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Research needs for community-based risk assessment: findings from a multi-disciplinary workshop

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Communities face exposures to multiple environmental toxicants and other non-chemical stressors. In addition, communities have unique activities and norms that influence exposure and vulnerability. Yet, few studies quantitatively consider the role of cumulative exposure and additive impacts. Community-based risk assessment (CBRA) is a new approach for risk assessment that aims to address the cumulative stressors faced by a particular community, while incorporating a community-based participatory research framework. This paper summarizes an Environmental Protection Agency (EPA) sponsored workshop, "Research Needs for Community-Based Risk Assessment." This workshop brought together environmental and public health scientists and practitioners for fostering an innovative discussion about tools, methods, models, and approaches for CBRA. This workshop was organized around three topics: (1) Data and Measurement Methods; (2) The Biological Impact of Non-Chemical Stressors and Interaction with Environmental Exposures; and (3) Statistical and Mathematical Modeling. This report summarizes the workshop discussions, presents identified research needs, and explores future research opportunities in this emerging field.
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Introduction

Communities face myriad exposures to environmental toxicants and other non-chemical stressors. Although environmental epidemiology studies do consider multiple risk factors, few studies quantitatively considered the full range of complex interactions between the multiple environmental agents (chemical, biological, and social stressors) within a targeted population or within a geographic area in influencing health outcomes. The handful of quantitative cumulative risk assessments, conducted to date, consider only the additive impacts of chemical agents that share a common mode of action (Castorina et al., 2003; Payne-Sturges et al., 2004a; Payne-Sturges et al., 2004b; Caldas et al., 2006; U.S. Environmental Protection Agency, 2006a) or a common exposure media (Fox et al., 2004; Teuschler et al., 2004). In addition, some studies have investigated the interaction of environmental stressors that lead to negative health outcomes (Cary et al., 1997; Morrison et al., 1998; Erren et al., 1999). These studies, however, provide little information on susceptibility factors, interactive effects of biological responses, or social stressors that may modify toxic response.

The 1996 Food Quality and Protection Act expanded risk assessment for evaluating chemical mixtures and environmental contaminants that target similar body mechanisms (U.S. Congress, 1996). Cumulative risk assessment was discussed extensively in the International Life Sciences Institute (ILSI, 1999) publication, titled *A Framework for Cumulative Risk Assessment*, which focused on the cumulative toxicity, exposure, and risk characterization of multiple environmental contaminants. However, the methods for cumulative risk assessment are still evolving (U.S. Environmental Protection Agency, 2003; U.S. Environmental Protection Agency, 2007a). The 2003 Environmental Protection Agency (EPA) publication, *Framework for Cumulative Risk Assessment*, widely expanded the definition of cumulative risk assessment to include non-chemical stressors and the concept of population vulnerability. The EPA defined cumulative risk assessment as "an analysis, characterization and possible quantification of the combined risks to health and or the environment from multiple agents or stressors (U.S. Environmental Protection Agency, 2003)."

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The key aspects of the *EPA Framework for Cumulative Risk Assessment* are: (1) understanding the combined effects of more than one agent/stressor; (2) considering non-chemical stressors; (3) focusing on identifying and characterizing vulnerable human and ecological populations; and (4) using a place-based or population-based analysis for risk assessments, which elicits community expertise. This EPA framework generated a paradigm shift in risk assessment by greatly expanding the concept of an environmental "stressor" to include chemical, biological, physical, and psychosocial agents (U.S. Environmental Protection Agency, 2003). The framework also includes the concept of population vulnerability — certain disadvantaged, underserved, and overburdened communities face conditions that can exacerbate environmental burdens. More specifically, mechanisms of vulnerability identified in the framework include differences in individual or population susceptibility, exposure, preparedness, and ability to recover (U.S. Environmental Protection Agency, 2003; National Environmental Justice Advisory Committee, 2004).

Communities generally share a common geographic location and/or common experience (traditions, diet, behavioral norms). Therefore, cumulative risk assessment for communities is inherently place based (for a discussion on place-based public health, see (Patychuk, 2007; Yeboah, 2005). Community norms influence diet and activities that determine how individuals come into contact with environmental contaminants (U.S. Environmental Protection Agency, 2003, 2006b; National Environmental Justice Advisory Committee, 2004). In addition, non-chemical stressors may affect the health outcome of exposure to environmental contaminants (White et al., 2007). For example, stress has been shown to exacerbate lead toxicity (Bellinger et al., 1988; Tong et al., 2000; Cory-Slechta et al., 2004). The EPA has reflected this understanding of place-based cumulative risk assessment in the 2006 Human Health Multi-Year Plan, by expanding the long-term goal of "Research on Cumulative Risk" to include research on community-based cumulative risk assessment. This includes the development and application of tools and approaches for assessing community risk, and the application of community-based tools, as well as approaches for assessing exposure to environmental contaminants and non-chemical stressors (U.S. Environmental Protection Agency, 2006b; U.S. Environmental Protection Agency, 2007a).

Therefore, community-based risk assessment (CBRA) is defined here as a model of risk assessment that addresses multiple chemical and non-chemical stressors faced by a particular community, while incorporating a community-based participatory research framework and a transparent process to instill confidence and trust among the community members (U.S. Environmental Protection Agency, 2003, 2007b; National Environmental Justice Advisory Committee, 2004). CBRA may include characteristics of a community that cannot be identified and assessed through traditional risk assessment paradigms, such as social and cultural dynamics of the community or resources, strengths, and relationships within the community (Israel et al., 1998). Community and stakeholder involvement is critical in harnessing community knowledge and to better understand complex cumulative exposures (U.S. Environmental Protection Agency, 2003; National Environmental Justice Advisory Committee, 2004; Menzie et al., 2007). Traditionally, this community knowledge has been difficult to obtain using conventional research and risk assessment methods (Israel et al., 1998; Israel et al., 2001; O'Fallon and Dearry, 2001; Corburn, 2005). Community-based participatory research frameworks can aid efforts to involve the community, and can integrate insightful community information that can advance environmental health research (O'Fallon and Dearry, 2002; Corburn, 2005; Israel et al., 2005) and risk assessment.

CBRA reflects the recommendations put forth in the National Environmental Justice Advisory Council's (NEJAC) report, titled "Ensuring Risk Reduction in Communities with Multiple Stressors: Environmental Justice and Cumulative Risks/Impacts," and echoes the interests of the EPA's Office of Environmental Justice and Office of Children's Health Protection (National Environmental Justice Advisory Committee, 2004; U.S. Environmental Protection Agency, 2006b). CBRA evolved from the EPA and the NEJAC publications regarding frameworks for cumulative risk assessment, which indicated the need for dealing with risk on a community-by-community basis (U.S. Environmental Protection Agency, 2003).

Including CBRA in the regulatory decision-making process poses some significant challenges. These challenges include the need to assess toxicity of mixtures, measure vulnerability of populations, and to evaluate interactions among multiple stressors, chemical or non-chemical (U.S. Environmental Protection Agency, 2003). Additional challenges are associated with the need to partner with stakeholders for obtaining community knowledge. The traditional EPA risk assessments evaluate the hazardous properties of substances, assess the extent of human exposure, and characterize the risk of adverse health effects (National Research Council, 1983). Many of these risk assessments aim to protect the most sensitive individuals and/or groups in the general population. In contrast, CBRA would characterize additional community-level stressors and measures of vulnerability to help inform risk evaluation and decision-making at the local level. This may include how community-level stressors and vulnerability factors interact with environmental contaminant exposures to impact the overall risk to the individuals within the defined community.

To address the scientific challenges inherent in CBRA, the Office of Research and Development (ORD) at EPA sponsored a workshop, titled "Research Needs for Community-Based Risk Assessment." This workshop focused on three topics: (1) Data and Measurement Methods; (2) The Biological Impact of Non-Chemical Stressors and Interaction with Environmental Exposures; and (3) Statistical and Mathematical Modeling. (U.S. Environmental Protection Agency, 2007b). This paper provides an overview of the workshop, presents research needs identified based on results of the workshop, and highlights themes to further advance the science behind CBRA.

Workshop overview

From 18 October 2007 to 19 October 2007, in the Research Triangle Park, NC, the EPA's ORD sponsored the "Research Needs for Community-Based Risk Assessment" workshop. This multi-disciplinary workshop was coordinated by a small organizing committee that developed four basic questions regarding CBRA, which became the framework of the workshop:

- What research has been conducted?
- What is the current state of the science?
- What are the research needs?
- How can community-based information be quantified in a way that is useful for EPA risk assessments?

Approximately 85 people attended the workshop. Participants included the EPA employees, contractors, or fellows, spanning eight offices and five regions. Other participants were affiliated with the National Institute of Environmental Health Sciences (NIEHS), academia, other research institutes, local government, or community advocacy groups. Before the workshop, participants were encouraged to read the 2007 *Environmental Health Perspectives* Mini-Monograph on cumulative risk assessment (Callahan and Sexton, 2007; DeFur et al., 2007; Menzie et al., 2007; Ryan et al., 2007; Sexton and Hattis, 2007). The workshop was divided into three topics, as described earlier. Day one of the workshop included presentations on the state of the science for each topic. Small breakout sessions on each topic occurred on day two, at which 10–20 participants discussed the research needs for their respective topics. Session chairs compiled and summarized the research needs identified by the breakout group participants, and these were presented back to the full group for further discussion. A summary report that included details of the workshop presentations and discussion was prepared (U.S. Environmental Protection Agency, 2007b).

Session I: Data and Measurement Methods

Measuring chemical and non-chemical stressors, susceptibility factors, and health outcomes at the community-level will play an important role in CBRA. Some examples include, measuring personal and community exposures to multiple chemical stressors, monitoring the time–activity behavior, measuring markers of susceptibility, and tracking early health outcomes. This session explored currently available tools and methods.

Session I included three presentations: "*Development of Nanoscaled Sensor Systems for Detecting and Monitoring Environmental Chemical Agents*," by Desmond Stubbs of Oak Ridge Center for Advanced Studies (ORCAS); "*Data Collection Platforms for Integrated Longitudinal Surveys of Human Exposure-Related Behavior*," by Paul Kizakevich of RTI International; and "*Assessment Methods for Community-Based Risk Assessment*" by Elaine Faustman of the University of Washington.

The first speaker, Dr. Stubbs, focused on the application of emerging technologies for measuring exposures to chemical stressors. He summarized results of an earlier workshop co-sponsored by the EPA and the ORCAS as the background and context for his presentation (U.S. Environmental Protection Agency and Oak Ridge Center for Advanced Studies, 2006c). Both the EPA and the NIEHS identified the need for a rugged, lightweight, low-cost, wearable, real-time sensor capable of multi-analyte detection with minimal burden to the individual. The "gold standard" was defined as the ability to simultaneously detect multiple chemical agents in the field with the same sensing system and to link this data to a specific biological event. Such a device would be capable of remote data acquisition, location recording, and measurement of both the concentration and frequency of environmental exposure. Dr. Stubbs identified the ongoing research on several devices for use in exposure assessment, including passive radio-frequency identification tags, an electronic nose (i.e., "dog-on-a-chip"), microelectromagnetic sensors, and interferometric optical sensors. He then discussed microfabricated cantilever array platforms and the potential for these to provide lightweight, wearable multi-analyte sensors. Dr. Stubbs also described the possibility of linking the pea-size sensing and telemetry unit to a receiver unit the size of a small personal digital assistant, designed to be carried in a pocket. The personal digital assistant unit could have analysis and display capability, and support global positioning and bio-monitoring device interfaces. Preliminary results suggest that these devices are capable of real-time detection (sub-second scale) of low vapor pressure chemical compounds in the subparts per billion range. The potential power of these new small-scale technologies for measuring personal and community-level exposures to a wide range of chemical constituents and stressors was recognized by many CBRA workshop participants.

The second speaker, Dr. Kizakevich, focused on approaches for measuring exposure-related behaviors for assessing risk. He presented details on the development of a system that integrates multiple real-time data collection streams and survey modes on a handheld Pocket PC platform (Whitmore and Kizakevich, 2004). The objectives of this research are to develop, validate, and evaluate innovative methods for the TALE (time/activity/location/exertion-level) data, dietary consumption data, and data on use of consumer products, including pesticide products, household cleaning products, and personal care products. The system integrates diaries and questionnaires with a collection of wireless peripheral devices for monitoring physical and physiological data.

The RTI researchers are also exploring different methods for collecting data and evaluating these methods using feedback from the study population. Three Pocket PC diary modes were studied: interactive menus, voice questionnaires, and passive periodic photos. Innovations, such as passive microenvironment identification (i.e., beacons), passive exertion assessment, wireless product use event markers, wireless interfaces, intelligent prompting, GPS tracking, and automated daily review for collecting the data both accurately and with a low participant burden are also being investigated. The system design emphasizes easy reconfiguration for supporting varied study requirements, investigator needs, and participant preferences. Dr. Kizakevich noted that data collected during piloting of these approaches will be made available after the next round of monitoring. Originally, the goal was to determine the best method for collecting the exposure-related behavior data. However, based on the first round of evaluation, it is clear that the best technology for collecting behavior data will be determined by the objectives of a given study or risk assessment. Results of the RTI research will provide information that will allow investigators and communities to determine which method is best for their needs.

In the third presentation, Dr. Faustman considered study approaches and data requirements for characterizing the exposure and risk factors to assess individual- and community-level risks. She presented three types of studies conducted by the University of Washington investigators to understand pesticide exposures in children (Thompson et al., 2003, 2008; Vigoren et al., 2007). The three studies presented were a community-based participatory research project, a longitudinal multiple sampling project aimed at understanding between- and within-family variability, and a longitudinal cohort study. Dr. Faustman also identified the importance of collaboration between researchers and community members, by presenting these three study examples. Throughout her presentation, Dr. Faustman emphasized the need for study designs to integrate the wide range of data required to conduct CBRAs. Although the researchers typically had access to general statistics on pesticide usage, an important insight into the potential sources and pathways was obtained from community participants that proved integral for understanding exposures. Her final message focused on the need to develop and incorporate biomarkers of exposure, susceptibility, and effect into studies for identifying vulnerable groups and to understand risks. Genomic and gene expression analysis technologies are being applied in some of the studies by the University of Washington, and have the potential to improve prediction of exposure-response and at-risk individuals in communities.

These presentations provided insight into the tremendous challenges and wide range of data needs associated with characterizing stressors for CBRA. All the speakers identified the need for efficient tools for monitoring personal exposures to better identify vulnerable groups, understand significant exposure pathways, and develop targeted interventions. Novel measurement methods for monitoring environmental stressors (small-scale sensors), collecting exposure-related behavior data (wireless, real-time survey methods), and developing biomarkers of exposure, susceptibility, and effect (genomic and gene expression analyses) were highlighted in the context of CBRA.

Session II: The Biological Impact of Non-Chemical Stressors and Interaction with other Environmental Exposures

There is a recognized need to incorporate non-chemical stressors into cumulative risk assessment (U.S. Environmental Protection Agency, 2003; National Environmental Justice Advisory Committee, 2004). Most public health research on non-chemical stressors have focused on the health effects from exposure to chronic stress (Negro-Vilar, 1993; Bjorntorp, 2001; Kramer et al., 2001; Maccari et al., 2003; Strine et al., 2004; Wright, 2005; Tamashiro et al., 2007; Suglia et al., 2008). However, CBRA provides an opportunity to investigate the non-chemical stressors that might interact with environmental contaminants. Therefore, this session focused on understanding the health impacts of non-chemical stressors, specifically chronic stress, and their ability to interact with exposure to environmental toxicants affecting the risk of adverse health outcomes.

Session II included three presentations: "*Social Stress, Stress Hormones, and Neurotoxins*", by James Herman of the University of Cincinnati; "*Intersections of Social Ecology, Neurobehavioral Development, and Environmental Contamination*," by Bernard Weiss of the University of Rochester; and "*Social Environment as a Modifier of Chemical Exposures*," by Robert Wright of the Harvard University School of Public Health.

Dr. Herman described the biological systems that mediate stress responses. Herman and Seroogy (2006) had broadly defined stress as a "real or perceived threat to homeostasis." The secretion of glucocorticoid hormones, particularly cortisol, function to return the body to homeostasis after stress. However, a prolonged secretion of cortisol and other glucocorticoids due to chronic stress inhibits neurogenesis. This can contribute to deleterious effects on the body and brain, including immune system dysfunction, depression, and cognitive decline (Herman and Seroogy, 2006). Dr. Herman also highlighted that this process can exacerbate other effective disease states, such as schizophrenia and bipolar disease. He also emphasized the potential for the interaction of specific environmental neurotoxicants and chronic stress, because they both represent "hits" on a target system in the multi-hit hypothesis of toxicity (White et al., 2007). Moreover, both environmental neurotoxicants and chronic stress can modulate glucocorticoid secretion, which can work together to potentiate the effects on nerve cells and neurons. This phenomenon has been shown by exposure to lead and chronic stress (Bellinger et al., 1988; Tong et al., 2000; Cory-Slechta et al., 2004; Bellinger, 2008).

Dr. Weiss, the second speaker, focused on the interaction between exposure to neurotoxicants and social disadvantage, referring to his review of children's vulnerability to environmental contaminants (Weiss and Bellinger, 2006). He used lead exposure as a case study and discussed the sometimes-difficult-to-quantify effects on intellectual quotient and behavior associated with lead exposure. Dr. Weiss also emphasized the disparate exposure of people of lower socioeconomic status to both lead and chronic stress, explaining that lead is only one example of differential exposure of neurotoxins to this population. Other examples of differential exposure to neurotoxins include environmental tobacco smoke (Barbeau et al., 2004a; Barbeau et al., 2004b), pesticides (Sexton et al., 2006), and mercury (Payne-Sturges and Gee, 2006).

The third speaker, Dr. Wright, integrated the information presented by the other speakers with his detailed discussion of the effects of environmental contaminants on neuronal function. He also used lead exposure as a case study. Lead exposure stimulates neurotransmitter release causing inappropriate firing of neurons and the blockage of calcium channels required for proper neuron function. Citing numerous animal studies, Dr. Wright illustrated that positive social environments can mitigate the effects of environmental toxicants, such as lead (Guilarte et al., 2003; Weaver et al., 2004). Similar studies in humans have shown that social determinants can alter susceptibility to environmental contaminants (Tong et al., 2000; Clougherty et al., 2007). A new birth cohort, the Early Life Exposure in Mexico to Environmental Toxicants Project (ELEMENT), has been established for investigating these interactions. This project will examine stress, lead exposure, iron deficiency, and neurodevelopment with a holistic perspective. The long-term goals of ELEMENT are to: (1) identify factors that increase and/or decrease metal toxicity; (2) understand the biology of metal neurotoxicity; (3) prevent toxicity; and (4) treat toxicity after it has occurred, by finding the appropriate intervention(s).

Together, these three presentations provided a comprehensive picture of current knowledge about how the brain responds to chronic stress and how this response can interact with exposure to environmental contaminants. This overview helped set the stage for the breakout sessions, which charged the session participants for identifying gaps in our understanding of the connections between the chronic stress and environmental contaminants toxicity.

Session III: Statistical and Mathematical Modeling

There are statistical and modeling challenges involved in viewing organisms and the environment as they really are an integrated whole. Traditional biostatistical approaches, such as linear regression, data stratification or transformation, and others are useful, yet have important limitations when handling high-dimensional data of disparate types. The Session III discussions included integrating data that vary across space and time, pooling datasets drawn from multiple sources, and creating accessible and user-friendly methods for public participation.

This session included three presentations: "*Community Based Risk Assessment—A Statistician's Perspective*," by Louise Ryan of the Harvard School of Public Health; "*A Multi-Site Time Series Study of Hospital Admissions and Fine Particles: A Case-Study for National Public Health Surveillance*," by Francesca Dominici of the Bloomberg School of Public Health at Johns Hopkins University; and "*Risk Assessment/Risk Communication: Understanding the Community*," by Thomas Schlenker of the Public Health Department of Madison-Dane County, WI.

The first speaker, Dr. Ryan, discussed examples of community-focused research studies that were similar in terms of having sparse data, a clever combination of data from multiple sources, and the inclusion of spatiotemporal modeling in the study designs. The most successful studies integrated both personal and community-level data to overcome issues of sparse data and unknown confounding factors (Ryan, 2008). As uncertainty tends to be large when dealing with data collected in real-world communities, it is important to measure characteristics of the community in addition to individuals. Appropriate statistical techniques, such as spatiotemporal and hierarchical models, are of great practical use in such studies that require synthesis of information from multiple sources. However, researchers must be cautioned against overinterpreting model results and placing too much emphasis on *P*-values disconnected from other relevant information. For complex problems, the results must undergo rigorous sensitivity analyses in order to fine-tune the models. Dr. Ryan called for continued work for developing tools capable of combining information measured on multiple scales and degrees of uncertainty, so that the community-based models are robust with respect to time, space, and other perturbations.

Dr. Dominici, the second speaker, discussed the utility of a national system for tracking population health. She stated that population health research could be advanced rapidly by integrating the existing databases (each containing separate information on environmental, social, and economic factors that impact health) and by designing new statistical models to describe the associated risk factors. Dr. Dominici highlighted how multi-site studies comparing day-to-day variations in hospital admission rates with day-to-day variations in pollution levels within the same community are used to estimate city-specific pollution effects relative to confounding effects, such as trend, season, and weather (Dominici et al., 2006). Results have indicated that effects are consistent across location, and that there is a lag between air pollution exposure and respiratory effect. These preliminary results indicate that flux in the levels of air pollution affect health. Such studies provide an impetus for linking national databases and developing appropriate analysis methods to investigate risk at the local level. Owing to the small attributable risk for air pollution and the large number of potential confounders, single-site studies generally display increased statistical error. Therefore, a national system for analyzing data from multiple locations in a systematic fashion is necessary to reliably assess population health.

Dr. Schlenker, the final session speaker, emphasized that accurate and valid risk assessments cannot be carried out unless there is an understanding of the community and communication between the community and researchers. He illustrated this point with examples of community-based studies involving lead and manganese, in which communicating a story about the "life" of these metals in the body instead of merely providing data and scientific jargon about internal disposition was crucial to success (Schlenker, 1989). Dr. Schlenker proposed that providing examples of how a model has been (or can be) used at the community level is the best way to take complicated models and move them into a context, in which they can be trusted and understood by the community. The research can benefit fully from community guidance and case-specific advice, by including communities in the analysis process.

Collectively, the speakers for Session III identified several key requirements for successful modeling for CBRA— including data collected across spatiotemporal scales, information on multiple communities for elucidating community-specific risk factors, comprehensive community involvement, and appropriate statistical analysis methods. The speakers identified the need for continued development of methods for analyzing disparate data types, integrating existing (and nascent) databases, and working to meaningfully include communities in all stages of research.

Workshop results

Emerging Themes

The major outcome of the workshop is the resulting list of research needs (see Table 1) and a list of suggestions to enhance CBRA (see Table 2) elicited from the summary document. Many broad ideas were mentioned in more than one workshop session topic, suggesting emerging and crosscutting themes. The three overarching themes, which are inclusive of the individual research needs, were identified: (1) scientific tools and methods to better measure and evaluate exposures and health outcomes at a community level; (2) environmental health infrastructure; and (3) community involvement processes.

The need for scientific tools (methods and models) to better measure and evaluate exposures and health outcomes at a community level was identified throughout the workshop. On the basis of workshop presentations of the state of the art for monitoring and modeling, it was clear that some very sophisticated tools are available and that much of the research effort could be focused on adapting and applying these tools to the specific objectives of a CBRA. In Session I, the potential for emerging monitoring technologies to provide low-burden, real-time data on the full range of community environmental stressors was identified. Furthermore, Session III participants suggested that statistical techniques are needed to better evaluate health outcomes at the community level, including techniques for synthesizing information from multiple datasets, reduce limitations of small population size, and characterize group-level effects. Workshop participants also identified the need for adjustments to the traditional risk framework. Session II participants recommended amendments in the risk paradigm to incorporate vulnerability and non-chemical stressors. Session I participants identified a need for methodology and modeling changes to include qualitative data and incorporate social (e.g., poverty, access to medical care, chronic stress) variables as modeling parameters. A major outcome of the workshop was the recognition that a new conceptual model for risk assessment may be needed.

A second theme that emerged throughout the workshop was the need for an environmental health infrastructure to address the current gaps in data and data accessibility to foster multidisciplinary research required for CBRA. Session III participants suggested a better infrastructure is needed to create an enhanced access to existing databases and develop transparent modeling methods for diverse disciplines, entities of government, research groups, and community organizations. All the three sessions advocated for an enhanced infrastructure, which could ensure multiple levels of local, state, tribal, and federal entities working together on CBRA. In addition, all the sessions resulted in the acknowledgment of the need to facilitate cross-disciplinary teams within public health practice and research, social science, and environmental health science.

A final reoccurring theme was the need for community involvement. This will require the establishment and fostering of effective working relationships between the community and researchers in addition to the community and government agencies. This may involve training on the options available for community involvement (such as the use of a community-based participatory research framework) within government agencies and among research institutes. In

Table 1. Research needs for community-based risk assessment (CBRA) by workshop session and emerging theme

	Emerging themes		
	#1	#2	#3
Session I: Data Needs and Measurement Methods for CBRA		X	
Develop metrics, indicators, and biomarkers for exposure and health tracking surveillance			
Develop simple and low-cost monitoring methods for pollutants and pathogens at the individual and community level over space and through time (including real time)	X		
Develop simple and low-cost monitoring methods for non-chemical stressors at the individual and community level over space and through time (including real time)	X		
Develop enhanced sensor technologies for providing real-time data on individual and community level measures of exposure to environmental stressors	X		
Create accessible and well-documented databases with links to the full range of exposure information, to include an infrastructure for facilitating addition of data by investigators and the sharing of data and tools used to characterize environmental stressors		X	
Identify and adapt indices used currently in social sciences for measuring community-level psychosocial health	X		
Translate more qualitative social indices into a form that is useful for quantitative risk assessments	X		
Session II: The Biological Impact of Non-Chemical Stressors and Interaction with Other Environmental Exposures			
Review social variables of importance for health in the context of the EPA risk assessment	X		
Develop approaches for incorporating vulnerability into risk assessment models	X		
Develop techniques to incorporate important social variables as modeling parameters	X		
Develop techniques to use community characteristics as proxies of psychosocial exposure	X		
Understand the interaction (chemical dose–response relationships) of chemical and non-chemical stressors, specifically psychosocial stress	X		
Obtain data on baseline variability of psychosocial stress hormones among the population in order to understand inter- and intra-individual variability		X	
Develop tools to monitor psychosocial stress levels in real time (develop biomarkers) at individual and community levels	X		
Incorporate psychosocial stress into physiologically based pharmacokinetic (PBPK) and physiologically based pharmacodynamic (PBPD) models	X		
Examine differential activity patterns between social groups	X		
Session III: Statistical and Mathematical Modeling for CBRA			
Compare various monitoring and modeling techniques to assess value and ease of use	X		
Develop techniques to integrate existing datasets on population health for future predictions/modeling	X		
Develop and apply advanced statistical techniques to: characterize group-level effects, synthesize information from multiple datasets, extrapolate data across communities, reduce limitations of small population studies, account for possible underestimation of exposure, etc.	X		
Increase the ability of Hierarchical Bayesian Model to add data from multiple sources and scales	X		
Develop spatiotemporal models that can adjust for information at multiple scales and levels of accuracy (temporal, spatial, or data from multiple sources)	X		
Develop better geospatial techniques to characterize communities	X		
Explore emerging geospatial tools (e.g., Google Earth)	X		
Develop hierarchical datasets gathered at multiple levels that can be mapped collected, organized, and accessed by community members		X	
Improve methods for interpreting biomonitoring data	X		
Develop transparent modeling methods that can be used collaboratively with the community	X	X	
Better communicate methods and results of complex models	X		

Emerging themes: #1, Scientific tools and methods to better evaluate health outcomes at a community level (including a new framework for risk assessment); #2, Environmental health infrastructure; #3, Community involvement processes.

addition, paradigm shifts within agencies and research institutes may be necessary to initiate CBRA (U.S. Environmental Protection Agency, 1999; National Environmental Justice Advisory Committee, 2004). Although not discussed explicitly, the community-based participatory research or community involvement in decision-making is not without challenges. For example, truly involving the community as active participants in research or decision-making is expensive and requires a great deal of resources. Additionally, there may be a lack of trust, as well as differences in goals, values, and perspectives between the community members, scientists (Israel et al., 2005), and risk assessors.

Review of Research Needs

Some research needs and other suggestions identified at the workshop (Tables 1 and 2) include using tools, methods, or approaches that exist, but are not currently being applied to risk assessment. Session I indicated the need to refine sensor technologies for providing real-time data on commu-

Table 2. Crosscutting suggestions to enhance community-based risk assessment (CBRA) by emerging theme

	Emerging themes #1	#2	#3
Cross-Cutting Suggestions			
Develop a new framework to integrate all chemical, non-chemical, and vulnerability issues into risk assessment	X		X
Establish attributes of successful and unsuccessful case studies (deliberative processes where communities partner with the EPA).	X	X	
Integrate community knowledge for risk assessment	X		X
Develop tools/methods to elicit community knowledge for risk assessment	X		X
Establish models, tools, and frameworks from other disciplines (specifically the ecological sciences) that would be useful for human health risk assessment	X	X	X
Create access to databases that give information at the local level	X		X
Integrate multidisciplinary teams to undertake CBRA research	X	X	X
Integrate multi-agency (federal, state, local) partnerships to address CBRA	X	X	X
Utilize community training modules on basic environmental health and risk assessment	X		X
Focus on research that is directly usable by community or its local health or environmental department (community-driven research)	X	X	X
Establish training modules in academia/agencies on how to conduct community-based participatory research	X	X	X

Emerging themes: #1, Scientific tools and methods to better evaluate health outcomes at a community level (including a new framework for risk assessment); #2, Environmental health infrastructure; #3, Community involvement processes.

nity environmental stressors. Further examples of the existing tools and methods are techniques in use by social scientists or ecologists. Session II suggested the need to identify and apply indices for measuring community-level psychosocial health (e.g., community cohesion) and use community characteristics as proxies of psychosocial exposure. All the session groups identified the need for methods to work effectively with community members, such as how to elicit community knowledge and address research problems that are applicable to the community. Such approaches may already be in use among social science and public health disciplines, but risk assessors may be able to further refine these methods for their work. Altogether, it is important to understand models, tools, and frameworks from other disciplines that would be useful for human health risk assessment.

Other identified research needs included the development of new tools and methods that could be useful for CBRA. This may require multidisciplinary collaborations to create novel techniques and modeling approaches. For example, techniques used for translating more qualitative social indices into quantitative risk assessments were addressed in Session I. Session III identified the need to develop transparent modeling methods that can be used collaboratively within the community. Additional needs addressed in Session II include approaches for incorporating vulnerability into risk assessment models and techniques for including important social variables (e.g., poverty, access to medical care, chronic stress, etc.) as modeling parameters.

Next steps

There have been multiple actions taken, such as the workshop to advance CBRA research. First, EPA's National Center for Environmental Research (NCER) compiled the workshop proceedings, which are now available online. This document includes a copy of most presentations, a final agenda, and a summary report capturing all the presentations and discussions of the workshop (U.S. Environmental Protection Agency, 2007b). Second, the NCER created a Listserv to disseminate information and resources relevant to CBRA (to enlist, see: http://www.epa.gov/ncer/CBRA web site *forthcoming*). Most of the information is digested in a monthly bulletin. Third, NCER is establishing a CBRA *Science Page* on its Web site, which will provide information regarding CBRA to the general public and to the research community. In addition to these NCER activities, other parts of the EPA are supporting CBRA. For example, the EPA's Risk Assessment Forum has been a proponent of CBRA. The EPA's CARE (Community Action for a Renewed Environment) program is a community-based cooperative agreement program, which helps to build broad-based partnerships for reducing environmental risks at the local level. Also, the EPA's Region 6 is partnering with the Ponca Tribe of Northern Oklahoma, EPA's Office of Research and Development, the University of North Texas, and the Oklahoma State University to conduct a cumulative risk assessment of the Tribe, examining holistically the effects of numerous environmental stressors on tribal lands.

The next step to support CBRA within the EPA is for NCER to incorporate CBRA into its extramural research program. NCER's mission is to support high-quality research by the nation's leading scientists, which will improve the scientific basis for decisions on national environmental issues to help the EPA achieve its goals. In 2009, EPA/NCER plans to issue a Request for Applications (RFA) soliciting research to further the field of CBRA. This RFA will aim to address some of the major research needs identified in this workshop.

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References

Barbeau E.M., Krieger N., and Soobader M.J. Working class matters: socioeconomic disadvantage, race/ethnicity, gender, and smoking in NHIS 2000. *Am J Public Health* 2004a: 94(2): 269–278.

Barbeau E.M., McLellan D., Levenstein C., DeLaurier G.F., Kelder G., and Sorensen G. Reducing occupation-based disparities related to tobacco: roles for occupational health and organized labor. *Am J Ind Med* 2004b: 46(2): 170–179.

Bellinger D., Leviton A., Waternaux C., Needleman H., and Rabinowitz M. Low-level lead exposure, social class, and infant development. *Neurotoxicol Teratol* 1988: 10(6): 497–503.

Bellinger D.C. Lead neurotoxicity and socioeconomic status: conceptual and analytical issues. *Neurotoxicology* 2008: 29(5): 828–832.

Bjorntorp P. Do stress reactions cause abdominal obesity and comorbidities? *Obes Rev* 2001: 2(2): 73–86.

Caldas E.D., Boon P.E., and Tressou J. Probabilistic assessment of the cumulative acute exposure to organophosphorus and carbamate insecticides in the Brazilian diet. *Toxicology* 2006: 222(1–2): 132–142.

Cary R., Clarke S., and Delic J. Effects of combined exposure to noise and toxic substances–critical review of the literature. *Ann Occup Hyg* 1997: 41(4): 455–465.

Callahan M.A., and Sexton K. If cumulative risk assessment is the answer, what is the question? *Environ Health Perspect* 2007: 115(5): 799–806.

Castorina R., Bradman A., McKone T.E., Barr D.B., Harnly M.E., and Eskenazi B. Cumulative organophosphate pesticide exposure and risk assessment among pregnant women living in an agricultural community: a case study from the CHAMACOS cohort. *Environ Health Perspect* 2003: 111(13): 1640–1648.

Clougherty J.E., Levy J.I., Kubzansky L.D., Ryan P.B., Suglia S.F., Canner M.J., and Wright R.J. Synergistic effects of traffic-related air pollution and exposure to violence on urban asthma etiology. *Environ Health Perspect* 2007: 115(8): 1140–1146.

Corburn J. *Street Science: Community Knowledge and Environmental Health Justice*. MIT Press, Cambridge, Massachusetts, 2005.

Cory-Slechta D.A., Virgolini M.B., Thiruchelvam M., Weston D.D., and Bauter M.R. Maternal stress modulates the effects of developmental lead exposure. *Environ Health Perspect* 2004: 112(6): 717–730.

DeFur P.L., Evans G.W., Cohen Hubal E.A., Kyle A.D., Morello-Frosch R.A., and Williams D.R. Vulnerability as a function of individual and group resources in cumulative risk assessment. *Environ Health Perspect* 2007: 115(5): 817–824.

Dominici F., Peng R.D., Bell M.L., Pham L., McDermott A., Zeger S.L., and Samet J.M. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. *JAMA* 2006: 295(10): 1127–1134.

Erren T.C., Jacobsen M., and Piekarski C. Synergy between asbestos and smoking on lung cancer risks. *Epidemiology* 1999: 10(4): 405–411.

Fox M.A., Tran N.L., Groopman J.D., and Burke T.A. Toxicological resources for cumulative risk: an example with hazardous air pollutants. *Regul Toxicol Pharmacol* 2004: 40(3): 305–311.

Guilarte T.R., Toscano C.D., McGlothan J.L., and Weaver S.A. Environmental enrichment reverses cognitive and molecular deficits induced by developmental lead exposure. *Ann Neurol* 2003: 53(1): 50–56.

Herman J.P., and Seroogy K. Hypothalamic-pituitary-adrenal axis, glucocorticoids, and neurologic disease. *Neurol Clin* 2006: 24(3): 461–481, vi.

International Life Sciences Institute. A Framework for Cumulative Risk Assessment. In: Mileson B., Faustman E., Olin S., Ryan P.B., Ferenc S., and Burke T. (eds.). Washington, DC, 1999.

Israel B.A., Schulz A.J., Parker E.A., and Becker A.B. Review of community-based research: assessing partnership approaches to improve public health. *Annu Rev Public Health* 1998: 19: 173–202.

Israel B.A., Schulz A.J., Parker E.A., and Becker A.B. Community-based participatory research: policy recommendations for promoting a partnership approach in health research. *Educ Health (Abingdon)* 2001: 14(2): 182–197.

Israel B.A., Parker E.A., Rowe Z., Salvatore A., Minkler M., Lopez J., Butz A., Mosley A., Coates L., Lambert G., Potito P.A., Brenner B., Rivera M., Romero H., Thompson B., Coronado G., and Halstead S. Community-based participatory research: lessons learned from the Centers for Children's Environmental Health and Disease Prevention Research. *Environ Health Perspect* 2005: 113(10): 1463–1471.

Kramer M.S., Goulet L., Lydon J., Seguin L., McNamara H., Dassa C., Platt R.W., Chen M.F., Gauthier H., Genest J., Kahn S., Libman M., Rozen R., Masse A., Miner L., Asselin G., Benjamin A., Klein J., and Koren G. Socio-economic disparities in preterm birth: causal pathways and mechanisms. *Paediatr Perinat Epidemiol* 2001: 15(Suppl 2): 104–123.

Maccari S., Darnaudery M., Morley-Fletcher S., Zuena A.R., Cinque C., and Van Reeth O. Prenatal stress and long-term consequences: implications of glucocorticoid hormones. *Neurosci Biobehav Rev* 2003: 27(1–2): 119–127.

Menzie C.A., MacDonell M.M., and Mumtaz M. A phased approach for assessing combined effects from multiple stressors. *Environ Health Perspect* 2007: 115(5): 807–816.

Morrison H.I., Villeneuve P.J., Lubin J.H., and Schaubel D.E. Radon-progeny exposure and lung cancer risk in a cohort of Newfoundland fluorspar miners. *Radiat Res* 1998: 150(1): 58–65.

National Environmental Justice Advisory Committee. *Ensuring Risk Reduction in Communities with Multiple Stressors: Environmental Justice and Cumulative Risks/Impacts*, Vol. EPA 300/R-04/903. U.S. Environmental Protection Agency, Washington, DC, 2004.

National Research Council. *Risk Assessment in the Federal Government: Managing the Process*. National Academy Press, Washington, DC, 1983.

Negro-Vilar A. Stress and other environmental factors affecting fertility in men and women: overview. *Environ Health Perspect* 1993: 101(Suppl 2): 59–64.

O'Fallon L.R., and Dearry A. Commitment of the National Institute of Environmental Health Sciences to community-based participatory research for rural health. *Environ Health Perspect* 2001: 109(Suppl 3): 469–473.

O'Fallon L.R., and Dearry A. Community-based participatory research as a tool to advance environmental health sciences. *Environ Health Perspect* 2002: 110(Suppl 2): 155–159.

Patychuk D.L. Bridging place-based research and action for health. *Can J Public Health* 2007: 98(Suppl 1): S70–S73.

Payne-Sturges D., and Gee G.C. National environmental health measures for minority and low-income populations: tracking social disparities in environmental health. *Environ Res* 2006: 102(2): 154–171.

Payne-Sturges D.C., Burke T.A., Breysse P., Diener-West M., and Buckley T.J. Personal exposure meets risk assessment: a comparison of measured and modeled exposures and risks in an urban community. *Environ Health Perspect* 2004a: 112(5): 589–598.

Payne-Sturges D.C., Schwab M., and Buckley T.J. Closing the research loop: a risk-based approach for communicating results of air pollution exposure studies. *Environ Health Perspect* 2004b: 112(1): 28–34.

Ryan L. Combining data from multiple sources, with applications to environmental risk assessment. *Stat Med* 2008: 27(5): 698–710.

Ryan P.B., Burke T.A., Cohen Hubal E.A., Cura J.J., and McKone T.E. Using biomarkers to inform cumulative risk assessment. *Environ Health Perspect* 2007: 115(5): 833–840.

Schlenker T. The effects of lead in Milwaukee's water. *Wis Med J* 1989: 88(10): 13–15.

Sexton K., Adgate J.L., Fredrickson A.L., Ryan A.D., Needham L.L., and Ashley D.L. Using biologic markers in blood to assess exposure to multiple environmental chemicals for inner-city children 3-6 years of age. *Environ Health Perspect* 2006: 114(3): 453–459.

Sexton K., and Hattis D. Assessing cumulative health risks from exposure to environmental mixtures - three fundamental questions. *Environ Health Perspect* 2007: 115(5): 825–832.

Strine T.W., Ford E.S., Balluz L., Chapman D.P., and Mokdad A.H. Risk behaviors and health-related quality of life among adults with asthma: the role of mental health status. *Chest* 2004: 126(6): 1849–1854.

Suglia S.F., Ryan L., Laden F., Dockery D.W., and Wright R.J. Violence exposure, a chronic psychosocial stressor, and childhood lung function. *Psychosom Med* 2008: 70(2): 160–169.

Tamashiro K.L., Nguyen M.M., Ostrander M.M., Gardner S.R., Ma L.Y., Woods S.C., and Sakai R.R. Social stress and recovery: implications for body weight and body composition. *Am J Physiol Regul Integr Comp Physiol* 2007: 293(5): R1864–R1874.

Teuschler L.K., Rice G.E., Wilkes C.R., Lipscomb J.C., and Power F.W. A feasibility study of cumulative risk assessment methods for drinking water disinfection by-product mixtures. *J Toxicol Environ Health A* 2004: 67(8–10): 755–777.

Thompson B., Coronado G.D., Grossman J.E., Puschel K., Solomon C.C., Islas I., Curl C.L., Shirai J.H., Kissel J.C., and Fenske R.A. Pesticide take-home pathway among children of agricultural workers: study design, methods, and baseline findings. *J Occup Environ Med* 2003: 45(1): 42–53.

Thompson B., Coronado G.D., Vigoren E.M., Griffith W.C., Fenske R.A., Kissel J.C., Shirai J.H., and Faustman E.M. Para ninos saludables: a community intervention trial to reduce organophosphate pesticide exposure in children of farmworkers. *Environ Health Perspect* 2008: 116(5): 687–694.

Tong S., McMichael A.J., and Baghurst P.A. Interactions between environmental lead exposure and sociodemographic factors on cognitive development. *Arch Environ Health* 2000: 55(5): 330–335.

U.S. Congress. Food Quality Protection Act of 1996. *Public Law 104-170*, United States of America; 1996.

U.S. Environmental Protection Agency. *Concepts, Methods, and Data Sources for Cumulative Health Risk Assessment of Multiple Chemicals, Exposures and Effects: A Resource Document*. EPA Office of Research and Development, Washington, DC, 2007a. EPA/600/R-06/013F.

U.S. Environmental Protection Agency. *EPA's Framework for Community-Based Environmental Protection*. EPA Office of Policy and Office of Reinvention, Washington, DC, 1999. EPA 237/K-99/001.

U.S. Environmental Protection Agency. *EPA's Framework for Cumulative Risk Assessment*. EPA Office of Research and Development, Washington, DC, 2003. EPA 630/P-02/001F.

U.S. Environmental Protection Agency Organophosphorus Cumulative Risk Assessment—2006 Update. EPA Office of Pesticide Programs, Washington, DC, 2006a. EPA HQ-OPP-2006-0618.

U.S. Environmental Protection Agency. *Human Health Research Program Multi-Year Plan (FY 2006-2013)*. EPA Office of Research and Development, Washington, DC, 2006b.

U.S. Environmental Protection Agency Proceedings of the U.S. EPA Workshop on Research Needs for Community-Based Risk Assessment. EPA Office of Research and Development, Research Triangle Park, NC, 2007b. Available at: http://es.epa.gov/ncer/cbra/presentations/11_18_07/11_18_07_workshop.html.

U.S. Environmental Protection Agency and Oak Ridge Center for Advanced Studies. *Nanotechnology Applications in Environmental Health: Big Plans for Little Particles*. EPA Office of Research and Development, Research Triangle Park, NC, 2006c. Available at: http://www.epa.gov/ncct/communications.html.

Vigoren E.M., Griffith W.C., Krogstad F.T.O., Coronado G.D., Thompson B., and Faustman E. Formal Uncertainty Analysis in the Interpretation of Organophosphate Pesticide Metabolite Concentrations. In: Society for Risk Analysis Annual Meeting; Dec 9-12, 2007; San Antonio, TX, 2007.

Weaver I.C., Cervoni N., Champagne F.A., D'Alessio A.C., Sharma S., Seckl J.R., Dymov S., Szyf M., and Meaney M.J. Epigenetic programming by maternal behavior. *Nat Neurosci* 2004: 7(8): 847–854.

Weiss B., and Bellinger D.C. Social ecology of children's vulnerability to environmental pollutants. *Environ Health Perspect* 2006: 114(10): 1479–1485.

White L.D., Cory-Slechta D.A., Gilbert M.E., Tiffany-Castiglioni E., Zawia N.H., Virgolini M., Rossi-George A., Lasley S.M., Qian Y.C., and Basha M.R. New and evolving concepts in the neurotoxicology of lead. *Toxicol Appl Pharmacol* 2007: 225(1): 1–27.

Whitmore R., and Kizakevich P. Progress Report: Data Collection Platforms for Integrated Longitudinal Surveys of Human Exposure-Related Behavior. EPA Grant Number R831541; 2004.

Wright R.J. Stress and atopic disorders. *J Allergy Clin Immunol* 2005: 116(6): 1301–1306.

Yeboah D.A. A framework for place based health planning. *Aust Health Rev* 2005: 29(1): 30–36.