Behavior, Environment, and Health in Developing Countries: Evaluation and Valuation

Subhrendu K. Pattanayak[1,2] and Alexander Pfaff[1]

[1]Sanford School of Public Policy, Duke University, Durham, North Carolina 27708; email: subhrendu.pattanayak@duke.edu, alex.pfaff@duke.edu

[2]Nicholas School of the Environment, Duke University, Durham, North Carolina 27708

Annu. Rev. Resour. Econ. 2009. 1:183–217

The *Annual Review of Resource Economics* is online at resource.annualreviews.org

This article's doi:
10.1146/annurev.resource.050708.144053

1941-1340/09/1010-0183$20.00

Key Words

policy interventions, water quality, arsenic, indoor air pollution, diarrhea, malaria, acute respiratory infections, stove, toilets, bed nets, fuel

Abstract

We consider health and environmental quality in developing countries, where limited resources constrain behaviors that combat enormously burdensome health challenges. We focus on four huge challenges that are preventable (i.e., are resolved in rich countries). We distinguish them as special cases in a general model of household behavior, which is critical and depends on risk information. Simply informing households may achieve a lot in the simplest challenge (groundwater arsenic); yet, for the three infectious situations discussed (respiratory, diarrhea, and malaria), community coordination and public provision may also be necessary. More generally, social interactions may justify additional policies. For each situation, we discuss the valuation of private spillovers (i.e., externalities) and evaluation of public policies to reduce environmental risks and spillovers. Finally, we reflect on open questions in our model and knowledge gaps in the empirical literature including the challenges of scaling up and climate change.

1. INTRODUCTION

In 400 BC, Hippocrates noted the ecological basis for disease in *On Airs, Waters, and Place*. As elaborated by Wilson (1995), our understanding and control of disease is inadequate without an "ecological" perspective on the life cycles of parasitic microorganisms and associated infectious diseases. Certainly ecology per se has a key role. However, we contend that a broad ecological perspective must include examination of behaviors. Behavioral choice plays central roles in the understanding and control of diseases. Pattanayak & Yasuoka (2008), for example, argued that prevention behaviors respond to disease levels in an exposure-management dynamic. Furthermore, if impacts on others are ignored, private behavior is socially inefficient in the absence of coercion.

In assessing the state of health across the globe, Smith et al. 1999 (p. 583) contend that "many of the critical health problems in the world today cannot be solved without major improvement in environmental quality." A recent updating of this analysis "confirms that approximately one-quarter of the global disease burden, and more than one-third of the burden among children, is due to modifiable environmental factors" (Prüss-Üstün & Corvalan 2006, p. 6).

These assessments suggest three regularities: Children are most vulnerable; environmental disease[1] is concentrated in the poorer countries (**Figure 1**, see color insert); and infectious diseases such as diarrhea, malaria, and acute respiratory infections are a larger share of the global burden than are noncommunicable chronic diseases (Smith et al. 1999) (**Figure 2**, see color insert).

In light of **Figure 1**, we focus on developing countries in our review of environment and health. The question we pose is, What explains the concentration of environmentally driven health burdens in developing countries? Developing countries differ from developed ones in the following ways, at minimum: Average per capita GDP is low, while poverty is high; government and/or market institutions are weaker relative to community processes' influence; most locations are tropical (located between the Tropics of Cancer and Capricorn); and the levels and trends in climate, i.e., rainfall and temperature, as well as urban concentration expose populations to health risks. Thus, some countries simply start poor and with poor environment and health.

However, many of the most important health issues are affected by human behavior and the underlying incentives to act to improve environment and health. For instance, below we consider how incentives differ for infectious diseases and the implications of key externalities for individual, coordinated, and public action. As state action can be particularly productive in such settings, while developing-state governance can be weak, the findings in **Figure 2** may not be surprising.

Thus, starting from these informative global overviews of environmental health, which indicate that economic development matters, and given our focus on behavior, in this paper we attempt the following: Section 2 summarizes the linkages among development, environmental quality, and health from a macroperspective and then in a micromodel of household behavioral choices about whether and how to avoid health risks. Section 3 next describes

[1]By environmental, the World Health Organization (WHO) means all physical, chemical, and biological factors external to human and related behavior but excludes environments that cannot reasonably be modified. Thus, traffic risk is included because housing, roads, and land use are choices, whereas the diseases caused by vectors in natural environments such as wetlands are excluded because policy interventions are assumed by the experts supporting the WHO assessment to be infeasible.

four major health challenges in developing countries, providing background and then characterizing them in terms of the micromodel. Section 4 describes examples of research on behavior and policy for each of these four health challenges and then considers the overlap between the evaluation of such policy interventions and the valuation by households of improvements in environmental quality, which lower health risks. Section 5 then considers the basis for public policy in this area, starting with classical externalities then moving to other interactions between households, with a final emphasis on the many spillovers involved in infectious diseases. Finally, Section 6 concludes by listing a few apparent hurdles to come for future analyses that could inform environmental health policy.

2. CONCEPTUAL FRAMEWORK

The findings of prior overviews of global environmental health motivate consideration of at least two scales. First, the global distribution of the environmental health burden is truly striking. Here then, from a macroperspective and bringing in behavioral choice at an aggregate level, we consider not only the differences in countries' or regions' initial endowments mentioned above, but also the simple yet critical trade-offs between consumption and health that may drive behaviors. Second, within this disease burden in developing countries, the dominance of infectious disease is also striking. Thus, from a microperspective, we consider what is common and what is different for infectious diseases by setting out a micro- or household-level model that can be applied to varied settings.

2.1. Macroperspective

A very broad macroframework helps to organize external and endogenous drivers. Our interests lie in the conditions with the least clear predictions in that framework, in which low income discourages prohealth actions while low environmental quality encourages such actions. This describes many poor tropical countries and environmental health challenges.

We consider diarrhea, respiratory infections, and malaria (i.e., ranked first, second, and fourth, respectively, in **Figure 2**) alongside groundwater arsenic ("the largest mass poisoning"). As our goal is for research to inform policy, we further focus on where the environment can be modified yet may not currently be modified within a given development setting. For considering these cases, in Section 2.2 below, we discuss a micro- or household-level model in more detail, including how a household's behavior can impact others, to distinguish these major health issues.

We assume multiple individual wants to illustrate the relationships among development, environment, and health (Gersovitz & Hammer 2003). We assume people like both consumption and health. Health is affected by prevention expenditures as well as one's environment. Quality of the environment is lowered by consumption but it is raised by prevention expenditures. Trade-offs arise because spending money to help environment and health lowers consumption, whereas consumption, which is valued separately, degrades the environment and, thus, health.

Consider the case of high consumption and low environmental quality. High consumption is not a starting point but a result of activities that may also lower environmental quality. Having raised consumption, individuals may value additional consumption less than additional environmental quality. Thus, citizens may be willing to invest in environmental quality or to improve health given environment (e.g., buy water or filters). This seems to be a common recent history for developed countries (e.g., Preston 1996).

Within that history, consider the implications for a nation's health. We see health rises with income (Smith & Ezzati 2005) (**Figure 3**, see color insert) as spending to help environment and to improve health given environment also rises. Yet, earlier in the development path, as economic activities were causing consumption to rise but countervailing expenditures were not yet considered worthwhile, health could fall as income rises. Thus at some income trends could shift, though that exact income level responds to multiple parameters (Pfaff & Chaudhuri 2004).

Consider next the opposite case of low consumption and high environmental quality. This could be an exogenous or predevelopment starting point if a country has good environmental quality. Here, citizens may prefer to invest in consumption, as health will be fine given the environment. Should consumption be the only expenditure for some time, environment and thus health will fall. This situation should continue until expenditures on environment and health become worthwhile, which could prevent further falls in, or may even raise, health. This scenario may be the early history of the now-developed countries and may also represent the future of some developing countries.

Finally, a more challenging predevelopment situation is one in which both consumption and environment start low. Health is likely to be low because environmental quality is low and expenditures on health or environment are constrained by low income, i.e., consumption cannot easily be reduced to protect the environment and improve health. We note that this could also describe the case of a higher starting environment when even subsistence living rapidly degrades the environment relevant for health.

In this unfortunate (and unfortunately common) setting, the gains from small increases in either consumption or health may be very high and it is hard to predict where resources will go. Because a situation with low consumption and low environment and health is akin to starting at the origin, which is the typical starting point assumed in many economic models, we may expect resources will be allocated to advance consumption, environment, and health in a balanced way. Yet, the details of what is most critical for life will affect trends in environment as well as health.

Looking for support or refutation of this ambiguous prediction, one does see households with low consumption, environment, and health spending a great deal of scarce time collecting potable water in an effort to improve environment and health. Yet, other households let children forage in polluted waste dumps, which can greatly worsen health, to try to raise consumption. In short, all households in this situation are at risk and the details of their options affect behaviors.

2.2. Micromodel of Health-Risk Avoidance

For purposes of discussion, and organization of empirical analysis, it is helpful to have a single explicit model of the choices that households face when exposed to environmental health challenges. The basic economic explanation for household investments of time and other scarce resources to improve health is that investments will occur when their perceived benefits outweigh their perceived costs. To apply this, we must first define concepts common to our four cases.

Our household-level model below draws on a category of economic utility maximization theory called household production theory, which describes situations when something that is valued by the household cannot simply be bought off the shelf at some price. In our cases, that something is health. One cannot literally buy a unit of health. Rather, various inputs to health can be applied in an effort to be healthier and thus, it is assumed, also happier. Providing those inputs has costs as well as benefits. Although our focus is health benefits, other benefits of such actions may also matter for the impacts of health policies. The model below draws on Pattanayak et al. (2005, 2008), who adapted the averting behavior models (also called defensive expenditure or coping behavior models) described in Dickie & Gerking (1991) to consider demand for drinking water and sanitation services. See Larson & Gnedenko (1998), McConnell & Rosado (2000), Larson & Rosen (2002), and Dasgupta (2004) for other examples of this type of household and microeconometric behavioral modeling applied to environmental risks in developing countries.

A household maximizes utility by allocating its limited time and income across leisure (l), health (s represents the number of sick days), and a composite consumption good (c). Given the vector of values for l, s, and c, a household's utility will also be a function of preference parameters (θ) characterizing the shape of the utility curve. Empirically, socioeconomic data serve as proxies for these parameters. Preferences commonly cited as relevant are aversion to risk and interest in others' welfare.

A health production function (assumed to be twice differentiable, continuous, and convex) constrains choices and outcomes. s depends on environmental quality (e) and the extent of coping behavior, i.e. avoidance (a) of health risks. e can be a vector of health-relevant characteristics of the environment such as the density of biological or chemical contaminants in water. Optimal a is a choice. It depends on knowledge (k) of different kinds, a vector that includes an awareness of the threat to health from poor quality of the environment and an understanding of the impacts of avoidance. As such, k is typically not free. Avoidance can raise e, for example, when a is the use of a toilet instead of a stream; avoidance can also improve health given the overall quality of the environment, e.g., when a reduces exposure as a result of wearing a mask or drinking bottled water. Community avoidance totals (A), the result of many households employing a, could in turn affect each household. e depends on government actions (G), which respond in part to ambient environmental quality (E). Note that a capital letter signifies an amount that applies equally to and is therefore shared by all households. In purely biophysical terms, $e_E >= 0$; for instance, some of a household's exposure to air pollution (lowering e) results from the ambient air quality common to all households and influenced by regulations. However, behavioral adjustments to E by households, such as the prevalence elasticity idea discussed in Sections 3.4 and 4.4 in which public action crowds out private avoidance, could result in a net $e_E < 0$ correlation. Returning to a household, production of avoidance has costs because it requires inputs of time (t) as well as material (m) along with some of the types of knowledge (k).

Avoidance (a) may contribute not only to health but also directly to utility. For example, women may benefit from the convenience afforded by a latrine or private tube well as a substitute for walking long distances and/or always traveling and defecating in the company of other women. The household budget also constrains choices and outcomes. Expenditures on l and c, as well as on avoidance inputs (t, m, k), must be no greater than the sum of exogenous income (y) and earned income. Income is earned at a wage rate per hour (w) in all hours not spent on leisure (l), avoidance (t), or being sick (s). Materials and knowledge have known market prices (p and r, respectively), and all prices are normalized by a unitary price of consumption (c).

We assume that the time and the health-production constraints are binding and use a full-income constraint below. The Lagrangian for this problem is presented in Equation 1, where μ and λ are Lagrangian multipliers that represent the marginal utility of income and averting behavior.

$$\begin{aligned} L\{_{l,t,c,k,m,\lambda,\mu}\} = \max \quad & u[\theta, l, c, a, s(a, A, G, e\{a, A, G\})] - \lambda[f(a, t, m, k)] \\ + \quad & \mu[y - c - pm - rk + w(24 - s - l - t)]. \end{aligned} \tag{1}$$

Solution of the first-order conditions from Equation 1 determines optimal sickness (s), consumption (c), and leisure (l) on the basis of the optimal avoidance (a). Time and money are allocated so that their marginal opportunity costs are equal to the marginal utilities generated by efforts to generate consumption and leisure and minimize sickness. The household's choices (l, t, c, m, k) and the resulting a and s will vary with exogenous parameters like the opportunity cost of time (w) and the prices of material (p) and knowledge (r) (i.e., the inputs to avoidance) and the preference parameters (θ) as well as exogenous income (y), government policies (G), and community-averting behavior that affects environmental quality (A independent of a in large communities).

We move directly to consideration of a reduced-form characterization (instead of a structural representation) of the first-order conditions from above. However, we devote extra attention to derivation of optimal avoidance. In doing so, we can rewrite the first-order condition in the following way:

$$u_a + u_s.s_a - \mu.w.s_a = \lambda \cdot f_a. \tag{2}$$

The left-hand side of Equation 2 represents the marginal benefits of avoidance (a). These include direct effects on utility such as psychic benefits (safety, privacy, convenience). They also include health effects as well as productivity gains, recalling that avoidance lowers sickness ($s_a < 0$). As Pattanayak et al. (2008) showed, we can get a clearer intuition for the averting costs by substituting f_a by its constituent elements (f_t, f_m, and f_k) and replacing the Lagrangian multipliers (using the first-order conditions) to obtain

$$\frac{u_a + u_s.s_a}{\mu} - w.s_a = w \cdot a_t + p \cdot a_m + r \cdot a_k. \tag{3}$$

Now the marginal benefits are in money terms (normalized by marginal utility of money) and the marginal costs are the marginal productivity of time (t), materials (m), and knowledge (k) in the production of avoidance (a). Thus, Equation 3 represents the Marshallian interior solution, which states that the household will invest time and money in avoidance up to the level that the costs of the marginal unit of avoidance are equal to the perceived psychic and health benefits.

Starting with the result in the seminal article by Harrington & Portney (1987), this type of model has repeatedly been used to derive a microeconomic measure of the value of improvement in environmental quality. It suggests that four economic concepts taken together—avoidance costs, costs of illness, opportunity costs of lost work days, and monetary value of pain and suffering—indicate the value of a better environment (which may result from either improving environmental quality or reducing the household's exposure to a given environment).

We can see that this is the case within a derivation of the household's willingness to pay (WTP) for improvement in environmental quality (e). This inference is based on a comparative static analysis of the avoidance (a) a household chooses to undertake to improve e or to lower s given the environment. An intuitive explanation suggests that the demand for avoidance activities increases if

1. inputs to avoidance (time, materials, knowledge) are subsidized,
2. technical knowledge of best/better avoidance is enhanced,
3. perceptions of avoidance's nonhealth benefits (dignity, prestige) rise, and
4. knowledge of health benefits of avoidance is better disseminated.

Recent studies suggest the relevance of each of these predictions to how households will respond to various policy interventions (e.g., information provision or subsidized material) and to how the response will vary across households with levels of environmental quality.

3. DISTINGUISHING HEALTH CHALLENGES

Millions are at risk from diarrhea, acute respiratory infections, malaria, and arsenic exposure. Furthermore, each of these major health challenges permits choices that can reduce the risks faced, with some behaviors affecting environmental quality and others reducing exposure. From the macroperspective, each arises primarily when low income constrains the preventive expenditures critical for basic health. From the microperspective, however, there are significant differences among the four challenges we review. In this section, for each challenge, first we provide background on the health problem and then we represent the problem in our model.

3.1. Groundwater Arsenic

A Millennium Development Goal is to halve by 2015 the population without safe drinking water. Arsenic is now recognized as a major contaminant of drinking water in Asia. The many countries affected by arsenic contamination of drinking water include Bangladesh, India, Myanmar, Nepal, Pakistan, Cambodia, China, Lao People's Democratic Republic, and Vietnam (World Bank 1993). Long-term arsenic exposure causes health problems over 5 to 15 years for early adverse health effects and over 20 years or more for cancers. The incidence of symptoms is rising (World Health Organization 2001).

In Bangladesh, starting in the 1970s UNICEF advocated drinking groundwater and facilitated the digging of tube wells. By the early 1990s, more than 90% of the population had switched to groundwater, the vast majority from privately installed tube wells, and infant and child mortality declined from 211 per 1000 in 1980 to 104 per 1000 in 1997 (World Bank 2001) largely due to the fall in waterborne diseases.[2] When the switch to groundwater was being advocated, neither the local government(s) nor UNICEF was aware of the potential of arsenic contamination.

Recent studies suggest that approximately one-third of the tube wells in Bangladesh should be officially considered contaminated (concentrations > $50 \mu g L^{-1}$), with 35 million

[2]This may not be entirely due to safer drinking water. Changes in medical treatment, e.g., the use of oral rehydration therapy, and improvements in access to medical care and nutrition may have mattered. However, the decline is almost twice as large as the average decline for low-income countries (World Bank 2001).

people thought to be drinking such contaminated water and 57 million drinking water with arsenic above 10μgL^{-1}. UNICEF estimates that 1.4 million out of 6–10 million tube wells in the country were tested by the end of 2001 and then testing reached over 5 million wells by 2004 as a result of the BAMWSP (Bangladesh Arsenic Mitigation Water Supply Project) unit funded by the World Bank. Thus, many wells remain untested, especially in the cleaner areas. Equally important, new wells are drilled regularly in all areas. Therefore, there is a need for ongoing well tests.

Most arsenic studies have been technical, concentrating on geochemical and engineering aspects. Prevention can take two forms: removing the arsenic, e.g., using either household- or community-level treatment systems, or shifting one's source of drinking water. Removal can be costly and debate about its effectiveness remains (World Bank 2009), although progress is being made. Next, we consider behaviors that can lower exposure and what drives them.

Of the four issues we discuss, arsenic in groundwater presents the simplest situation. In Bangladesh, where it has been considered and addressed extensively, arsenic exposure can be and mostly has been addressed at household level. To start, environmental quality (e) varies by household or, more specifically, by tube well. Often, a single tube well serves one household, which may be an extended family, though many wells also serve a small neighborhood, comprising a few households.

One reason this is a simpler setting is that $e_a = 0$, i.e., avoidance does not affect the level of environmental quality for the household or for that matter other households, at least to first order. The dominant avoidance behavior is to switch to another tube well; other options include buying a filter to place on the well, which is rare, or purchasing clean water, even rarer. All these options show $s_a |e < 0$ because avoidance changes exposure and sickness, but not arsenic levels.

The spatial heterogeneity of contamination (low e) is considerable. Thus, switching to another well often means using another household's uncontaminated well (usually within 100 m). Drilling a new well in a different location also occurs, and because the older and deeper aquifers are lower in arsenic, higher-cost deep drilling may occur (and cost may be shared so that $s_A < 0$). In a city, public filtration and piping may bring clean water to the household ($s_{E(G)} |e < 0$).

One critical constraint on avoidance is knowledge ($a_k > 0$). In Bangladesh, a national television campaign provided information in a general way, alerting citizens to the existence of groundwater arsenic as a health threat. This public subsidy to knowledge could have led to a costly household search for a more actionable, household-specific k such as finding the right local government or agency actors and convincing them to come to test household wells. That appears not to have happened, i.e., the costs r of that path to knowledge were too large given the current situation. However, because BAMWSP is no longer conducting free well tests in Bangladesh, households may need to acquire these tests themselves.[3]

What led to avoidance (see Section 4.1 below) was another subsidy to knowledge, i.e., free well tests.[4] Thus, we learn that $a_r < 0$. However, the broad knowledge about arsenic

[3]Thornton (2008) considered such a situation in a randomized experiment about the demand for learning HIV status and any subsequent behavior change. Of more than 2700 individuals, less than half attended a clinic to learn their HIV status without any incentive, but even a small incentive increased that share by 50%.

[4]Development economics has recently given more attention to the potential impact of information. However, research on households' responses to information about risks from drinking water exists but has been limited for development settings (e.g., Jalan & Somanathan, 2008).

being unhealthy ($s_e < 0$) complements the household-specific well-test knowledge. Knowing the level of arsenic in the well water will not lead to walking (at cost w) or purchasing (cost p) if no risk is perceived.

3.2. Acute Respiratory Infections

More than 3 billion people in developing countries face health risks associated with biomass use for energy, e.g., the burning of wood, dung, and crop residues (Reddy et al. 1996). The World Health Organization found that ARI caused by indoor smoke already accounts for 3.7% of the burden of disease in developing countries, and current trends suggest that the number exposed to such risks will increase over time (World Health Organization 1997).[5]

Smith et al. (2004) emphasized the combination of high indoor exposure and high indoor pollutant concentration, making indoor air pollution an important factor in terms of health. Total exposure to air pollution occurs largely indoors even if more total pollution is emitted outdoors. Biomass fuels are often used in poorly ventilated places with open fires or inefficient stoves, yielding pollutant levels well above the ambient air pollution levels, even worse than those of dirty cities (Smith 1993). Smith et al. (2004) also emphasized that such indoor exposure to air pollution is not the same for all members of a household. On average, men tend to spend more time outdoors and cook less, while children and women spend more time indoors, thus increasing their exposure.

The severity of the problem has inspired studies evaluating health risks associated with biomass fuel use. Published papers suggest that changing what biomass is used as well as how it is used could reduce health risks. Bruce et al. (1998) found fewer respiratory symptoms when women use *plancha* stoves with enclosed combustion chambers and chimneys, whereas McCracken et al. (2007) found *plancha* stoves impacted blood pressure, an indicator for cardiovascular disease (He et al. 1999). Along these lines, also see research by Bruce et al. (2000, 2004).

Ezzati & Kammen (2002) summarized studies concerning the contributions from biomass and coal smoke to the incidence of acute respiratory infections, middle-ear infection, chronic obstructive pulmonary disorder, lung and other cancers, asthma, tuberculosis, low birth weight, and eye diseases (Smith et al. 2000; Bruce et al. 2000; Ezzati & Kammen 2001a, 2001b), with the main focus on acute lung and respiratory infection, middle-ear infection, and chronic obstructive pulmonary disorder (Bruce et al. 2000, Smith et al. 2000). They noted that, in 2000, 1.5 to 2 million deaths, i.e., 3% to 4% of total mortality, were attributable to these risks.

This type of research has been successful in inspiring projects worldwide to spread the use of and to commercialize emission-reducing stoves. However, such attempts to inspire preventive action on the part of households have been less successful in influencing perceived environmental health risks sufficiently to impact individuals' willingness to bear the costs of prevention. This finding is based on personal communications with researchers and other commentators, leading us to conclude it is an important feature of the policy

[5]Given recent attention to mitigating the emissions thought to cause long-run climate change, even though we focus on direct local health impacts, it is worth noting that biomass emissions also become outdoor and atmospheric pollution. This adds externalities even from household prevention (such as switching of fuels) that lowers emissions and thus could add to the basis for public action to facilitate such prevention behaviors.

landscape regarding acute respiratory infection (and a distinguishing feature relative to arsenic exposure).

Characterizing this challenge in the model, a distinguishing feature of it relative to the arsenic problem is that the household-specific environment (e) can be affected by avoidance ($e_a > 0$). Thus, we can change particulate levels in indoor air by changing fuels or combustion efficiency. This suggests that individuals can be affected by others' avoidance. For example, to improve his indoor air, an individual may add a chimney that then relocates particulates to the rest of the neighborhood and thus lowers ambient air quality. Depending on conditions such as wind strength, we see $E_a < 0$. Although individuals' exposure occurs mostly indoors, a significant fraction of personal exposure can result from ambient air quality levels ($e_E > 0$). Thus, given that ambient air quality will be affected by others' avoidance via chimneys ($E_A < 0$), others' avoidance can hurt ($e_A < 0$, but see Section 5 for discussion of the possible positive spillovers from other households being healthy).

Avoidance can also reduce exposure given the quality of the environment ($s_a \mid e < 0$). For air quality, this may be achieved by staying away from stoves while the cooking is taking place. This avoidance has time cost (w) if cooking takes longer at lower temperature to avoid burning while individuals are away. It could also have a direct utility cost ($u_a < 0$) if, for instance, this revised cooking method affects the way traditional food tastes.

In determining whether these costly acts are worthwhile, we found that local knowledge (k) is imperfect. As noted above, we believe efforts to inform households about risk (at $r = 0$) have not driven much avoidance (i.e., to first order $a_r = 0$). Sickness has disutility ($U_s < 0$) but households do not see the relevant linkages (low k about $s_e < 0$ or $e_a > 0$). Thus, little adoption occurs.

Nonetheless, avoidance such as stove adoption occurred. To some extent, this happened because of subsidies such as the distribution of free stoves ($p = 0$). In addition to the potential disutility from prevention, there is also potential (nonhealth) utility gains from avoidance such as piping out smoke, which reduces discomfort from getting smoke in one's eyes ($u_a > 0$). That alone, however, is unlikely to explain why some households have paid for stoves within various distribution programs in which price $p > 0$, even though some amount of subsidy was provided.

Assuming that in the short term the households do not believe in valued health gains, one reason such prevention could be scaled up is the potential for savings in fuel costs. If that is a leading dynamic, then loans (such as microcredit) for purchasing expensive materials, e.g., stoves, may be a leading policy if the stoves do more than pay for themselves in fuel ($y_a > 0$). Such an approach still may not reach everybody, however, and some households may prefer not to pay. Another option currently being pursued is subsidizing the use of better stoves. Such an approach is based on the belief that a global E_a is positive so the globe wants to support stoves.

3.3. Diarrhea

Inadequate water and sanitation infrastructure, coupled with unsafe hygiene behaviors, cause diarrheal diseases, which are blamed for 2 million child deaths annually, approximately half of which are in India. Women, children, and other marginalized subpopulations typically bear the brunt of the burden related to inadequate water sanitation. They lack the political voice and/or the financial capital to force investments in sanitation goods and services in ways that improve their health. Policies have often focused on the supply of health-related technologies. However, there is growing recognition that a lack of demand contributes to policy failures (Figueroa & Kincaid 2007). Thus, if understanding and motivation are not present, expenditures on supply of technologies may have little impact on outcomes.

Reflecting on the choice about where to intervene, public health practitioners disagree about where to focus: at either the source of water or the point of use. Traditionally (as with the arsenic situation), water-source treatment and provision of piped water and sewage have been emphasized (Van der Slice & Briscoe, 1995). However, proponents of supply-led interventions have been frustrated by local governments and community management of water resources. Furthermore, the way people habitually use water can introduce contamination between source and consumption. This suggests the potential value of point-of-use water treatment. Clasen et al. (2007) compared the effectiveness of community-level water-supply interventions against household-level interventions. Their meta-analysis suggests that water treatment at the household level may be more effective in preventing enteric disease, yet they noted that methodological flaws limit comparability of the existing studies of such policies.

Patil & Pattanayak (2007) emphasized the multiplicity of possible intervention points given the complex web of exposure pathways through which fecal-oral pathogens can cause diarrhea. For example, using an F diagram, Wagner & Lanois (1958) illustrated many potential links among feces, food, and health via fingers, flies, fields, and fluids. A suite of avoidance behaviors could disrupt these links. Literature typically classifies these interventions or their outputs as water quantity [source (well, tap) and quantity], water quality (e.g., home water storage and handling), sanitation (e.g., pit latrine), and hygiene (e.g., hand washing). In fact, because of the singular lack of progress with sanitation, 2008 was declared the International Year of Sanitation.

Overall, consensus exists that *Escherichia coli* is the best biomarker for microbiological or (microbial) water quality, which is likely to vary at the household level (e). As discussed above, $s_e < 0$; yet beyond this first derivative, there is little agreement on functional form (e.g., Do e thresholds matter?). As important, there is disagreement about what types and combinations of avoidance actions (a) either change e or prevent low e from causing sickness s [i.e., $s(a)|e$ when a influences exposure]. Because microbes are not observed by the naked eye, it is harder for people to learn about these linkages.

The difficulty of knowing when a clean source water has been contaminated as a result of habits of use suggests the need to pay attention to point-of-use avoidance. As such, source-intervention advocates cite developed-country policies and outcomes in stressing the potentially large $s_{E(G,A)} < 0$, i.e., drops in sickness due to public investments to improve water quality. For example, Cutler & Miller (2004) suggested that water purification alone can explain half of the mortality reduction in United States cities in the first third of the twentieth century. In Section 5, we return to the issue of externalities with additional focus on social spillovers in environmental health problems.

The role of multiplicity of interventions requires further attention. In general, we must expect the marginal impacts of interventions (either on e or on $s|e$) to be affected by other interventions, such as $e_{a1}(a_2, E[A,G])$ or $s_{a1}|e\ (a_2, E[A,G])$ (Van der Slice & Briscoe 1995, Corey et al. 2007, Patil & Pattanayak 2007). In addition, when households know this or otherwise view practices as substitutes for each other, they may shift their behaviors (e.g., Bennett 2008, Jessoe, 2009).

Different disciplines have focused on various points of the exposure pathway and impacts. Epidemiologists have largely focused on the size and sign of s_a (or S_A for those studying population health outcomes of community interventions), and environmental scientists on e_a. and E_A. Economists have focused on household perceived $u_s.s_e$. and e_a in examining stated WTP for hypothetical improvement in water quality (or the sanitation infrastructure that can provide it) or revealed preferences for water quality in the form of expenses that households incur for avoidance or capitalized value in rental prices. For a brief summary of this literature, see Pattanayak et al. (2009a) or the original papers cited in this summary, including Hope (2006), Larson et al. (2006), Whittington et al. (2002), World Bank (1993), Anselin et al. (2008), North & Griffin (1993), Jalan et al. (2009) and Pattanayak et al. (2005).

Other behavioral empirics focus more directly on the constituents of a and the marginal products a_k, a_m, and a_t (sometimes measured as impacts on sickness s). Thus, the question becomes, Do knowledge, materials, and time statistically and significantly generate avoidance because of interventions that change their costs? The model predicts a_r, a_p, $a_w < 0$, but the magnitudes of all these derivatives remain empirical questions. For example, Jalan & Somanathan (2008) conducted a randomized trial in Delhi, India, that informed households about the fecal contamination of their household's drinking water, and they determined that informed households were more likely to purify their home water compared with control households that did not know the quality of their drinking water. Curtis et al. (2007) offered a parallel example in the case of hand-washing behaviors in Ghana, whereas Pattanayak et al. (2009d) provided an example of toilet construction in Orissa, India.

Other researchers have employed a social marketing strategy to improve the salience of subsidized knowledge. In a study of toilets in Benin, Jenkins & Curtis (2005) showed that "prestige" and "well-being," such as identifying with the urban elite or increasing convenience and comfort, play a key in avoidance of fecal-oral disease transmission. This suggests direct contributions to utility ($u_a > 0$) from avoidance. Cornes & Sandler (1994) argued that focusing exclusively on public or private dimensions may have limits because such an approach fails to recognize impure public good dimensions. They explained, "If the joint products are complementary, then private outputs have a privatizing effect, not unlike the establishment of property rights. As a result, free-riding motives are attenuated" (p. 404). In addition, Heal (2003) explicitly suggested that, through "bundling," private gains can promote the adoption of publicly beneficial actions.

3.4. Malaria

Despite the investment of billions of dollars, approximately one-third of the world (2 billion people) lives in areas infected by malaria, and more people die from it today than did 40 years ago. Re-emerging with its distribution expanded; higher local incidence; and increased severity, duration, and resistance to treatment (Wilcox & Colwell 2003, Greenwood et al. 2005), malaria causes 2 million deaths annually, ranking as the top vector-borne disease. Beyond mortality, malaria causes morbidity through fever, weakness, malnutrition, anemia, spleen diseases, and vulnerability to other diseases.

Response can be broadly grouped into prevention (vector control) and mitigation (treatment). Predominant prevention strategies include the use of insecticide-treated bed nets or indoor residual spraying of insecticides. Vaccinations represent another prevention strategy that could prove beneficial in the long run. Prompt and effective case management (treatment) using chemophrophylaxis has represented the other major strategy in society's efforts to combat malaria. Because the rate of infectious contact is a key factor in disease transmission, prompt individual treatment is an important form of population-level prevention (Wilson 2001).

Additional options derive from the environmental bases for malaria. Breeding sites, survival probability, density, biting rates, and incubation periods all are profoundly impacted by ecosystem changes, particularly land transformation (Pattanayak & Yasuoka 2008). A recent comparative risk assessment suggests that "practices regarding land use, deforestation, water resource management, settlement siting and modified house design" contribute to 42% of cases worldwide (Prüss-Üstün & Corvalan 2006).[6]

Avoidance via management of water and vegetation is gaining support, particularly in light of mosquito resistance to insecticides and antimalarials (Lindsay & Birley 2004). A recent synthesis proposes numerous paths through which forest degradation (including disturbance, fragmentation, and deforestation) can affect malaria infection and disease (Pattanayak et al. 2006a). Mechanisms involve changes in vector ecology (Yasuoka & Levins 2007), mosquito predators, microclimate (Walsh et al. 1993), and behaviors such as irrigation and migration that increase exposure (Wilson 2001). The following are specific ways in which environmental changes can impact the spread of malaria: First, deforestation changes vector ecology. For example, cleared lands are generally more sunlit and prone to the formation of puddles with more neutral pH that can favor specific *Anopheline* larvae development (Patz et al. 2000). Second, deforestation can negatively impact biodiversity, thereby favoring proliferation of malaria-related species by eliminating species such as dragonflies that prey on anophele larvae. Third, deforestation can change local climate and thus affect the spread of disease by raising ground temperatures, which in turn can increase the rate at which mosquitoes develop into adults, the frequency of their blood feeding, the rate at which parasites are acquired, and the incubation of the parasite within mosquitoes (Patz & Olson 2006b, Walsh et al. 1993). Fourth, forest degradation may yield land-use changes that not only result in mosquito populations that have higher rates of malaria transmission, but also lead to increased human contact and transmission (Petney 2001). Finally, deforestation is accompanied by human migration, which aids transmission. Not only do migrants have little previous exposure and lower natural immunity, but administering health services to transient populations is also difficult.

Within our model, household-varying environmental quality (e) is the environmental conditions (or lack thereof) that encourage mosquito breeding, survival, and biting. Then, $s_e < 0$ and $e_a > 0$, e.g., a household can lower sickness by eliminating standing water and by applying oil to water bodies. A review of 24 studies by Keiser et al. (2005) suggests that environmental management can reduce the malaria risk ratio by 88%.

Yet, as with indoor air quality, the ability to change environmental quality raises the question of how avoidance by others affects you. Here, in contrast to indoor air quality, when others change environmental quality is most likely to help. This may be best

[6]The fraction amenable to environmental management varied slightly, depending on the region: 36% (25–47%) in the Eastern Mediterranean region, 40% (34–46%) in the Western Pacific region, 42% (28–55%) in Sub-Saharan Africa, 42% (30–54%) in the Southeast Asia region; 50% (38–63%) in the European region, and 64% (51–77%) in the North and South America regions.

expressed in our model as $e_A > 0$, i.e., having others manage their water supply improves conditions such that mosquitoes are less likely to infect you. Economies of scale in environmental management may also exist that are relevant for malaria (e.g., draining swamps or larval control, controlling deforestation), which could lead to public action with $e_{E(G,A)} > 0$ or could lower the cost of household action ($p_A < 0$).

Empirical economics research on vegetation and water management for malaria is rare. Part of the problem is that the k regarding mosquito-parasite ecology and malaria epidemiology is low. This could simply reflect high costs (r) of searching for and obtaining this knowledge and, more generally, the high costs of other inputs (p), particularly those relative to income levels in settings where malaria prevails. Below, we discuss intensive education and communication with respect to rice farmers in Sri Lanka, finding $a_r < 0$ and $a_p < 0$ (presumably because other inputs are effectively subsidized).

Even if households are fully informed, two behavioral tendencies may limit the effectiveness of malaria-prevention strategies. First, as with diarrhea, interactions may exist across interventions as $e_{a1}(a_2, E[A,G])$ or $s_{a1}|e\ (a_2, E[A,G])$. The effectiveness of environmental management, for instance, could well be conditional on the extent of use of insecticide-treated bed nets and indoor residual spraying of insecticides within the community. If actions are seen as substitutes, correctly or not, then arriving at the best choices will involve coordination.

Second, prevalence elasticity of prevention demand is likely to be positive (see Philipson 2000). The broader literature suggests that public health interventions are characterized by diminishing returns given increasing opportunity costs of prevention and declining demand for prevention as prevalence decreases. The key idea is that, whereas disease prevalence depends on the prevalence of safe behaviors ($s_A < 0$), the choice of safe behaviors is correlated with disease prevalence ($a_S > 0$, at least for lower values of S; very high S may also discourage some actions).

Section 5 focuses explicitly on spillovers, but for the case of malaria, this is fundamental enough to bear mention here. The environmental ($s_E < 0$) and contagious ($s_S > 0$) nature of these risks create classic coordination failure problems related to the optimal provision of local public goods—most notably free riding (or easy riding). Thus, if everyone else in the community manages vegetation and water to reduce mosquito-borne transmission, then an individual's risk of getting malaria falls ($s_E < 0$). Presumably then, any given household might free ride ($a_A < 0$) unless there is some form of community monitoring and enforcement strategies (e.g., informal norms that induce conformity, as within the sanitation case that is described in Section 4.3).

4. EMPIRICAL RESEARCH

Above, we treat each of our four health challenges in a broad manner, with an overview sketch and then a general conceptual characterization, albeit one distinguishing challenges. Here, we present some concrete examples of empirical research illuminating one piece of each of our four environmental health challenges. In each case, we review how specific interventions were studied and then we turn to consideration of how the evaluation of those interventions and the valuation of changes in environmental health risks can facilitate and inform each other.

4.1. Groundwater Arsenic

Continuing on our discussion of the Bangladeshi case, Madajewicz et al. (2007) examined households' responses to having the arsenic levels of their well water tested for free in Araihazar *thana*.[7] Conclusions about the impact of this information are bolstered by the fact that the natural distribution of arsenic across tube wells is independent of socioeconomic processes affecting responses. Here, we distinguish this exogenous arrival of risk information, when all wells are tested and only some are unsafe, from endogenous communication that occurs when households choose to attend an information session about arsenic (also discussed in Madajewicz et al. 2007). In the latter case, those who are seeking health-risk information by making a choice to attend an information session may represent those households who were more likely to take preventive action on their own. In contrast, bad news about well water arsenic is exogenous.

In Araihazar, the well water was tested for approximately 2500 people, and wells were labeled either safe or unsafe. The test results were then reported to the users within the sample. Households in the study site and in four control areas where no well testing was conducted were also exposed to information about arsenic. This information was disseminated by the government through television, radio, and newspapers.

The most striking result was the strong response to the well tests. Even before the information campaign, 60% of people who learned that the well they used was unsafe changed to another well within one year. Only 14% of people whose baseline well was safe changed, and only 8% of people changed in control areas. Controlling for other factors that may affect the decision to switch, learning that a well was unsafe increased the probability that a household changed to another well by 0.37.

As a result of the study, 98% of people in Araihazar can correctly state whether the baseline well is safe. Few people in control areas claim to know the status of their well, even though the television and radio campaigns on arsenic led almost everyone to become generally aware of the arsenic issue. Therefore, the change in behavior in Araihazar appears to be a response to the specific arsenic information about the concentration in individuals' primary drinking wells, not to other factors.

Opar et al. (2006) followed up one year later in the same location but with three times as many households. They found slightly higher impacts of receiving information regarding the well-water tests. This finding helps to address a concern (e.g., see Hanchett 2001) that switching is only temporary. Schoenfeld et al. (2005) then started to explore whether other locations showed similar responses. In a similar, nearby location without an ongoing health-impacts study (which could have inadvertently heightened arsenic sensitivity in the prior study site), they found that approximately one-third of those receiving news of unsafe arsenic levels in their well water switched to a safe source. These findings are significantly lower than the findings near the original health study site, yet they are still significantly higher than those previously found for responses to other health-risk information provisions (see, e.g., Jalan & Somanathan 2008).

In terms of evaluation of an intervention overlapping with valuation of improvements in environmental quality, the groundwater-arsenic setting provides us with a simple scenario. Avoidance was not occurring before the intervention that provided test knowledge,

[7]Different approaches to facilitating communal adoption and use of deep wells is being studied in ongoing research under a grant from the National Science Foundation (M. Madajewicz & A. Pfaff, unpublished results) in which Madajewicz is working with nongovernmental organizations on a randomized approach.

because households did not know which wells to avoid. Thus, although the knowledge was free, such that no value-revealing choice was required to make avoidance feasible, having a well test made feasible another value-revealing choice, most typically a costly choice to walk to another well.

If we know to which well a household switches, we can directly measure the change in arsenic exposure (i.e., environmental quality e) that results from avoidance. In addition, by knowing how far away the well is and thus how long it takes to avoid the health risk, we can measure time that can be valued at the wage. This combination of information, a measured costly action that changes e, is not always present in other cases. Very directly, then, this intervention provides an estimate of WTP to avoid the risk. Put another way, this setting is tailor-made to suggest a value of safe water. Having that value plus the fraction of people who switch and the cost of the intervention permits evaluation of the net benefits of publicly subsidizing the testing of arsenic levels in well water.

4.2. Acute Respiratory Infections

Mueller et al. (2009) re-examined data on approximately 3500 Chinese households, following a comparison by Peabody et al. (2005) that found significant effects of improved biomass stoves.[8] Mueller et al. (2009) compared different stoves with an emphasis on how nonrandom provision and adoption of cleaner stoves can confound impact evaluation. We note that randomization of stove distribution is now also being tried to avoid such confounding (McCracken et al. 2007, World Bank 2009). This is a small fraction of existing and ongoing studies, and such work avoids, but does not demonstrate the magnitude of, the bias from nonrandom allocation. Furthermore, household members' choices, such as where to be during cooking, can still confound evaluation of stove impacts.

Much of the existing literature supporting such stove interventions is subject to selection biases (Heckman & Smith 1995) because stove choice may be correlated with health outcomes for reasons other than the impact of the stove itself on health. Any such correlation confounds the accurate estimation of how the cleaner stove impacts health. Cleaner stoves may be more likely to be adopted by households with poor ventilation or by those that already have generally poor health. In each case, nonlinear responses of air quality to emissions and/or of health status to exposure may imply that the adopting households' marginal benefits of lower stove emissions are greater than those of nonadopters. If so, and if the characteristics of poor ventilation (e.g., see Bruce et al. 1998, Dasgupta et al. 2006) and poor prior health are associated with worse health outcomes, then well-intended and reasonable analyses may underestimate the benefits of using a cleaner stove. Yet, for a study looking at this bias in the opposite direction, see Pitt et al. (2006).

Mueller et al. (2009) found that those owning different stoves do in fact differ in terms of their characteristics that affect health outcomes. Such differences across the improved-stove and other-stove groups create bias. To address such bias, matching techniques are applied to control explicitly for group differences in estimating the effects on health outcomes of moving from traditional biomass and coal stoves to improved biomass and clean-fuel stoves. The idea, common in policy evaluation settings, is to

[8]Exploring other causes of respiratory infections are Dasgupta et al. (2006), who examined more than 30,000 households in Bangladesh to explain air quality, as well as Boy et al. (2002) and Mishra et al. (2004), who studied thousands of households by focusing on birth weight as a health outcome.

compare like with like, i.e., the outcomes for those with cleaner stoves to the outcomes for similar households with the original stoves.[9] Such comparisons generally raised estimated benefits.

In Nepal, Malla et al. (2008) considered the co-benefits of improved cooking stoves in terms of fuel use, forest and biodiversity, time savings for women and children, and regional climate benefits. They conducted studies in the Syangja, Chitwan, and Rusuwa districts of Nepal, using socioeconomic surveys of approximately 1000 households and pollution monitoring to measure cooking technology, kitchen design, fuel type, fuel-wood consumption, time allocation, particulate matter concentration, health conditions, medical costs, and socioeconomic status.

Statistical comparisons of households across districts differing in sociodemographic and ecoclimatic dimensions show that stoves can reduce particulate matter concentration (10–70%), acute respiratory illnesses (10–30%), medical costs (10–50%), cooking and collection time (20%), fuel-wood consumption (25%), and greenhouse gas emissions (25%). These findings are supported by instrumental variables approaches that revisit such comparisons while accounting for omitted variable bias and endogenous household responses.

Such results suggest a question: If these impacts collectively imply high internal rates of return, why are not more households adopting the improved stove technology? Limited access to capital can be an answer. Malla et al. (2008) found that both credit and peer-pressure (see Section 5.1) are key constraints. Thus, there can be gains from microfinance programs and information-regulatory campaigns.

In our model, inferring a value for improvements in environmental quality within this setting is more complex than was the case for groundwater arsenic. Recall that in Section 3.2, we focus on the case in which households do not perceive the benefit of improving environment quality. Despite the free provision of environmental-health-risk information ($s_e < 0$ and $e_a < 0$), households may not see a sufficient link to health. Although avoidance has occurred, in the form of improved stove use, recall that many stoves were provided for free (not bought by households). With free provision, even if a perfectly random group receives the improved stoves, there are no value-revealing choices made by households that could indicate household WTP for the stoves.

Even when stoves are not free, learning the value of indoor air quality from these choices remains challenging not only because it may be zero but also because other gains (such as lowering fuel cost) explain some of the WTP (Larson & Rosen, 2002). As discussed below, this complication is common for these major health challenges. That is, leading interventions may provide a bundle of changes and thus estimating WTP for changes in environmental quality may be much less straightforward than desired for valuation to support policy evaluation.[10]

[9]Matching is used in various settings to identify the effect of policies. For instance, policy-relevant re-evaluations have been carried out for job training (Dehejia & Wahba 1999), health (Hill et al. 2003), and forest conservation (Andam et al. 2008). In these studies, the re-evaluations are used to estimate the effect of the cleaner stoves on self-reported health status.

[10]Whether impacts on other households matter for a household's choice is another important consideration. To learn θ from this case, recall the two effects on the broader world's environmental quality (as discussed previously). In terms of the Clean Development Mechanism, the *E* in question is the world's atmostpheric pollution, and it would be surprising if θ were meaningfully different from zero. In terms of impacts on others in the same village, θ could matter in some cases, but recall that here avoidance via chimney use could actually hurt the environmental quality of one's neighbors. Thus, other-regarding behavior could indicate less avoidance.

Even in the arsenic case, asking about bundles of changes raises the point that women who switched to tube wells from surface water often commented on water color, taste, and temperature as well as privacy. Thus, their avoidance behaviors provided a bundle of gains ($u_a > 0$ being a part). But this further highlights the convenience of the arsenic setting studied above, i.e., inducing switching from well to well, for which many of these bundled changed are fixed.

Yet, even if valuation is challenging in such situations, policy evaluation is not ruled out. As Larson & Rosen (2002) showed, the evaluation of improved stove provisions may involve many parameters (consistent with the discussion above) and can be approached using benefits transfer strategies (Smith et al. 2006). Some of these parameters could be learned by looking at different study sites and then transferred to a policy evaluation site to estimate the benefits of (or WTP for) improvements in air quality. For instance, providing free stoves to a random subset of households may enable researchers to estimate accurately the disease reductions from new stoves ($s_a < 0$, and information may permit learning that $s_e < 0$ as well as $e_a > 0$). Combining these s_a estimates with other u_s estimates enables us to determine whether the benefits of the provision outweigh its costs. This leaves open the question of why a public actor perceives benefits that the household may not. We return to this issue below.

4.3. Diarrhea

A cluster-randomized sanitation campaign in Orissa, India, provided a setting to examine responses to incentives and the resulting environmental health gains (Pattanayak et al. 2008). The study took place in 40 rural villages located in two adjacent blocks, Tihidi and Chandbali, in the Bhadrak district. Twenty villages were randomly selected and assigned to the treatment group, while the other villages served as controls.

The social mobilization campaign drew ideas from a model of community-led total sanitation that contends knowledge alone is not sufficient to generate lasting behavioral change. This models also seeks to generate strong, emotional responses at the community and individual level, culminating in a collective resolve to end open defecation by a community-defined target date by implementing a number of participatory activities. For example, the "walk of shame" activity involving a procession of village members drew attention to the volume and location of feces as well as the impact on the village environment.

Subsidies were offered to poor households because the campaign was implemented within the framework of the Indian government's nationwide Total Sanitation Campaign, which recognizes that low income constrains many households in the study area. Interviews and focus groups revealed that constructing the off-pit latrines promoted under this campaign was prohibitively expensive, and a baseline survey confirmed that cost was the main reason households did not construct latrines.

The intervention took place in the 20 treatment villages between January and May of 2006, and postintervention data were collected in August and September of 2006. A comprehensive household survey was conducted in all 40 villages in 2005 (baseline) and 2006 (follow-up), resulting in a balanced panel of 1050 households (529 treatment and 521 control households). Sample-size calculations indicated that 40 villages with 25 eligible households per village would provide sufficient power to identify differences between treatments and controls in toilet ownership and usage outcomes.

Pre- and postintervention data collection permits a difference-in-difference (DID) estimator to measure the treatment effect. These estimators compare changes in sanitation conditions across the two groups. The standard errors are inflated to correct for the clustered nature of survey data.

DID estimators suggest that the intervention increased latrine uptake by approximately 30%. *E. coli* levels rose from 1.3 to 3.7 colony-forming units per 100 ml in the control villages and declined from 0.9 to 0.1 colony-forming units per 100 ml in the treatment villages. Critically, the number of water sources with *E. coli* contamination increased from four to six in control villages and decreased from nine to two in treatment villages. Intention-to-treat and instrumental variables estimation of impacts of latrine adoption suggests (*a*) two-week diarrhea incidence in children under 5 may have decreased by 5%; (*b*) nutritional status of children under 5, measured by arm circumference, improved by 2%; and (*c*) time spent walking to open defecation site decreased by 72 min per household per day.

The study design permits the examination of two predictions of the model—household responses to free information (delivered in an intensive fashion) and cash subsidies—by stratifying the analysis by households below the poverty line (BPL) (subsidy eligible) and those not BPL (subsidy ineligible) households (Pattanayak et al. 2009d). The authors found a treatment effect of 36% in BPL households and 23% in non-BPL households in the treatment villages compared with their counterparts in control villages. Thus, by differencing the two DID estimates for BPL and non-BPL, they obtained a triple-difference estimate of 13% that suggests that subsidies caused approximately one-third of the impact, whereas the information-only scenario caused approximately two-thirds of the full impact.

However, this setting emphasizes a distinct challenge for valuation, as the water quality did not change significantly. Thus, even though households made costly choices that could in principle reveal their valuation of improved water quality, to first order the findings reveal that households not surprisingly prefer it when they can achieve relatively the same water quality (and health) at lower cost. This is useful for evaluating the provision of the latrine technology but is not nearly as helpful for the valuation of changes in household environmental quality e.

Specifically, before the new toilet technology was made available (at a subsidized positive cost), households achieved the health levels they desired by walking to defecate far enough from the village to avoid health consequences. Thus, an effective avoidance strategy had long existed, and the cost of time it requires reflects a household's value of a relatively clean environment. The existing avoidance strategy, then, certainly indicates environmental value.

Yet, water quality did improve to some degree. Given an effective, existing avoidance method, we may ask why, and one possible answer is the drop in the cost of avoidance. With higher cost avoidance, such as walking, many people avoid but some may not. As the cost of avoidance falls with improvements in toilet technology compliance with avoidance norms could reach 100%, thereby improving water quality. Looking for evidence of the relevance of imperfect compliance, we see that Pattanayak et al. (2009d) showed that toilet use increases by 25% among adults and 11% among children, even though toilet ownership increased by 30% on average.

The modest impacts on household health (s_a), in principle, provide some information to estimate values of improved water quality. If an independently reliable estimate of the impact of improved environmental quality (s_e) is available and the only role that a plays in the household economy is the prevention of water-quality risks, then household WTP for e can be $(p_a/s_a.).s_e$.

That said, recalling a theme from Section 4.2, the price paid for the toilet may not help if the technology generates a bundle of utility-yielding services. For example, if privacy or prestige also are associated with the toilet (much as prestige may be associated with a new stove, $u_a > 0$), then the WTP term above overestimates the contributions of this avoidance via water quality.

As with stoves, however, the health-impact information from such studies is still useful to evaluate interventions such as the information and communication campaign. One estimate of household benefits would be the sum of savings in cost of illness and prevention. Whittington et al. (2008) recently conducted such an exercise, with a Monte Carlo simulation to account for uncertainties, and concluded that the benefit/cost ratio significantly and typically exceeds 1 and that these types of interventions are generally viable.

4.4. Malaria

As noted in Section 3.4, Yasuoka et al. (2006) conducted a 20-week pilot education program to improve community knowledge about avoidance, particularly mosquito-control avoidance actions, using participatory and nonchemical approaches in Sri Lanka. In their study, households received free intensive training (knowledge) concerning s_E (the importance of environmental conditions for sickness) and E_a (household actions to manage the environment affecting those conditions). The authors evaluated program effectiveness using before-and-after surveys in two intervention and two control villages, and they found that the participatory education program led to improved knowledge of mosquito ecology and disease epidemiology, changes in agricultural practices, and an increase in environmentally sound measures for mosquito control and disease prevention.

Yasuoka et al. (2006) stated that household malaria history is correlated with malaria prevention but provided no direct estimates of the demand elasticities. In another study, Over et al. (2004) studied the effectiveness of indoor residual spraying of insecticides and insecticide-treated bed nets. They estimated two-stage regressions to account for the potential endogeneity of prevention concerning malaria prevalence, which they attributed to prevalence elasticity. To our knowledge, the existing literature provides little or no empirical evidence on the magnitudes of prevalence elasticity (Gersovitz & Hammer 2003).

However, the study by Pattanayak et al. (2006b) is an exception. They presented an empirical measurement of the prevalence elasticity of malaria prevention behaviors in the eastern ghats of India (Keonjhar district in the state of Orissa, which is a rural forested and malarial region of eastern India). Pattanayak et al. (2006b) examined links between village-level malaria prevalence and household-level prevention behaviors.

Approximately 600 randomly chosen households were interviewed from 20 villages in the towns of Joda and Keonjhar Sadar in the Keonjhar district. Topographical and infrastructure (e.g., road) data were also collected from administrative records and overlaid on the survey data by using a geographic information system. The survey contained many modules including self-reports on individual malaria prevalence, knowledge regarding the illness, and a variety of related prevention and treatment behaviors. Malaria prevalence is defined using data prior to 2005 to break direct simultaneity of household-level prevention behaviors in 2006 and village-level prevalence in prior years. Survey data showed that 34% of individuals in the sample had experienced malaria in the past 5 years (2001–2005), with approximately 75% of households having had someone suffer malaria in the past 2 years.

Seventy-three percent of the households practice at least one preventive behavior. Specifically, these behaviors included the following: 41% sleep under a mosquito net, 33% use repellants (mostly traditional, rather than commercial), 5% rely on public health spraying (indoors as well as outdoors), and only 4% clean drains and avoid standing water. The prevention measures were general, i.e., if households engage in any of the behaviors listed, and specific, i.e. if households sleep under insecticide-treated bed nets (the most popular prevention activity). These statistics also highlight the claim in Yasuoka et al. (2006) that environmental management for malaria is rare and needs incentives.

Regression models show prevention is positively and significantly correlated with prevalence. Controlling for demographic characteristics, caregiver characteristics, malaria knowledge, and socioeconomic factors, prevention decisions are more common when prevalence is higher. Whereas prevalence and prevention are simultaneously determined in other models, here identification is possible if a disease ecology complex enough to escape scientific consensus is not precisely understood by the households (as confirmed by Yasuoka et al. 2006). In this case, ecological factors, including extent of forest stock, irrigated farming, and distance to iron-ore mines, could be considered exogenous to behavior while explaining prevalence (see previous discussion on their links with malaria).[11] Thus, they are potential econometric instruments for prevalence as a determinant of prevention. The first stage finds the instruments to be individually and significantly correlated with village-level malaria prevalence, and overidentification tests confirm exogeneity. The second stage verifies that instrumented prevalence is positively correlated with prevention behaviors.

The explanation of intervention success by Yasuoka et al. (2006) has much in common with the arsenic situation. Yasuoka et al. (2006) contended residents' understanding of mosquito-borne disease rose as a result of community-based education. A twist here is the claim about how to transfer knowledge. In this case, that transfer was a function of a participatory approach involving hands-on experience in using nonchemical measures. Such an emphasis on the form and style of knowledge communication echoes the sanitation intervention.

In short, subsidized knowledge provision (lowering r) causes avoidance. The choice of communication strategies may also be modeled as ways of lowering r further. That said, these interventions may also effectively reduce other costs—for example, by lowering the supply costs of materials due to economies of scale or by offering technical assistance. Alternatively (or in addition), the externally driven campaign lowers transaction and coordination costs by guaranteeing a significant collective response by virtue of informal enforcement and external commitment.

The study by Yasuoka et al. (2006) is limited in allowing us to infer household valuation of the changes in E. The authors contended that success was in part due to a lack of

[11]Sachs (2003) discussed the use of tropical ecology indicators as predictors of disease ecology in his cross-country regressions of economic growth on malaria prevalence, but he did not implement his logic using econometric instrumental variables procedures. Carstensen & Gundlak (2006) implemented Sachs' logic and confirmed the usefulness of the instrumental variables approach.

costly materials or extensive inputs, whereas most economists suspect that households with more knowledge would already have been avoiding if this were the case (i.e., if modifying behavior was cheap or costless). Unfortunately, their study does not provide estimates of the changes in the time and material costs of household participation. If this avoidance cost information were available, as in the arsenic scenario, we could estimate household valuation of a lower-malaria environment (E).

In the India example as well, costs (p) of treated bed nets and repellants are not available. With these costs, we could derive what households' WTP (see formula in Section 4.3) for a given improvement in conditions or, given reliable estimates of s_E from either the study or other sources, for a specific reduction in sickness that would generate s_a.

Although these results contribute to the prevalence elasticity findings in developed countries (Philipson 2000), they do not resolve the issue of what is an appropriate role for public health. The results are consistent with Philipson's predictions that because public health investments (G) crowd out private averting behaviors (a), such investments are somewhat self-limiting. If households stop prevention when G lowers S and this significantly affects sickness, it may be necessary to accept endemic disease as a second-best outcome. So, are public health interventions not worthwhile because the disease reduction is lower than it would be if prevalence elasticity were zero and private prevention were held fixed? This is an overly negative view of public interventions because it ignores the fact that households will save the private costs of avoidance, owing to their endogenous private response (a) to public action (G).

5. EXTERNALITIES, SOCIAL INTERACTIONS, AND PUBLIC POLICY

5.1. The Case for Environmental Health Policy in Developing Countries

Up to this point in the article, we have described four major health challenges, discussed prevailing policies and programs, conveyed how these differing challenges and policies can be studied using a single modeling framework, and presented empirical research relevant for policy evaluation, including when evaluation is based on household valuation of environmental quality. We have not yet, however, focused on whether public action is merited. Below we describe interactions that could affect an agency's calculus concerning the decision to intervene.

5.1.1. Classical environmental externalities (policy and bargaining). For economists, externalities may justify interventions in the environmental health arena, such as the promotion of bed nets, toilets, and stoves. Credible and specific estimates of externalities' magnitudes are critical not only for determining the details of public programs but also for deciding whether to act publicly.[12] Limited public funds and concerns regarding efficiency suggest that governments must consider whether intervening is the best course of action.

Consider indoor air quality, noted above as improving with avoidance. Specifically, private air quality (e) improves. Two forms of externalities have been discussed: First, ambient air quality can fall if avoidance means venting via chimneys. Second, if avoidance is purchasing a costly stove to reduce fuel use and emissions, community and global

[12] Although the intent-to-treat and instrumental variables estimates of campaign impacts in the sanitation case study (Pattanayak et al. 2008) are indicative of externalities, this is not conclusive because of the contemporaneous nature of these data.

environmental quality may rise owing to household avoidance. In that setting complete internalization of individuals' global spillovers from the mixing of emissions of greenhouse gases cannot be expected, on the basis of households' other-regarding preferences or household-level bargaining. Some form of public intervention to limit emissions, for instance payments for emissions reductions under a program such as the Clean Development Mechanism, will be needed to attain social efficiency.

In contrast, consider the community spillover effects from venting via chimney. Here, what helps the household hurts its neighbors. Although such "dumping" could be taxed, repeated interactions in small villages may yield bargaining over processes, thus eliminating the need for a formal monitoring and monetary regulatory infrastructure. Such a process could involve local information that would make arranging efficient external solutions difficult. As a thought experiment, we can imagine a situation in which households establish coordination mechanisms to vent internal air while staying inside during cooking times, thereby efficiently responding to concavities in ambient air quality degradation. Recall that one reason this thought experiment remains in the realm of speculation is that households do not appear to perceive significant health risks from indoor air quality.

Similar to installing chimneys on stoves, environmental management to discourage mosquitoes affects not only the conditions relevant to the household in question, but also the environmental conditions relevant to other households. In our model, for other households such avoidance behavior likely provides only benefits. In terms of a pure prevention externality, however, we may not expect private decisions to take spillovers into account (Gersovitz & Hammer, 2003). Thus, in deciding on the use of larvicides, households will likely disregard that killing larvae lessens the probability that others will be bitten and infected.

5.1.2. Generic social interactions (public provision and learning). Consider the case of arsenic as represented above, where avoidance helps the household but does not raise environmental quality ($e_a = 0$). In this case, private avoidance required a public subsidy to information. But with knowledge having reached a considerable level and given that well tests and filters can in principle be purchased, it is possible that only poverty or equity will motivate ongoing public actions. Even though equity motivations may seem sufficient, the public well-testing program has ended. Thus, our description of the setting to date suggests privately efficient avoidance may be feasible if private options exist and they credit markets, e.g., are fully functional.

Yet, other characteristics of the problem suggest the value of community action. As noted, deeper wells are less likely to be contaminated with arsenic. They are also more costly, but many households can use a well and can thus share not only use but also installation and maintenance costs. Sharing raises free-rider and classic concerns of raising revenue and allocating effort to provide clean water. Public taxation and provision seem unlikely in rural Bangladesh at this time. Nonetheless, communities may advance health-risk avoidance in this setting, given the significant capacity of nongovernmental organizations in Bangladesh, including those with long-standing rural traditions. For a general discussion of analogous problems of common property resource management, see Ostrom (1990), which essentially is a response to Hardin (1968).

However, there may still be important uninternalized interactions, such as with learning. Although the government conducted a national television campaign and tested and painted wells, Madjajewicz et al. (2007) found many gaps in understanding. Thus, learning from others could have real value (see, e.g., Miguel & Kremer 2004, Munshi & Myaux 2006, Kremer & Miguel 2007, Conley & Udry 2009). This important interaction may be present in any setting including within any of the four major environmental health challenges that we have discussed here.

Returning to the issue of public intervention, such social interactions as described above can change the calculus for evaluation of public action. If avoidance by one household accurately raises the risk perceptions of others, then educating the first household has multiplier benefits.

5.1.3. Interactive private benefits. As noted above, private avoidance benefits could drive household decisions if external benefits are ignored [Heal (2003) advocated exploiting this channel through "bundling," which could apply to cases of either ignored or no externalities]. Many such private gains are purely individual, e.g., if an individual uses a big new free stove as a table rather than for cooking.

Other private benefits may have social or interactive elements. Social marketing of toilets may have contributed significantly to their adoption (and for indoor air quality an advanced stove may confer prestige). Benefits such as feeling one has joined the elite involve comparisons with the behaviors of others. They may yield multiple equilibria and various adoption dynamics. For example, Dickinson & Pattanayak (2009) suggested that low-level equilibrium traps could result from peer effects, particularly if private incentives related to regulations and price signals are weak. To avoid such low-level traps and to exploit multipliers, public policies that create the prestige of avoidance and/or subsidize avoidance by the first movers may be justified.

These alternative forms of public expenditures could be efficient, i.e., cheaper than other subsidies. In the case of $e_a = 0$, i.e., no externality exists, public expenditure would have to be justified (and perhaps funded) by gains across equilibria, such as reducing the mistakes made when households do not completely understand health risks. Then the cost of triggering any private dynamics could be compared with those of free education. Alternatively, a combination of education, learning from others, and private prestige may provide the best approach.

5.1.4. Infectious diseases. For acute respiratory infection, diarrhea, and malaria (as well as all the infectious diseases that dominate in **Figure 2**), externalities expand dramatically, perhaps explaining why the infectious diseases continue to figure prominently in statistics of health burdens. Given that a household's sickness here is part of the environmental conditions generating others' sickness, a new class of actions with infection externalities here exists, i.e., all the actions that keep others healthy when a household member is sick. Those actions could include prevention such as hand washing, as well as mitigation behaviors such as taking medicines to lessen sicknesss—both of which help others.

Unfortunately, private net benefits are likely to be lower than social net benefits from such actions, requiring some form of induced internalization of external gains from actions that curtail infections (Gersovitz & Hammer 2003). Accordingly, community leaders may invest in creating social norms to address both a household's lack of information (private inefficiency) and externalities (social inefficiency) as constraints on the avoidance of infection. Kosher rules and regular hand washing are examples of health-oriented norms.

Within our model, gains from conformity with norms could be seen as private ($u_a > 0$). Written that way, they appear to exclude entirely health or health externalities, as opposed to collateral avoidance benefits. Yet, if created to internalize unperceived or ignored health effects, such norms serve as health regulations, although mechanisms of enforcement could differ for this kind of regulation. They might take the form of public shaming versus monitoring and monetary instruments. Societies may choose between types of regulation on the basis of local feasibility.

5.2. Social Interactions Within a Case Study of Diarrhea

Empirical identification of social interactions is complicated (Manski 1993). Individuals' apparent influence on their neighbors could simply reflect shared characteristics (unobserved correlated effects) or identical exogenous influences (observed exogenous effects). Additional research on the specific mechanism of interaction—in constraints, expectations, or preferences—could not only provide clarification (i.e., Is this interaction related to epidemiology, imitation, conforming, or learning?), but also help to identify the magnitudes of key parameters relevant for policy choice (Manski 1995).

To provide one example, we revisit the sanitation case study. Dickinson & Pattanayak (2009) applied three econometric strategies to examine whether such apparent impacts, or correlations, were caused by social interactions: functional-form assumptions (Brock & Durlauf 2001), exclusion restrictions (Bajari et al. 2006), and an untargeted subpopulation (Moffitt 2001).

In the first approach, average adoption among other households in the village is a variable in a probit regression. This is a simple approach and the identification relies on functional-form assumptions.

In the second approach, neighbor characteristics with no direct effect on the household's adoption decision are critical. Any observed impact of such characteristics on choice of sanitation by the household must be measured through the impact on neighbors' behaviors, which in turn affect the original household. In the first stage, a neighbor's latrine adoption is explained as a function of the excludable characteristics—neighbor's housing materials—or as a robustness check yielding similar results, e.g., monthly expenditure and ownership of consumer durables. This regression generates predicted probabilities of adoption for each household. In the second stage, a household's latrine adoption is regressed on the full set of household and village characteristics expected to affect sanitation as well as the predicted level of adoption among other households in the village.

The third approach examines an intervention in incentives (e.g., prices) for only a subset of the sample. Changes in behavior by those not directly affected by the incentive change may provide evidence of interactions. The sanitation campaign involved a social component that was intended to address social norms as well as a subsidy for latrine adoption. The subsidy was offered only to households below the poverty line. Thus, observed increases in latrine uptake among households above the poverty line suggest that impact was partially due to social interactions. To test this, the adoption of latrines in the excluded group is regressed on own-household characteristics and the percentage of other households in the village that adopted latrines. The percentage of households below the poverty line in a village is an instrument for the percentage who have adopted the latrine.

Across these three econometric approaches, the empirical evidence consistently indicates that latrine adoption among other households in the village had a positive and significant effect on a household's own adoption decision. Thus, an individual's probability of adoption increases by 0.4% for every 1% increase adoption by everyone else in the community. Social effects are twice as large (0.8%) when analyses are limited to villages that were exposed to the communication campaign, indicating that the campaign caused households to place more weight on social components of utility and increased the social pressure to adopt latrines.

Collectively, these suggest that the campaign's impact was achieved by strengthening the social pressure to adopt latrines, and policies that target social drivers of behavior change may be more effective than those that focus only on private incentives such as subsidies. Thus, the social campaign may have increased the effectiveness of subsidies by creating a multiplier effect that shifted social norms.

6. HURDLES LOOKING AHEAD

6.1. Within These Four Health Challenges

Our overarching point is that behavioral choices are critical. This should be clear within each of the four major environmental health challenges we review, yet the findings suggest considerable nuance within and across settings. One common theme is that estimating households' WTP for changes in the quality of the environment is not simple, particularly if the technology that changes quality also delivers other benefits. Risk information and understanding are other common themes. In the simplest setting, policy makers can empower individuals' demand for health by providing risk information (Madajewicz et al. 2007). Yet, in more interactive settings, rational private choice can be prevalence elastic, for instance, even when each individual is fully informed. This suggests that rational individual participation in avoidance behaviors could fall despite the success of a public campaign, as was found for malaria (Pattanayak et al. 2006b).

The likelihood of the existence of many actions featuring externalities within the three infectious settings (respiratory ailments, diarrhea, and malaria) raised the issue of community coordination, particularly in areas where the actions of the state are limited. Incomplete capital (as well as other) markets may also hamper individual initiative. Generally, issues of behavioral interdependence raise ideas about communication via social channels, as in the sanitation case (Pattanayak et al. 2009c). For the highly burdensome infectious diseases, we find a complex frontier stressing social interactions, missing markets, and related responses (Malla et al. 2008).

6.2. The Challenges of Scaling Up

Existing empirical literature on global environmental health tests efficacy and effectiveness in the case in which intervention arrives exogenously. It focuses on the average treatment effect. Above, we also suggest the importance of differences from averages in considering the response heterogeneity implied by all of the different settings, exposure channels, and disease dynamics.

The effort to identify clearly the average treatment effects has led to holding randomized control trials (RCTs) as the "gold standard" for any policy evaluation, at least when political and ethical contexts permit. The parameters identified have clear value. That said, we note that they may not predict the outcomes of actual interventions, for instance those not randomly targeted. Many environmental health programs are and likely will remain nonrandomly targeted by program administrators and/or will be driven by local demands (Pattanayak et al. 2009b).

One nonrandom dynamic for scaling up programs is household choice. We can learn the impact of free well-water arsenic tests but yet not be able to predict what will happen when the funding for such knowledge subsidies ends and households must choose to test their own wells. An RCT could address the latter unknown by focusing on the household demand for information; however, that is best motivated by a concern with nonrandom scaling that is not always present.

More generally, as the causal chain of environment and health is neither short nor simple, external validity of treatment effect estimates is key to answer critical questions about whether interventions are sustainable and scalable (Pattanayak et al. 2009b). Victora et al. (2004) contended, "although some progress can be made by extension and adaptation of RCTs, . . . new designs that incorporate adequacy and plausibility approaches must be developed, tried, and taught."[13] Such concerns reflect a larger trend in public health to accelerate the translation of research findings into public health practice through implementation, dissemination, and diffusion research.[14] Translation research that predicts actual scaling of interventions must identify major practical impediments to successful application of strategies in order to enhance the widespread adoption and institutionalization of an intervention. In sum, RCTs usually stop short of such questions.

Looking beyond efficacy trials to permit further comment on scaled-up programs echoes academic (e.g., Heckman & Smith 1995, Deaton 2009) and practitioner (e.g. Ravallion 2007) interest in analysis of participant or program heterogeneity. The idea of "opening the black box of the conditional mean impact" explicitly notes heterogeneity in program delivery, acceptance, and impacts (Ravallion 2007). If the target population chose and received different environment and development packages at the baseline, for example, multiple interventions should be studied (Mueller et al. 2009). Quantile treatment effects represent a semiparametric way to examine treatment heterogeneity (Gamper-Rabindran et al. 2009). We can also estimate heterogeneous effects of intervention via explicit analysis of subgroups, for instance by separating out subgroups of households by poverty status, ethnicity, or household characteristics (Jalan & Ravallion 2003, Pattanayak et al. 2009d).

Our focus on spillovers also suggests limitations on traditional partial equilibrium impact estimation. If varied interactions drive shifts between distinct equilibria following interventions, then assessment could be enhanced via computable general equilibrium models. For instance, the health impacts of climate change could have economy-wide

[13]Adequacy relies on documentation of time trends in key indicators after the intervention. Plausibility examines causality by comparing with control groups (historical, geographic, or internal) and addressing confounding factors.

[14]Translation research characterizes the sequence of events (i.e., process) in which a proven scientific discovery (i.e., evidence-based public health intervention) is successfully institutionalized (i.e., seamlessly integrated into established practice and policy). Translation research comprises many complex components that include specialized fields of study, specifically (*a*) dissemination research: how the targeted distribution of information and intervention materials to a specific public health audience can be successfully executed to increase spread of knowledge and, ultimately, use and impact; (*b*) implementation research: how a specific set of activities and designed strategies are used to successfully integrate an evidence-based public health intervention within specific settings (e.g., primary care clinic, community center, school); and (*c*) diffusion research: the systematic study of the factors necessary for successful adoption by a targeted population, which results in widespread use (e.g., state or national level) and includes the uptake of new practices or the penetration of broad-scale recommendations through dissemination and implementation efforts, marketing, laws and regulations, systems research, and policies.

consequences due to labor-productivity effects (Pattanayak et al. 2009c). The empirical toolkit for analyzing shifts at such scale could also include locational equilibrium or sorting models (Sieg et al. 2004, Bayer et al. 2009). By allowing for key behavioral adjustments, such general equilibrium evaluations may suggest significantly different impacts relative to the purely partial equilibrium approaches.

6.3. Additional Challenges

The environmental health economics literature is small, particularly when considering rigorous empirical research in developing countries. Although our list below is neither exhaustive nor mutually exclusive, we believe that at least the following three topics need greater attention.

6.3.1. Nonlinearities. We start with a catchall of complications: nonlinearities arising at several points in the environmental health arena. First, we must acknowledge the tremendous range of magnitudes of threat or risk faced by individuals and communities across space and the associated nonconvexities, which we do not emphasize in our conceptual model in Section 2 or 3. Thus, we should not expect that understanding of shifts (for example, from zero to low, low to medium, medium to high, and high to extreme exposures) will accurately inform each other.

Starting at the physical level, the body has thresholds of resistance (which vary in the population) that are critical for evaluation. At the level of household decision making, we must consider the extensive margin (as opposed to the focus on the intensive margin in the model in Section 2), for instance an abrupt change in technology (e.g., using an electric stove) or behavior (e.g., sleeping under bed nets). Moving further to the community level, in particular when collective actions are desirable, additional forms of nonlinearity in response arise (see Section 5). For instance, because a household's contribution to the public good is likely to be affected by its expectations of others' actions, multiple equilbria are possible and can be shifted by any number of parameters. Equilibrium shifts can also be caused by a changed distribution of citizen types (e.g., less versus more likely to engage in avoidance), which in turn might have resulted as a function of nonrandom migration of these types (e.g., sorting).

Many of these concerns arise in the mainstream news accounts of environmental refugees initially made homeless by a natural disaster, such as an earthquake, tsunami, or drought, then caught up in a complex interaction among relief, aid, incapacities, and poverty. Climate change projections suggest more extreme stresses in the future: For instance, we may begin to expect the unexpected, such as "100-year" floods, droughts, or other extreme events. Empirical research on health impacts of natural hazards is still limited, despite empirical studies on coping with hazards in developed countries (e.g., Smith et al. 2006). As individuals, communities, and societies may begin to adapt to nonconvexities (perhaps by migrating), more research is needed on the careful assessment of a diverse range of policy instruments such as surveillance, early warning systems, and rainfall insurance. For example, Das & Vincent (2009) analyzed storm-protection benefits of coastal mangroves, using data before and after a super cyclone in Orissa, India, in 1999. They suggested that, although mangroves evidently saved fewer lives than an early warning issued by the government, the retention of remaining mangroves in Orissa is economically justified.

6.3.2. Migration. Consider the specific behavioral response of migration, one of the extreme situations discussed above. Migration has been an important concern for economists, not only because it reflects one of the most important, yet costly, choices exercised by households, but also because it reveals preferences for and values of geographic factors, potentially including the disease environment. In our context, households can engage in a whole menu of prevention and mitigation choices at the intensive margin to confront environmental health risks, e.g., hand washing and using bed nets. In contrast, migrating to escape the contagion represents a prevention choice at the extensive margin.

In a recent theoretical paper, Mesnard & Seabright (2008) developed a dynamic framework in which migration and prevention behavior are endogenous, responding to disease prevalence, migration and treatment costs, and current and anticipated health regulations. They explored how pressure for migration, which responds to differing equilibrium levels of disease prevalence, causes countervailing differences in city characteristics such as land rents. From a policy guidance perspective, the multiple equilibria in such models create a strong rationale for empirical testing of household choices on intensive and extensive margins. Although Timmins (2005) reviewed this migration literature (derived from a new economic geography), no one has empirically examined migration within an environmental and disease context.

6.3.3. Climate change. We close with a discussion of what may be the most profound environmental challenge confronting policy makers today: climate change. To some extent, this is related to the unequal distribution of health impacts of climate change (Haines et al. 2006). In the past 50 years, global mean temperature has risen by 0.6°C, sea level has risen by a mean of 1–2 cm/decade, and ocean heat content has also measurably increased. According to the United Nations Intergovernmental Panel on Climate Change (IPCC), mean global temperatures will increase by 1.4–5.8°C, sea level will rise by 9–88 cm, additional greenhouse gas releases from warmer oceans and warmer soils will increase temperatures by another 2°C, and floods and droughts will increase. Many health outcomes and diseases are sensitive to climate; these include the following:

- Climate change, excessive temperatures, and heat waves can alter arterial pressure, blood viscosity, and heart rate, thereby causing cardiovascular and cerebrovascular diseases among the elderly.
- Thermal stress and temperature-related air pollution (thermal inversion), pollen counts, mold growth, and pollution precursor (nitrogen oxide–based ground-level ozone) can cause a variety of respiratory diseases including asthma, bronchitis, pneumonia, cough, and cold.
- Increasing temperatures, humidity, and rainfall can affect proliferation, density, behavior, variety, viability, and maturation of insect vectors such as mosquitoes (which carry malaria and dengue parasites) as well as ticks and flies.
- Projected floods and droughts are expected to worsen water quantity and quality problems and impact water-washed diseases such as diarrhea and cholera.
- Finally, climate change can indirectly affect nutrition through its impact on agriculture yield, thereby affecting refugee health issues, which are linked to forced population migration.

Patz & Olson (2006a) contended that "changing landscapes can significantly affect local weather more acutely than long-term climate change" because land-cover change can influence microclimatic conditions (e.g., temperature, evapo-transpiration, and surface runoff), which influence the emergence of infectious diseases. **Figure 4** (see color insert) provides the direction and magnitude of health impacts of climate change according to the IPCC, taking into account the number of people impacted and potential adaptive capacity (Confalonieri et al. 2007). This latest health report from the IPCC also suggests the following:

- Health impacts will be greatest in African and Asian countries that already have high disease burdens. Those at greater risk include the urban poor, the elderly and children, traditional societies, subsistence farmers, and coastal populations.
- Adaptive capacity will need to improve everywhere. Although economic development is a major adaptation tool, it will not be sufficient to insulate millions from disease and injury.

Not surprisingly, significant knowledge gaps remain about not just whether major health outcomes will improve, but also how fast, where, when, at what cost, and whether all population groups will be able to share in these developments. Thus, key research priorities include improved empirical analyses of (*a*) health impacts of (and vulnerability to) climate change and (*b*) effectiveness and costs of adaptation. As Malla et al. (2008) contended, in this context, household energy technologies such as improved cook stoves are potentially win-win interventions by reducing respiratory infections and mitigating climate change (because traditional cooking technologies are not only dirty but also inefficient). In sum, adapting to avoid the adverse health impacts of climate change provides a clear and important final example of our paper's theme and title—i.e., the centrality of behavioral choices for understanding people's valuation of environmental risks and the social evaluation of environmental health policies.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We are grateful to V. Kerry Smith for encouraging us to work on this review and for extensive helpful comments. As this review draws directly from research each of us has done with others, we also acknowledge various coauthors and the funding from employers and grantors. S.K.P. acknowledges his collaboration with Jui-Chen Yang, Sumeet Patil, Christine Poulos, Katie Dickinson, Dale Whittington, George Van Houtven, Min Malla, Krishna Pant, Jack Colford, and Ben Arnold as well as funding from the World Bank and the Duke Global Health Institute. A.P. acknowledges his collaboration with Shubham Chaudhuri, Malgosia Madajewicz, Lex van Geen, Alisa Opar, Amy Schoenfeld, Kazi Matin, Joseph Graziano, Lori Bennear, Alessandro Tarozzi, and Soumya Balasubramanya on arsenic; and with Shubham Chaudhuri, Howard Nye, Valerie Mueller, Kirk Smith, John Peabody, Darby Jack, and Niels Tomijima on indoor air quality as well as funding from the Earth Institute at Columbia University and the CCBVP at Duke University.

LITERATURE CITED

Andam K, Ferraro PJ, Pfaff A, Sanchez-Azofeifa A, Robalino J. 2008. Measuring the effectiveness of protected area networks in reducing deforestation: a rigorous impact evaluation approach. *Proc. Nat. Acad. Sci. USA* 105(42):16089–94

Anselin L, Lozano-Gracia N, Deichmann U, Lall S. 2008. *Valuing access to water—a spatial hedonic approach applied to Indian cities*. Policy Res. Work. Pap. 4533, World Bank

Bajari P, Hong H, Krainer J, Nekipelov D. 2006. *Estimating Static Models of Strategic Interactions*. Stanford, CA: Stanford Univ. Press

Bayer P, Keohane N, Timmins C. 2009. Migration and hedonic valuation: the case of air quality. *J. Environ. Econ. Manag.* 58(1):1–14

Bennett D. 2008. *Clean water makes you dirty: water supply and sanitation behavior in the Philippines*. Work. Pap., Univ. Chicago

Boy E, Bruce N, Delgado H. 2002. Birth weight and exposure to kitchen wood smoke during pregnancy in rural Guatemala. *Environ. Health Perspect.* 110(11):109–14

Brock WA, Durlauf SN. 2001. Discrete choice with social interactions. *Rev. Econ. Stud.* 68(2):235–60

Bruce N, McCracken J, Albalak R, Schei M, Smith KR, et al. 2004. Impact of improved stoves, house construction, and child location on levels of indoor air pollution exposure in young Guatemalan children. *J. Expo. Anal. Environ. Epidemiol.* 14:S26–33

Bruce N, Neufeld L, Boy E, West C. 1998. Indoor biofuel air pollution and respiratory health: the role of confounding factors among women in highland Guatemala. *Int. J. Epidemiol.* 27:454–58

Bruce N, Perez-Padilla R, Albalak R. 2000. Indoor air pollution in developing countries: a major environmental and public health challenge. *Bull. World Health Organ.* 78:1078–92

Carstensen K, Gundlach E. 2006. The primacy of institutions reconsidered: direct income effects of malaria prevalence. *World Bank Res. Obs.* 20(3):309–39

Clasen T, Schmidt W-P, Rabie T, Roberts I, Cairncross S. 2007. Interventions to improve water quality for preventing diarrhea: systematic review and meta-analysis. *Br. Med. J.* 334(7597):782

Confalonieri U, Menne B, Akhtar R, Ebi KL, Hauengue M, et al. 2007. *Human Health. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson, pp. 391–431. Cambridge, UK: Cambridge Univ. Press

Conley TG, Udry CR. 2009. Learning about a new technology: pineapple in Ghana. *Am. Econ. Rev.* In press

Corey CG, Yang J-C, Pattanayak SK. 2007. *Seasonal variation in risk factors associated with diarrheal diseases, rural Maharashtra, India*. Work. Pap. 07_01, RTI

Cornes R, Sandler T. 1994. Easy riders, joint production, and public goods. *Econ. J.* 94:580–98

Curtis V, Garbrah Aidoo N, Scott MB. 2007. Masters of marketing: bridging private sector to skills to public health partnerships. *Am. J. Public Health* 97(4):634–41

Cutler D, Miller G. 2004. The role of public health improvements in health advances: the twentieth-century United States. *Demography* 42(1):1–22

Das S, Vincent JR. 2009. Mangroves protected villages and reduced death toll during Indian super cyclone. *Proc. Natl. Acad. Sci. USA* 106:7357–60

Dasgupta S, Huq M, Khaliquuzaman M, Pandey K, Wheeler D. 2006. Indoor air quality for poor families: new evidence from Bangladesh. *Indoor Air* 16:426–44

Deaton A. 2009. *Instruments of development: randomization in the tropics, and the search for the elusive keys to economic development*. Work. Pap.14690, NBER

Dehejia R, Wahba S. 1999. Causal effects in nonexperimental studies: re-evaluating the evaluation of training programs. *J. Am. Stat. Assoc.* 94:1053–62

Dickinson K, Pattanayak SK. 2009. *Social reinforcing in the case of a (very) impure public good*. Work. Pap., Duke Univ.

Ezzati M, Kammen D. 2001a. Indoor air pollution from biomass comubstion and acute respiratory infections in Kenya: an exposure-response study. *Lancet* 358:619–24

Ezzati M, Kammen D. 2001b. Quantifying the effects of exposure to indoor air pollution from biomass combustion on acute respiratory infections in developing countries. *Environ. Health Perspect.* 109(5):481–88

Ezzati M, Kammen D. 2002. Household energy, indoor air pollution, and health in developing countries: knowledge base for effective interventions. *Annu. Rev. Energy Environ.* 27:233–70

Figueroa ME, Kincaid DL. 2007. Social, cultural, and behavioral correlates of household water treatment and storage. In *Household Water Treatment and Safe Storage*, ed. M Sobsey, T Clasen. Geneva: WHO

Ferriman A. 2007. BMJ readers choose the "sanitary revolution" as greatest medical advance since 1840. *Br. Med. J.* 334:111

Gamper-Rabindran S, Timmins C, Khan S. 2009. The impact of piped water provision on infant mortality in Brazil: a quantile panel data approach. *J. Dev. Econ.* In press. doi:10.1016/j.jdeveco.2009.02.006

Gersovitz M, Hammer JS. 2003. Infectious diseases, public policy, and the marriage of economics and epidemiology. *World Bank Res. Obs.* 18:129–57

Gordon B, Mackay R, Rehfuess E. 2004. *Inheriting the World: the Atlas of Children's Health and the Environment*. Washington, DC: WHO

Greenwood BM, Bojang K, Whitty CJM, Targett GAT. 2005. Malaria. *Lancet* 365:1487–98

Haines A, Kovats RS, Campbell-Lendrum D, Corvalan C. 2006. Climate change and human health: impacts, vulnerability, and mitigation. 367:2101–9

Hanchett S, Nahar Q, van Agrhoven A, Geers C, Ferdous Jamil Rezvi MD. 2001. Increasing awareness of arsenic in Bangladesh: lessons from a public education programme. *Health Policy Plan.* 17(4):393–401

Hardin G. 1968. The tragedy of the commons. *Science* 162:1243–48

Harrington W, Portney P. 1987. Valuing the benefits of health and safety regulation. *J. Urban Econ.* 22(1):101–12

He J, Vupputuri S, Allen K, Prerost MR, Hughes J, Whelton PK. 1999. Passive smoking and the risk of coronary heart disease—a meta-analysis of epidemiologic studies. *N. Engl. J. Med.* 340(12):920–26

Heal GM. 2003. Bundling biodiversity. *J. Eur. Econ. Assoc.* 1:553–60

Heckman J, Smith J. 1995 Assessing the case for social experiments. *J. Econ. Perspect.* 9(2):85–110

Hill JL, Brooks-Gunn J, Waldfogel J. 2003. Sustained effects of high participation in an early intervention for low-birth-weight premature infants. *Dev. Psychol.* 39(4):730–44

Hope RA. 2006. Evaluating water policy scenarios against the priorities of the rural poor. *World Dev.* 34(1):167–79

Jalan J, Ravallion M. 2003. Does piped water reduce diarrhea for children in rural India? *J. Econ.* 112(1):153–73

Jalan J, Somanathan E. 2008. The importance of being informed: experimental evidence on demand for environmental quality. *J. Dev. Econ.* 87(1):14–28

Jalan J, Somanathan E, Chaudhuri S. 2009. Awareness and the demand for environmental quality: drinking water in urban India. *Environ. Dev. Econ.* In press. doi: 10.1017/S1355770X08005020

Jessoe KJ. 2009. *Improved source, improved quality? Demand for drinking water quality in rural India*. Work. Pap., Yale Univ.

Jenkins MW, Curtis V. 2005. Achieving the 'good life': why some people want latrines in rural Benin. *Soc. Sci. Med.* 61:2446–59

Kenkel D. 2000. Prevention. In *Handbook of Health Economics*, Vol. 1, ed. AJ Culyer, JP Newhouse. Amsterdam: Elsevier

Kremer M, Miguel E. 2007. The illusion of sustainability. *Q. J. Econ.* 122(3):1007–65

Larson BA, Rosen S. 2002. Understanding household demand for indoor air pollution control in developing countries. *Soc. Sci. Med.* 55(4):571–84

Larson B, Minten B, Razafindralambo R. 2006. Unravelling the linkages between the Millennium Development Goals for poverty, education, access to water and household water use in developing countries: evidence from Madagascar. *J. Dev. Stud.* 42(1):22–40

Lindsay SW, Birley M. 2004. Rural development and malaria control in Sub-Saharan Africa. *EcoHealth* 1:129–37

Madajewicz M, Pfaff A, Graziano J, van Geen A, Hussein I, et al. 2007. Can information alone both improve awareness and change behavior? Arsenic contamination of groundwater in Bangladesh. *J. Dev. Econ.* 84:731–54

Malla MB, Pant KP, Pattanayak SK. 2008. *Climate change, cook stoves, and coughs and colds: evidence from rural Nepal on thinking global, and acting local*. Presented at Am. Public Health Assoc. Meet., San Diego, CA

Manski CF. 1993. Identification of endogenous social effects: the reflection problem. *Rev. Econ. Stud.* 60(3):531–42

Manski CF. 1995. Economic analysis of social interactions. *J. Econ. Perspect.* 14(3):115–36

McCracken JP, Diaz A, Smith KR, Mittleman MA, Schwartz J. 2007. Chimney stove intervention to reduce long-term wood smoke exposure lowers blood pressure among Guatemalan women. *Environ. Health Perspect.* 115(7):996–1001

Mesnard A, Seabright P. 2008. *Migration and the equilibrium prevalence of infectious diseases*. Discuss. Pap. DP6651, CEPR

Miguel E, Kremer M. 2004. Worms: identifying impacts on education and health in the presence of treatment externalities. *Econometrica* 72(1):159–217

Mishra V, Dai X, Smith K, Mika L. 2004. Maternal exposure to biomass smoke and reduced birth weight in Zimbabwe. *Ann. Epidemiol.* 14(1):740–47

Moffitt RA. 2001. Policy interventions, low-level equilibria, and social interactions. In *Social Dynamics*, ed. SN Durlauf, HP Young. Cambridge, MA: MIT Press

Moshammer H, Hutter H-P, Neuberger M. 2006. Gas cooking and reduced lung function in school children. *Atmos. Environ.* 40:3349–54

Mueller V, Pfaff A, Peabody J, Liu Y, Riddell T, Smith KR. 2009. *Who adopts matters: evaluating the health impacts of improved stoves in China using matching methods*. Work. Pap., Duke Univ.

Munshi K, Myaux J. 2006. Social norms and the fertility transition. *J. Dev. Econ.* 80:1–38

North JH, Griffin CC. 1993. Water as a housing characteristic: hedonic property valuation and willingness to pay for water. *Water Resour. Res.* 29(7):1923–29

Opar A, Pfaff A, Seddique AA, Ahmed KM, Graziano JH, van Geen A. 2007. Responses of 6500 households to arsenic mitigation in Araihazar, Bangladesh. *Health Place* 13(1):164–72

Ostrom E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge, UK: Cambridge Univ. Press

Over M, Bakote'e B, Velayudhan R, Wilkai P, Graves PM. 2004. Impregnated nets or DDT residual spraying? Field effectiveness of malaria prevention techniques in Solomon Islands, 1993–1999. *Am. J. Trop. Med. Hyg.* 71(Suppl. 2):214–23

Patil SR, Pattanayak SK. 2007. *Behaviors exposed: household production of microbial exposure*. Work. Pap. 07_03, RTI

Pattanayak SK, Dickinson K, Corey C, Sills EO, Murray BC, Kramer R. 2006a. Deforestation, malaria, and poverty: a call for transdisciplinary research to design cross-sectoral policies. *Sustain. Sci. Pract. Policy* 2(2):1–12

Pattanayak SK, Dickinson K, Yang J-C, Patil SR, Poulos C, et al. 2008. *Nature's call: health and welfare impacts of latrines in Orissa, India*. Work. Pap., Duke Univ.

Pattanayak SK, Poulos C, Yang J-C, Patil SR. 2009a. *How valuable are environmental health interventions? Economic evaluation of a water and sanitation project in Maharashtra, India*. Presented at the Assoc. Environ. Resour. Econ. Annu. Work., Berkeley, Calif.

Pattanayak SK, Poulos C, Yang J-C, Patil SR, Wendland KJ. 2009b. Of taps and toilets: quasi-experimental protocols for evaluating community-demand driven projects. *J. Water Health* 7(3):434–51

Pattanayak SK, Poulos C, Yang J-C, Wendland KJ, Van Houtven G. 2006b. *Economics modeling self-protection against infectious disease: towards a theory of the economics of environmental epidemiology.* Work. Pap., Res. Triangle Inst. Int.

Pattanayak SK, Ross MT, Depro BM, Bauch SC, Timmins C, et al. 2009c. *Evaluating the health impacts of climate change and conservation policies using applied CGE*. Work. Pap., Duke Univ.

Pattanayak SK, Yang J-C, Dickinson K, Poulos C, Patil SR, et al. 2009d. Shame or subsidy revisited: social mobilization for sanitation in Orissa, India. *Bull. World Health Organ.* In press. doi: 10.2471/BLT.08.057422

Pattanayak SK, Yasuoka J. 2008. Deforestation and malaria: revisiting the human ecology perspective. In *Forests, People and Health: A Global Interdisciplinary Overview*, ed. CJP Colfer, pp. 197–217. London: Earthscan Publ.

Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. 2005a. Impact of regional climate change on human health. *Nature* 438:310–17

Patz JA, Confalonieri UEC, Amerasinghe FE, Chua KB, Daszak P, et al. 2005b. Human infectious disease agents. In *Ecosystems and Human Well-Being: Current State and Trends*, 1:391–415. Washington, DC: Island Press

Patz JA, Graczyk TK, Geller N, Vittor AY. 2000. Effects of environmental change on emerging parasitic diseases. *Int. J. Parasitol.* 30(12–13):1395–405

Patz JA, Olson SH. 2006a. Climate change and health: global to local influences on disease risk. *Ann. Trop. Med. Parasitol.* 100(5-6):535–49

Patz JA, Olson SH. 2006b. Malaria risk and temperature: influences from global climate change and local land use practices. *Proc. Natl. Acad. Sci. USA* 103(15):5635–36

Peabody JW, Riddell TJ, Smith KR, Liu Y, Zhao Y, Gong J, et al. 2005. Indoor air pollution in rural china: cooking fuels, stoves, and health status. *Arch. Environ. Occup. Health* 60(2):1–10

Petney TN. 2001. Environmental, cultural, and social changes and their influence on parasite infections. *Int. J. Parasitol.* 31(9):919–32

Philipson T. 2000. Economic epidemiology and infectious diseases. In *Handbook of Health Economics*, Vol. 1, ed. AJ Culyer, JP Newhouse. Amsterdam: Elsevier

Pitt M, Rosenzweig M, Hassan MN. 2006. *Sharing the burden of disease: gender, the household division of labor and the health effects of indoor air pollution in Bangladesh and India*. Work. Pap., Cent. Int. Dev.

Preston SH. 1996. *American longevity: past, present, and future*. Policy Brief 7, Syracuse Univ.

Prüss-Üstün A, Corvalan C. 2006. *Preventing Disease Through Healthy Environments. Towards an Estimate of the Environmental Burden of Disease*. Geneva: WHO

Ravallion M. 2007. Evaluating anti-poverty programs. In *Handbook of Development Economics*, ed. TP Schultz, J Strauss, 4:3787–846. Amsterdam: Elsevier

Reddy AKN, Williams RH, Johansson TB, eds. 1996. *Energy After Rio: Prospects and Challenges*. New York: United Nations Publ.

Sachs J. 2003. *Institutions don't rule: direct effects of geography on per capita income*. Work. Pap. 9490, NBER

Sieg H, Smith VK, Banzhaf HS, Walsh R. 2004. Estimating the general equilibrium benefits of large changes in spatially delineated public goods. *Int. Econ. Rev.* 45(4):1047–77

Smith KR, Corvalán CF, Kjellstrom T. 1999. How much global ill health is attributable to environmental factors? *Epidemiology* 10:573–84

Smith KR, Ezzati M. 2005. How environmental health risks change with development: the epidemiologic and environmental risk transitions revisited. *Annu. Rev. Environ. Resour.* 30:291–33

Smith KR, Mehta S, Maeusezahl-Feuz M. 2004. Indoor smoke from household solid fuels. In *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Due to Selected*

Major Risk Factors, ed. M Ezzati, AD Rodgers, AD Lopez, CJL Murray, 2:1435–93. Geneva: WHO

Smith KR, Samet JM, Romieu I, Bruce N. 2000. Indoor air pollution in developing countries and acute lower respiratory infections in children. *Thorax* 55:518–32

Smith VK, Carbone JC, Pope JC, Hallstrom DG, Darden ME. 2006. Adjusting to natural hazards. *J. Risk Uncertain.* 33:37–54

Smith VK, Pattanayak SK, Van Houtven G. 2006. Structural benefits transfer: an example using VSL estimation. *Ecol. Econ.* 60(2):361–71

Thornton RL. 2008. The demand for, and impact of, learning HIV status. *Am. Econ. Rev.* 98(5):1829–63

Timmins C. 2005. Estimable equilibrium models of locational sorting and their role in development economics. *J. Econ. Geogr.* 5:83–100

Van der Slice J, Briscoe J. 1995. Environmental interventions in developing countries: interactions and their implications. *Am. J. Epidemiol.* 141(2):135–44

Victora CG, Habitch JP, Bryce J. 2004. Evidence-based public health: moving beyond randomized trials. *Am. J. Public Health* 94(3):400–5

Wagner EG, Lanoix JN. 1958. *Excreta disposal for rural areas and small communities*. Monogr. Ser. 39, World Health Organ.

Walsh JF, Molyneux DH, Birley MH. 1993. Deforestation: effects on vector-borne disease. *Parasitology* 106(Suppl.) S55–75

Whittington D, Hanemann WM, Sadoff C, Jeuland M. 2008. *Water and sanitation*. Chall. Pap., Copenhagen Consens. Cent., Copenhagen Bus. Sch.

Whittington D, Pattanayak SK, Yang J-C, Bal Kumar KC. 2002. Household demand for improved piped water services: evidence from Kathmandu, Nepal. *Water Policy* 4(6):531–56

Wilcox BA, Colwell RR. 2003. Emerging and reemerging infectious diseases: biocomplexity as an interdisciplinary paradigm. *EcoHealth* 2:244–57

Wilson ME. 1995. Infectious diseases: an ecological perspective. *Br. Med. J.* 311(7021):1681–84

Wilson ML. 2001. Ecology and infectious disease. In *Ecosystem Change and Public Health*, ed. J Aron, JA Patz, pp. 285–91. Baltimore, MD: Johns Hopkins Univ. Press

World Bank. 1993. The demand for water in rural areas: determinants and policy implications. *World Bank Res. Obs.* 8(1):47–70

World Bank. 2001. *World Development Report 2000/2001: Attacking Poverty.* Washington, DC: World Bank

World Bank. 2009. *No smoke without fire: fresh perspectives on indoor air pollution*, Vol. 2. Tech. Rep., World Bank

World Health Organ. 1997. *Health and Environment in Sustainable Development. WHO/EHG/97.8*. Geneva: WHO

World Health Organ. 2005. *Indoor air pollution and health*. Fact sheet 292. http://www.who.int/mediacentre/factsheets/fs292/en/index.html

Yasuoka J, Levins R. 2007. Impact of deforestation and agricultural development on anopheline ecology and malaria epidemiology. *Am. J. Trop. Med. Hyg.* 76(3):450–60

Yasuoka J, Mangione TW, Spielman A, Levins R. 2006. Impact of education on knowledge, agricultural practices, and community actions for mosquito control and mosquito-borne disease prevention in rice ecosystems in Sri Lanka. *Am. J. Trop. Med. Hyg.* 74(6):1034–42

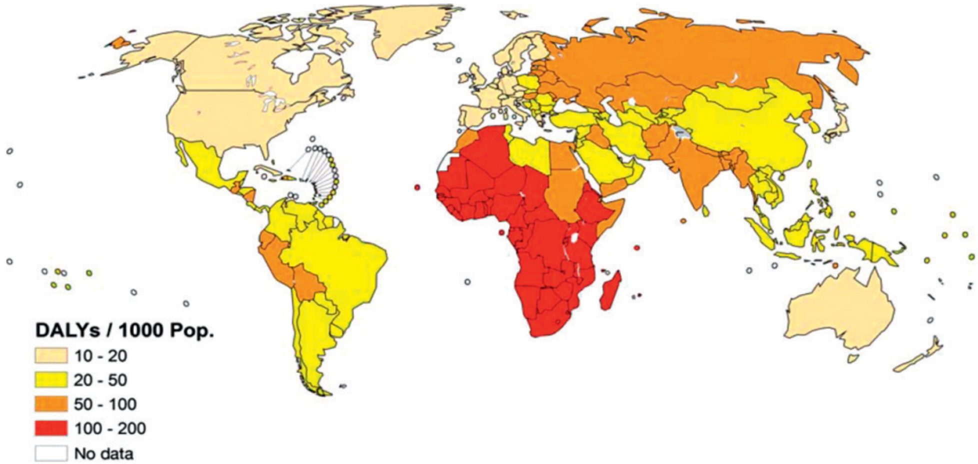

Figure 1

Environmental disease burden; incidence per unit population is shown, i.e., population weights do not emphasize China, India, Brazil, etc. Measured in disability-adjusted life years (DALYs) per 1000 people by World Health Organization subregion. Source: Prüss-Üstün & Corvalan (2006).

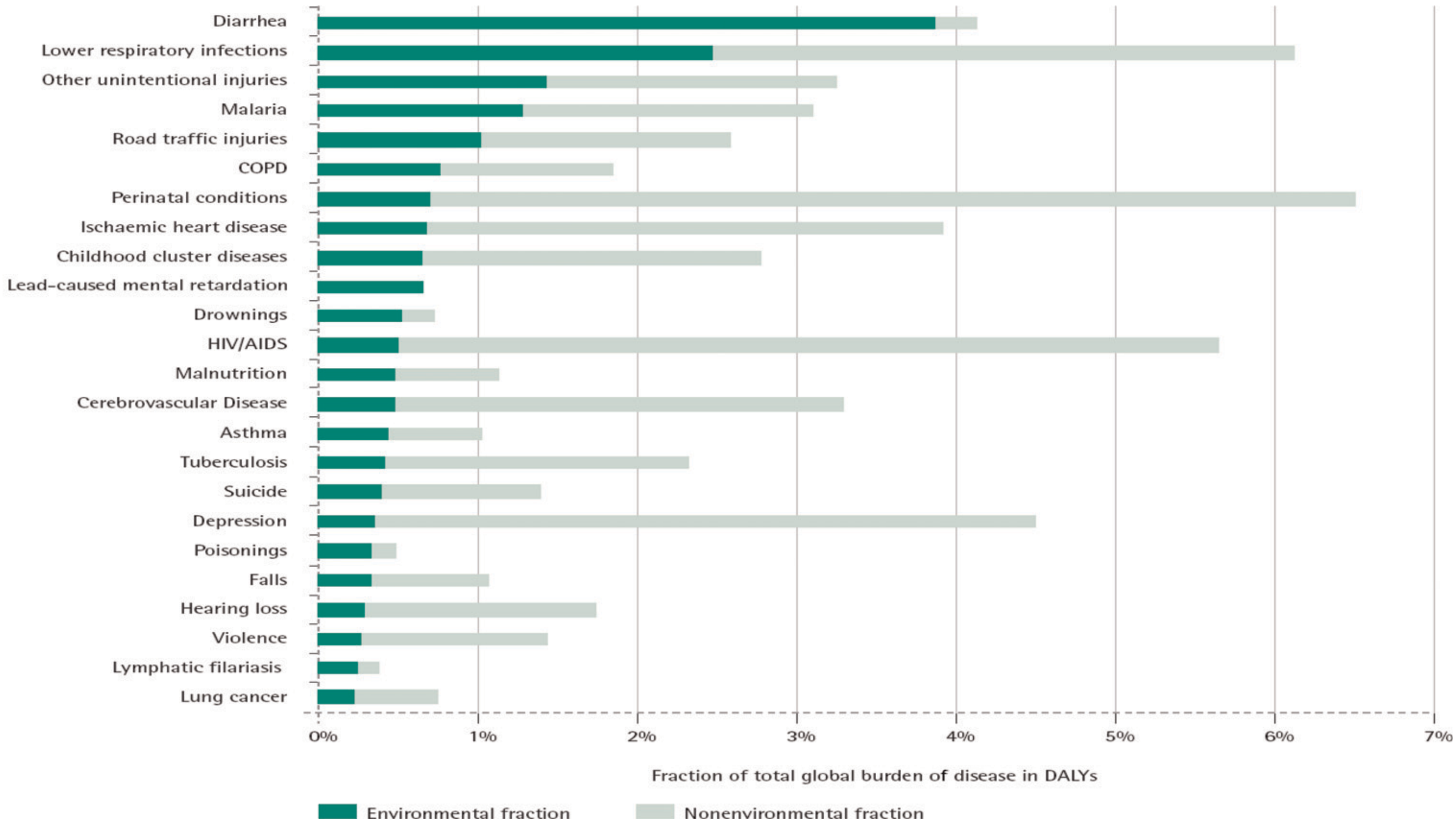

Figure 2

Diseases with the largest environmental contribution. Abbreviations: COPD, chronic obstructive pulmonary disease; DALYs, disability-adjusted life years. Source: Prüss-Üstün & Corvalan (2006).

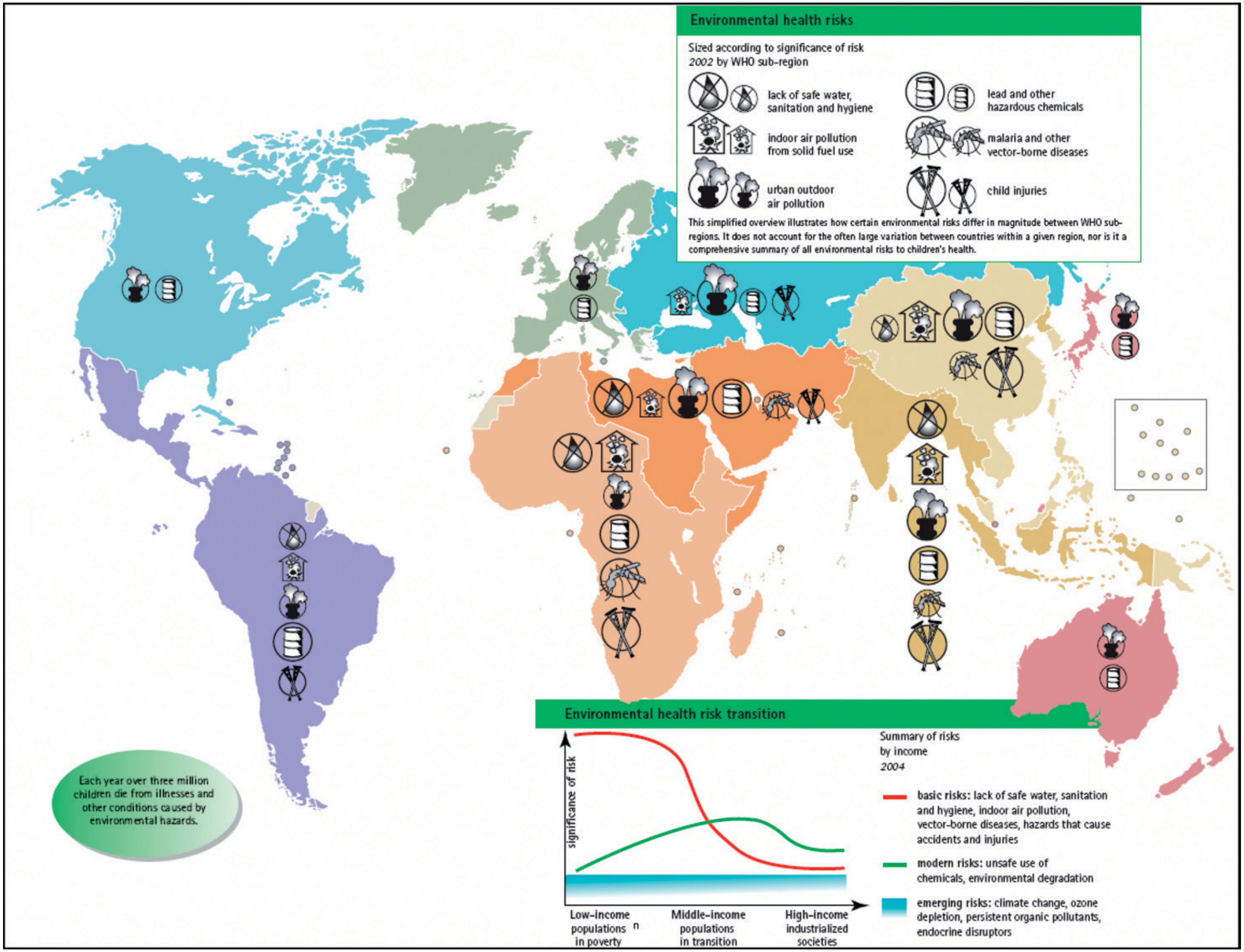

Figure 3
Traditional health hazards and new health risks. Source: Gordon et al. (2004).

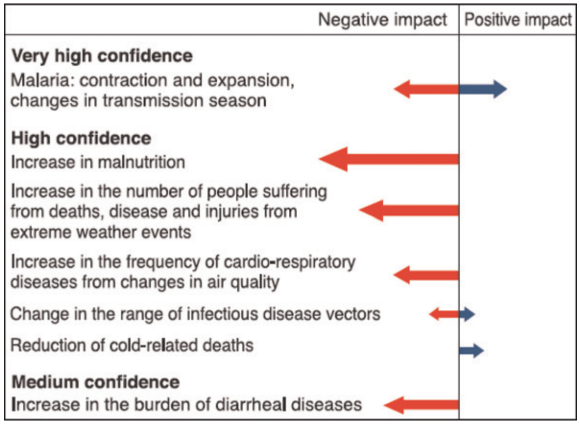

Figure 4

Impacts of climate change on health. For a description of how confidence levels are established, see http://www.ipcc.ch/activity/uncertaintyguidancenote.pdf.

Annual Review of
Resource Economics

Volume 1, 2009

Contents

Resource Dynamics

Ecology and Space

Technology and Innovation

Errata

An online log of corrections to *Annual Review of Resource Economics* articles may be found at http://resource.AnnualReviews.org