The significance of the environment for health is increasingly being recognized. There is a need for systematic approaches to assessment of environmental factors most relevant to health, health outcomes most influenced by the environment, and the relationships between them, as well as for approaches to representing the results of such assessments in policy deliberations. As a step in the development of such methods, we used findings and data from the environmental protection and public health sectors to develop a set of measures representing topics relevant to children’s environmental health. We used a definition of the environment that emphasized contaminants and a process that involved both analytic and deliberative elements. The steps in this process were to:

1. Develop a conceptual framework to depict relationships between environment and health with relevant types of data and information.
2. Select topic areas of significance for children.
3. Identify best available data sources and devise measures.
4. Assess possible surrogate data sources and measures when needed.
5. Design and implement metrics for computation of measures using specified data elements.
6. Select graphical representations of measures.
7. Identify related measures.
8. Identify data gaps.

Representatives of policy and stakeholder audiences participated in this process. The measures are presented in three groups that reflect contaminants in the environment, contaminants in human tissues, and diseases and disorders. The measures present scientifically based representations of data understandable to stakeholders and policy makers that integrate key information from the health and environment sectors in a consistent format. Key words: child, child welfare, children’s environmental health, environmental contaminants, environmental exposure, environmental health, environmental health indicators, environmental health framework, environmental pollutants, integrated assessment. Environ Health Perspect 114:447–452 (2006). doi:10.1289/ehp.8321 available via http://dx.doi.org/ [Online 21 September 2005]
We incorporated some elements of a widely developed framework to depict relationships we identified the best available data sources and stakeholders into a consistent approach and to meld the views of technical experts and stakeholders and experts in toxicology, epidemiology, children’s health, exposure assessment, and public health surveillance to discuss conceptual approaches, topics to be addressed, data sources, metrics, graphical representations, and data gaps. We consulted with technical and policy experts from key federal agencies. This analytic–deliberative process allowed us to meld the views of technical experts and stakeholders into a consistent approach and to identify the best available data sources and methods to address questions of interest.

**Develop framework to depict the relationship between environment and health.** We developed a framework to depict relationships between environmental factors and health. We incorporated some elements of a widely used WHO model, which includes: driving forces → pressures → environmental states → exposures → health conditions or effects, shown in Figure 2 (Briggs et al. 1996; Furgal and Gosselin 2002; von Schirnding 2002). Driving forces include major social and economic changes and practices such as urbanization, poverty and inequality, scientific and technical advances, and patterns of production and consumption. Pressures include sources or releases of environmental agents. Environmental states include conditions of environmental media such as lakes or streams. Our framework, shown in Figure 3, includes driving forces; sources of releases of environmental agents of concern; concentrations of environmental agents of concern measured or estimated in environmental ambient or exposure media; concentrations of agents of concern in human tissues; and health outcomes (diseases and disorders) in populations. We included driving forces and sources of agents in the framework because control or elimination of sources is the policy strategy that reflects primary prevention. However, we did not develop measures for them because of resource limitations. We do not use the terms “pressures,” “states,” or “responses” because we have found them ambiguous.

Figure 3 shows types of information relevant to each component. Ambient environmental media include outdoor air, water, soil, or agricultural products; exposure media include outdoor air, indoor air, drinking water, food products, and dust. Concentrations in ambient media are often significant determinants of exposure. For example, epidemiologic studies have measured pollutant contaminants in ambient media and quantified relationships to health effects (i.e., relationships between outdoor measurements of fine particulate matter and mortality). In this approach, we consider data about concentrations of environmental agents in exposure media and concentrations of agents of concern in human tissues.

**Identify topic areas to address.** The second step was to identify topic areas of interest. For environmental contaminants, these areas included outdoor air pollutants, indoor air pollutants, drinking water contaminants, contaminants in foods, and contaminants in soil. For contaminants in humans, we included topic areas identified as a concern in the environment and for children for which we could produce a meaningful interpretation of data available from the nationally representative sample developed by CDC (2003b). For diseases and disorders, we included examples important to the health of children for which there was also published research that showed an established or suggested link to one or more environmental contaminants, based on previous analysis, consultation with experts, survey of the scientific literature, and use of standard references and existing reviews (Woodruff et al. 2004). We reviewed.
emerging research on the links between air pollutants and respiratory outcomes in children and adults, evidence for environmental factors that contribute to cancer in children, and studies that examined links between environmental exposures and neurodevelopmental disorders (Woodruff et al. 2003).

We did not attempt at the outset to identify all topic areas that might be relevant; rather, we endeavored to identify a scope of work that could be accomplished with available resources. We identified agents and outcomes of concern first and then sought data sources for these agents and outcomes to allow for identification of data gaps.

Assess and select data sources and develop measures. For each topic area, we concurrently identified and assessed potential data sources and considered relevant ways to represent data. For each candidate data source, we assessed accessibility, validity and reliability, data elements, time period for which data were available, geographic area and resolution, and applicability to children. We sought data sources with sufficient documentation, standard collection procedures, and quality assurance. We consulted key references and knowledgeable parties. When multiple sources were available, we selected the source with the best representation of the United States and best coverage of the study period.

For some topic areas, we could not identify usable data sources.

In conjunction with the review of data sources, we developed measures for the topic areas. We reviewed measures included in Healthy People 2010 (U.S. Department of Health and Human Services 2000). In some cases, we concluded that more than one measure was needed. For example, for criteria air pollutants, we included one measure that reflected air quality on a daily basis, which is related to health effects associated with short-term, high concentrations of pollutants. Because chronic exposures to lower concentrations of pollutants are also relevant, we included a measure based on annual concentrations for some pollutants. To reflect the coverage of data sources, we estimated the percent of the population represented.

Investigate surrogates where data are not available. If a data source directly representative of a condition of interest was not available, we investigated surrogates that reflected related conditions. For example, we used reported violations of drinking water standards as a surrogate for concentrations of contaminants in drinking water. We assessed data for surrogate measures using the same approach used for other sources.

Specify computational approach and data elements and implement the measure. The sixth step was to devise the method to be used to compute or generate the measure, to select the metric, and to identify data elements to be used and their sources. Measures were then computed.

Design graphical representation of the measure. Along with the computation of the measure, we selected an approach to present results graphically for each measure. We considered how to show limitations, distributions, and coverage of the data. When possible, presentations showed trends over time and differences by race/ethnicity and SES.

Identify related measures. To highlight relationships between contaminants and outcomes, we identified measures that were related. For example, measures that reflect concentrations of mercury in foods would be related to measures that reflect concentrations of mercury in blood of women of childbearing age. Table 1 shows measures that may be viewed as related. Related measures can be considered together to look at patterns with regard to time, geography, race/ethnicity, and SES. This approach can identify additional areas for research, needs for further review or consideration of existing research, or areas in need of policy development or intervention.

Identify data gaps. The last step was to describe data gaps. In some cases, we included a narrative description of the topic area as an emerging issue. Other topic areas were identified as data gaps. For even the best data sources, there are usually limitations on coverage or representativeness. We addressed some of these issues in the final step. There are many important topics for children’s environmental health with little or no coverage in the set of measures assembled.

Results and Discussion

The analysis resulted in the development of measures for environmental contaminants, human body burdens, and diseases and disorders. Table 2 shows the full set of measures and their coverage.

The development of measures raises numerous issues. One issue for environmental contaminant and body burden measures is whether a point of comparison should be used. Measured or estimated values can be compared to regulatory standards, such as ambient air quality standards, or other benchmarks. Such comparisons can be useful because most people understand that concentrations that exceed such standards may be related to potential for disease. However, regulatory standards may result from balancing of health with other factors, such as cost or technological feasibility of control technologies. Such standards would not represent an appropriate point of comparison from a health perspective. Comparison to a fixed standard can create an impression that there is a “safe” concentration below which exposures would not pose any risk to health. However, for many pollutants, there may be no threshold, as is the case for particulate matter, ozone, and blood concentrations of lead (American Academy of Pediatrics Committee on Environmental Health 2004;
What to include in an assessment is an important consideration. The working definition of “the environment” used for these measures corresponded closely to the mandates of the U.S. EPA. It included environmental agents that can contaminate environmental media resulting in exposure. Such agents fall under regulatory mandates of the U.S. EPA. However, many other factors can be viewed as falling under the rubric of the environment. It may be more difficult to identify data sources if a more expansive definition of environmental factors is used in future work. Even with this relatively narrow scope, there are significant limits to our understanding of the links between environmental factors and health outcomes. In conducting an assessment that is geared to reporting progress and identifying areas in need of attention, it is important to consider probable contributors to disease and diseases that are likely caused at least partly by environmental factors, even when these relationships have not been fully established.

It is helpful to look at available information in two ways. It is beneficial to look at toxicology and other experimental results, to see what can be learned about possible relationships of environmental factors to health outcomes or related biologic effects. Such literature will be available for compounds that have not been included in epidemiologic studies, including agents for which widespread human exposure has not yet occurred or has not yet been measured. Conversely, it is useful to consider results of epidemiologic studies that identify environmental factors that contribute to disease, recognizing that such studies can be conducted only after significant human exposure has occurred.

Defining the type of data appropriate to assess components of a conceptual framework is an important step. The commonly used terms “hazard” and “exposure” represent general concepts rather than particular approaches to measurement. “Hazard” has been used to refer to several different types of data, including those that reflect production, uses, releases, concentrations in environmental media, and concentrations in exposure media of chemicals. All of these types of data can be important, but they also provide different types of information that can be explicated more carefully. Types of “hazard” metrics need to be defined better, and distinctions must be clarified.

Using measures that address different parts of the framework can be informative. Ideally, increasing trends in concentration of environmental contaminants or body burdens would lead to further investigation and policy action aimed at reversing the trend. Monitoring trends in illnesses that are both known and suspected of being associated with environmental factors is important, given the limitations of scientific knowledge of relationships between environmental factors and diseases. Increasing trends in illnesses also are worthy of attention and action to identify and address possible causal factors.

Work that focuses on children’s environmental health has led to the development of the Multiple Exposure–Multiple Effects (MEME) model (Briggs 2003), which emphasizes the multiple relationships between environmental factors and health outcomes. A single environmental agent or factor may contribute to multiple health outcomes, and a single outcome may be affected by multiple environmental factors. How to address the genuine complexity posed by these “many-to-many” relationships remains an important question. There are different ways in which linkages between environment and health can be conceptualized and implemented. Because of the multiple relationships between many environmental factors and health outcomes, it would be enormously complex to model all relationships or to represent the results of such a model. However, it is possible to synthesize and present available data in ways that identify environmental factors relevant to health and diseases or disorders with possible or likely environmental causes and to show likely relationships in ways that are cognizant of the “many-to-many” nature of these relationships.

For future work, it is important to consider what determinants of exposure can be systematically tracked on a large scale. Exposure of individuals cannot be easily monitored or tracked on a large scale partly because individuals’ actions mediate it. Determinants can be further understood through use of models that integrate environmental determinants of exposure with behavioral determinants of exposure, to provide useful data for understanding the relationship between environment and health.

### Table 1. Measures that may be viewed as related.

<table>
<thead>
<tr>
<th>Environmental contaminants</th>
<th>Body burdens</th>
<th>Diseases or disorders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor air pollutants: criteria pollutants</td>
<td>Blood lead concentrations</td>
<td>Respiratory illnesses</td>
</tr>
<tr>
<td>Outdoor air pollutants: lead</td>
<td></td>
<td>Neurodevelopmental disorders</td>
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<tr>
<td>Special features: lead in schools</td>
<td></td>
<td></td>
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<tr>
<td>Drinking water: lead violations</td>
<td>Cotinine (marker of tobacco smoke exposure) in blood</td>
<td>Respiratory illnesses</td>
</tr>
<tr>
<td>Indoor air pollutants: smoking in homes</td>
<td>Pesticide use in schools</td>
<td></td>
</tr>
<tr>
<td>Pesticides detected in foods</td>
<td>Mercury in blood of pregnant women</td>
<td>Neurodevelopmental disorders</td>
</tr>
<tr>
<td>Warnings of methylmercury in fish</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topic area</td>
<td>Description of measure</td>
<td>Time period</td>
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</tr>
<tr>
<td>Measures for environmental contaminants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common air pollutants</td>
<td>E1: Percentage of children living in counties in which air quality standards were exceeded</td>
<td>1990–2000</td>
</tr>
<tr>
<td>Common air pollutants</td>
<td>E2: Percentage of children’s days with good, moderate, or unhealthy air quality</td>
<td>1990–2000</td>
</tr>
<tr>
<td>Common air pollutants</td>
<td>E3a: Long-term trends in PM_{10} for U.S. population</td>
<td>1990–2000</td>
</tr>
<tr>
<td>Common air pollutants</td>
<td>E3b: Number of children living in counties with high annual concentrations of PM_{10}</td>
<td>1990–2000</td>
</tr>
<tr>
<td>Hazardous air pollutants</td>
<td>E4: Percentage of children living in counties where hazardous air pollutant concentrations exceeded benchmarks</td>
<td>1996</td>
</tr>
<tr>
<td>Environmental tobacco smoke</td>
<td>E5: Percentage of homes with children &lt; 7 years of age where someone smokes regularly</td>
<td>1994–1999</td>
</tr>
<tr>
<td>Drinking water contaminants</td>
<td>E6: Percentage of children living in areas served by public water systems that exceeded a drinking water standard or violated treatment requirements</td>
<td>1993–1999</td>
</tr>
<tr>
<td>Drinking water contaminants</td>
<td>E7: Percentage of children living in areas with major violations of drinking water monitoring and reporting requirements</td>
<td>1993–1999</td>
</tr>
<tr>
<td>Food contaminants</td>
<td>E8: Percentage of fruits, vegetables, and grains with detectable residues of organophosphate pesticides</td>
<td>1994–2001</td>
</tr>
<tr>
<td>Land contaminants</td>
<td>E10: Percentage of children residing within 1 mile of a Superfund site</td>
<td>1990–2000</td>
</tr>
<tr>
<td>Measures for body burdens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead in blood</td>
<td>B2: Median concentrations of lead in blood of children 1–5 years of age, by race/ethnicity and family income</td>
<td>1999–2000</td>
</tr>
<tr>
<td>Lead in blood</td>
<td>B3: Distribution of concentrations of lead in blood of children 1–5 years of age</td>
<td>1999–2000</td>
</tr>
<tr>
<td>Measures for childhood diseases and disorders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory disease</td>
<td>D2: Percentage of children having an asthma attack in the previous 12 months, by race/ethnicity and family income</td>
<td>1997–2000</td>
</tr>
<tr>
<td>Respiratory disease</td>
<td>D3: Children’s emergency room visits for asthma and other respiratory causes</td>
<td>1992–1999</td>
</tr>
<tr>
<td>Respiratory disease</td>
<td>D4: Children’s hospital admissions for asthma and other respiratory causes</td>
<td>1980–1999</td>
</tr>
<tr>
<td>Neurodevelopmental disorders</td>
<td>D7: Children reported to have mental retardation, by race/ethnicity and family income</td>
<td>1997–2000</td>
</tr>
</tbody>
</table>

Designations E, B, and D, are from the original report (Woodruff et al. 2003). 
^{4}Ozone, about 80% of children; PM_{10} (particulate matter < 10 µm in aerodynamic diameter), about 70% of children; sulfur dioxide (SO_{2}), about 50% of children; CO, about 45% of children; nitrogen dioxide (NO_{2}), about 50% of children; lead, about 40% of children.
Further development of a concept of determinants of population exposure is needed, along with research to better identify these determinants. Much of the assessment work conducted in environmental health relates to estimation of exposure and consequent doses of environmental contaminants for individuals, as well as research on the relationships between such exposures or doses and adverse health outcomes.

Such work establishes understanding of the relationships between environmental factors and health. However, the primary goal is not to establish such relationships. Rather, it is to identify and track the elements that contribute to exposure and to adverse health outcomes on a broad scale in ways that are informative to stakeholders and policy communities. The purpose is to identify needs for specific actions to improve health. In this context, it is the determinants of exposure that are, in most cases, going to be amenable to measurement or estimation on a broad scale and also to intervention. Further, analysis of such determinants is critical to better linkage between assessment and intervention.

Because the purposes of tracking or integrated assessment are to improve public health and reduce environmental factors that contribute to disease, consideration of the needs of stakeholders and policy makers who are in a position to take the necessary actions is a key priority from the outset. This work represents a beginning to develop such methods, but more needs to be done.

It would also be relevant to consider administrative or policy actions that contribute to the various environmental conditions portrayed. For example, permit requirements for power plants have a bearing on emissions of several key air pollutants. Such "administrative" measures could be developed to address these concerns, and this process would more directly link results to policy change or evaluation.

An integrated assessment can provide a framework to portray diverse data sources to reflect key elements that affect environmental health status. It may rely on data generated for a variety of purposes and adapted to forms that can reflect the purposes of the assessment. Additional challenges include further development of data sources and means to address some of the key data gaps; to strengthen the measures for driving forces, sources, and other sectors; to explore the implications of the MEME models; to elucidate better the relationship between links in the chain from environment to health; and to identify policy approaches that could reduce the determinants of ill health and promote determinants of good health.

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