A Section 508–conformant HTML version of this article is available at https://doi.org/10.1289/EHP9889.

The Interplay of Environmental Exposures and Mental Health: Setting an Agenda

Aaron Reuben,[1] *Erika M. Manczak,*[2] *Laura Y. Cabrera,*[3] *Margarita Alegria,*[4,5] *Meghan L. Bucher,*[6] *Emily C. Freeman,*[7] *Gary W. Miller,*[6] *Gina M. Solomon,*[8,9] *and Melissa J. Perry*[10]

[1]Department of Psychology & Neuroscience, Duke University, Durham, North Carolina, USA
[2]Department of Psychology, University of Denver, Denver, Colorado, USA
[3]Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, Pennsylvania, USA
[4]Departments of Medicine and Psychiatry, Harvard Medical School, Boston, Massachusetts, USA
[5]Disparities Research Unit, Department of Medicine, Massachusetts General Hospital, Boston, Massachusetts, USA
[6]Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, New York, New York, USA
[7]Lundbeck, LLC, Deerfield, Illinois, USA
[8]Department of Medicine, University of California San Francisco, San Francisco, CA
[9]Public Health Institute, Oakland, CA
[10]Department of Environmental and Occupational Health, George Washington University, Washington, District of Colombia, USA

Background: To date, health-effects research on environmental stressors has rarely focused on behavioral and mental health outcomes. That lack of research is beginning to change. Science and policy experts in the environmental and behavioral health sciences are coming together to explore converging evidence on the relationship—harmful or beneficial—between environmental factors and mental health.

Objectives: To organize evidence and catalyze new findings, the National Academy of Sciences, Engineering, and Medicine (NASEM) hosted a workshop 2–3 February 2021 on the interplay of environmental exposures and mental health outcomes.

Methods: This commentary provides a nonsystematic, expert-guided conceptual review and interdisciplinary perspective on the convergence of environmental and mental health, drawing from hypotheses, findings, and research gaps presented and discussed at the workshop. Featured is an overview of what is known about the intersection of the environment and mental health, focusing on the effects of neurotoxic pollutants, threats related to climate change, and the importance of health promoting environments, such as urban green spaces.

Discussion: We describe what can be gained by bridging environmental and psychological research disciplines and present a synthesis of what is needed to advance interdisciplinary investigations. We also consider the implications of the current evidence for *a*) foundational knowledge of the etiology of mental health and illness, *b*) toxicant policy and regulation, *c*) definitions of climate adaptation and community resilience, *d*) interventions targeting marginalized communities, and *e*) the future of research training and funding. We include a call to action for environmental and mental health researchers, focusing on the environmental contributions to mental health to unlock primary prevention strategies at the population level and open equitable paths for preventing mental disorders and achieving optimal mental health for all. https://doi.org/10.1289/EHP9889

Introduction

From psychiatric sequelae of neurotoxicants such as pesticides and heavy metals, to chronic and post-traumatic stress from climate change-driven natural disasters or legacy environmental injustice to the mental health benefits of green spaces and neighborhood amenities, the physical environment can influence mental health in important ways. To date, health-effects research on environmental stressors has rarely focused on behavioral and mental health outcomes. That is beginning to change. Science and policy experts in environmental, psychiatric, genetic, social, and behavioral epidemiology, toxicology, and neuro and developmental psychology are coming together to explore converging evidence on the relationship - harmful or beneficial - between environmental factors and mental health.

Address correspondence to Melissa J. Perry, Department of Enviromental and Occupational Health, Milken Institute School of Public Health, 955 New Hampshire Avenue, Washington, D.C., 20052. Email: mperry@gwu.edu

M.J.P. and G.M.S. have provided expert witness testimony on issues pertaining to environmental and occupational health. G.W.M. receives royalties from his book on the exposome and an honorarium for his role as editor of Exposome published by Oxford University Press. M.A. serves as a Senior Program Associate of the William T. Grant Foundation, commission member of the Robert Wood Johnson Foundation National Commission to Transform Public Health Data Systems, and consultant for the Robert Wood Johnson Foundation Advancing Change Worldwide initiative.

Received 24 June 2021; Revised 6 October 2021; Accepted 20 December 2021; Published 16 February 2022.

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The National Academies of Sciences, Engineering, and Medicine (NASEM) Standing Committee on Emerging Science for Environmental Health Decisions is charged with scoping the field of environmental health to identify and discuss new areas of science and research methodologies with the potential to inform decision-making. In 2020, the committee identified mental health and the environment as a priority emerging science topic and appointed a multidisciplinary planning committee that met weekly for several months, culminating in a 2 day workshop on "The Interplay Between Environmental Exposures and Mental Health Outcomes," summarized in detail elsewhere (NASEM 2021a). After the workshop, members of the standing committee and the planning committee continued to meet to further develop ideas generated at the workshop. The structure of the process followed an iterative strategy, in which the planning committee conducted an expert-guided conceptual review of the existing literature to identify potential priority areas for research and policy, refined these priorities with input from presenters and the audience at the public workshop, and individuals after the workshop organized the priority concepts into a framework and specific actions to advance the field. This commentary summarizes the framework and priorities identified through the multidisciplinary expert process. Although key papers are cited in this commentary to illustrate the concepts discussed, this paper does not constitute a systematic review of the literature on this topic.

Mental Health as an Overlooked Outcome

Mental health disorders are leading contributors to disabilities and morbidity (Vigo et al. 2016), and have considerable negative social, professional, personal, and economic consequences (Murray et al. 2020). They are also strikingly prevalent (Schaefer et al. 2017). Repeated assessments in population-representative cohorts have identified the lifetime prevalence of mental disorder

diagnoses to be above 70% by age 30 y (Schaefer et al. 2017), and above 85% by age 45 y (Caspi et al. 2020). To date, relatively little research has examined the interplay of nonsocial environmental factors (e.g., toxicants, climate change, etc.) with mental health.

To assist in the goal to bridge psychological and environmental science, we briefly review here some leading approaches to identifying and measuring mental disorders. To differentiate between normal emotional experiences and psychological disorders, scientists and clinicians rely on diagnostic taxonomies, such as those in the U.S.-based *Diagnostic and Statistical Manual of Mental Disorders: Fifth Edition* (*DSM-5*) (American Psychiatric Association 2013) and the more global International Classification of Diseases (ICD)-10. Within these taxonomies, sets of disorders are grouped into clusters that share common themes, including neurodevelopmental disorders [e.g., attention deficit/hyperactivity disorder (ADHD)], anxiety disorders (e.g., specific phobias or generalized anxiety), mood disorders (e.g., major depressive disorder), schizophrenia spectrum disorders, disruptive-impulsive disorders (conduct disorder), and substance use disorders, among others (American Psychiatric Association 2013). Although the medical community frequently relies on categorical diagnoses for assessment and treatment frameworks (i.e., a person does or does not have a particular disorder according to the *DSM*), alternative research frameworks emphasize dimensional assessments of psychopathology, which recognize that symptoms fall along a spectrum of severity. In this way, mental health can be studied as discrete, categorical diagnoses or as quantitative levels of symptoms across a continuum of distress or impairment.

Nongenetic Drivers of Mental Health and the Potential Benefits of an Exposomic Approach

Genetic contributions to psychiatric disorders continue to be identified and characterized, and these discoveries represent important advances in our understanding of psychiatric conditions and symptoms (Geschwind and Flint 2015). However, inheritance studies clearly demonstrate that genetics alone can explain only a portion of brain or behavioral dysfunction (the heritability of depression, for example, is $\sim 37\%$; Sullivan et al. 2000), leaving the rest to nongenetic influences. If the environment includes all nongenetic components, it is necessary to consider toxicant exposures, activity, diet, physical surroundings, and social forces (McHale et al. 2018). The exposome provides an example of a holistic characterization of the environment and provides a scientific framework to uncover the wide breadth of nongenetic contributors to mental health as well as the biological consequences of exposures (Burkett and Miller 2021; Vermeulen et al. 2020). This broadly defined environmental component can range from toxicant exposures (e.g., metals, pesticides, solvents, air pollution, etc.) to psychosocial exposures (e.g., interpersonal interactions, socioeconomic factors, etc.), or combinations of and interactions between these exposures over the course of a lifetime (Vermeulen et al. 2020).

Research Challenges in Human and Animal Studies

For many environmental stressors, it is unethical to design human studies that maximize causal inference, such as experiments and randomized control trials. Most evidence thus comes from observational clinical and epidemiological studies and from animal studies. However, understanding the effects of environmental factors on mental health is difficult to approach at the bench. Where other fields of toxicology have objective biological end points that are typically easy to quantify, mental health research is limited both by the difficulty in measuring complex cognitive, psychological, and emotional states in humans and by the difficulty in replicating human-specific experiences in animals. Many mental health conditions cannot currently be evaluated in animals, such as dissociation or experiencing uncontrollable repetitive thoughts, necessitating the use of simplified indices of behavioral features as proxies for these complex conditions (Nestler and Hyman 2010).

Single toxicant exposures are translatable to animal models because equivalent exposure doses can be calculated and tested in experimental protocols (findings from such models are reviewed below). However, we know that this approach captures only part of the equation and is insufficient for addressing human-specific exposures. How does a scientist model chronic stress due to job insecurity in an animal? How does one account for known social contributors to substance use such as social networks and societal pressures in animal experiments? How can

Table 1. Examples of human features and animal model correlates for mental health conditions: behavioral features and correlates.

	Human behavioral features	Behavioral correlates in animal models
Attention deficit/hyperactivity disorder	Hyperactivity	Increased activity in the open field test
	Inattention	Slow reaction times and inaccuracy during operant tasks
	Impulsivity	Perseverance in accessing stimulus despite aversive consequence
Substance use disorder	Substance seeking regardless of conflict or punishment	Animals preferentially choosing to use substances over eating or drinking
	Pathological choice of drug over other necessities (e.g., food, water)	Animals tolerating aversive stimulus (e.g., foot shock or pharmacological agents such as histamine) to access drug
		Persistence of drug-associated behavior(s) during extinction paradigm
Major depressive disorder	Apathy	Impaired nest-building, disturbed grooming regimen
	Anhedonia	Reduced preference for palatable solutions or food (e.g., sucrose water or cookies)
	Despair	Decreased escape attempts in forced swim test
	Irritability	Increased aggression when intruder animal is introduced to resident animal's cage
Obsessive compulsive disorder	Uncontrollable repetitive thoughts	NA
	Uncontrollable repetitive behaviors	Excessive grooming
		Schedule induced polydipsia
Post-traumatic stress disorder	Recurring, involuntary, and intrusive memories	NA
	Derealization or dissociation	NA
	Hypervigilance	Increased startle response

Note: NA, Not Applicable.

Table 2. Examples of human features and animal model correlates for mental health conditions: Neuroimaging and neurochemical correlates.

		Human neuroimaging features	Neurochemical correlates in animal models
ADHD	fMRI	Reduced blood flow in fronto-striatal, fronto-cerebellar, and fronto-striato-parieto-cerebellar networks	Dysregulated dopamine metabolism and transmission
		Increased blood flow in posterior parietal lobe, PCC, and regions of dlPFC	
	PET	Abnormal dopamine transporter binding, dopamine receptor binding, and dopamine metabolism in right caudate	Dysregulated (increased or decreased) extracellular dopamine and/or norepinephrine concentrations
		Decreased D_2/D_3 receptor availability in left caudate	
		Decreased dopamine transporter density in midbrain	Decreased spontaneously active ventral tegmental area dopaminergic neurons
	DTI	Abnormal white matter structural anatomical connectivity in fronto-striatal circuitry, fronto-cerebellar circuitry, and executive functioning and attentional networks	Impaired modulation of cortico-striato-thalamo-cortical circuits
SUD	fMRI	Hypoactive PFC during cognitive tasks	Increased dopamine signaling
	rsMRI	Decreased connectivity in the default mode network	Increased activity in mesolimbic pathway
	PET	Reduced regional brain glucose metabolism in PFC and ACC	
	EEG	Altered P300 on reward processing tasks	Dysregulated hypothalamic-pituitary-adrenal activity
MDD	fMRI	Increased activity in mPFC, amygdala, and hippocampus	Increased circulating glucocorticoids and decreased glucocorticoid receptors
		Decreased activity in lPFC, and striatum	
	PET	Hyperactivity in the mPFC	Increased pro-inflammatory cytokines and decreased anti-inflammatory cytokines
		Altered metabolism and neural activity in the PCC, insula, hippocampus, and amygdala	
		Altered serotonin receptor binding	Decreased serotonin levels
	DTI	Abnormal white matter integrity in superior longitudinal fasciculus, corpus callosum, and uncinate fasciculus	Decreased hippocampal brain derived neurotrophic factor expression
	MRI/VBM	Decreased volume in mPFC, lPFC, striatum, amygdala, and hippocampus	
OCD	rsMRI	Abnormal functional connectivity in OFC and ACC	Altered cortico-basal ganglia-thalamo-cortical activity
	PET/SPECT	Intrusive thought-induced hyperactivity in the OFC	Altered dopamine receptor subtype composition and dopamine receptor binding
		Anxiety related hyperactivity in the ACC	Disturbed redox balance
		OCD stimuli-induced increased activity in OFC and ACC	Altered firing and postsynaptic currents in bed nucleus of the stria terminalis neurons
	MRI/CT/VBM	Structural changes in OFC, ACC, basal ganglia, and thalamus	Altered cyclic adenosine-monophosphate phosphodiesterase signaling
			Altered serotonin reuptake transporter expression
PTSD	fMRI	Hyperactivity in the amygdala	Increased stress hormones
		Hypoactivity in the mPFC and ACC	Increased epigenetic methylation of brain-derived neurotrophic factor gene in hippocampus
		Reduced hippocampal activity	Upregulated corticotropin releasing factor receptors in stria terminalis
	MRI/MRS	Structural changes in hippocampus, amygdala, and mPFC	Decreased hippocampal plasticity
			Increased cortical and hippocampal expression of glucocorticoid receptors

Note: ADHD findings summarized in Weyandt et al. (2013) and Russell (2005, 2007). SUD findings summarized in Cabrera et al. (2016) and Koob and Simon (2009). MDD findings summarized in Wise et al. (2014), Krishnan and Nestler (2011), and Wang et al. (2017). OCD findings summarized in Holzschneider and Mulert (2011) and Szechtman et al. (2017). PTSD findings summarized in Holzschneider and Mulert (2011) and Borghans and Homberg (2015). Endogenous event-related potentials between 300–600 ms after cue (P300). ACC, anterior cingulate cortex; ADHD, attention deficit/hyperactivity disorder; CT, computerized tomography; d, dorsal; DTI, diffusion tensor imaging; EEG, electroencephalogram; fMRI, functional MRI; lPFC, inferior prefrontal cortex; l, lateral; m, medial; MDD, major depressive disorder; mPFC, medial prefrontal cortex; MRI, magnetic resonance imaging; MRS, magnetic resonance spectroscopy; OCD, obsessive compulsive disorder; OFC, orbitofrontal cortex; PET, positron emission tomography; PFC, prefrontal cortex; PCC, posterior cingulate cortex; PTSD, posttraumatic stress disorder; rsMRI, resting state MRI; SPECT, single photon emission computerized tomography; SUD, substance use disorder; VBM, voxel based morphometry.

animals be used to understand the consequences of environmental and systemic racism on mental health?

As Tables 1 and 2 illustrate, the measurable neurochemical and behavioral features of mental health conditions in animal models translate with variable efficacy to human correlates. Animal models of mental health disorders are often evaluated based on their face, construct, and predictive validity (Willner 1984). Face validity refers to how well the animal model replicates the human condition based on behavioral and biological features. Construct validity refers to how authentically the etiological conditions used to create the animal model relate to the etiological conditions under which the disorder arises in humans. Finally, predictive validity refers to how well the model responds to treatments that are effective in the human condition (e.g., excessive grooming is considered a compulsive behavior in obsessive-compulsive disorder animal models because it diminishes following treatment with antidepressants). Overall, animal models can provide invaluable insights into human mental health conditions, but they will also invariably have limitations.

Domains of Environmental Exposures and Mental Health Research

Notwithstanding unique research challenges in this field, a considerable body of evidence already suggests that the physical environment may influence mental health outcomes. Here we summarize the evidence on neurotoxicants, environmental disasters, and urban natural spaces as examples of this influence because these have the largest literature base, but there are other equally important examples that we could have selected, including psychological reactions to environmental racism and systemic injustice, species loss and climate change (solastalgia), and community initiatives to improve environmental conditions. Figure 1

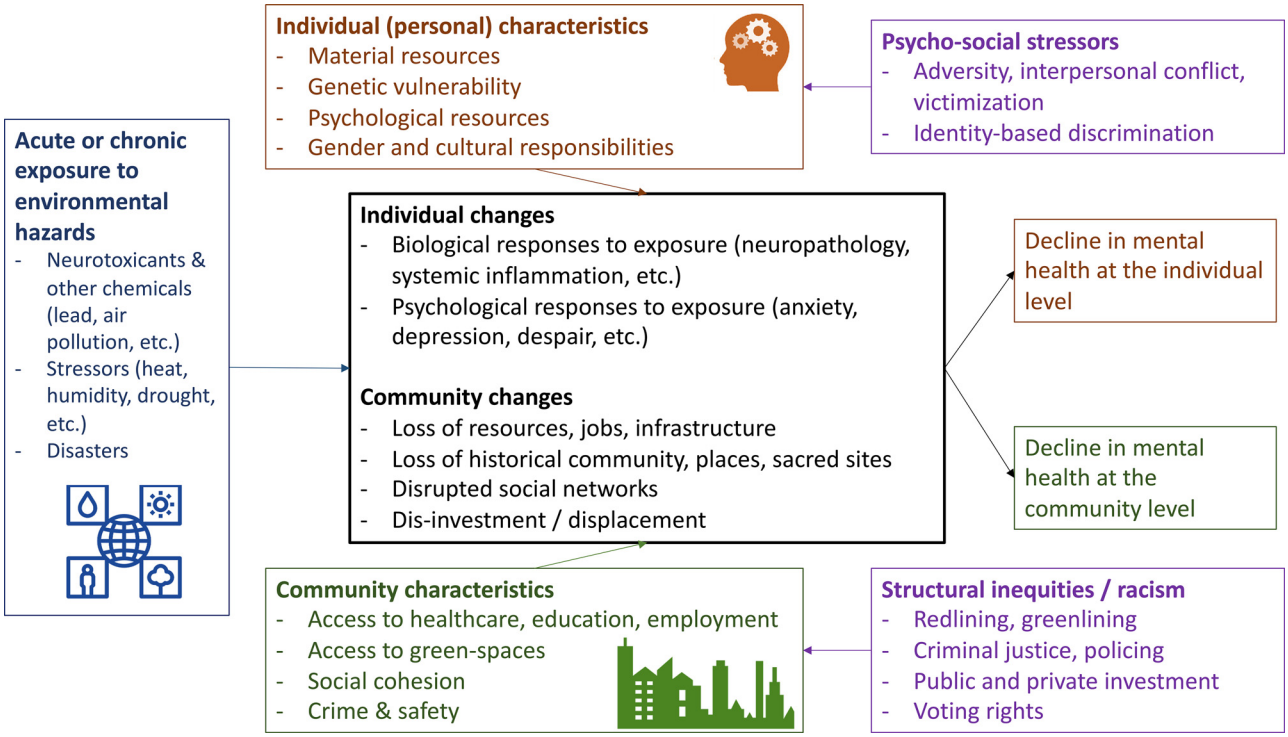

Figure 1. Conceptual model of the association of environmental hazards with mental health outcomes at the individual and community level.

ties together these diverse domains of environmental influence on mental health through an illustrative conceptual model.

Psychiatric Effects of Environmental Toxicants

What is known already. Hundreds of natural and synthetic toxicants have been implicated in human psychiatric disorders and psychological functioning; heavy metals, solvents, and pesticides represent some of the best studied classes (Table 3). Although evidence continues to emerge, the neurotoxicity of these agents has been well-characterized in epidemiological research, focusing on end points such as impairments of motor function or visuospatial ability or impairments in learning, memory, and attention (White et al. 2014). Less well-studied are the effects of these agents on psychological, noncognitive end points, such as personality, emotion regulation, impulse control, or symptoms of mental disorder. Early neuro-epidemiology studies often considered changes in mood, affect, and personality following toxicant exposures to be the result of psychological reactions to the exposure (i.e., distressing thoughts and beliefs about having been exposed), rather than the result of actual observable pathology (White et al. 2014). In the most biased designs, participants with psychiatric symptoms were excluded from observational studies to identify the "pure" effects of toxicants on cognitive and neurological outcomes.

Neurotoxicant exposures, both acute and chronic, can result in subtle and lasting mental health consequences. For example, adults occupationally exposed to metals, particularly lead, have long been known to demonstrate alterations in mood, energy, and irritability (Baker et al. 1985). Children exposed to lead demonstrate greater externalizing symptoms, such as hyperactivity and antisocial behavior (Marcus et al. 2010; Needleman et al. 1996), and, in adulthood, tend to develop more disadvantageous personality profiles (Reuben et al. 2019; Schwaba et al. 2021), schizophrenia diagnoses (Opler et al. 2004), and psychiatric symptomatology across diagnostic categories (McFarlane et al. 2013; Reuben et al. 2019).

Similar findings exist for other classes of neurotoxicants. Solvent exposure has been linked to changes in personality, motivation, and impulsivity (Condray et al. 2000; van Valen et al. 2012) and to higher rates of mood, anxiety, bipolar, and psychotic disorders (Aschengrau et al. 2012; Visser et al. 2011). Exposure to pesticides, particularly acetylcholinesterase-inhibiting organophosphates, has been linked to increases in depressive symptomatology, anxiety and depression diagnoses (Suarez-Lopez et al. 2021), suicides (Khan et al. 2019), and general neuropsychiatric symptomatology (Rauh and Margolis 2016). In addition, individual and mixtures of pollutants with neurotoxic properties such as perfluoro- and polyfluoroalkyl substances and outdoor air pollutants (e.g., nitrogen oxides and particulate matter) (de Prado-Bert et al. 2018), have been linked to risk of autism (Long et al. 2019), ADHD (Jorcano et al. 2019; Liew et al. 2015), depression, anxiety (Braithwaite et al. 2019), and schizophrenia (Newbury et al. 2019), and to elevations in risk of mental illness across diagnostic categories (Brokamp et al. 2019; Reuben et al. 2021).

What we still need to know.

- How do psychological reactions to toxicant exposure (i.e., beliefs and feelings about having been exposed) interact with biological reactions (e.g., neuronal and glial cell dysfunction)?
- What are the psychological mechanisms (e.g., enhanced emotional arousal, impaired cognitive control) that mediate biologically driven mood, personality, and psychopathology changes following toxicant exposures?
- How do early life toxicant exposures alter life-course trajectories relevant to health, happiness, and productivity, including educational and occupational attainment, interpersonal relationship quality, and healthy aging and longevity?
- How do multitoxicant exposures, both concurrent and sequential, interact to differentially alter mental health outcomes?

Table 3. Major classes of neurotoxicants and their typical exposure sources and neurotoxic action.

Class of toxicant	Typical exposure sources	Typical neurotoxic action	Animal model examples
Metals	Metals are naturally occurring, but human exposure is usually due to current or historical uses. Current sources include mining, smelting, battery manufacturing and recycling, construction, automotive, and electronics.	Toxicity and action vary by metal and dose (e.g., lead is toxic at all levels, whereas copper is essential at low levels and harmful at high). Metals generally harm the CNS by substituting for necessary minerals (e.g., lead substitutes for calcium, which is critical to neuronal signaling), binding to and inactivating necessary enzymes (e.g., arsenic can inactivate >200 enzymes), or generating reactive oxygen species.	Prenatal and neonatal lead exposure in mice results in learning deficits and hyperactivity that is attenuated by amphetamine or methylphenidate (Silbergeld and Goldberg 1974, 1975).
Organic solvents	Solvents are used as vehicle and equipment fuels; in almost all chemical and industrial processes; and as ingredients in cleaning and degreasing products, pesticides, paints, adhesives, cosmetics, coatings, and ink.	Toxicity and action vary by solvent and dose, but typically organic solvents are lipophilic and concentrate in lipid-rich brain white matter. Mechanisms of toxicity remain poorly characterized but are related to generation of toxic reactive oxygen species. Consequences can involve dysregulation of glial cells, demyelination of nerve fibers, ischemic damage, and white matter necrosis.	Adult mice acutely exposed to toluene show depressive symptoms as measured by increased time spent immobile during the tail suspension test and forced swim test, which is indicative of despair. These symptoms are not the result of an overall decrease in movement and are reversed via treatment with antidepressants (Yang 2010).
Pesticides	Pesticides are applied in agriculture and manufacturing processes, in parks, golf courses, rights of way, and home and garden use.	Toxicity and action vary by pesticide, but the best-studied classes, organophosphates and carbamate pesticides, inhibit acetylcholinesterase resulting in accumulation of acetylcholine and disrupted neurotransmission in the parasympathetic nervous system.	Young mice (1 month of age) exposed subchronically or chronically to glyphosate demonstrate both depressive and anxiety behaviors including decreased time spent in open arms of an elevated plus maze (Ait Bali 2017).

Note: CNS, central nervous system.

- What genetic, sex, gender, ethnic, and cultural factors alter individual vulnerability and resilience to toxicant effects on mental health?

Environmental Disasters and Mental Health

What is known already. Human-caused and natural environmental disasters, such as oil spills, drinking-water contamination, drought, floods, and wildfires often result in widespread mental health consequences (Beaglehole et al. 2018; Morganstein and Ursano 2020), most commonly posttraumatic stress disorder (PTSD) (Marshall et al. 2007), depression (Sastry and VanLandingham 2009), anxiety, and substance use (North et al. 2011; Heard-Garris et al. 2017). Rises in violence and suicide have been associated with the postdisaster period and increase during extreme heat events (Mares 2013). A notable proportion of individuals (e.g., >9%) who develop mental health sequelae after an environmental disaster go on to develop chronic psychological dysfunction (McLaughlin 2009). Meta-analyses have identified perceived health effects from the events and institutional delegitimization of community concerns as factors that increase psychological consequences, particularly from chemical disasters (Schmitt et al. 2021). Similarly, climate disasters can bring inordinate stress to communities, although studies of the specific mental health impacts are rare (Cianconi et al. 2020). Slow-moving disasters, such as drought or melting permafrost can also have clinically meaningful, rarely studied mental health effects, particularly depression and suicide, in populations directly dependent on the land, such as farmers (Guiney 2012) and indigenous populations (Obrien 2014; Middleton et al. 2020). Anxiety from the general threat of climate change can also be a stressor contributing to psychological distress (Clayton 2020).

What we still need to know.

- Do the mental health outcomes from disaster vary based on the type of disaster (e.g., chronic, ongoing vs. single event, natural vs. human-generated). Do ethnic and cultural factors alter community vulnerability and resilience?
- Can conceptual models of community resilience accurately predict the psychological impact of disasters? If so, can community resilience assessments help plan responses to disasters to limit mental health impacts?
- When should psychological intervention be deployed in communities to mitigate the mental health impacts of disasters (e.g., pre, during, post)? Can psychological first aid–style interventions be tailored to address community resilience needs in the disaster context, at-scale?
- What are the costs and benefits of community resilience investments in the short and long run? Which institutions (federal, state, local) should bear the costs?

Beneficial Outcomes of Natural Environments on Mental Health

What is known already. Environmental factors may also help promote mental health (Palinkas et al. 2020), particularly exposure to green spaces (i.e., nature reserves, wilderness environments, and urban parks) (Barton and Rogerson 2017). A recent review of studies reported a link between exposure to natural environments and a decrease in symptoms of mental illness (Bratman et al. 2019) while increasing happiness and subjective well-being (White et al. 2013). A multidecade nationwide study in Denmark found that children raised in neighborhoods with the least green space had up to a 55% greater risk of developing a psychiatric disorder in adulthood than their peers raised in greener settings regardless of other assessed risk factors, including level of urbanization, socioeconomic factors, parental history of mental illness, and parental age (Engemann 2019). Another study found that self-reported mental health improves with every hour of contact with natural settings each week, with peak mental health reported after 3–5 h of weekly contact (White et al. 2019).

Mechanisms driving these associations are an active area of investigation (Bratman et al. 2019), and several pathways have been proposed (Markevych et al. 2017) including: *a*) reduction of

physiological stressors impacting mental health, including heat, noise, and air pollution; *b*) promotion of behaviors that improve mental health, including social interaction, self-reflection, and physical activity; and *c*) direct restoration of cognitive resources (e.g., attention) and/or alteration of nervous system activity (e.g., activation of the parasympathetic nervous system) in ways that improve mental health. Causal inference in this domain has been hindered to date by a lack of common metrics for the assessment of green space "exposure" (Holland et al. 2021), although innovations in measurement, including wearable and geospatial technology to dynamically assess individuals' locations and activities throughout time, hold promise for more fully characterizing the experiences of people exposed to nature settings (Barnes et al. 2018).

Exposure to nature and green spaces is now considered a mental health intervention at both the community and individual level, particularly in low-resourced areas (South et al. 2020). In a randomized control trial, such greening initiatives significantly reduced feelings of depression and self-reported poor mental health for adults living near greened lots (South et al. 2018). Randomized trials among low-income minority families show park prescriptions from pediatric health care providers can increase family park visits, reduce stress among parents, and improve resilience among youth (Razani et al. 2018, 2019).

What we still need to know.

- How do sociodemographic and cultural factors affect the association of natural environment contact and mental health outcomes?
- What intensity, duration, and frequency of green-environment exposure are needed to yield a mental health benefit? At what levels of green-environment *deprivation* do negative mental health outcomes emerge?
- Which of the many proposed mechanisms of effect (e.g., stress reduction, physical activity, social engagement, attention restoration, etc.) best explain green-environment associations with specific mental health outcomes? Which exposure metrics (e.g., active park use, passive greenery exposure, etc.) best predict various mental health outcomes?
- What are the systemic injustices in access to green space, where urban green spaces are typically most accessible in wealthier, higher-educated, and predominantly White neighborhoods (Nesbitt et al. 2019; Williams et al. 2020)?
- What are the social, economic, and ethical implications of current interventions to restore or create green environments? Are there potential unintended consequences (e.g., can greening interventions inadvertently price residents out of their neighborhood)? Are there any *adverse* mental health effects of natural environment exposure?

Vulnerability and Environmental Risks in Groups and Communities

What is known already. Previous research at the intersection of vulnerability and environmental risks has focused on understanding environmental factors that put people and communities at risk. Children (Carroquino et al. 2012; Mitro et al. 2015), the elderly, pregnant and postpartum women (Lowe et al. 2020), people with preexisting mental illness, people facing economic and social disadvantage, and first responders (Osofsky et al. 2011) are among the groups identified as being uniquely vulnerable to environmental exposures and disasters (Gee and Payne-Sturges 2004; Lowe and Rhodes 2013; La Greca 2013). Differential patterns of exposure may be exacerbated by environmental injustices that disproportionately affect Black, Indigenous, and people of color (BIPOC) (Hoover et al. 2015). BIPOC populations are more likely to live near toxic waste sites, breathe polluted air, or work in jobs that involve harmful exposures (e.g., Ard 2015; Bell and Ebisu 2012). Structural racism is now recognized as one driver of these disproportionate hazards. These same populations may have less access to *a*) quality information on effects of environmental exposures; *b*) economic and social resources to buffer stress in response to exposures and disasters; and *c*) timely health care for prevention or treatment of mental illness. Another vulnerability factor that has been largely overlooked until now is that environmental factors can worsen health outcomes for people with preexisting mental illness. For example, extreme heat can increase the risk of disease and death for people with mental illness, people with health comorbidities, or those moved to temporary shelters (Taioli et al. 2018) because some antipsychotic and anxiolytic drugs can impair temperature regulation (Martin-Latry 2007).

What we still need to know.

- What are the direct and indirect mental health consequences of environmental harms disproportionately sited in or near BIPOC communities—e.g., refineries, Superfund sites, confined animal feeding operations—and how do they interact with other stressors, including exposure to racism and discrimination?
- What do BIPOC communities most care about when it comes to the mental health effects of the environment? What priorities do they have for research and interventions in this area?
- What are the features of organizations (funding, training, culture) that effectively support scientists of color conducting research into the intersections between environmental health and mental health?
- What tool(s) for measuring cumulative environmental and social stressors in communities can be deployed in research and policy-making at a *national level*?
- What are the specific vulnerabilities to environmental hazards among people experiencing mental illness?

Emerging Research Opportunities

Opportunities for environmental and mental health researchers range from including psychiatric and behavioral outcomes among the end points that toxicologists and epidemiologists study to including biomarkers of toxicant exposures in psychosocial studies of health and well-being. Advancing these opportunities will require bridging distinct disciplinary perspectives. Psychological and social phenomena should not be considered separate from biological processes; rather, the biological reality of these disorders are still too complex to fully model with existing tools. In the meantime, although much of psychiatry and psychology incorporates self- and observer-reported assessments, these methods (such as structured clinical interviews or neuropsychological tests) have well-documented reliability and validity, and biomarker, neuroimaging, and animal model correlates (Tables 1 and 2).

In addition to opportunities to merge toxicant measures with psychological end points in experimental animal studies and observational epidemiological studies, emerging research opportunities in this field include:

Omics approaches. Genome-wide search for genetic drivers of psychiatric illness has revealed new ways to investigate disease etiology (Kitsios and Zintzaras 2009). Similar approaches have been adopted for the study of proteins, metabolites, and the microbiome. More recently, mass spectrometry methods are making it possible to measure environmental exposures in a similar manner under the full "exposome" banner (Vermeulen et al. 2020). These advances provide opportunities for determining intersections between environmental exposures, genetic predispositions, and mental health disorders. By combining multi-omic analysis of human biofluids with advanced imaging techniques (see Table 2) and psychological evaluation, it is possible to systematically study the effects of complex environmental stressors on advanced brain functions. When

coupled with other omic-scale markers such as epigenetics, proteomics, and metabolomics, it becomes possible to associate biological changes with specific patterns of exposure. Another emerging area of research is the isolation and characterization of brain-derived extracellular vesicles (Brenna et al. 2021). Although primarily considered to be a source of microRNA, these vesicles can also serve as a window to toxicant deposition in brain tissue. By taking advantage of the range of omic-based approaches, we may advance the science on etiology and prevention of mental health disorders in a manner akin to recent advances using genomic approaches, such as the finding that clinically distinct disorders share common genetic risks (Geschwind and Flint 2015).

Community-based participatory research. Community-based participatory research (CBPR) is a dual research-practice approach to deploy and study interventions in partnership with communities to improve physical and mental health and resilience. CPBR is rooted in shared decision-making power that can build trust among community members (Viswanathan et al. 2004). For example, the Harvard–UMass Boston Metropolitan Immigrant Health and Legal Status Survey (BM-IHLSS; Holmes and Marcelli 2020) tested interventions to improve neighborhood social cohesion to buffer recent immigrants against psychological distress. Academic investigators (Bateman et al. 2017) partnered with low-income neighborhood residents to plan and plant a neighborhood garden to enhance social cohesion and increase safety in the neighborhood. Similar CBPR studies have been conducted in multiple other populations (Stalker et al. 2020; Bang et al. 2014). The collaborative approach of CPBR is a strength, which ensures that the community's voice and preferences are embedded in the structure of the research process (Hoover et al. 2015; Viswanathan et al. 2004). CBPR methods can be extended into studies of natural disaster response and resilience, industrial disasters, climate change, and mental health in disadvantaged neighborhoods so that communities are equal cocreators of the study design and questions.

New technologies. Recent advances in assessment instruments, methodologies, and statistical approaches offer exciting opportunities to significantly advance the study of environmental exposures and mental health. For example, wearables and smart phone–based technologies are areas that offer opportunities to monitor and assess an individual's activity, exposures, symptoms, and social interactions for early warning signs and even deliver mental health interventions (NASEM 2020). Advances in remote geospatial sensing technologies that could be relevant to mental health research were also addressed in a recent NASEM workshop (NASEM 2021b).

Ecological momentary assessment (EMA) approaches can provide temporally and/or geospatially precise links to human emotion and behavior and are among the approaches enabled by wearables and mobile technologies. Under EMA approaches, participants are prompted to provide information on their mood or psychological state through their smartphone at either random or predesignated times throughout the day. These responses can be geo-located and even structured so that participants are prompted in response to particular locations of interest (e.g., when participants arrive at their work locations).

Statistical methods that are appropriate for evaluating the combined impacts of environmental and social stressors, rather than simply controlling for covariates, are also ripe for broader deployment. Such approaches include machine learning and other data-mining techniques (Huang et al. 2018). The concept of "neighborhood-specific epigenetic markers" also offers promise by potentially allowing identification of epigenetic patterns associated with combined environmental and social stressors and mental health effects (Olden et al. 2014; Reuben et al. 2020).

A Call to Action

As summarized above, much information is already known about how environmental hazards can harm mental health (Table 3), how clean and green environments can benefit mental health, and how burdens of environmental exposures disproportionately fall on marginalized communities and communities of color. Although not exhaustive, we seek to catalyze increasing interdisciplinary action by listing some early implications of the current evidence.

Implications for foundational thinking about the etiology of mental illness. Given the high prevalence, population burden, and lasting consequences of mental illness, it is important to move past the confines of a specific discipline to more fully identify the causes of mental health and disease. We argue that mental health researchers must expand conventional approaches to incorporate the physical environment into etiological models of mental illness as well as social factors of resilience. In turn, identifying new environmental contributors holds the potential to reveal novel modifiable targets for interventions, with implications for individual- and community-level treatment and preventive medicine. For example, mental health interventions that focus on reducing environmental exposures may be less stigmatized, more cost effective, and better tolerated than exclusively pharmacological or psychotherapeutic approaches.

Actions to Take

- Conduct research that employs an exposome framework to systematically examine environmental, social, and biological exposures in relation to psychopathology outcomes.
- Investigate the potential mechanisms linking social and cultural environments (e.g., diet, norms, responsibilities, social cohesion, family structure, etc.) to differences in mental health outcomes following environmental exposures.
- Develop and test novel therapeutic interventions that target reduction of exposures to environmental contaminants, or increase exposure to beneficial environmental conditions, for the treatment or prevention of psychopathology—at both the individual and community level.
- Include mental health assessments and treatment infrastructure in public responses to natural disasters and disasters created by people and policies (e.g., long-term response programming for children exposed to lead during the Flint drinking water crisis).

Implications for the regulation of toxicants. Environmental health policy currently fails to adequately address the mental health impacts of the environment on individuals and communities. For example, communities facing health concerns around local pollution sources (Downey and Van Willigen 2005) or drinking-water contamination (Cuthbertson et al. 2016) may experience high levels of stress, anxiety, and depression. These signs of distress are either overlooked or viewed by regulators and policymakers as ancillary, or as a risk-communication challenge. The mental health impacts of environmental stressors need more focused attention for prevention, assessment, and mitigation.

Historically the challenges of studying mental health outcomes in laboratory animals, the lack of mechanistic or *in vitro* models, and the limitations inherent in observational epidemiology have made it difficult to regulate toxicant exposures based on mental and behavioral adverse impacts. Yet accumulated evidence, as reviewed above, demonstrates that there are both direct and indirect effects of neurotoxicants on mental functioning, making behavioral impacts critical end points for population protection. From incorporating behavioral targets in standard toxicology assessments to requiring human studies for chemical approval, research to inform future regulatory action in this sphere is a challenge that must be met.

There also remains the question of whether "secondary" symptoms arising from increased stress in a community should be considered as related to environmental contaminants (e.g., feelings of anxiety following a community-exposure event). Against a background of other chronic social stressors, and a history of environmental racism, an added stressor—such as the discovery of lead in the Flint water system—likely results in measurable increases in adverse mental health outcomes beyond the neurotoxic effect of the exposure itself (e.g., Cuthbertson et al. 2016). Measuring the cumulative impacts of toxic exposures and increased stress and the resulting impacts on mental functioning is needed to address the underlying inequities that contribute to poorer health status in many disadvantaged communities.

Actions to Take

- Agencies charged with responding to environmental disasters or oversight of environmental hazards should develop and implement strategies to mitigate mental health effects in exposed communities.
- Clinicians and researchers should evaluate mental health effects of neurotoxicants. Regulators should develop methods to use mental health endpoints in quantitative risk assessments.
- Develop a national policy and regulatory framework to document, measure, and incorporate cumulative impacts of combined environmental and social stressors in regulatory decision making.

Implications for justice and community resilience. The disparities in community exposure to environmental hazards and vulnerability to environmental disasters reviewed above suggest that research and governance activities concerning the environment and mental health are also matters of social equity and justice. More effort must be taken to improve vulnerable communities' psychological resilience to environmental harms (Gray et al. 2020). Such efforts (c.f., Norris et al. 2008), could involve: *a*) initiating activities to improve economic and social resources in vulnerable communities before disasters/exposures; *b*) using social cohesion and social capital–building as part of the disaster mitigation process; *c*) mobilizing preexisting organizational networks and relationships to deploy resources after harmful events; and *d*) creating effective and trusted information and communication channels to confront uncertainty and deploy health information quickly. Other pre- and postdisaster activities should leverage known but often overlooked social components of community resilience, including cultural resilience, the social capital of local networks, and traditional heritage around local knowledge and connections to place (Clarke and Mayer 2017). It is also important for researchers to understand past controversies that have resulted in community distrust (Pinder 2002), such as the Baltimore Lead Paint study in which families were not appropriately informed about the effectiveness of different lead-abatement strategies being tested (Buchanan and Miller 2006).

Critical for targeting interventions to vulnerable communities, multiple teams from state and federal government, academia, and the nonprofit sectors have developed methods for measuring aggregate community environmental and social stressors, including the CalEnviroScreen (already being used for multiple public policy purposes; Cushing et al. 2015), Maryland EJ Screen (Driver et al. 2019), and the Healthy Places Index (Maizlish et al. 2019). Currently, no clear gold-standard method for cumulative-impacts mapping exists at a national level.

Actions to Take

- Environmental health scientists should broaden their research, clinical, advocacy, and communication work to include natural disasters as priority components of environmental health.
- Federal, state, and county-level policymakers should prioritize community resilience in pre-disaster planning—and be held accountable for failing to address community needs in advance of disaster events.
- Impacted communities should be active partners in needs-assessments to comprehensively understand their psychosocial needs, build trust, and identify factors that will contribute to community resiliency before environmental events.
- Communication about exposure, health risks, and mitigation responses should include focus on the psychological impacts of environmental events and natural disasters. These communications should be timely, transparent, accessible, consistent, and ongoing.
- A national standard for cumulative environmental and social stressors assessment should be developed to facilitate research and policy approaches to mitigate mental health burdens in disadvantaged communities.

Implications for research training and funding. Interdisciplinary collaboration is needed to answer critical research questions about the environment and mental health (questions around community vulnerabilities, gene-by-environment interactions, disruption of neurobiological pathways, or lifespan consequences of exposures). The challenge is to develop the multidisciplinary collaborative research teams of environmental health scientists, mental health professionals, and community members to disentangle these complex relationships, generate new evidence, and translate evidence into meaningful policies at local and national levels. Training programs that bridge environmental and mental health disciplines and funding programs supporting research projects examining nontraditional collaborations are essential to advance these research intersections, as are opportunities to support CBPR and other nontraditional approaches to evidence-building. Symposia cohosted by multiple National Institutes of Health (NIH) organizations and cosponsored research programs (Request for Applications, Request for Proposals, Program Announcements) could incentivize interdisciplinary collaboration, particularly from the National Institute of Mental Health (NIMH), the National Institute on Drug Abuse (NIDA), the National Institute of Neurological Disease and Stroke (NINDS), the National Institute of Child Health and Human Development (NICHD), the National Institute of Aging (NIA), and the National Institute of Environmental Health Sciences (NIEHS).

Actions to Take

- Include basic training on effects of exposures to toxicants in psychology and psychiatry training programs. Include basic training on mental health effects in environmental science and toxicology training programs.
- Develop and promote new funding opportunities that require interdisciplinary teams of environmental science, mental health, and social and behavioral science researchers focused not just on understanding mental health consequences of environmental exposures but also on developing tools for community engagement, intervention, and mitigation of harm.
- The NIH should fund interdisciplinary research centers on mental health and the environment. These centers should include multiyear longitudinal investigation to illuminate consequences across the life span, including lifelong prospective registries in vulnerable communities.
- Support training and funding in CBPR that includes community partners who take equal part in setting research questions and agendas.
- Ensure investigators of color are given full access to training opportunities and supported to lead new investigations in environmental exposures and mental health. Consider targeting additional resources for BIPOC investigator recruitment and retention at early and midcareer stages.

Conclusion

Historical efforts, many funded by the NIH, have revealed a wealth of information on the molecular and cellular underpinnings of mental health disorders, but these discoveries have yet to be scaled to the population level, widespread use of pharmacotherapy notwithstanding. People who have access to more green space, better food options, cleaner air and water, and more affordable health care may experience better mental health, and these changes can be measured with advancing scientific tools as shown in Table 2. How communities are organized, cities are designed, and societies are supported all have ramifications for mental health, and these population-level factors have individual-level biological impacts. It is no longer acceptable to dismiss population-level and public mental health interventions as being unempirical or less scientific. Interventions at a population scale have the potential to improve the mental health of far more people than the individual patient approach of treating one mental disorder at a time (Albee 1982). Because environmental stressors may disproportionately affect the mental health of under-resourced communities and communities of color in the United States and globally, it is imperative to address these issues if we truly want to ameliorate chronic health disparities and provide for a healthy, just society. Environmental and mental health scientists working together to answer our call to action will shed new light on the etiology of mental illness, build new avenues for treatment and primary prevention, and begin to address the large and ever-growing unmet need for mental health services.

Acknowledgments

The authors thank the many presenters and participants at the NASEM Workshop on The Interplay Between Environmental Exposures and Mental Health Outcomes. A special thanks goes to the Workshop planning committee members and the NASEM staff members A. Andrada, K. Sawyer, J. De Mouy, and C. Rea. The NASEM Standing Committee on Emerging Science for Environmental Health Decisions is supported by funding from NIEHS.

A.R. was supported by the NIEHS, grant F31ES029358. M.A. was supported by the NIMH, grant R01MH117247 and the NIA, grant R01AG046149. G.M.S. was supported by the NIEHS, grant R21ES031501. M.B. was supported by the NIEHS, grant T32007322. G.W.M. was supported by the NIEHS, grant R01023839, and the NIDA, grant U18052498. Figure icons courtesy of M. and N. Tatah from the Noun Project.

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