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Risk Assessment and Life-Cycle Impact Assessment (LCIA) for Human Health Cancerous and Noncancerous Emissions: Integrated and Complementary with Consistency within the USEPA

Jane C. Bare
U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, Ohio, USA

ABSTRACT

The historical parallels, complementary roles, and potential for integration of human health risk assessment (RA) and Life-Cycle Impact Assessment (LCIA) are explored. Previous authors have considered the comparison of LCA and risk assessment recognizing the inherent differences in LCA and risk assessment (*e.g.*, LCA's focus on the functional unit, and the differences in perspective of LCA and risk assessment), and also the commonalities (*e.g.*, the basis for the modeling). Until this time, however, no one has proposed a coordinated approach for conducting LCA and risk assessment using models consistent with the U.S. Environmental Protection Agency's (USEPA's) handbooks, policies, and guidelines. The current status of LCIA methodology development can be compared to the early days of human health RA when practitioners were overwhelmed with the model choices, assumptions, lack of data, and poor data quality. Although methodology developers can build on the shoulders of the giant, LCIA requires more innovation to deal with more impact categories, more life-cycle stages, and less data for a greater number of stressors. For certain impact categories, LCIA can use many of the guidelines, methodologies, and default parameters that have been developed for human health RA, in conjunction with sensitivity and uncertainty analysis to determine the level of detail necessary for various applications. LCIA can then identify "hot spots" that require the additional detail and level of certainty provided by RA. A comparison of the USEPA's Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) and the USEPA's Risk-Screening Environmental Indicators (RSEI) will be explored.

Key Words: LCA, Life-Cycle Assessment, LCIA, life-cycle impact assessment, risk assessment, environmental tools.

Address correspondence to Jane C. Bare, Systems Analysis Branch, Sustainable Technology Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, 26 W. MLK Dr., Cincinnati, OH 45268, USA. E-mail: bare.jane@epa.gov

INTRODUCTION

Today's environmental decision-makers have many different roles and perspectives. Government environmental agencies, such as the U.S. Environmental Protection Agency (USEPA), may be faced with decisions concerning regulation of the emissions and eporting of individual chemicals, the cleanup of a hazardous waste site, the publication of guidance about community risks based on chemical concentrations, and even providing guidance to assist in environmentally preferable purchasing. Industry may conduct environmental assessments to analyze their vulnerabilities in terms of environmental costs, upcoming regulations, reporting requirements, or to support environmentally sustainable decisions that can be further communicated to their consumers, stockholders, and local communities. Even an unaffiliated citizen may be involved in local emergency planning for the community, may monitor air quality status to ascertain their optimal level of outdoor exercise, and may choose to invest or purchase more environmentally friendly products. Each of these environmental decisions requires tools to assist in communicating the potential human health (and environmental health) impacts, yet these tools need to be carefully selected and structured to ensure that proper information is developed to support the decision at hand. The roles and potential for integration of human health risk assessment (RA) and Life-Cycle Impact Assessment (LCIA) will be explored with the intention that the reader should better understand the strengths, weaknesses, and perspectives of each. The complementary roles of both tools will be emphasized to show a more balanced perspective.

HUMAN HEALTH RISK ASSESSMENT—HISTORY AND BACKGROUND

The USEPA first published a set of risk assessment guidelines (including carcinogen guidelines) in 1986 (USEPA 1986). These guidelines provided uniform procedures for scientists to conduct RA on a consistent basis. Revision of these guidelines began shortly after the original publication. In 1996 the Agency made available for public comment "Proposed Guidelines for Carcinogen Risk Assessment" (USEPA 1996). These Guidelines received three Science Advisory Board reviews and public review and comment. In 2001 another draft of the Guidelines were made available for public comment (USEPA 1999) and again on March 3, 2003, the most recent version of guidelines for carcinogen risk assessment was made available (USEPA 2003a). In each of these documents the USEPA's focus has been on providing guidance that will be protective of public health and scientifically sound. During the most recent comment period, the USEPA asked especially for comments in the following areas: "1) the use of default options, 2) hazard descriptors, 3) mode of action, 4) extrapolation to lower doses, and 5) susceptible populations and lifestages." When the most recent guidelines were released, an external review draft Supplemental Guidance was also released to allow a more specific RA for exposure to potential carcinogens at a young age (USEPA 2003b).

The USEPA's Citizen's Guide to Risk Assessment lists RA as one tool useful within risk management (USEPA 1991). Using the 4-step process listed in Figure 1, this publication notes that RA allows estimates of "increased risk of health problems in people who are exposed to different amounts of toxic substances" using animal

Figure 1. The 4 step Risk Assessment Process. (Taken from EPA 450/3-90-024).

and human health data together with estimates of exposure levels experienced by people at various distances from the release location. The document admits that the assessments are "far from perfect," but acknowledges that the risk estimates are useful for regulatory standard setting (USEPA 1991).

Even though Risk Assessment Guidelines (RAGs) have been available since 1986, the USEPA continues to point out that this is a science that is still in a state of development (USEPA 1986). The 2003 Draft Final RAGs state:

> ". . . . EPA believes that the guidelines represent a sound and up-to-date approach to cancer risk assessment, and the guidelines enhance the application of the best available science in EPA's risk assessments. However, EPA cancer risk assessments may be conducted differently than envisioned in the guidelines for many reasons, including (but not limited to) new information, new scientific understanding, or new science policy judgment. The science of risk assessment continues to develop rapidly, and specific components of the guidelines may become outdated or may otherwise require modification in individual settings. Use of the guidelines in future risk assessments will be based on decisions by EPA that approaches are suitable and appropriate in the context of those particular risk assessments. These judgments will be tested through peer review and risk assessments will be modified to use different approaches if appropriate." (USEPA 2003a).

Generally, these decisions strive to be "scientifically defensible, consistent with the agency's statutory mission, and responsive to the needs of decision-makers. . . " (p. 86). (NRC 1994). "Consistency with the Agency's statutory mission would consider whether the risk assessment overall supports the USEPA's mission to protect human health and safeguard the natural environment. Responsiveness to the needs of decision makers would take into account pragmatic considerations such as the nature of the decision; the required depth of analysis; the utility, time, and cost of

generating new scientific data; and the time, personnel, and resources allotted to the risk assessment" (USEPA 2003a).

LCIA—HISTORY AND BACKGROUND

Life-Cycle Assessment (LCA) allows the decision-maker environmental information about a product or service. It is holistic in perspective—including a variety of life-cycle stages, locations, stressors, and potential impacts. International Organization for Standardization (ISO) 14040 recognizes four phases to an LCA: (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation (ISO 14040 1997). The phases of LCA are shown in Figure 2. Within LCA, the goal and scope definition allow ample time for the determination of the functional unit basis for comparison among the alternatives, the level of comprehensiveness and sophistication (Bare *et al.* 1999), and the modeling level (Bare *et al.* 2000) recommended for the particular application. The inventory includes the emissions to the air, water, and soil, as well as the raw materials used within each life-cycle stage included within the study. Inventory results are all scaled to the functional unit basis. The impact assessment phase allows an aggregation of effects that are similar providing greater understandability of the potential for impacts within each impact category. Finally, the interpretation phase allows a complete review of the results in the other phases including the level of uncertainty, sophistication, and comprehensiveness of the data and models used. ISO guidance is available for LCA, Life-Cycle Inventory (LCI), and LCIA in ISO 14040, 14041, 14042, and 14043, respectively (ISO 14040 1997; ISO 14041 1998; ISO 14042 2000; ISO 14043 2000).

Rather than being a linear process, LCA is seen as an iterative process, sometimes even incorporating information from other studies to provide additional information that leads to more focused and accurate information that can be used to support a decision. Additional iterations may provide more accurate inventory or

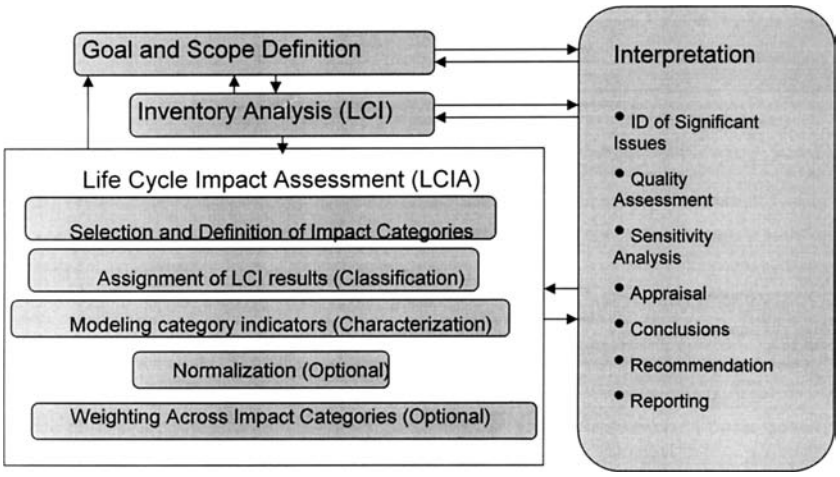

Figure 2. LCA framework adapted from ISO 14040 series (ISO 14040 1997).

impact assessment data about places, processes, and stressors that appear significant, or may allow sensitivity analysis on specific elements within an LCA.

Although precursors of LCA had been around since the 1960s, the first official SETAC meeting concerning LCA was held in Smugglers Notch, Vermont in August 1990. This meeting resulted in a SETAC document: *A Technical Framework for LCA* (Fava *et al.* 1991). The 1991 document was followed by a Code of Practice published in 1993, and *A Conceptual Framework for Life-Cycle Impact Assessment*, also published in 1993 (Consoli *et al.* 1993; Fava *et al.* 1993). More prescriptive guidance was given within the SETAC-Europe document *Towards a Methodology for Life Cycle Impact Assessment*, (Udo de Haes 1996), but in 1998, the North American working group from SETAC was very clear about what they saw as the limitations of LCA and cautioned against overselling the scientific basis of LCA and minimizing the poor data quality and availability and values incorporated within LCA. "Life-cycle impact assessment indicators are approximations and simplifications of aggregated loadings and resources used. Thus, in LCIA actual impacts are not measured, potential impacts are not predicted, risks are not estimated, and there is no direct linkage to actual impacts" (p. 7). It also recognized that LCA should not be considered in isolation. "Sound decisions often require information generated using different techniques. Depending upon the question at hand and the application, LCA may provide some of the information. Additionally, many decisions may benefit from a combination of both relative and absolute approaches. The relative LCA approach can be seen to identify and frame possible system issues and trade-offs, where other absolute techniques analyze the details of possible issues raised by LCA" (pp. 7–8) (Barnthouse *et al.* 1998). More recently, *LCIA: Striving Towards Best Practice* (Udo de Haes *et al.* 2002), provided a review of the practice and made recommendations for many of the common impact categories. Near the end of the working group discussions, additional debate focused on what elements, and categories of elements, should be protected (*i.e.*, Areas of Protection) (Udo de Haes 2001; Udo de Haes and Lindeijer 2002).

The limitations of LCIA have been cited by many authors and will not be repeated in detail here, but will be simply listed (Owens 1997; Barnthouse *et al.* 1998; Bare *et al.* 1999; Hertwich *et al.* 1999; Bare *et al.* 2000; Hofstetter *et al.* 2002; Bare *et al.* 2003). These limitations can differ widely depending on the particular model that is being analyzed, but some of the common complaints include the following:

- There is no consensus on what should be included within LCIA, the treatment of impact categories (*e.g.*, human health), or the stressors that should be included within an LCIA.
- LCIA may not consider the temporal and spatial detail necessary to conduct scientifically defensible analyses (*e.g.*, background concentrations, thresholds, stack heights, emission release timing). Although global impacts on a longer term scale (*e.g.*, global warming potentials and stratospheric ozone potentials) are easier to characterize with less spatial and temporal detail (and thus are much easier to reach global consensus), categories that require additional temporal and spatial detail (*e.g.*, smog formation) often must be specially developed with the spatial and temporal details necessary for the region and situation.

- For some impact categories (*e.g.*, human health) it is difficult to include issues of severity and/or potency (*e.g.*, metals) in a manner that is consistent for all stressors within the impact category.
- Uncertainty is not completely characterized. Uncertainties relate to data uncertainties, and the ability of the model to accurately represent the impacts that are being modeled.
- It can be difficult to understand impact assessment results (*e.g.*, results may be expressed compared to a reference chemical).
- Allocation based on a functional unit is dependent on the terms of reference, allocation method, and functional unit chosen.
- For aggregation of impacts and/or impact categories, weighting that will include values will be involved.

Although these limitations are applicable to some models, they are not necessarily applicable to all LCIA models available. When selecting a model, it is important to understand how each of the above limitations are addressed and/or recognized. Within this article, the various models will not be explored; one model will simply be chosen and analyzed.

COMPARISON OF LCIA HUMAN HEALTH AND HUMAN HEALTH RISK ASSESSMENT

The focus of this article will be on the comparison of a specific LCIA tool (*i.e.*, TRACI) to a specific risk assessment tool (*i.e.*, RSEI) (Bare *et al.* 2003; USEPA 2004). Previous authors have considered the comparison of LCA and risk assessment recognizing the inherent differences in LCA and risk assessment, for example, LCA's focus on the functional unit, and the differences in perspective of LCA and risk assessment (Hofstetter *et al.* 2002; Olsen *et al.* 2001; Wegener *et al.* 2001), and also the commonalities (*e.g.*, the basis for the modeling). Until this time, however, no one has proposed a coordinated approach for conducting LCA and risk assessment using models consistent with the USEPA's handbooks, policies, and guidelines (USEPA 1989, 1999, 2003a). Prior to this more detailed discussion a simpler list comparing LCIA (in general) with RA (in general) will be presented.

- In general, LCIA is more comprehensive in covering a larger number of impacts than RA. Although an LCIA can be set up to include just about any impact, it is not unusual for LCIA to include: stratospheric ozone protection, smog formation, acidification, eutrophication, human health, ecotoxicity, radiation, fossil fuel depletion, land use, and water use. In principle, LCIA could also include categories such as noise, human fatalities due to accidents, indoor air pollution, and many other issues.
- In general, LCIA is more comprehensive in covering a larger number of stressors, and locations than RA. This fact will affect the manner in which LCIA is conducted in many ways, including the level of spatial and temporal detail that is included within the modeling. For example, whereas a RA may provide detailed groundwater modeling that includes all of the local characteristics (*e.g.*, soil and rock type, flow patterns, local meteorology), LCIA generally does

not have this level of spatial detail available, especially because many locations and even transportation pathways are being represented. This lack of modeling sophistication is one of the many reasons why LCIA is said to characterize the potential for impacts and is not expected to actually characterize the risks themselves.

- LCIA's more comprehensive coverage of stressors, locations, and impacts generally results in a decreased ability to address impacts with a high level of certainty. Additionally inventory data are often of varying quality. Many practitioners do not conduct uncertainty analyses.

From this list it is obvious that human health risk assessment is just one, two, or three of the impact categories in a LCIA that may contain anywhere from 6 or more impact categories, however this article will focus on the difference between human health risk assessment and the subset category (or categories) of LCIA that relate to human health. Although previous papers have included indirect risks, risks due to changes in disposable income, and other risks related to the many changes in the system (Hofstetter *et al.* 2002), this article will only focus on human health risks as predicted by direct impacts related to releases to chemicals that are known, or suspected, to cause human health effects.

LCA can be used in conjunction with other environmental tools, such as RA, because together they provide important perspectives on environmental issues, and all of this analytical information should be considered within the context of a complex decision. For this reason, LCA is simply one more supporting piece of information that may be considered within the context of a complex decision.

The role of human health RA is to protect the local population while not exceeding a certain level of acceptable protective risk, whereas the role of LCIA is to compare two or more options to determine which is more environmentally friendly, and from where the primary sources of potential impact are projected. Based on these perspectives, RA may be structured in a manner that is overly protective of the local populations using assumptions that err on the side of higher dosages calculated, whereas LCIA may try to represent more of the average impact on society. Given these differing perspectives, it is easy to see why both tools are valuable to see the complete environmental picture. Without RA, LCIA cannot assure that all locations of release will be appropriately protective of the local populations. Without LCIA, a decision-maker may choose an option that may look better for the local populations, but may negatively impact other locations and/or other populations.

On a related point, RA often takes background concentrations into account and thus can give absolute risk calculations. Given the broad perspective of LCIA, the background concentrations for specific sites cannot generally be incorporated into the LCIA, but LCIA can provide a bigger view of the emissions occurring over the full life cycle. Instead, because LCIA often does not have a site-specific location for emissions, LCIA may rely on default values for landscape, and meteorology. One analysis showed that these parameters are not a significant source of uncertainty when compared to the uncertainty incorporated into the analysis based on the poor data quality of the chemical, physical, and toxicity data for a large set of chemicals (Hertwich *et al.* 1999). However the very site-specific air dispersion models and

groundwater models can simulate the fate and transport of emissions in a more sophisticated manner.

For these reasons, the results of a human health LCIA may point to specific areas and chemicals that require additional analysis (*e.g.*, more detailed RA), but because LCA has a broader perspective of looking at the full life cycle of the products or services to be compared, LCIA should not be solely relied on as the only method to identify hotspots. As an example, in a recent USEPA study of three alternatives fuels including the following additives: methyl tert-butyl ether (MTBE), ethanol, and a non-oxy additive, it was expected that the LCIA would show the localized underground storage tank spills to be the single largest source of human health impacts (Abraham *et al.* 2004). Even though those conducting the study were well aware of the issue and intentionally modified the LCA to include underground storage tank leaks at a high rate of emission, this location and source was never identified as a problem showing 2% or more of the total contribution to human health. Upon further inspection the reason appeared to be multi-faceted: (1) MTBE leaks presented themselves as a significant environmental issue precisely because there were localized issues. Longer range and more persistent contaminants such as mercury may actually be considered more damaging in the long run, but seldom are they as easy to pinpoint and trace back to the original source of emission. In general, the LCA perspective is usually more comprehensive in impact categories and stressor coverage, but includes less spatial and temporal detail in the impact assessment modeling. LCA is best at addressing issues that are larger in perspective (*e.g.*, global and regional issues) and not at predicting very site-specific localized effects; (2) The MTBE leakage issue did not surface as an issue of high environmental concern within this LCA because this LCA was not set up to address issues of taste and odor. Leaking underground storage tanks were initially flagged as being an environmental concern because of the taste and odor that impacted the local drinking water. Human health impacts of MTBE linked to drinking water would have been difficult to discover and attribute to the source without the foul taste and odor that was present to provide the initial concern for human health consequences.

Previous authors have considered the comparison of LCA and risk assessment (Cowell *et al.* 2002; Olsen *et al.* 2001; Hofstetter *et al.* 2002; Wegener Sleeswijk and Heijungs 2001; Owens 1997). Although each recognized the inherent differences in LCA and risk assessment (*e.g.*, LCA's focus on the functional unit, and the differences in perspective of LCA and risk assessment), they also recognized the commonalities (*e.g.*, the basis for the modeling). One of the authors (Owens 1997) was critical of LCIA in its attempt to provide accurate results while ignoring the temporal and spatial details that are more typically included within risk assessment. None of the authors proposed a coordinated approach for conducting LCA and risk assessment using models consistent with the USEPA's handbooks, policies, and guidelines.

The comparisons between the human health characterization within LCIA and human health risk assessment are many; however, because no universal or internationally agreed-on models exist for either of these analyses, the models and guidance released by the USEPA for RA–RSEI and LCIA–TRACI were primarily considered for the comparison within Table 1. These two models were selected based on their consistency with the USEPA handbooks, policies, and guidelines and the data available

Table 1. Comparison of characteristics of LCIA human health assessment and RA for human health (using TRACI and RSEI as guidelines for comparison).

Characteristic	LCIA Human Health	RA Human Health
Model development	Has taken years to develop the models and assumptions, but was able to utilize many of the input parameters from RA. Is considered to be "still developing."	Has taken years to develop the models and assumptions upon which to base the calculations. Is considered to be "still developing."
Inclusion of human health impacts	Includes carcinogens, noncarcinogens, and criteria contaminants. Here criteria contaminants are only those that are called out in USEPA regulation and do not include overlaps with the carcinogen and noncarcinogen categories.	Includes carcinogens, noncarcinogens, and criteria contaminants.
Development of the structure of the study	Recognizes that the structure of the study may depend on the decision at hand and other details that may be specific to the location and nature of the releases and/or site.	Although more narrow in focus, recognizes that the structure of the study may depend on the decision at hand and other details that may be specific to the location and nature of the releases and/or site.
Inclusion of emissions, fate, transport, and toxicity	Incorporates the emissions, fate, transport, and toxicity of the chemicals being released. For TRACI, underlying models for cancer and noncancer are multimedia models followed by human exposure pathways. Criteria contaminants also make more extensive use of the epidemiological data available and more individualized fate and transport modeling.	Incorporates the emissions (or background concentrations), fate, transport, and toxicity of the chemicals being released. Underlying models for cancer and noncancer are more site-specific Gaussian air dispersion models and ground water models followed by human exposure pathways.
Data quality issues	Recognizes the absence and/or poor data quality of chemical, physical, and toxicological data to support the wide range and number of stressors involved.	
Recognition of complementary role	Recognizes that other tools can provide additional information that may assist in the decision.	
Comprehensiveness of impacts	Includes extensive list of environmental impacts (*e.g.*, global warming, acidification, eutrophication) in addition to human health.	Primarily human health focus. Local environmental health related to individual chemicals may be conducted however.

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Table 1. Comparison of characteristics of LCIA human health assessment and RA for human health (using TRACI and RSEI as guidelines for comparison). (Continued)

Characteristic	LCIA Human Health	RA Human Health
Spatial perspective	Has a unique system perspective that allows a life cycle boundary and a functional unit focus. It is best used as a "view from a distance."	Provides a localized view of potential impacts that may result based on background concentrations, on-site concentrations, and/or emissions at a single site.
Conservative vs. comparative approach	The intent of LCIA is to compare two or more options, so if uncertainty can be calculated and maintained separately, and if the data can be provided on an even basis in terms of data quality, it may be better to make the comparison with realistic as opposed to overly conservative scenarios.	Because the intent of a risk assessment is to maintain levels that are conservative and protective, the modeling may incorporate overly protective defaults and assumptions (*e.g.*, quantity of soil ingestion).
Perspective (relative or absolute)	Provides a relative rather than absolute perspective. Without the incorporation of background data and emissions from other sources, it is impossible for LCIA to calculate actual expected impacts, instead the impacts modeled represent a marginal potential for change.	Provides a more absolute perspective. Allows incorporation of background data and emissions from other sources.
Modeling sophistication	Uses some of the same standardized methods that were developed for RA, but because the LCIA covers many more stressors and locations, it is generally conducted with less sophistication than a risk assessment (*e.g.*, details such as stack height are generally not incorporated within the model).	Model sophistication is generally higher than LCIA, and will often include site-specific details. However, some recent advances in LCA have provided more sophisticated models than those typically used within certain countries.
Temporal and spatial aggregation	Because of application issues, and the marginal perspective, LCIA often aggregates stressors across locations and timeframes.	Maintains independent spatial and temporal results.

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Table 1. Comparison of characteristics of LCIA human health assessment and RA for human health (using TRACI and RSEI as guidelines for comparison). (Continued)

Characteristic	LCIA Human Health	RA Human Health
Human health impact aggregation	To present the vast amount of data in a format that is more digestible within the interpretation process, human health impacts are often aggregated.	Because the data analyzed are minimal when compared to LCIA, aggregation across human health impacts is not necessary, nor generally conducted.
External normalization	Because LCIA provides a relative perspective, it is useful to also provide an external normalization database to allow additional perspective during the interpretation process. Although many options exist, a normalization database would typically provide the perspective of the nation's annual emissions.	Analyses result in units of risk that relate to the chances of contracting the human health impairment of concern. No external normalization is required or conducted.
Uncertainty of results	Data uncertainties are a result of toxicity, half-life, and other chemical, physical, and toxicology measurements. Model uncertainties also exist and are similar for RA and LCIA.	
National guidelines	LCIAs may be developed to be consistent with the policies, regulations, and guidelines of a particular nation, but large-scale case studies may include locations outside the original national borders.	Risk assessment guidelines often are developed within an individual nation to reflect policies and regulations within the country.

within the United States. They are not intended to be a global recommendation for best practice.

POTENTIAL FOR INTEGRATION

The following discussion will demonstrate the integration of two specific tools that can be used to represent the more comprehensive LCIA (using the USEPA's TRACI) and the more sophisticated modeling available using the USEPA's RSEI.

TRACI—The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) was developed by the USEPA's Office of Research and Development's National Risk Management Research Laboratory to allow the use of impact assessment within LCIA, Sustainability Metrics, and Pollution Prevention. TRACI

allows the characterization of potential effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone formation, ecotoxicity, human criteria, human cancer, human non-cancer, and fossil fuel depletion effects. To develop TRACI, impact categories were selected, available methodologies were reviewed, and categories were prioritized for further research. Impact categories were characterized at the midpoint level, for various reasons, including a higher level of societal consensus concerning the certainties of modeling at this point in the cause-effect chain. "Midpoints are considered to be links in the cause-effect chain (environmental mechanism) of an impact category prior to the endpoints, at which characterization factors or indicators can be derived to reflect the relative importance of emissions or extractions" (p. 319) (Bare *et al.* 2000). Research in the following impact categories—acidification, smog formation, eutrophication, land use, human criteria, human cancer, human noncancer, and human criteria effects—was conducted to construct methodologies for representing potential effects in the United States. Probabilistic analyses allowed the determination of an appropriate level of sophistication and spatial resolution necessary for impact modeling for several categories, yet the tool was designed to accommodate current inconsistencies in practice (*e.g.*, site specific information is often not available). A diagram disclosing the structure of TRACI can be seen in Figure 3. Impact categories were selected based on their level of commonality with the existing literature in this area, their consistency with EPA regulations and policies, their current state of development, and their perceived societal value. Human health was subdivided to better reflect the focus of EPA regulations and to allow methodology development consistent with the regulation, handbooks, and guidelines (Bare *et al.* 2003).

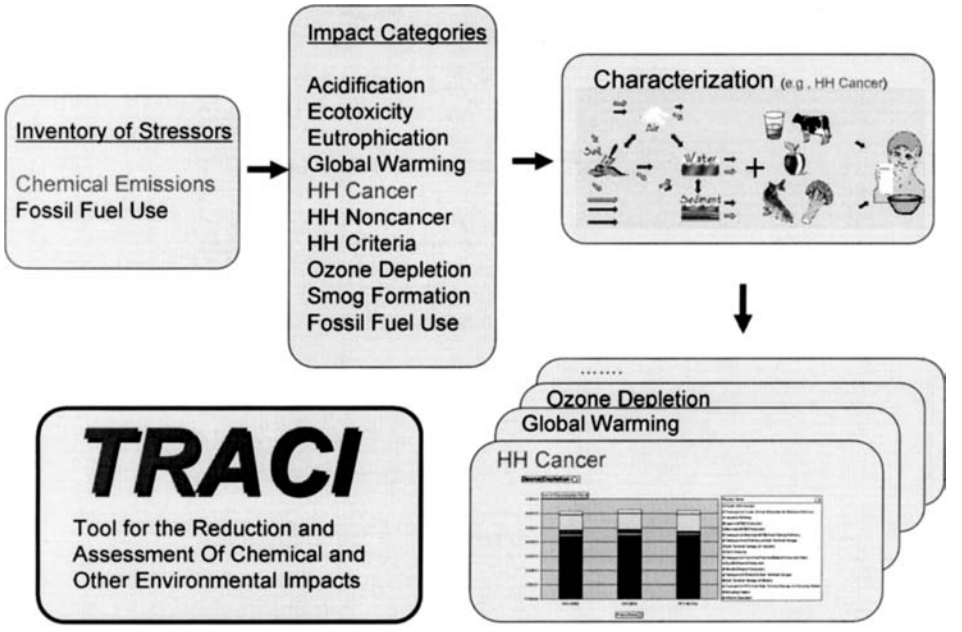

Figure 3. TRACI's framework (taken from Bare *et al.* 2002).

TRACI's human health cancer and noncancer categories were heavily based on the assumptions made for the USEPA Risk Assessment Guidance for Superfund (USEPA 1989). The EPA's Exposure Factors Handbook (USEPA 1997) was utilized to make decisions related to the various input parameters for both of these categories as well. The relative toxicity potential of individual chemicals is calculated based on human toxicity potentials (Hertwich *et al.* 2001). The Human Toxicity Potentials (HTPs) were derived using a closed-system, steady-state version of a multimedia-based system that incorporates 23 human exposure pathways (*i.e.*, CalTOX 2.2; McKone 1993). An updated version of TRACI (including updated human toxicity categories) is expected in 2006.

Because of the compatibility of TRACI and RSEI (description follows), TRACI could be used in conjunction with the USEPA's Risk-Screening Environmental Indicators (RSEI) for an expanded LCIA followed by a more in-depth analysis of the "hotspots," perhaps followed by additional iterations with TRACI (USEPA 2004). As mentioned earlier, the LCIA may identify some specific emissions that may require further analysis, however LCIA should not be considered the only information to determine emissions that may have the potential for significant or noticeable impacts, but those emissions that contribute significantly to the total impacts in the human health categories of cancer and noncancer may benefit from further analysis within RSEI.

RSEI—The Risk-Screening Environmental Indicators

The USEPA's Risk-Screening Environmental Indicators (RSEI) tool was developed to allow further assessment of the chronic human health concerns associated with industrial releases. RSEI results may be displayed based on: pounds only, hazard only (*i.e.*, toxicity), or risk-based (*i.e.*, including toxicity, fate, transport, exposure, and population data). The analysis within this article will be conducted using the more sophisticated risk-based analysis as opposed to the mass or hazard only scores.

RSEI is consistent with TRACI in many ways: 1) Both are separated into cancer and noncancer categories. 2) Both allow fate, transport, and toxicity information to be used within the analysis. 3) Both were developed to focus on allowing analyses of the TRI chemical releases.

RSEI is more sophisticated than TRACI in the following ways: 1) RSEI incorporates the TRI data within the system, whereas TRACI users need to determine the emissions that are pertinent to the analyzed LCIA, 2) RSEI allows more sophisticated Gaussian air dispersion modeling that takes advantage of the local conditions (*e.g.*, meteorology), 3) RSEI incorporates local census data and allows integration of population features and density within the calculation of risk.

RSEI was developed to allow a quick screening of trends within the TRI data in a variety of ways. RSEI can be used to analyze localities that may be under greater burden for specific chemicals, or to rank and prioritize chemicals within a locality. Like TRACI, RSEI includes the following information within the analyses: the pounds of chemical released, the chemical's toxicity, fate, transport, and exposure. Additionally, RSEI considers the location of the release and the number of people potentially impacted. RSEI guidance emphasizes that RSEI results are not detailed or quantitative risk assessments, but are a screening-level perspective (USEPA 2004).

On the other hand, TRACI is more suited for LCIA analysis in the following ways: 1) TRACI uses a multimedia model that includes better determination of the intermedia transfer that is expected to occur at steady-state, 2) TRACI uses a closed system that better includes the long-range and persistent chemicals that may go beyond the 50 km recommended distance of Gaussian dispersion models, 3) TRACI provides a more complete human exposure model, incorporating 23 human exposure pathways.

Using TRACI and RSEI together allows the wider perspective of the comprehensiveness of life cycle stages and impact categories within TRACI as well as the more focused site-specific modeling at individual TRI locations that is provided by RSEI. Using both models together in an iterative approach would allow more in-depth coverage from both the local and wider perspective. The iterative approach may also allow for more sophisticated coverage of the inventory or emissions occurring within both analyses.

For example, if the goal is to conduct an analysis with an LCIA perspective, TRACI should be used first for all impact categories. Together with a normalization database, TRACI would identify those impact categories that are the most significant contributors to the national emissions within that category. If human health is considered to be significant, either because of the LCIA results, or because of the focus of the study, RSEI could be used to analyze those locations and chemicals that contribute most significantly to impacts for the cancer and noncancer categories. (In the MTBE, ethanol, non-oxygenated fuel additives study, chemicals being emitted at a single location which contributed greater than 2% of the total impacts within the impact category were considered significant.) RSEI's more sophisticated models used in conjunction with the population data could then be used to determine more precisely which populations would be impacted by these emissions. The TRI reporting form could also be further analyzed to determine if there was any additional information that could shed further light on the analysis (*e.g.*, speciation of certain chemicals). Results for the MTBE, ethanol, non-oxygenated fuel additives study showed that very few chemicals contributed to the vast majority of the potential for impacts in these categories (Abraham *et al.* 2004).

SUMMARY

The similarities and differences between human health risk assessment and the human health categories within Life-Cycle Impact Assessment are discussed with the intention that the reader should better understand the strengths, weaknesses, and perspectives of each. In general, the LCA perspective is usually more comprehensive in impact categories and stressor coverage, but includes less spatial and temporal detail in the impact assessment modeling. LCA is usually not inclusive of background concentrations and therefore cannot address threshold issues or actual quantification of risk, but does a better job of calculating the potential for marginal risks for a larger number of stressors and emission locations. LCA generally estimates the potential for risk in a broader range of impact categories that can include human toxicity, acidification, ozone depletion, and resource depletion issues such as fossil fuel depletion, The complementary roles of both tools are emphasized and it is

noted that neither one should be used in isolation, but that both are necessary to have a balanced perspective.

Two tools are chosen as examples to illustrate how LCIA and RA can be used in combination. TRACI and RSEI are analyzed with special notes made about their consistency, yet complementary roles that each could play within an integrated study. Finally, a recent EPA case study provided additional insight into the utility of integration, and the problems associated with depending only on one tool. This case study and the discussion within the article emphasize the point that the beginning of any environmental analysis should spend significant time devoted to the selection of the tools necessary to support environmental decisions and the structuring of those tools (*e.g.*, boundary setting, impact category selection) to best answer the questions at hand.

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