assessment. Margaret was a contributing author to the 2007 EPA NCEA cumulative risk resource document and is a member of three National Research Council committees addressing toxicity and exposure guidelines. She has a PhD in civil engineering/environmental health engineering from Northwestern University, an MS in the same from Notre Dame, and a BS in biology from Notre Dame.

A.12. YVONNE MICHAEL

Dr. Yvonne Michael is an epidemiologist known for research on multilevel influences on population health. She has led research projects on the impact of neighborhood environments on health, the role of psychosocial factors in health, healthy aging, and women's health. She developed an audit instrument for research evaluating neighborhood walkability (Senior Walking Environmental Assessment Tool) and has developed modified versions for use with community members. She is the Associate Dean for Academic and Faculty Affairs and an associate professor of epidemiology at the Drexel School of Public Health. She completed doctoral degrees in epidemiology and health and social behavior at Harvard T.H. Chan School of Public Health and a postdoctoral research fellowship in the epidemiology of aging at Johns Hopkins Bloomberg School of Public Health.

A.13. TRAVIS MILLER

Travis Miller is the regional planning manager for the Ohio-Kentucky-Indiana (OKI) Regional Council of Governments with 20 years of land use, economic development, and environmental planning experience. Travis heads OKI's Water Quality and Greenspace Office and is directly involved in the region's Water Quality Management Plan. He has been instrumental in the launch and continued growth of the region's Taking Root campaign and has recently led efforts to inform regional stakeholders about solar energy opportunities through participation in the U.S. Department of Energy SunShot Initiative and Solar Ready project. He holds an MS in community planning (University of Cincinnati) and a BS in landscape architecture (The Ohio State University).

A.14. RICHARD MITCHELL

Dr. Richard Mitchell is a professor of health and environment, and head of the Public Health Group at the Institute for Health and Wellbeing, University of Glasgow. He is also a codirector of the Centre for Research on Environment, Society, and Health (CRESH, http://cresh.org.uk), an interdisciplinary and interinstitute center, focused on exploring how physical and social environments can influence population health, for better and for worse. Dr. Mitchell is an epidemiologist and geographer. Earlier in his career, he focused on monitoring and exploring socioeconomic and geographic inequalities in health. Today, his focus is on the potential for environments, and natural environments in particular, to positively influence population health and health inequalities.

A.15. MARK NIEUWENHUIJSEN

Dr. Mark Nieuwenhuijsen is an expert in environmental exposure assessment, epidemiology, and health risk/impact assessment. He has experience and expertise in areas of respiratory and cardiovascular morbidity and mortality, mental health, cognitive function, cancer and reproductive health, and exposure measurement and modelling of indoor and outdoor air pollution, pesticides, greenspace, ultraviolet exposure, chlorination by-products in drinking water, and heavy metals, using new technology such as GIS, smartphones, and remote sensing. He leads the European Commission-funded PHENOTYPE (www.phenotype.eu) study, examining the relations between greenspace and health. He is a coinvestigator in other programs, notably CITISENSE (http://citi-sense.eu/), which aims to empower citizens using smartphone technology; HELIX (http://www.projecthelix.eu/), which examines the early life exposome and childhood diseases; EXPOsOMICs (http://www.exposomicsproject.eu/), which examines the air pollution and water exposome and health; and PASTA (http://www.pastaproject.eu), which promotes active transportation through sustainable transport.

A.16. GLENN RICE

Dr. Glenn Rice has served as an environmental health scientist at EPA NCEA since 1990. His research interests focus on developing human health risk assessment methods for chemical mixtures and cumulative risk scenarios. He is one of the primary authors of the EPA's *Supplementary Guidance for the Health Risk Assessment of Chemical Mixtures* and the EPA's *Mercury Study: Report to Congress*. He holds a ScD in environmental health and health policy management from the Harvard School of Public Health, an MS in microbiology from Miami University, as well as undergraduate degrees in biology and chemistry from Thomas More College.

A.17. PATRICK RYAN

Dr. Patrick Ryan is an associate professor of pediatrics and environmental health at Cincinnati Children's Hospital Medical Center and the University of Cincinnati. Dr. Ryan is an environmental epidemiologist with research interests in the fields of air pollution epidemiology and exposure assessment. He is the principal investigator on multiple National Institutes of Health-funded studies of air pollution and respiratory and neurobehavioral development in childhood, the use of sensor technology to characterize personal exposure to ultrafine particles, and the impact of traffic-related air pollution at schools. Other research interests include studies of indoor pollutants and mold, environmental exposure to naturally occurring asbestos, and the elemental composition of fine particulate matter ($PM_{2.5}$).

A.18. WILLIAM SULLIVAN

Dr. William Sullivan works to create healthier, more sustainable communities. He is Professor of Landscape Architecture at the University of Illinois where he, his students, and collaborators examine the health benefits that come from having regular exposure to urban landscapes containing green infrastructure. Together, they have found that regular contact with urban green infrastructure—places with trees, grass, rain gardens, and the like—has profound, positive impacts for individuals and communities. These urban greenspaces need not be large or pristine to convey a variety of broad-ranging outcomes. They must, however, be easily accessible from a person's home or workplace. He is a senior fellow at the National Council for Science and the Environment and is an active member of the University's Education Justice Project. Sullivan holds a PhD in Natural Resources with a concentration in Environment and Behavior from the University of Michigan. (For more about his work, see http://willsull.net.)

A.19. J. MICHAEL WRIGHT

Dr. J. Michael Wright has served as an epidemiologist with EPA NCEA for 14 years. He has conducted epidemiologic studies on the relationship between waterborne contaminants and adverse reproductive outcomes and neurodegenerative disorders. In addition, he conducts exposure assessment research, some of which quantifies the magnitude of bias due to exposure misclassification in epidemiologic settings. Dr. Wright has served on several advisory committees and technical panels on various topics including drinking water quality, epidemiology, and cumulative risk assessment. He earned his Doctor of Science degree in Environmental Health from the Environmental Epidemiology Program at the Harvard School of Public Health.

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APPENDIX B: MEETING AGENDA AND TECHNICAL PRESENTATIONS

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APPENDIX C: WORKING DRAFT GLOSSARY

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APPENDIX C:
WORKING DRAFT GLOSSARY

The working draft glossary provided to participants at the meeting as a preliminary draft, subject to change, is presented in Section C.1. Sources of the definitions reflected in the glossary (as indicated by the superscript following the definition) are identified in Section C.2. Other than greenspace, the individual terms and definitions were not discussed at the meeting. (See Section 1.2 for the definition of greenspace used in this report.)

C.1. PRELIMINARY GLOSSARY FOR DISCUSSION

Biophysical services: Ecosystem services provided by the physical environment (water, soil, air, etc.) and the biological activity within it (plants, animals, etc.).[1]

Built environment: All the physical (human-made) parts of where people live, work, and play (e.g., homes, buildings, streets, open spaces, and infrastructure).[2]

Buffer: A factor that reduces risk associated with a stressor(s).[3]

Cultural ecosystem services: Nonmaterial benefits people obtain from ecosystems, such as cultural diversity, spiritual and religious values, knowledge systems, educational values, inspiration, aesthetic values, social relations, sense of place, cultural heritage values, recreation, and ecotourism.[1]

Dose-response assessment: A determination of the relationship between the magnitude of an administered, applied, or internal dose and a specific biological response.[4]

Dose-response relationship: The relationship between a quantified exposure and the proportion of subjects demonstrating specific biologically significant changes in incidence and/or in degree of change (response).[4]

Disservices: Negative or unintended consequences.[1]

Ecosystem services: Life-sustaining benefits humans receive from nature, such as clean air and water, fertile soil, pollination, and flood control.[1]

Effect measure modification: Occurs when the magnitude of the effect of the primary exposure on an outcome (i.e., the association) differs depending on the level of a third variable.[6]

Gray infrastructure: Traditional practices (or systems) for stormwater management and wastewater treatment, such as pipes and sewers.[1]

Green infrastructure: A variety of natural elements (trees, grasses, gardens) designed and landscaped to manage water naturally.[1]

Greenspace: Open land partly or completely covered by vegetation.[6]

Hyperfunctional or hyperfunctionality (referring to systems of managed landscapes, infrastructure): Because cities can only afford to allocate limited space to infrastructure and land, each unit needs to be hyperefficient to achieve its goal (e.g., reductions in pollution, runoff, temperature, etc.).[1]

Receptor: The individual or population group actually or potentially exposed to a chemical (receptors can be real or hypothetical). For contaminated sites, various receptors are typically hypothesized to evaluate potential risks under likely future uses to help guide risk management decisions. In cases where real people might be incurring exposures (e.g., including cleanup workers), these should clearly be assessed.[4]

Response: Response can be expressed as measured or observed incidence or change in level of response in a population over a specified period of time, or change in level of response, percentage response in groups of subjects (or populations), or the probability of occurrence or change in level of response within a population.[4]

Street tree: Trees located on a strip of land between a roadway and a sidewalk.[1]

Urban forest: A collection of trees (including any woody plants) that grows within a city, town, or suburb.[1]

Urban forestry: The care and management of urban forests.[1]

Urban heat island: A phenomenon where air temperatures in urban areas are 2−10°F hotter than surrounding rural areas due to the high concentrations of buildings and pavement in urban areas.[1]

Urban metabolism: Quantification of the total resource inputs, outputs, and transformations in a city stemming from urban socioeconomic activities and regional and global biogeochemical processes.[1]

C.2. SOURCES

Note that some of the definitions in Section C.1 reflect slight refinements from those indicated in these sources.

1. Thomas, K; Geller, L. (2013) Urban forestry: Toward an ecosystem services research agenda: A workshop summary. Washington, DC: National Academies Press. http://www.nap.edu/catalog/18370/urban-forestry-toward-an-ecosystem-services-research-agenda-a-workshop (last accessed May 1, 2015).

2. CDC (Centers for Disease Control and Prevention). (2011) Impact of the built environment on health. Healthy community design fact sheet series. (June) Atlanta, GA: CDC National Center for Environmental Health, Division of Emergency and Environmental Health Services (June) http://www.cdc.gov/nceh/publications/factsheets/impactofthebuiltenvironmentonhealth.pdf (last accessed July 15, 2015).

3. Sexton, K; Lindner, SH. (2011) Cumulative risk assessment for combined health effects from chemical and nonchemical stressors. Am J Public Health 101(Suppl. 1):S81−S88.

4. U.S. EPA (U.S. Environmental Protection Agency). (2011) Integrated Risk Information System (IRIS) Glossary. http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&glossaryName=IRIS Glossary (Vocabulary Catalog, last update Aug. 31, 2011; last accessed May 1, 2015).

5. BUSPH (Boston University School of Public Health). (Undated) Confounding and effect measure modification (module used for both BS704 and EP713); http://www.cdc.gov/nceh/publications/factsheets/impactofthebuiltenvironmentonhealth.pdf (last accessed October 28, 2015).

6. U.S. EPA (U.S. Environmental Protection Agency). (2014) Urban environmental program in New England, Region 1. http://www.epa.gov/region1/eco/uep/ (last updated May 6, 2014; last accessed May 1, 2015).