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Comparative risk assessment: an international comparison of methodologies and results

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Abstract

Comparative risk assessment (CRA) is a systematic procedure for evaluating the environmental problems affecting a geographic area. This paper looks beyond the U.S. border and examines the experience with CRAs conducted in various developing countries and economies in transition, including Bangkok, Thailand, Cairo, Egypt and Quito, Ecuador, as well as other locations in Eastern Europe, Asia and Central and South America. A recent pilot CRA conducted in Taiwan is also considered. Comparisons are made of both the methodologies and the results across the relatively diverse international literature.

The most robust finding is that conventional air pollutants (e.g., particulate matter and lead) consistently rank as high health risks across all of the CRAs examined. Given the varied nature of the settings studied in the CRAs, including level of economic development, urban–rural differences, and climate, this finding is particularly significant. Problems involving drinking water are also ranked as a high or medium health risk in almost all the countries studied. This is consistent with the results of analyses conducted by the World Bank suggesting contamination, limited coverage and erratic service by water supply systems.

Beyond the major air pollutants and drinking water, the CRA results diverge significantly across countries. A number of problems involving toxic chemicals, e.g., hazardous air pollutants, rank as high health risks in the US but do not appear as consistent areas of concerns in the other countries studied. This likely reflects the so-called "risk transition" — the shift from sanitation and infection disease problems to those involving industry, vehicles and toxic substances — that

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often occurs with economic development. It may also reflect the greater information about sources of toxic pollutants in the U.S.

For other problems, there are important differences across the developing countries and economies in transition. For example, hazardous and (industrial) non-hazardous waste issues ranked as medium or low health risks in all the countries studied, except for Taiwan where unmanaged toxic waste sites were considered to pose high risks. While the generally low ranking is consistent with the notion that few people are directly exposed to hazardous and (industrial) non-hazardous waste, it is not entirely surprising that views might be different in Taiwan, where space is so limited and population density is so high.

We suggest that the wide range of findings likely reflect genuine differences among the countries studied. However, we cannot entirely rule out the possibility that some of the observed similarities (and differences) arise from the (relatively) common methodologies employed.

Keywords: Comparative risk assessment; Risk management; Setting environmental priorities; Risk ranking

1. Introduction

In the face of multiple environmental objectives and limited resources, priorities must be set. In practice, environmental protection initiatives are often motivated by legal mandates, public clamor, scientific evidence, benefits, costs, and other factors. Comparative risk assessment (CRA) provides a systematic framework for first evaluating different environmental problems that pose different types and degrees of risks to human health and the environment, and then for deciding what to do about them. The basic premise of CRA is that risk provides an objective[3] measure for comparing the relative severity of different environmental problems, and risk reduction provides a metric for organizing and evaluating efforts to address the problems. CRA generally has the following two stages.

Risk Assessment. In this stage, the environmental problems facing the area are identified, evaluated and compared, with the aim of developing a ranking of the problems in order of their relative severity. The problems are ranked based on the risks they pose. The ranking process involves assembling and analyzing relevant data on the environmental problems (including data from existing scientific risk analyses) and using structured judgments to fill gaps in data. Although the risk ranking aim of this stage is scientific, there is extensive need for value judgments. The hazards to be considered in the risk assessment, how "risk" is to be measured, how different risks should be weighted, and how uncertainty should be treated are matters involving local values and social choice.

Risk Management. In this stage, initiatives, action plans or budgetary alternatives are developed and assessed. The considerations in this stage extend beyond risk to include a broad balancing of economic, technical, institutional, legal and political factors.

[3] Without entering in discussions whether it is possible to speak of objectivity when dealing with risk, we indicate as "objective risk" the risk estimated after a structured assessment according to the methodology adopted for the prioritization process.

CRA was originally developed at the U.S. Environmental Protection Agency and published as an Agency report, *Unfinished Business* [1]. *Unfinished Business* did not lead to a major re-allocation of resources at the U.S. EPA. Nor did it radically change public perception of environmental risks. Yet, it did help broaden thinking in the policy community on the need to prioritize efforts on the basis of risk reduction potential [2,3]. Since the original publication of *Unfinished Business*, more than half of the states in the U.S. and more than 50 localities have employed the comparative risk approach for identifying and addressing important environmental issues. Several papers have chronicled the lessons learned from these projects and they are now a well-established part of the American policy folklore [2,4].

The present paper looks beyond the U.S. border and examines the experience with CRAs conducted in various developing countries and economies in transition, including Bangkok, Thailand, Cairo, Egypt, Quito, Ecuador, as well as other locations in Eastern Europe, Asia and Central and South America. It also reports on a previously unpublished pilot CRA conducted in Taiwan in 1998. Both the methodologies and results are compared to *Unfinished Business*.

Section 2 provides both a historical and an analytical background of CRA and reviews the various approaches used in the domestic and international literature. Section 3 introduces the Taiwan pilot and considers the methodologies of the various international studies, including *Unfinished Business*. Section 4 compares the results across the full international literature. Section 5 offers some general conclusions.

2. Background

Although CRA projects can be motivated by many factors, Feldman et al. [5] identify the four principal goals of such activities:

- To involve the public in the priority-setting process and to identify and incorporate their concerns;
- To identify the greatest environmental threats and rank them accordingly;
- To establish environmental priorities; and
- To develop action plans/strategies to reduce risks.[4]

Individual CRAs vary in their methodological approaches and in the extent to which they fulfill these objectives. The first (risk assessment) phase of a CRA project determines the environmental problems to be addressed, analyzes the risks they pose, and ranks the problems based on their severity. The second (risk management) phase of a CRA project transforms the risk ranking activity into a set of priorities for action by incorporating risk management factors into the overall process.

All CRAs include the risk assessment phase, while only some incorporate an explicit risk management process. The relative ranking of environmental problems developed in

[4] Feldman et al. [5], pp. 34–35.

the first stage can provide a useful guide to setting priorities (i.e., risk reduction efforts should largely be directed to the worst problems first). Some CRA project sponsors have felt that translation of these risk findings into specific environmental priorities can be accomplished effectively through traditional planning and budgeting processes and that there is no need for a separate (and perhaps competing) risk management stage in the CRA project.

Given the diversity in both the scope and methods of the different CRAs, choices must be made about the particular elements selected as the basis of any comparative analysis. In an attempt to be comprehensive while at the same time maintaining a high degree of transparency, we follow the approach used by Konisky [6] and focus on the following three particular elements.

(1) *Environmental problem list*: determination of the set of environmental problem areas to be analyzed and compared. This list typically includes a core set of common environmental pollution problems (e.g., air pollution, surface water pollution, drinking water contamination, hazardous and non-hazardous waste) defined in varying ways, as well as a set of other problems that reflect the particulars of the local area being studied and the range of concerns held by the study's sponsors (e.g., pesticides, ground-water depletion, occupational exposures to toxic substances, traffic accidents, deforestation). Although *Unfinished Business* included 31 problem areas, most CRAs look at fewer than a dozen.

(2) *Criteria for evaluating problems*: what the participants think is important to evaluate in comparing problems. Across all CRAs, risk provides the common denominator for comparing the disparate impacts of different environmental problems. Judging problems on the basis of the risks they pose captures the ultimate impacts of the environmental problems and the reasons that most people are concerned with them. Significant differences exist, though, in the sorts of risks that CRA project sponsors have addressed: health and ecological risks, risks to economic well-being, risks to quality of life generally. Even greater differences exist in the criteria that have been chosen for measuring the magnitude of these different endpoints (e.g., lives lost, numbers of cases of illnesses, area extent of ecological damage, recovery time, and monetized economic losses). Some of the criteria allow for strict quantitative estimates of harm or risk (e.g., where adequate data exist, the number of cases of an illness can be estimated through health risk assessment). Other criteria are more qualitative (e.g., aesthetic damages). Given the variation in criteria considered, the nature of the data and analysis can differ widely across CRA projects.

(3) *Ranking:* the process by which participants sort through the data and draw conclusions about the relative risk of the various problems under consideration. Typically the ranking involves comparing problems along one or more different dimensions and integrating the results into an overall evaluation. Rankings generally consist of ordered (e.g. 1–10) or categorized lists (e.g., high, medium, or low) [7].

2.1. Environmental problem list

Establishing the list of environmental problems to be considered in a CRA involves determining both the span of issues to be considered (e.g., how far beyond the traditional

air, water and waste pollution problems should the project's purview extend?) and how the project scope is to be divided into discrete problems for comparison and ranking with respect to one other. One can classify the individual environmental problems in various ways. In the domestic literature, the most common are by pollutant (e.g., particulate matter, pesticides, pathogens), by sources (e.g., motor vehicles, power plants), by pathways (e.g., air, water), or by receptors (e.g., people, forests) (Konisky [6]). In *Unfinished Business*, EPA did not use any single one of these classification schemes. Instead, the Agency defined environmental problems on the basis of the relevant statutes and the Agency's organizational structure. Despite the resulting overlap across problem areas (i.e., the same risk could potentially be addressed by several of the Agency's programs) and the lack of analytical consistency, the principal advantage of this approach is that the environmental problems areas considered by EPA were highly relevant to the Agency's political and bureaucratic milieu. With problem areas defined in this manner, the risk rankings provided findings that could be translated directly into implications for priorities across EPA's programs. It has also been suggested that isolating environmental problems as mutually exclusive elements may oversimplify the complex, interrelated causes and manifestations of many environmental issues [8]. Not surprisingly, the program/bureaucratic approach used in *Unfinished Business* was adopted (with minor modifications) in many subsequent CRAs, particularly those performed at the state and local level in the U.S. Overall, the lack of consistent definitions of environmental problem areas is important both for the problems it presents in analyzing the results of any single CRA and for making comparisons across CRAs.

2.2. Types of risk

Choices regarding which risks to include and how to group the risks are critical to the interpretation of CRAs [2]. *Unfinished Business* considered four endpoints: cancer, non-cancer health impacts, ecosystems and economic welfare. Subsequent CRAs conducted in the US and abroad have generally considered fewer endpoints. "Health" and "ecological" are the most common categories considered, although there is considerable variation among the CRAs. Several of the state and local projects conducted in the U.S. have attempted to consider all endpoints in a single category.[5] Others have considered separate endpoints initially but then combined the rankings for health, ecosystems and the quality of life into a single category [5,9].[6] The international studies have mostly focused on public health. Generally, this is because the CRA project organizers (particularly those focusing on large cities in developing countries) have felt that the most important impacts of environmental problems were those involving human health, with the impacts of pollution on ecological or economic values being of lesser concern.

[5] Examples of the single category approach are the CRAs conducted in New Hampshire and in Athens County, OH.

[6] The State of Texas Environmental Priorities Project used this approach.

2.3. Residual or inherent risk

A further element of CRAs that potentially complicates cross-study comparisons is whether residual or inherent risk is considered [6]. Residual risk refers to the current level of risk, assuming full compliance with current laws and regulations.[7] In contrast, inherent risk is that which exists in the 'no control' world, i.e., without the present control programs in place. Although it was a widely discussed issue at the time, *Unfinished Business* was based exclusively on the notion of residual risk. The focus was on prospective actions that could be taken to mitigate current risks. Most of the state and local CRAs focus on residual risk. As discussed below, all of the international analyses also focus on residual risk.

2.4. The participants in a CRA

Apart from what is being ranked, it is also important to focus on who is doing the ranking. Work by Slovic [10] and others suggest that while individuals trained in science and related fields generally employ formal risk assessment to draw conclusions about relative risk, most ordinary citizens instead rely on intuitive judgements. Thus, despite the wide bands of uncertainty surrounding most risk assessments, it is not surprising that experts and the general public tend to rank the same set of environmental problems quite differently. Relatively large differences in such rankings have been noted by various authors (Morgenstern and Sessions [11]; U.S. EPA, Science Advisory Board [3]).

The existence of large differences in public and expert risk perception highlights the normative issue of who in society should be conducting the rankings. Over time there has been increased recognition that CRA requires extensive value judgements in addition to more objective data analysis, and that public input is important in making these judgments. In the U.S., *Unfinished Business* relied exclusively on the expert judgements of government scientists and program managers. More recently, there has been increased public involvement in the process, both in the U.S. and internationally [12]. Most CRAs are now overseen by multidisciplinary working groups including technical experts and interested individuals from institutions concerned with environmental management: government agencies, universities, business, environmental groups, consulting firms, research organizations, community groups, and the general public. The increasing interest in public participation is designed to incorporate public values into the many judgments that are necessary to assess systematically the relative risks posed by the different environmental problems.

3. The international studies: comparing the methodologies

The results of international CRAs appear in published reports by USAID and other US government agencies, consulting firms, universities and the World Bank. In addition,

[7] In practice the distinction between inherent and residual risk is not so crisp. When laws or regulations designed to address particular environmental problems are not fully complied with the definition of "residual" is more problematic.

this paper presents the findings of a previously unpublished pilot CRA developed as part of a day-long workshop on CRA conducted in Taiwan in the Spring of 1998.

Table 1 lists the location, sponsor and date of each of the international CRAs completed by Spring 1999 (including the Taiwan pilot), along with a description of key methodological characteristics. Interestingly, all the identified international studies were conducted in developing countries or economies in transition. We are not aware of any CRAs conducted in OECD countries outside the U.S.[8] Perusal of Table 1, which includes comparable information from *Unfinished Business*, indicates both similarities and differences in the approaches of the international CRAs. For example, the number of problem areas considered in the international studies ranges from 3 to 16. This compares to the 31 problem areas considered in *Unfinished Business*. Like *Unfinished Business*, all the studies employed a heterogeneous classification scheme as opposed to a more homogenous one (e.g., using a single dimension — pollutant, source, pathway or receptor — to define the problems). All studies developed rankings of problems reflecting their relative health risks, while a few also developed separate rankings based on ecological risks and risks to quality of life. All the studies addressed residual as opposed to inherent risks.

The groups developing the rankings differed substantially across the projects. At one extreme, the risk rankings were developed by a small group of technical experts (generally less than 10 people), including consultants retained to conduct the project. At the other extreme, several projects developed their risk rankings through a broad participatory process involving representatives of the general public as well as scores of experts from both governmental and non-governmental organizations. A few projects involved only consultants, more involved only government officials, and most were multi-sectoral. There has been a clear trend over time in the design of CRAs toward broader participation in developing the risk rankings. Nearly all CRA risk ranking processes were informed by extensive collection and analysis of technical information.

Overall, about half the non-U.S. CRAs proceeded beyond the risk assessment phase to a risk management phase in which priorities, action plans or initiatives were developed while considering a range of management factors in addition to risk reduction. This differs from *Unfinished Business* which was strictly a risk ranking exercise.

Some of the international CRAs incorporated novel features not widely used in the U.S. studies. For example, the AID-sponsored CRA conducted in Quito, Ecuador included so-called ethnographic methods (focus groups, structured observations, and in-depth interviews) to improve the risk assessments. Researchers studied people's behaviors that affected how they were exposed to environmental pollutants (e.g., how much drinking water did they consume, how was it stored, did they boil it before use) in order to replace the typical default exposure assumptions with estimates reflecting actual

[8] Many studies in OECD countries have assessed the risks associated with environmental problems, and many have aimed to compare risks across several environmental issues. A particularly sophisticated series of studies have compared the risks associated with different energy technologies, for example [25]. However, we are not aware of any studies that meet our particular definition of CRA as including: (1) a comparative assessment of most or all of the environmental problems facing a geographic area; (2) use of risk as the metric for comparison; and (3) priority-setting as the fundamental purpose of the work.

Table 1
Method comparison of international comparative risk analysis

Study location	No. of prob. areas	Types of risk for which rankings were developed	Inherent or residual risk	Formal ranking	Project participants	Extent of data collection and analysis	Notable features of risk ranking method	Risk management activities performed
US (US EPA, 1987 [1])	31	cancer, non-cancer, ecological, welfare	residual	some ranking, some categorizing	gov't experts	extensive	each work group (one for each of the four types of risk) developed its own system of criteria and scoring to rank problems	N
Taiwan, ROC (This article)	15	cancer, non cancer, ecological, welfare	residual	some ranking, some categorizing	gov't and non gov't experts	none	experts identify and rank environmental problems based on their own expert judgment	N
Lima, Peru (Sessions et al., 1997 [13])	12	health only	residual	some ranking, some categorizing	gov't and non gov't experts, public	extensive	ranking reflects summary judgment of committee after reviewing information on incidence and severity of health effects and quality and biases in data	Y
Bangkok, Thailand (US AID, 1990 [14])	11	health only	residual	categorizing	consultants	extensive	used estimated incidence and severity index to rank problems	N
Cairo, Egypt (US AID, 1994 [15])	16	health only	residual	categorizing	consultants	extensive	ranking based on estimated incidence and severity of health effects associated with each problem	N
Quito, Ecuador (US AID, 1993 [16])	9	health only	residual	categorizing	consultants	extensive	used both quantitative risk assessment and health outcome data, performed site specific ethnographic study, performed explicit scoring of problems based on probability and severity	N
Silesia Region, Czech Republic and Poland (US EPA, 1992; 1994 [17, 18])	6	health, ecological	residual	none	gov't and non gov't experts	extensive	examined ecological as well as human health risks; used two dimensions — severity and scale — to characterize risk	Y

Central America (USAID, 1996 [19])	7	health, ecological, quality of life	residual	categorizing	mixed. Project staff did initial risk ranking; multi-sectoral committee adjusted it	extensive	different criteria and scoring systems were used for each type of risk. Identical procedures were used in each of six countries, then for region as a whole	Y
Troyan, Bulgaria (ICLEI, 1995 [20])	at least 4	health, ecological, quality of life	residual	categorizing	mixed	some	technical committee identified a list of environmental problems. rank problem based on risk analysis and public input into high, medium and low risk	Y
Zilina, Slovakia (US EPA, 1997 [21])	up to 6	health, ecological	residual	categorizing	mixed	some	work groups established for six different problems and conducted risk assessment; risk ranking is very qualitative	Y
Radom and Elk, Poland (ISC, 1997 [22])	at least 3	health, ecological	residual	categorizing	mixed	some	two cities identify environmental problems bases upon the relative risk and public opinion; ranking were based upon extensive discussion among all members	Y
Ahmedebad City, India (US AID, 1995 [23])	11	health, ecological, quality of life	residual	categorizing	gov't and non gov't experts	extensive	evaluated only aggregated human health risks; focus on residual risk from current controls to guide future action plans	Y
West Bengal (Ghosh, Bose & Associate, 1997 [24])	up to 10	health, ecological, quality of life	residual	categorizing	non gov't experts	extensive	integrated risk assessment and participatory methods based on a health and ecological impacts, and quality of life	Y

local practices. The researchers also studied and asked about people's attitudes in order to reflect local values in the risk assessment — what aspects of "severity of a health effect" matter (e.g., in the local culture, is an illness of more concern if it affects a child, a working adult, or an elderly person?); what sorts of "quality of life" risks should be evaluated?

In contrast, several CRAs sponsored by the World Bank employed economic methodologies to inform the risk ranking process.[9] Several CRAs conducted in Eastern Europe and Asia employed public opinion polling to inform both the risk assessment phase (which environmental risks are people concerned with?) and the risk management phase (what degree of public support might there be for various possible initiatives to address risks?).

3.1. The Taiwan workshop

The purpose of the Taiwan workshop was to introduce the concept of comparative risk analysis to the participants and teach them how to develop a risk ranking. The actual ranking was a byproduct of the workshop. Participants were environmental professionals, drawn equally from government, universities, consulting companies and research organizations based in Taiwan. During the first half of the workshop, general background information about risk assessment, risk management, risk ranking, *Unfinished Business*, and risk perception were introduced. The methods of comparative risk analysis as used in the United States and elsewhere were discussed. In the second half of the workshop participants were asked to identify what they believed to be the 15 most serious environmental problems in Taiwan. Participants then discussed and ranked these 15 problems based on explicit risk-related criteria. In effect, participants went through the typical steps of a CRA's risk assessment phase in a highly accelerated manner. Thus, while the Taiwan workshop was less formal and less rigorous than the CRAs reviewed here, it nonetheless contains a number of the key elements of these other studies. A more complete description of this Taiwan pilot study is presented in Appendix A.

4. International CRAs: comparing the risk ranking results

Despite the variety of methods used in the international CRAs, it is nonetheless useful to try to compare the risk rankings across the different studies. Is there uniformity across different settings in the risk rankings? Are there any environmental problems that are consistently found to be among the most serious? To make even the most

[9] Unlike CRAs, economic (benefit-cost) analyses attempt to value the importance of particular health endpoints, based on people's willingness to pay to avoid such consequences. For further discussion of the differences in methodologies see Morgenstern [26].

rudimentary attempt to answer these questions, one has to consider a number of factors, e.g., (1) the varying definitions for the environmental problems considered in the different CRAs; (2) the particular problems considered in some CRAs but not others; (3) the comparability of the methodologies and (4) the nature of the risk being considered (e.g., health, ecological, quality of life).

Unfinished Business relied on problem definitions widely in use in U.S. environmental management programs in the late 1980s. Although fewer than 31 problems were considered in the subsequent state and local CRAs conducted in the U.S., the definitions of the environmental problems used in the state and local projects were virtually identical to those used in *Unfinished Business*. The same cannot be said about CRAs conducted in other countries. Definitional differences involve both issues of aggregation and issues of organizing structure.

· *Aggregation*. Something that was considered a single environmental problem in one CRA was often split into several problems that were individually ranked in other CRAs. For example, *Unfinished Business* defined the problem of "criteria air pollutants" to include particulate matter, ozone, sulfur dioxide, nitrogen oxides, carbon monoxide, and lead. Many other projects considered one or more of these air pollutants to be separate problems, ranking them individually.

· *Organizing structure*. Projects often chose different approaches in organizing problem definitions primarily as pollutants, sources, pathways, or receptors. For example, the Central America project defined "pesticides" as a single problem, posing both human health risks by some pathways and ecological risks by others. Other projects had no explicit "pesticides" problem, but instead counted pesticides as a portion of "drinking water contamination", "food contamination", or "worker exposures".

A second issue relates to the range of the problems considered. How does one interpret the fact that in considering only six environmental problems, the Silesia CRA omitted many of the 31 problems specifically analyzed in *Unfinished Business*? In making cross-CRA comparisons, one is tempted to interpret exclusion of a problem as at least tacit acknowledgment that the omitted problem is of lesser importance than the included ones. However, it is also true that some CRA projects have defined different boundaries for "environmental problems". Are traffic hazards an environmental problem? How about occupational exposures and illnesses? How about ground-water depletion (as opposed to ground-water contamination)? One CRA project may omit such problems from study while another CRA includes them for reasons having nothing to do with risks. For example, the organizers of a CRA may be uninterested in studying a particular problem because it is not within the potential sphere of responsibility of the government agency sponsoring the CRA.

Cross-CRA comparisons are also hindered by the substantial differences in data and methodologies. For example, all the studies tend to rely on similar dose–response functions in estimating health risks for key pollutants. These dose–response functions are typically (but not always) derived from U.S. studies. Thus, the principal differences in the results of the CRAs derive from measurable differences in exposure in the different countries. If the underlying does–response function is, in fact, similar across countries then the simplicity of this approach is appropriate. If, however, the true dose–response function varies substantially across countries as a function of culture,

race, ethnicity, age distribution or other factors, then the simplifying assumption of a uniform (non-culture-specific, non-age-weighted) dose–response function would not be appropriate.

As part of their health risk assessment, most international CRAs have adopted the practice common in U.S. analyses of aggregating and then comparing the number of fatalities associated with different environmental problems. Guided by typical U.S. practice, most international CRAs did not draw distinctions among different sorts of fatalities. A statistical death of an infant from diarrhea, of a working adult from an occupational accident, or of an elderly respiratory patient from air pollution are counted as equal in developing the relative ranking of problems. Had the CRAs used other approaches that weighed these different sorts of fatalities differently (e.g., the World Bank's quality-adjusted life year approach, or a culture-specific judgment about the relative import of these different events), the risk rankings of the environmental problems might be significantly different. The consistency of the risk assessment approaches used across the international CRAs may obscure some of the variation in risk rankings that would occur if the countries had developed their own analytical methodologies.

Notwithstanding these issues, we have no real choice but to compare the basic findings across studies. Table 2 displays the health risk rankings developed by the 13 CRAs examined. Health, as opposed to ecological or quality of life, risk rankings were chosen because that was the only category that was uniformly considered in the 13 studies. To present the maximum information, the rankings are disaggregated by the 31 *Unfinished Business* categories [only 27 are shown] plus 14 others considered in the international studies but not explicitly examined in *Unfinished Business*. In some cases, the results have been transformed to make them compatible with this reporting format. For example, both *Unfinished Business* and the Taiwan pilot developed separate rankings for cancer and non-cancer health risks. To combine them into a single ranking of high, medium or low health risk we chose the most risky individual category as the overall risk category. Thus, gas stations, which were ranked as high in terms of cancer risk in Taiwan but medium for non-cancer risks, were given an overall ranking of high.

Several observations emerge after reviewing the risk rankings developed by the following diverse CRAs.

(1) The most robust finding is that criteria air pollutants consistently rank as high health risks across all 13 CRAs. Given the diverse nature of the settings studied in the CRAs, including level of economic development, urban–rural differences and climate, this finding is particularly important. At the same time, some differences in findings are apparent with regard to specific air pollutants. Particulate matter and lead are found to pose high risks in virtually all settings. The ranking for sulfur dioxide is much more variable, tending to be high in areas where high sulfur coal is used extensively in cities (Eastern Europe) and much lower in areas where the there is little urban coal use and the predominant fuels have lower sulfur content (Bangkok, Cairo, Lima).

(2) Drinking water appears to be ranked as a high or medium health risk in almost all the countries studied. On close examination, though, the reasons for this ranking differ significantly across studies. The high health risk ranking in the U.S. and several Eastern European communities reflects a judgment about the magnitude of the health effects that

result from contaminants found in drinking water. Several other CRAs (Lima, West Bengal) expressed very different concerns about the limited and erratic supply of drinking water available to much of the population, resulting in an inability to follow basic sanitary practices (e.g., bathing, washing food, hand-washing). Interestingly, a number of the projects found that the level of contaminants in publicly supplied drinking water, for those residents fortunate enough to have it, was *not* sufficiently high to pose relatively high health risks.

(3) Problems involving toxic chemicals, e.g., hazardous air pollutants, pesticides, accidental toxic releases, radon and radiation in general tend to rank as higher health risks in the U.S. than in the other countries, although dioxin and gasoline station emissions are ranked as high health risks in Taiwan. At the same time, several problems involving pathogens are recognized as significant problems only in developing country settings. This likely reflects the so-called "risk transition" — the shift from sanitation and infectious disease problems to problems involving industry, vehicles, consumers and toxic substances — that often occurs with economic development (Smith [27]). Alternatively, it may simply reflect the greater availability of information on sources of toxic pollutants in the U.S.

(4) The pollution of surface water (as opposed to drinking water) is generally ranked as a medium or low health risk in all the countries studied. Exposure to contaminated surface water (through eating fish and shellfish, swimming and other water contact activities) was judged to be limited. Surface water used as a source of drinking water was often felt to be contaminated, but for all locations studied the drinking water treatment processes were thought to be acceptable and the treated water, at least as it left the plant, was of reasonable quality. Two projects (Lima and Central America) ranked sewage as causing high health risks. However, this was because of direct exposure to sewage before it reaches waterways and not because of impacts after sewage has contaminated surface waters. If separate rankings were performed for ecological risks, as they were in *Unfinished Business*, pollution of surface water would undoubtedly be of greater concern.

(5) Hazardous and (industrial) non-hazardous waste issues ranked as medium or low health risks in all the countries studied, except for Taiwan where unmanaged toxic waste sites were considered to pose high risks. This is consistent with the notion that few people are directly exposed to hazardous and (industrial) non-hazardous waste. It is not entirely surprising that views might be different in Taiwan, where geographic space is an important issue and population density is so great.

(6) Household waste, including sites containing household waste, was not consistently ranked in the different CRAs. An equal number of studies ranked it low as ranked it high risk. None of the projects performed formal quantitative health risk assessments for this problem area. The risk rankings given to this problem seemed ultimately to depend on whether the rankers were more impressed by the potential for widespread exposure to garbage or, conversely, by the low concentration of toxic or pathogenic materials in garbage and the attenuated nature of any exposure to garbage through ingestion, inhalation or direct contact. Several CRAs that ranked household waste as posing low or medium health risks nevertheless mentioned the high risks that it may pose to relatively small populations of dump scavengers or recyclers.

Table 2
Health risk ranking comparison

No.	Problem area	UB	Taiwan	Bangkok/ Thailand	Quito/ Ecuador	Lima/ Peru	Cairo/ Egypt	Silesia	Ahmedebd City, India	Central America	Troyan Bulgaria	Zilina Solvakia	Radom and Elk, Poland	West Bengal
U1	Criteria air pollutants	H	H (dust) H (auto tailpipe)	H(PM) H(lead) M(CO) L(other criteria p.)	H	M	H (PM) H (lead) M (ozone) M/L (CO) M/L (SO_2)	H	H	H	H	H	H	H
U2	Hazardous air pollutants	H	H (dioxin) H (gas station)	L			L							
U3	Other air pollutants	H												
U4	Radon (indoor)	H												
U5	Other indoor air pollutants	H	M		M	L	M/L		H					
U6	Radiation	M												
U7	Ozone depletion substance	H												
U8	Direct point source discharges	L	M (industrial wastewater) H (heavy metals)		M									
U9	Indirect point source discharges	M												
U10	Nonpoint source discharges	M												
U11	Contaminated sludge	L												
U12	Estuaries and coastal waters	M												
U13	Wetlands	L												
U14	Drinking water	H	H (drinking water)	L(surface water contamination)	M	H (limited, erratic water supply)	M/L (cont by chem) M/L (cont by microbes)	L	H	M	H	H		H (water supply)
U15	Active hazardous waste sites	L	H (toxic Substance)	L		L (toxic substance)	M/L (hazardous waste)							
U16	Inactive hazardous waste sites	L												
U17	Non-hazardous waste sites, municipal	M	M (solid waste)	L	L(solid waste)	H	M/L (solid waste)	L		H		M/L		

U18	Non-hazardous waste sites, industrial	M												
U19	Mining waste	L												
U20	Accidental toxic releases	H												
U21	Accidental oil spills	UR												
U22	Storage tank releases	L												
U23	Other groundwater contamination	NR	M (GW)	L(GW)		M						M/L	H (depletion)	H (depletion)
U24	Pesticide residues on foods	H	H (pesticides)	L	L	M				H				
U25	Application of pesticides	H												
U26	Other pesticides risks	M												
U27	New toxics chemicals	NR												
I1	Odor		M											
I2	Noise		M											
I3	Endangered species		L											
I4	Microbiological disease			H			H							
I5	Sea contamination					M								
I6	Loss of agr and green land					L								
I7	Food contamination: microorganism				H									
I8	Traffic hazards				M				L					
I9	Food contamination (general)			L		M		M	L					
I10	Occupational disease							H	L					
I11	Nickel											M		
I12	Sewage					H				H				
I13	Surface water contamination			L		M	L							
I14	Soil contamination											L		

(7) Storage tanks, mining wastes, accidental releases and oil spills were generally judged to pose relatively low risks to human health in all countries. This should not be terribly surprising as few people come into contact with these potential environmental problems.

(8) Pesticides on foods are believed to pose a high health risk in the US, Taiwan and Central America. In the other countries they are believed to pose lower risks. Interestingly, the CRAs in Quito, Bangkok, and Cairo ranked microorganisms on foods as high risks to health, but not pesticides. These results may reflect genuine differences in the various countries. Alternatively, they may be an artifact of differences in the scientific understanding of the various risks.

5. Conclusions

While some may view CRA as a tyranny of the experts, it can instead be seen as a framework for making progress in setting environmental priorities that fairly and realistically recognizes the importance of both science and values. The fact that more than 100 CRAs have been conducted over the past decade — more than a dozen of them outside the U.S. — reflects the widespread acceptance of two major premises: (1) that objective risks should be a major factor in determining environmental priorities; and (2) that available data and expert judgement provide a useful source of such information. Yet even these modest conclusions need to be qualified by the following limited comparisons we were able to make across the international studies and the vast differences in the underlying studies themselves.

(1) Unlike *Unfinished Business*, we have compared the rank of problem areas with respect to human health risks only. A focus on ecological or quality of life risks — which was not possible because so few studies considered these different dimensions — would likely lead to different outcomes.

(2) The CRA methodology itself imposes certain basic limitations. CRA tends to emphasize aggregate risks that affect entire populations, and high individual risks to sub-populations are often ignored. Thus, the finding that conventional air pollution and drinking water are consistently ranked as serious sources of health risks in locations around the world should not come as a great surprise, since we all breathe the air and drink the water.

(3) The rankings of the individual CRAs were intended to reflect the health risks that will result from the current level of the various environmental problems. As further economic development occurs and environmental management programs become more sophisticated, the nature of the problems will likely evolve and the relative risk rankings may change over time. The fact that the various studies were conducted over a period of a decade means that our cross-CRA comparisons do not represent a simultaneous, snapshot comparison of the countries studied.

(4) The CRA rankings examined in this paper represent *risk* rather than *priority* rankings. Although a number of the underlying CRAs did include risk management factors and did develop some form of priority ranking, these are not the focus of our cross-CRA comparisons. Thus the rankings considered here do not necessarily match the

rankings that *should* be given to environmental programs once cost, technical feasibility and other factors are considered. In fact, one might find particularly cost-effective opportunities to reduce risks associated with a low risk problem while there is little or nothing that can be done about a higher risk problem.

Finally, there is the nagging question of whether the observed similarities (and differences) in the results of the CRAs reflect genuine patterns of risks across the countries studied or are simply an artifact of the methods used. Certainly the simplicity of the comparisons and the uniformity of many of the assumptions used in CRAs (e.g., the use of dose–response functions derived largely from U.S. experience) gives us pause. It would be interesting to see whether entirely different methods for judging the relative seriousness of different environmental problems (e.g., World Bank Environmental Action Plans, OECD Environmental Performance Reviews) would show a similar picture. Corroboration by other methods would certainly strengthen our confidence in the conclusion that the observed similarities and the observed differences in the results of the international CRAs are genuine. Even without this corroboration, though, the pattern of relative environmental risks found by looking across CRAs seems plausible and meets at least a soft test of internal consistency.

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Appendix 1. Taiwan Pilot Study

This appendix provides additional information on the Taiwan Pilot Study. We first describe the survey method, sample characteristics and definitions of environmental problems used in the study. We then discuss the methods and results of the risk rankings performed for the identified problems.

At the outset it should be stated that the methodology used in this pilot study is not as rigorous as those in the published CRAs. Both data and analysis are quite limited. Unlike the published CRAs, this project included only technical experts as "rankers" of the various environmental problems, rather than the more disciplinarily and occupationally diverse groups used by other CRAs. For example, members of the general public and/or interest groups — who are thought to bring public values into the decision-making process — were not included. Thus, this pilot study should probably be considered as a study in expert risk perception rather than as a strict comparative risk analysis.

A.1. Survey method and sample characteristics

The participants in the study were environmental professionals from government, universities, consulting companies and research organizations working in Taiwan who

participated in a day long workshop in the Spring of 1998. During the first half of the workshop, general background information about *Unfinished Business*, risk perception, risk ranking, risk assessment and risk management was introduced. The methodology of comparative risk analysis as used in the United States and how this analysis has been used to set priorities for environmental protection was also discussed. In the second half of the workshop, participants were asked to identify what they viewed as the 15 most serious environmental problems in the country.

The total number of available questionnaires for analysis is 24 (out of 26). Table A1 presents a breakdown of survey respondents by sector. Overall, the participants were almost evenly distributed among government, industry and research communities.

Table A2 lists the 15 environmental problems identified by the workshop participants. Problems not on the list may still be important, but they were not brought up by the participants.

A.2. Criteria for evaluating problems

Quantitative risk assessment usually involves considerable effort to develop information and inform participants on pollutant generation and concentration, exposure path and dose–response relationships. Such assessments can be conducted on some of the identified issues for some endpoints. For others, only qualitative analysis is feasible. Because the risk assessment process is time consuming it was not possible to conduct rigorous assessments in the context of a single workshop. The workshop was primarily designed to introduce the concept of CRA. Given the (expert) backgrounds of the participants, it was assumed they were knowledgeable about the different types of risks posed by the identified environmental problems. Thus, the risk ranking was conducted without explicitly considering the type of technical information typically involved in CRAs.

A.3. Risk Ranking

Commonly used approaches for ranking include: (1) categorization, (2) negotiation or voting, (3) assigning scores based on specific criteria, (4) weighted scoring and (5) formal decision theory approaches, such as analytical hierarchy procedure or multi-attribute utility theory. In this study, we assigned scores based on specific types of risks.

Table A1
Sample characteristics

Organization	Male	Female	Total
Government	5	3	8
Industry	7	0	7
Research institute	2	1	3
University	3	0	3
Unknown	1	2	3
Total	18	6	24

Table A2
Identified environmental problems

No.	Environmental problem	No.	Environmental problem
1	Auto tailpipe emission	9	Indoor PM
2	Dioxin	10	Industrial wastewater
3	Contaminated drinking water	11	Noise
4	Dust	12	Odor
5	Endangered species	13	Pesticide residues
6	Emissions from gas station	14	Solid waste
7	Contaminated groundwater	15	Toxic substance
8	Heavy metals		

Auto tailpipe emission: include hot exhaust, smoke, NO_x, VOC and CO.
Dioxin: potential carcinogen from municipal incinerators, coal-fired power plants.
Contaminated drinking water: water supply contaminated by, especially, non-point source pollution.
Dust: construction debris, interim construction, soil erosion and windblown.
Endangered species: species of fish, wildlife, and plants have been so depleted in numbers that they are in danger of or threatened with extinction.
Emissions from gas station: emissions from gas pumping station.
Contaminated groundwater: groundwater depletion and groundwater contamination at, such as landfill sites, industrial facilities and so on.
Heavy metals: as a result of industrial wastewater discharge.
Industrial wastewater: from family own medium or small business, is general not connected to specific industrial wastewater treatment plant.
Indoor PM: indoor particulate matters.
Noise: from road traffic, jet planes, garbage trucks, construction equipment and manufacturing processes.
Odor: emission from municipal and industrial facilities, such as wastewater treatment plant, landfill site and petroleum refinery plant.
Pesticide residues: pesticide residues on agricultural products.
Solid waste: landfill site and solid waste disposal become one of the most emerging and political issue in the country.
Toxic substances: toxic chemical substances produced or derived from various production and disposal processes.

Participants were asked to rank environmental problems, identified in the previous section, according to the *Unfinished Business* categories of cancer, non-cancer, ecological and welfare (quality of life) risk, using a scale of 1 to 10: 1 represents the most risk; 10 the least.

Table A3 summarizes the average value of risk ranking for the four different types of risks considered in *Unfinished Business*. In contrast, the international comparisons discussed in the text of this paper address human health risks only. To make the (health) risk results of the Taiwan workshop comparable to the international studies, we categorize the numerical ranking results from the workshop as high (H) if the mean value is between 1 and 4, medium (M) if the mean value is between 4 and 7, and low (L) if the mean value is between 7 and 10.

Because most international studies do not distinguish between cancer and non-cancer risk but aggregate them as a single health risk, we derived a single health risk ranking by combining ranking results from cancer and non-cancer risks. To aggregate cancer and non-cancer risk into a single health risk ranking of High, Medium or Low, we chose the

Table A3
Risk ranking for different types of risk

Problem	Cancer		Non-cancer		Ecological		Welfare		Health
Toxic substances	1.71	H	2.22	H	2.54	H	4.00	H	H
Dioxin	1.96	H	3.83	H	4.29	M	4.13	M	H
Pesticide residues	2.63	H	3.67	H	3.21	H	4.65	M	H
Emissions from gas station	3.25	H	4.04	M	6.87	M	4.27	M	H
Heavy metal	3.38	H	3.54	H	3.57	H	4.96	M	H
Auto tailpipe emission	3.58	H	2.96	H	4.27	M	3.32	H	H
Contaminated drinking water	4.25	M	3.13	H	5.09	M	4.58	M	H
Industrial wastewater	4.48	M	3.68	H	3.35	H	4.75	M	H
Solid waste	5.30	M	4.09	M	3.58	H	3.58	H	M
Contaminated groundwater	5.65	M	4.91	M	4.27	M	5.17	M	M
Dust	5.83	M	3.71	H	5.42	M	3.54	H	H
Indoor PM	6.08	M	4.54	M	7.71	M	5.63	M	M
Odor	6.23	M	4.17	M	6.04	M	4.08	M	M
Noise	8.23	L	5.13	M	6.04	M	4.43	M	M
Endangered species	9.45	L	8.23	L	3.04	H	5.59	M	L

most risky category for cancer and non-cancer as the ranking for health risk. For example, although emissions from gas station were considered a high cancer but medium non-cancer risk we classified it has high (H) health risk. Based on this decision rule, we obtain the health risk ranking for 15 environmental problems listed in the last column of Table A3. Nine out of the fifteen identified environmental problems are ranked as high health risk (toxic substance, dioxin, pesticide residues, emissions from gas stations, auto tailpipe, contaminated drinking water, industrial wastewater, heavy metal and dust). Five of them ranked as medium risk (solid waste, contaminated groundwater, indoor PM, odor and noise). One ranked as low health risk (endangered species).

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