ECO-EPIDEMIOLOGICAL ENQUIRY UNDER GLOBAL ECOLOGICAL CHANGE: AN INTEGRATED ASSESSMENT TOOLKIT FOR BEGINNERS

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Abbreviations:

AIDS	acquired immunodeficiency syndrome
BAU	business as usual
DPSEEA	driving forces, pressures, states, exposures, effects, actions
EF	ecological footprint
EFA	eclogical footprint analysis
EKCs	Environmental Kuznets Curves
GDP	gross domestic product

HEADLAMP	Linkage Methods for Environment and Health Analysis, HEADLAMP Project
HIV	human immunodeficiency virus
IA	integrated assessment
I=PAT	impact equals the product of population, affluence, and technology
PLCA	product life-cycle analysis
SARS	Severe Acute Respiratory Syndrome
STIRPAT	Stochastic Impacts by Regression on Population, Affluence, and Technology
UNEP	United Nations Environment Programme
WHO	World Health Organization

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ABSTRACT

Eco-epidemiology is a sub-specialty of epidemiology, focusing on the relationships between human health and the dynamics of global ecological change. Under escalating global change, new conceptual and analytical tools are needed if we are to contribute to the development of prevention and adaptation strategies for reducing negative health effects of changing ecosystems. This paper provides an overview of methodological approaches and tools for advancing eco-epidemiological research. Several Integrated Assessment methods are discussed (integrated modeling, scenario analysis, and participatory methods), each combining knowledge elements from various disciplines into an analytical framework for identifying the cross-linkages and interactions among different contextual circumstances and processes underlying complex (eco-epidemiological) phenomena that we are facing today. Building on environmental (impact) studies, we additionally discuss some promising tools that can support more systematic approaches: conventional and disaggregated Ecological Footprint analysis, the DPSEEA-framework, Product Life-Cycle Analysis, the I = PAT identity, and Environmental Kuznets Curves. We argue that the methods and tools discussed can help to advance our understanding of the complex pathways among socio-economic and environmental determinants of health, improving the exploration and modeling of human health under global ecological change. They help us to focus research attention on key features of complex systems to improve our understanding of systemic (“upstream”) drivers, and to facilitate a more complete characterization of proximate (“downstream”) exposures and their effects. Their application in problem-oriented transdisciplinary research encourages the adaptation and adoption of formerly discipline-specific methods into other disciplines; new, conceptual frameworks then emerge. Their continued employment and evaluation are encouraged.

INTRODUCTION

Epidemiologists study where diseases, ill-health and premature mortality occur, how these phenomena are distributed in communities, what trajectories they follow, and what causes them. Throughout its history, epidemiology has undergone numerous methodological and conceptual developments, as well as changes in the scale at which epidemiologists focus their research (March and Susser 2006). Consequently, it has been characterized in terms of its eras, such as the “infectious disease era” and the “risk factor era” (Susser and Morabia 2006). Developments in the field of epidemiology have trailed, anticipated, and paralleled changes in understandings of disease causation, and have been influenced by society’s need to effectively treat illness and prevent disease and premature mortality, as well as by secular advancements in other areas (e.g., in computing, communications, and genomics).

Over the past several decades, questions of closely related cause-and-effect relationships have dominated epidemiological practice. Reductionist approaches to research questions, focusing on proximate and linear cause-and-effect relationships, have characterized much of what epidemiology has contributed to public health in the second half of the 20th century, and a large array of important individual-level risk factors have been identified. However, this focus on individual risk has left understudied the forces that act at other levels to determine health (Pearce 1996), and has done little to prevent the recruitment of new high-risk individuals to replace those whose risks have been reduced. Also, only recently have eco-epidemiologists begun to grapple with the population health implications of the total ecological impress of human activity. Confronting human health risks from processes on as grand a scale as regional or even global ecological change inevitably draws us into the study of complex systems.

Epidemiology’s methods and its research foci have been challenged by the unprecedented scale of change in ecosystems that support life itself at a basic level, and which until recently had been taken for granted (e.g., predictable ranges of seasonal temperature variation, and the perceived infinite capacity of natural sinks to assimilate wastes) (McMichael et al 2003). Changes now recognized by the public and broader scientific community alike, such as those to the global climate system, have been occurring in concert with social changes. These changes include: increased forced and voluntary movements of people internationally, urbanization, the expansion of consumption-intensive lifestyles, global trade, growing gaps between rich and poor within and among countries and regions, catastrophic failures of technology and management such as the Chernobyl nuclear disaster and the deadly chemical release at Bhopal, the resurgence of known infectious diseases such as tuberculosis, and threats posed by new-found pathogens such as the human immunodeficiency virus (HIV) and avian influenza. Alone, risk factor epidemiology is inadequate for dealing effectively with these processes and events, not because individual risk variance is unimportant, but because the larger forces shaping the distribution of individual risk are constituted in dynamic systems to which reductionist forms of analysis are not suited.

Only recently did eco-epidemiologists begin to grapple with the population health implications of ecological declines caused by human activity, including population growth, the consumption of material and energy resources, waste and hazardous waste disposal, and the use and abuse of technologies. Recognizing these challenges, the term “eco-epidemiology” has been used to describe epidemiological research that embraces:

- the multi-level causation of disease,
- the importance of gene-environment interactions,
- the need to consider exposures over the life course and even over multiple generations,
- the utility of methodological cross-fertilization between communicable- and chronic-disease-focused epidemiology, and
- the importance of broad contextual factors in the determination of population health states (Martens 1998; Susser 2004).

Soskolne (2008) further distinguished eco-epidemiology by discussing it in terms of its focus of inquiry as well as its methodological features: relationships between ecosystem disintegrity and human health. Even prior to this, Soskolne and Bertollini (1999) were urging epidemiologists, as well as scientists and practitioners in other disciplines, to extend their conventional conceptual and methodological boundaries. They recommended systematic approaches to important questions of sustainability and health at multiple scales, and advocated primordial prevention (Beaglehole et al. 2002) as the dominant strategy, recognizing that it is policies and institutional arrangements, and the ideologies and worldviews that foster them, that drive ecosystem-scale effects. Confronting human health risks from processes on as grand a scale as regional or even global ecological change inevitably draws us into the study of complex, adaptive systems.

Epidemiologists need new research approaches as well as new conceptual and analytical tools if they are to contribute to reducing negative health consequences from the broad range of health determinants associated with global ecological change. Tools that can help focus research on the key features of complex systems are needed to improve our understanding of the systemic drivers, and facilitate a more context-sensitive characterization of more proximate exposures and their effects. Indeed, this holistic and systems-based approach is part of what characterizes the emerging field of eco-epidemiology under global ecological change.

To introduce these concepts, we describe the systems-based approach and methods of Integrated Assessment (IA), discussing the complexities involved in studying the health impacts of global environmental change; we build upon complexity theory and discuss the broader global context of population health. Accordingly, we provide some challenging food for thought on how to move forward in the field of eco-epidemiology, building upon research approaches and tools emerging from the environmental sciences. We then review several conceptual and analytical tools that can be used to support and advance eco-epidemiological research.

GLOBAL CHANGE AND POPULATION HEALTH: COMPLEXITIES AND URGENCY

Awareness is increasing that a more systems-based approach is essential for understanding (global) population health. This approach is consistent with the more general complexity thrust in science. Growing recognition exists that many issues should be studied holistically, instead of studying the different parts of the whole separately, and this has played an important role in the development of complexity theory.

Various scientists studying the processes of global change—often implicitly—draw upon concepts and ideas that abound in the field of complexity theory (Pearce and Merletti 2006); the many interacting processes of global change are perceived to adapt and co-evolve as they organize through time, which results in inherent uncertainty, and multiple futures. Hence, the global context of population health comprises a variety of systems operating at various levels or scales, and each constitutes the environment for the other. As Soskolne et al. (2007) state, we "must embrace greater complexity" because "the traditionally used, reductionist, linear approaches are inferior for understanding the interactive webs that are critical for sustainable development and for the health and well-being of future generations". With an escalating number of ecosystem changes taking effect across the planet, attention to developing and evaluating epidemiological methods that will generate data to inform policy that might help to change the present course is critical. Indeed, Soskolne (2003) has drawn attention to the even greater need for precaution under global change. And, primordial prevention (Beaglehole et al. 2002) is the level at which precaution must be exercised.

FROM THE NEWTONIAN TO THE COMPLEXITY PARADIGM (based on Amelung 2006)

For centuries, the dominant scientific worldview has been a mechanistic image of a fundamentally material, static, repetitive, predictable, linear, and clockwork universe. This so-called Newtonian approach to science—named after Isaac Newton—seeks full knowledge of a system via analysis or "reduction" of the system into its parts followed by study of those parts, typically in highly controlled environments. In the 20th century, however, elements of Newtonian science were being supplanted.

Einstein changed our Newtonian perception of time (i.e., time is invariant, infinitely divisible into space-like units, measurable in length, expressible as a number and reversible) by showing that there is no fixed or absolute time independent of the system to which it refers. Thermodynamics showed that there is an irreversible flow of time; the arrow or flow of time results in futures that are unstable, relatively unpredictable and characterized by various possibilities (Prigogine 1997).

Scientists continued to find physical phenomena that were not approachable through traditional Newtonian scientific constructs. Limits to the usefulness of the Newtonian approach—based on reductionism, linear relationships, negative feedback and a tendency toward equilibrium—across the scientific spectrum resulted in a need for a new research paradigm. The physical sciences began to distinguish between “linear” and “non-linear” phenomena (see e.g., Prigogine and Stenger 1984). In linear systems, causes lead to known effects in a predictable and repeatable manner; systems can be disassembled to understand the behaviour of their constituent elements and then reassembled, in a clockwork fashion, to model the behaviour of the whole system under differing conditions. Non-linear systems, however, are composed of numerous elements that interact locally according to simple rules, but the resulting internal dynamics of such systems create complex, disproportional and unpredictable outcomes. In general, these non-linear phenomena clearly reflect the uncertainty and complex nature of the majority of social and natural processes that we are trying to comprehend, including those processes encountered in the field of eco-epidemiology under global change.

The development of chaos and complexity theories spurred a revolution in the natural sciences. Lorenz (1963) discovered that even simple deterministic systems could exhibit non-linear behaviour. The development of chaos theory involved rejecting the Newtonian notion that only large changes in causes can produce large changes in effects. Infinitesimally small differences in initial conditions were found to produce hugely divergent evolutions of the system (Prigogine and Stenger 1984; Gleick 1987), a characteristic that became known as the butterfly effect: “a butterfly stirring the air today in Peking can transform storm systems next month in New York” (Gleick 1987). Paradoxically, the same positive feedback mechanisms that cause butterfly effects, emblems of volatility, can also be responsible for inertia.

Hypersensitivity to initial conditions implies path dependency, which sometimes produces a strong network of mutually reinforcing relationships that endure long after the initiating conditions have been superseded, creating a “lock-in” effect (Waldrop 1992). Non-linearities occur in complex systems of many kinds, ranging from fluid systems to the global weather system and the economy. In many of these systems, long periods of relative stability (phases) are interrupted by bursts of turbulence (phase shifts) that mark periods of accelerated evolutionary change (Faulkner 2001).

Complexity is the study of emergent, dynamic and self-organizing systems that interact in ways that heavily influence the probabilities of later events. Such complex systems encompass many entities interacting with each other, but the richness of these interactions allows the system as a whole to undergo self-organization. As a result, complex systems have the ability to adapt and co-evolve as they organize through time. They are also characterized by non-linearity, positive feedback loops, and points of bifurcation (Waldrop 1992).

Table 1 provides an overview of the most important differences between the (traditional) Newtonian and complexity paradigms. Following its growing influence in the natural sciences, complexity theory has begun to spill onto the edges of the social sciences (Urry 2005).

THE BROADER CONTEXT OF POPULATION HEALTH (based on Huynen 2008)

Causality in human health is multi-factorial, and many population health problems are invariably embedded within a global context. McMichael (1999), for example, argues that a global approach towards population health and epidemiology should not ignore the

importance of individual level proximate risk factors, but should indicate the importance of studying these proximate causes in their broader context. In line with this, Colwell (2004) argues that the health issues of the 21st century should be placed within the web of life, recognizing the linkages between our health and processes that operate at the global scale.

As our attention moves to multiple levels of the causal matrix of health determinants, there is an increasing interest in multilevel- and systems-approaches (Martens 1998; McMichael 1995, 1999; Pearce 2004; Pearce and Merletti 2006). Hence, a growing number of health researchers (Albrecht et al. 1998; Colwell 2004; McMichael 2005; Wilcox and Colwell 2005; Pearce and Merletti 2006) argue that the health of a population can—or must—be viewed within the broader system of health determinants. Populations are not simply the collection of individuals, but are shaped by, and shape, the systematic context in which they operate (Pearce and Merletti 2006).

Risk factors for disease do not operate in isolation, but occur in a particular population context; in fact, in multiple nested contexts. Upstream forces play an important role in global health research (Sreenivasan and Benatar 2006). The more upstream or larger context factors may have greater impacts, but their effects are non-linear and less predictable (Philippe and Mansi 1998). Various terms have been used to describe such broader approaches to population health, such as eco-epidemiology (Susser and Susser

1996; Martens 1998; Soskolne 2008; Ladd and Soskolne 2008), ecological perspective on health (McLaren and Hawe 2005), social-ecological systems perspective on health (McMichael 1999), and bio-complexity approach to health (Colwell 2004; Wilcox and Colwell 2005).

The majority of literature addressing population health as an interacting system of many different factors concerns research into communicable diseases. Disease transmission depends on contextual factors such as environmental change and cultural practices affecting landscapes, communities and population densities. These factors, in turn, interact with host-pathogen biology via evolutionary ecological processes to contribute to the (re)emergence of communicable diseases (Kapan et al. 2006).

Parkes et al. (2005), among others, urge new systems-based approaches to address communicable diseases. They argue that the worldwide (re)emergence of infectious diseases (e.g., SARS, Nipah virus, Lyme disease, HIV/AIDS, malaria) demonstrate that the rate and scale of global change in agriculture, trade demographics, species translocations and invasions, microbial adaptation, and other complex factors have outstripped our ability to understand and respond to emerging infectious diseases, and expose serious limitations of approaches that fail to engage with the wider contexts from which infectious diseases emerge. For example, the risk of highland malaria moving to higher altitudes depends on the interplay between regional climate change, land-use change, population movement, agricultural practice (e.g., pesticide use, irrigation systems), public health programmes (e.g., monitoring and treatment) and socio-economic status (Hales and Woodward 2003; McMichael and Woodruff 2005). The dynamic interaction of these various factors is but one of the many examples of the broader population context in which infectious diseases develop (Albrecht et al. 1998; Kapan et al. 2006).

Applications of a systems-based epidemiological approach to non-communicable diseases are rarer. However, such an approach is necessary because social and economic conditions at the population level can explain substantive differences in exposure to individual-level risk factors. Individual “lifestyle attributes”, for example a high-fat/low-fibre diet, can be understood only in the historical, cultural and socio-economic context in which they occur (Pearce and Merletti 2006). Albrecht et al. (1998) apply a complexity approach to coronary heart disease in the Australian Coalfields, resulting in an improved understanding of the dynamic interplay among industrial history, health-disease risk factors, gender promotion, and community responses to both the health problem and the health promotion campaigns.

In our effort to asses the health impacts of global (environmental) change, we have to be aware of the limitations of the traditional reductionist approaches (Albrecht et al. 1998; Pearce 2004; Pearce and Merletti 2006); population health and global change cannot be disassembled to their constituent elements and then reassembled in order to develop an understanding of the system as a whole. The individual scientific disciplines can offer only partial analyses and solutions. In order to fully address complex, interconnected, system-based health topics, transdisciplinary approaches are required to facilitate newer modes of science that transcend the disciplinary boundaries (Soskolne et al. 2007). Although complexity theory has had relatively little influence in the fields of population health and epidemiology (Pearce and Merletti 2006), the above shows that the past few years have witnessed a growing recognition of the multi-dimensional and multilevel causation of population health and the importance of a holistic systems-based approach. Epidemiologists are among the latest to grapple with the implications for their discipline, and with the global population health implications of a complex global village. Hence, emergent concepts and methods, as revealed through integrated assessment approaches, are the hallmark of eco-epidemiology.

INTEGRATED ASSESSMENT: A SYSTEMS-BASED RESEARCH APPROACH

(based on Huynen 2008)

The increasing complexity of the interactions between global (environmental) change and human health requires new ways of thinking and research; and eco-epidemiology requires an integrated approach to ensure that key interactions, feedbacks and effects are not inadvertently omitted from the analysis. Such a systems-based approach is offered by the new research paradigm “Integrated Assessment” (IA).

IA emerged as a new field in global environmental change research because the traditional disciplinary approach was unable to put global change issues in the broader context of interacting socio-cultural, economic, and environmental conditions and developments (Rotmans 1998). As the various pieces of this complex puzzle can no longer be examined in isolation, this new research paradigm aims to fit the pieces of the puzzle together, thereby indicating priorities for policy. A number of authors (Weyant et al. 1996; Gough et al. 1998; Rotmans 1998; Rotmans and Dowlatabadi 1998; Rotmans 1999; Harremoës and Turner 2001; Harris 2002) set about scoping and defining the field of IA. Rotmans (1998) defines IA as “a structured process of dealing with complex issues, using knowledge from various scientific disciplines and/or stakeholders, such that integrated insights are made available to decision makers.” Thus, IA is not simply another type of policy-support; it addresses only complex issues, which it aims to understand and structure.

The methods that were developed and applied in the context of IA projects are commonly grouped together into two categories: analytical tools and participatory methods. While analytical methods are often rooted in natural sciences, participatory methods, also labeled as interactive or communicative methods, stem from the social sciences. The most widely used analytical methods are “model analysis” and “scenario analysis”. These methods are considered more mature than “participatory methods”: they are reasonably well-defined, and there is at least a workable amount of common understanding of their scope, advantages and disadvantages (Rotmans 1998). Not only is there more experience with the use and application of these methods in IA contexts, they are also more widely accepted and used as legitimate scientific tools in disciplinary, “normal” science than participatory methods. Their commonality is that they provide analytical frameworks for representing and structuring scientific knowledge in an integrated manner. The group of participatory methods, however, involves a plethora of methods, all of which have in common the aim to involve non-scientists as stakeholders in the process, where the assessment effort is driven by stakeholder-scientist interaction. However, there is no such thing as a ready-made, one-size-fits-all IA "toolkit." The selection of a specific method for performing an integrated assessment depends almost entirely on the context of the assessment. Additionally, an IA is best supported by a combination of tools.

Integrated Assessment (IA) Models

Models were arguably the first tools used in IA. One of the earliest examples of such models was the one underlying the famous “Limits to Growth” report from the Club of Rome, by Meadows et al. (1972). In a limited number of equations, the authors tried to combine knowledge about a number of key issues such as demography, economy and resource use, to explore the future of mankind's interaction with the natural environment. Later, in the 1970s, scientists exploring the issue of acidification took a similar approach in institutes such as the International Institute for Applied Systems Analysis (IIASA) and the Dutch National Institute of Public Health and the Environment (RIVM) (Rotmans and Dowlatabadi 1998).

IA models are simplified representations of complex real-world phenomena. They combine knowledge elements from various disciplines in an analytical framework to assess the socio-economic and environmental consequences of human activities. In general, IA models try to describe quantitatively as much as possible the cause-effect relationships of a phenomenon, and the cross-linkages and interactions between different contextual circumstances and processes (Rotmans 1998; Martens 2006). They are never intended as 'truth machines' that perfectly replicate systems or predict the future. Rather, they are used for structuring information, and for exploring interactions and sensitivities (Rotmans 1998; van Asselt et al. 2001; Valkering et al. 2006).

In modeling population health dynamics, regression techniques are usually used to explore the relations between health determinants such as literacy rate, income level and income equity, nutritional status, water supply and sanitation, and education and medical services, and health status measures such as health-adjusted life expectancy. However, these regression techniques can only give some suggestive evidence on the causes of population and health changes. Statistical models to estimate future health states are based on extrapolation of past and current data, and they usually provide only limited insight into the dynamics behind changing health patterns. Therefore, there is a need for integrated approaches that take into account multiple risk factors at various levels in the causal chain. Such an integrated approach cannot be used in the clinical area on an individual basis, but is appropriate at the population level (Martens 2006).

In IA, modeling primarily refers to mathematical simulation models, which work on the basis of quantitative information and which require quantitative data inputs as they provide quantitative outputs. However, one of the first--but often hidden--steps in building a quantitative simulation model is the formulation of a conceptual model. This is a qualitative model that helps to understand and structure real-world systems and processes. Integrated conceptual models provide a structured representation of a system and they are not limited by the availability of quantitative data. Especially in the phase of issue- or problem-framing, the development of a conceptual model improves the integrated understanding of all key components and processes involved. In the case of complex systems, this process should explicitly acknowledge the uncertainties and the consequent plurality involved. In this sense, developing a conceptual framework is a means in itself. Additionally, well-described conceptual frameworks provide a sound basis for further research, whether this consists of carrying out a scenario analysis, organising a participatory process, building a quantitative model, or a combination of these tools. For an example of an integrated conceptual modeling approach towards global health, we refer to Huynen et al (2005) and Huynen (2008).

Integrated scenario analysis

The fact that the future can never be known with certainty does not mean that little of value can be said about it (Butler 2005). A systems-based approach implies a lower emphasis on prediction, but an accompanying greater emphasis on understanding the processes involved, acknowledging inherent uncertainties, and exploring alternative health futures. Thinking about what happens in the future provides a means to share our understanding about particular systems and situations, and the concerns we have in relation to these. Given the uncertainty about which of these complex issues may actually come to pass, it is useful to explore alternative options. Scenarios analysis is a means for structured thinking about the future (Rothman 2006).

Scenarios can be defined as descriptions of journeys to possible futures that reflect different assumptions about how current trends will unfold, how critical uncertainties will play out and what new factors will come into play (UNEP 2002). A key point in this definition is that a scenario of the future includes not only the state of the system at the end of the scenario period, i.e., the future vision, but also the path from today to the specified future (Rothman 2006). Scenarios describe hypothetical future pathways that consist of states, events, actions and consequences that are causally linked. In other words, scenarios are described as plausible but simplified descriptions of how the future may develop, according to a coherent and internally consistent set of assumptions about key driving forces and relationships (Swart et al. 2004). As such, scenario analysis is an often-used tool to deal with uncertainties by making the different legitimate interpretations explicit; scenarios are usually developed in sets, in which each scenario explores the implications of different assumptions concerning uncertain relationships or uncertain developments in key drivers.

Scenario analysis has evolved significantly over the past decades (van Notten et al. 2003). In the early days, scenarios were used primarily as planning and forecasting tools reflective of a rather mechanistic and deterministic worldview. In these traditional types of scenario analyses, there is considerable confidence in the predictability of the future. Based on information about the current situation and current trends, projections for the future state or development are constructed. Such projections are typically referred to as "business as usual" (BAU) scenarios. Uncertainties were presumed to originate from "noise" and lack of knowledge about original conditions. The complexity paradigm challenges the traditional approach of exploring the future. IA, being an issue-centred rather than disciplinary approach, challenges the BAU-type of scenario analysis; it rejects the disciplinary way of making projections and proposes an integration of projections and insights into coherent integrated scenarios. As such, the value of scenario studies to explore possible future events and provide sound policy-relevant guidance for decision-makers is increasingly and widely recognized; scenario analysis is a well-established response to uncertainty about what the future will bring.

In IA, scenarios are perceived as powerful exploratory tools. They do not predict the future, but rather they paint pictures of possible futures and explore the various outcomes that might result if certain basic assumptions are changed (UNEP 2002). In addition, scenario analysis has moved beyond merely fulfilling a decision-support function to supporting a more open form of exploration. According to Rotmans (1998), scenario analysis can be used to articulate key assumptions and expand our thinking beyond the conventional.

Over the years, a variety of scenarios have been developed, differing in terms of subject (issue-based, area-based, institution-based), and temporal and spatial scales (see e.g., van Notten et al (2003) or Greeuw et al (2000) for an overview). Typical integrated scenarios are issue-based or area-based and employ a time horizon of a few decades. Some scenarios look forward; they begin at the present day, pose one or more “what-if” questions, and then proceed to explore the ensuing futures. Other scenarios begin with an explicit image of a future state and then try to work out how we might reach that state starting from the present situation; this is done by posing “how-could” questions (Rothman 2006). A number of spatial scopes have been used for scenario development, ranging from the local scale to the continental and global scales.

Scenarios can be developed using qualitative and quantitative representations. These should be seen as complementary. Qualitative scenarios can explore relationships and trends for which few or no numerical data are available, including shocks and discontinuities. They can more easily incorporate human motivations, values and behaviour and create images that capture the imagination of those for whom they are intended (UNEP 2002; Rothman 2006). Alternatively, quantitative scenarios involve an interaction between narratives and computerized models. In such modeled scenarios, key assumptions are applied to quantitative data to produce quantifiable explorations of elements that will exist at a given point in the future (Butler 2005); the effects of changes in assumptions can then be easily checked, pointing to important uncertainties (UNEP 2002; Rothman 2006).

An integrated set of global health scenarios could provide a useful contribution to the ongoing discussions on the health effects of globalization, and could help to stimulate scientists, governments and other stakeholders to take a more integrated approach towards global health in order to find ways to ensure good global health governance, a healthy environment and good health for the future world population. Unfortunately, the health dimension is largely missing in past global scenario exercises (Martens and Huynen 2003; Huynen 2008). Hence, developing health scenarios can provide important insights into the diverse health effects of global (environmental) change by describing a range of possible interactions and their consequences. Martens and Huynen (2003) and Huynen (2008) provide examples of how future health can be incorporated in existing global scenarios.

PARTICIPATORY METHODS

It is commonly accepted that “a useful IA should be able to cope with a plurality of perspectives on a particular issue” (Gough et al. 1998). This requirement stems directly from an essential feature of many systems: uncertainty. Lack of knowledge is one obvious source of uncertainty, but there are also fundamental uncertainties that cannot be reduced by doing more research (Rotmans 1998). The omnipresence of uncertainty in the complex systems that IA aims to structure and assess allows for different valid views on the essence and functioning of these systems. van Asselt (2000, 2006) argues that plurality plays an important role in IA, because uncertainty legitimates different perspectives, such as different disciplinary perspectives, actor/stakeholder perspectives, or world views (e.g., norms and value systems).

Participatory methods - such as policy exercises and focus groups - are more exclusively linked to the emerging paradigm of post-normal science (Funtowicz and Ravetz 1994). The scientific movements of post-modernism and social constructivism have challenged the monopolistic position of positivistic science in the production of knowledge. They argue that the quality of research can be improved by involving relevant stakeholders, because these can contribute practical knowledge and experience, as well as a range of different perspectives (van Asselt and Rijkens-Klomp 2002).

Funtowicz and Ravetz (1994) and Ravetz (1999) see the involvement of an “extended peer community”, consisting of all relevant stakeholders, as a superior form of quality control in the context of complex issues. Although this more modest view of science's role has gained ground over the last few decades, it still meets with considerable opposition and hostility. Many researchers hesitate to accept the full implications of the existence of fundamental uncertainties, being that “searching for the truth or for universal answers” must be abandoned (Rotmans 1999). The set of participatory methods that is used in IA is not clear-cut, and the methods themselves are not clearly defined.

The five participatory methods that have been used in IA are focus groups, participatory modeling, scientist-stakeholder workshops, scenario analysis, and policy exercises (van Asselt and Rijkens-Klomp 2002). They all help assessors in structuring, eliciting tacit knowledge about and identifying perspectives on the complex issue being studied, albeit in different ways. Specifically:

- Focus groups consist of a limited number of stakeholders who engage in structured moderated discussions to elicit preferences, opinions and viewpoints.

- Participatory modeling takes the additional step of allowing stakeholders to explore, while they discuss, the implications of their ideas by formalizing them in a model.
- In scientist-stakeholder workshops, stakeholders aid scientific experts by discussing scientific findings and helping to identify key research priorities and to formulate a research agenda.
- Stakeholder identification of key issues is also a main aim of scenario analysis, but in this case the participants take the additional step of constructing plots for the future development of these issues. As a next step, these plots can be knitted together into a set of full-blown scenarios that explore a range of possible futures.
- In policy exercises, a heterogeneous group of stakeholders synthesizes the complex issue at hand. Subsequently, the participants assume different roles to simulate a decision-making process in order to explore the dynamics of such a process.

PROMISING TOOLS FOR ECO-EPIDEMIOLOGY (based on Ladd and Soskolne, 2008)

To support more systematic approaches to emerging ecology-health problems, we have built upon some of the existing tools that have been developed in environmental (impact) studies. In this section, we discuss a selection of potentially useful conceptual and analytical tools for eco-epidemiological research into the health implications of global change: conventional and disaggregated Ecological Footprint (EF) analysis, the DPSEEA framework, Product Life-Cycle Analysis (PCLA), the I = PAT identity, and

Environmental Kuznets Curves. These tools cannot by themselves deal with the problem of complex systems where multiple factors vary simultaneously—an appropriate integrated system-based (modeling) approach is needed for that. However, these tools may help us better understand and frame our investigations of the upstream drivers of multi-scale ecosystem impacts—notably, the forces that fuel modern industrial enterprises and their markets—and their implications for human health. These tools are windows through which, among other factors, our often unexamined consumption and production patterns can be viewed as ecologically and epidemiologically relevant dynamics.

Conventional and disaggregated ecological footprint analyses as health determinants

Pioneering work by Sieswerda et al. (2001), and subsequent confirming and enhancing work by Huynen et al. (2004), revealed important obstacles in the search for a clear relationship between indicators of ecological disintegrity and human health at the country level. These included the complicating factor of international trade, where raw and processed products and wastes cross international boundaries; the need to use multiple proxy measures to approximate the meaning of ecological disintegrity; and the questionable utility in these kinds of investigations of conventional multivariate regression techniques which require that other factors are held or assumed constant as relationships between pairs of variables are estimated.

Rainham and McDowell (2005) found that life expectancy was correlated strongly with the size of a country’s Ecological Footprint, with some notable exceptions. Since EF and monetary wealth (GDP) are strongly linked, this finding is not remarkable. It does remind us, however, that increases in wealth and improvements in life expectancy within countries have paralleled large and apparently unsustainable demands on the ecological foundations of the planet. In cases where the EF of a nation is greater than its geographical area of bioproductive ecosystems, these kinds of societal gains are connected to, or even derivative of ecosystems outside of the benefiting country's political boundaries. Some groups in countries from which ecological capital has been extracted and processed for export, or into which wastes from other countries have been dumped, have benefited financially from these transactions; however, this has often enhanced intra-national wealth disparities (Firebaugh 2006).

Ecological Footprint Analysis (EFA) has experienced wide popular uptake and appreciation. EFA has been applied to consuming entities or units at various scales, such as the individual, household, institutional, city, and national scales, and has been utilized in governmental policy and planning (e.g., Germain 2001; Tyedmers 2000; Bicknell et al. 1998; and Wackernagel and Rees 1996).

EFA requires first scoping and taking inventory of consumption. In a nation, for example, this would involve accounting for the tons of wheat, steel, and timber used by its citizens on an annual basis. Mineral resource use is not counted, and is assumed inherently unsustainable, but energy derived from carbon-based fuels is tracked and broken down into tonnes of carbon emitted. Once all the consumable goods are identified, the bioproductive land or water area required to support the annual provision of each consumable good is assigned, based on the world-average productivity of the specific ecosystems supplying these goods.

For example, a country's annual wheat consumption would be translated into the number of hectares of cropland required to provide this amount of wheat in a year—

again, based not on the productivity of the actual cropland supplying the good, but rather on the average productivity of this type of land use. For carbon emissions from energy consumed, hectares of “energy land” are added. The assumption here is that any emissions of carbon into the atmosphere are unsustainable if they are not offset at least equivalently by land-based sequestration. Once all of the average land and water areas are defined, they can be summed to arrive at the total Ecological Footprint (EF) for the unit being analyzed. The EF is expressed in terms of global hectares, and thus provides a measure of the total bioproductive space demanded by the analyzed entity, regardless of where on Earth that space is located.

Specific criticisms of, and adaptations made to EFA, can be found elsewhere (e.g., Lenzen and Murray 2003, 2001; van den Bergh and Verbruggen 1999; Levett 1998), but it is useful to note that the critiques can be grouped into three main areas:

- criticisms of sustainability assumptions, such as the implied assumption that atmospheric carbon dioxide concentration above that present at the time of analysis is unsustainable;
- problems with calculating world-average productivities of the different ecosystem types employed in EFA; and
- the meaning and usefulness of the aggregate EF as a tool for policy development or evaluation.

These criticisms suggest both limits and opportunities for the application of EFA to eco-epidemiological enquiries. The question of "sustainable" atmospheric carbon dioxide concentration, for instance, shows us that EFA is best interpreted in a multidisciplinary context that includes current knowledge of climate dynamics and the ecological implications of increased atmospheric carbon dioxide. Also, both the problems inherent in estimating the average bioproductivity of different ecosystem types and the questionable utility to health researchers of aggregate EF values prompt us to ask further questions about impacts in specific ecosystems and on specific human populations. Aggregate EF values show us that the macro system is overstressed, and provide impetus for more particularized investigations. Epidemiologically speaking, global ecological overshoot is an unprecedented universal "exposure" with very different implications for the population health of specific human communities on Earth. Whose health in particular is impacted, and when, because of unsustainable rates of exploitation of ecological capital?

Identifying the actual ecosystems from which resources are being drawn to support the consumption patterns in a specified entity (such as a country) entails disaggregating the Ecological Footprint. Once an EF of a particular size has been identified, the various particular ecosystems from which the analyzed unit is drawing resources can be located. This may be relatively straightforward for basic agricultural products such as wheat, and considerably more difficult for multi-material manufactured goods with an international history.

Ideally, threats to the integrity of source ecosystems would be measured in terms demonstrably linked to population health, and the consumption patterns of particular nations or institutions could then be evaluated in terms familiar to epidemiology: comparative rates of disease, population attributable fractions, the distribution of exposure to known risks or health promoting factors across subpopulations, and so on. However, because links between ecosystem disintegrity and human health are only rarely linear, direct, or immediate (trade and technological buffers complicate matters), a systemic view and systemic approaches are necessary. Transdisciplinary investigations of the systemic drivers of global ecological overshoot and of impacts on specific ecosystems could open up new dimensions of debate and practice in the fields of epidemiology, global health, and public health ethics, as well as informing scale-appropriate policy change for ecological and social sustainability.

The DPSEEA framework

In the late 1990s, in connection with the HEADLAMP environment-health linkages project, the World Health Organization (WHO) began using the DPSEEA (Driving forces—Pressures—States—Exposures—Effects—Actions) framework for understanding complex systems that affect human population health (see Corvalán et al. 1996, for a thorough description of the early formulation). Closely related and foundational to the DPSEEA framework is the earlier Pressure-State-Response (PSR) framework, often attributed to the Organization for Economic Cooperation and Development (Spangenberg and Bonnioto 1998). Seen through the lens of PSR, the (conventional) EFA approach discussed immediately above is basically a “PS” approach, since it aims to identify the human load (Pressure) on Earth’s ecological capacity, and to determine if that load creates an unsustainable (S)tate such as an eroding biological resource base stemming from planetary ecological overshoot. The DPSEEA framework, in comparison, directs the researcher to look for specific systemic drivers (Driving Forces) as well as to more specific implications of the entire system and to intervention possibilities (Exposures, Effects, and Actions).

Almost any organized human activity can be viewed through the DPSEEA framework. For example, Kjellström and Hill (2002) applied the DPSEEA framework to the analysis of transport-related health impacts in New Zealand. They noted:

- Driving forces such as population growth and an increased demand for transport from a growing economy;
- Pressures such as more cars and trucks on the road, more noise, and more toxic emissions;
- States such as diminished air quality and more congested roads;
- Exposures such as air pollutants and physical traffic risks;
- Effects such as respiratory problems, injuries, and fatalities from traffic accidents; and
- Actions for health promotion and protection, including educational initiatives and changes in legislation.

Theoretically, any of the elements in the DPSEEA framework can be the point of entry for investigation; a researcher might be aware of (E)ffects, and then look both retrospectively to determine (E)xposures, (S)tates, (P)ressures, and (D)rivers, and prospectively toward effective (A)ctions.

However, the elements of the DPSEEA framework are connected by positive and negative feedback loops, and are not necessarily connected linearly. Thus, for example, an Effect may change the States or Pressures in other parts of the framework. Because the DPSEEA framework is understood mainly as an environmental health framework, the WHO (1999) does caution that it is less useful (or, at least, must be carefully adapted) in situations involving physical risks where “Pressure” is difficult to quantify and interpret.

These include risks posed by natural hazards (e.g., earthquakes and volcanoes) and technology (e.g., automobiles, as in the Kjellström and Hill study), and risks such as those posed by the products of nanotechnology or the synergistic action of multiple chemical exposures.

The DPSEEA framework is oriented toward public health (A)ction, as informed by improved understanding of the underlying forces that perpetuate or amplify certain health conditions. It is a tool for thinking systemically about the relationships among exposures, outcomes, and their causal relationships. The DPSEEA framework is also useful for structuring a broadly causal description, or even creating future ecological and health scenarios associated with the activity of particular economic enterprises. Recent trends in the use of traditional food and feed crops, such as corn for biofuel synthesis, and the global, rapidly-growing palm oil industry, are two modern examples of where the DPSEEA framework could usefully direct eco-epidemiologic research. Eco-epidemiologists might inquire into what health-relevant (E)xposures are associated with (S)tates—such as a higher-priced food supply in producing countries or their markets—and also into the (P)ressures and the (D)riving forces—such as increased demand for low-cost automotive fuel—that are responsible for those food price increases.

The DPSEEA framework does not endorse or describe particular methods for analyzing and interpreting the relationships that it describes, but it can suggest critical areas for research attention. It can also help identify the parameters of testable models or the original conditions from which future scenarios are then envisioned, and it can help identify potential points for intervention. The DPSEEA framework fosters recognition of the interplay between micro-, meso-, and macro-level determinants of health risks and impacts within particular socio-political and economic systems. The DPSEEA framework is likely to be especially helpful in analyzing specific industries (e.g., the tobacco and automotive industries) that have expanded to take advantage of new markets in jurisdictions where political resistance to ecological degradation or negative health impacts may be overshadowed by the promise of quick profits.

Product life-cycle analysis

In our world, where growing global markets drive the mass production and movement of goods over long distances, Product Life-Cycle Analysis techniques may be used to help identify the ecological impacts and associated human health impacts of global industries, and thus help frame eco-epidemiological studies of these enterprises. Product Life-Cycle Analysis (PLCA) grew out of the field of global energy audits in the 1960s and 1970s as a means of improving process efficiency in production, reducing costs and wastes, and minimizing certain types of environmental impact (Ciambrone 1997).

PLCA can help determine a product’s impact in terms of gross material flows, pollutants and emissions. PLCA is also useful for identifying points in a product’s life-cycle where interventions can be made to improve the relative material or energy efficiency of production, use, or deposition. PLCA generally does not go as far as EFA in that it focuses on emissions or gross material and energetic demands throughout a product’s life-cycle but does not translate these demands into measures of appropriated biocapacity, such as the standardized global hectares of EFA. For example, a sample PLCA data collection sheet from the International Standards Organization (ISO 1998) recommends quantifying emissions to air, water, and land, but does not suggest what levels of emissions are unsustainable or pose health risks. PLCA as currently structured can help in the identification of a more complete collection of relevant (D)rivers and (P)ressures, and perhaps (S)tates (see description of the DPSEEA framework), but typically not (E)xposures or (E)ffects, since clarification of these elements requires reliable contextual information on the human interface with product manufacture, use, and deposition after use. PLCA's strongest selling point for eco-epidemiological enquiry is its attention to detail; for example, it renders useful ecological data from complex manufacturing processes.

The I=PAT identity

The I=PAT identity specifies that environmental Impacts (I) are functionally related to the product of Population (P), Affluence (A = per capita consumption or production, often expressed in monetary terms), and Technology (T = impact per unit of consumption or production) (York et al. 2003). Since its original proposition, often attributed to Ehrlich and Holdren (1971), the I=PAT identity has served as a focus for dialogue about the relationship between key population-level factors contributing to the aggregate impacts on the planet of modern human life. As a theoretical equation, each of the terms is open to multiple operational definitions, and the relationships between them remains a topic of ongoing debate.

Fischer-Kowalski and Amann (2001) note that the debate has been somewhat cyclical, shifting back and forth over the years from the individual factors and what constitutes "I," to systemic features. Waggoner and Ausubel (2002) stress that determining and using correct dimensions in the I=PAT identity can generate information on the drivers of environmental impacts and thereby effectively predict the result of interventions aimed at altering one or more of the factors or the relationships among them.

The “I” side of the formulation often has been identified with impacts on local or regional air or water quality by particular pollutants, and not usually conceived as the sum of all measurable types of environmental impact, nor as a measure of global ecological integrity or carrying capacity—as proposed by Sieswerda et al. (2001). The I=PAT identity does not suggest what kind or amount of “I” is desirable (or equitable) for a region, country, or planet. It also provides no indication as to how much “I” Earth can sustain without fundamental damage to the bioproductivity of its ecosystems, nor (without much clearer definitions of the factors and better empirical data) how (P)opulation, (A)ffluence, and (T)echnology are actually related at community, region, country, eco-regional, global North versus global South, or whole-planet scales. As such, the I=PAT identity, simply stated, has limited value as a tool for informing environmental policy.

In order for the I = PAT identity to be useful for eco-epidemiological investigations involving the material relationships between nations, the factor definitions in the equation, and the manipulation of them, would have to incorporate the recognition that the prevalence of international trade—understood in material/energetic and not monetary terms—“splits” the factors spatially and complicates interpretation. For example, a measure of regional biodiversity loss from export-oriented banana cultivation in a tropical country—the (I)mpact—might follow from the application of a range of (T)echnologies that include heavy chemical pesticide, herbicide, and fertilizer use and mono-cropping. However, if consumption is entirely international, then the (P)opulation and per capita level of banana consumption, or (A)ffluence, within the consuming countries will be powerfully determinative of the (I)mpact, assuming that the amount of

(T)echnology is tied closely to international demand. The context-dependence of both the relative magnitude of the input factors and the nature of the relationships between them, as well as the extent of international trade, suggests that the simple form of the I=PAT identity has utility mainly as a springboard for further debate and research.

Even so, constructive criticism of the shortcomings of the I=PAT identity has attempted to remedy the problem of defining “I” (and the contributing factors) simply by whatever results in an equality. For example, the identity has been reformulated as a probabilistic model. Dietz and Rosa (1994) call this revised version “STIRPAT” (Stochastic Impacts by Regression on Population, Affluence, and Technology).

The reformulated version of the I=PAT identity allows some hypothesis testing and regression analyses, since it takes the form of a multiplicative regression equation that includes (T)echnology as the error term. This error term is likely to include many factors other than strictly technological ones—indeed, any social, economic, ecological, or other factors not subsumed in the (P) and (A) terms. In such a model, population health terms could be employed as outcome variables (I’s), which, given clearly defined (P) and (A) terms, could help focus research on the relationship between (P) and (A) in all the contexts noted earlier, as well as on the content and relative explanatory power of the error term. Great care would still need to be applied in interpreting models or statistical tests where (I)mpacts are the result of (T)echnologies applied in one location but determined in large part by the (P)opulation and (A)ffluence of a distant consumer base. Also, treating the I=PAT identity as a regression equation may depart substantially from the original intent of the formulation, which was primarily to provide a concise statement of the formulators' general beliefs about the interplay of societal forces as they relate to environmental impacts.

In short, the greatest value of the I=PAT identity to the field of public health, and to eco-epidemiological research, may lie in its revelation of the contextually-modified interdependence of variables often viewed as "independent" factors in academic and advocacy circles. Population growth, materially-intensive consumption and/or the accumulation of monetary wealth through materially-intensive production in distant regions, and the expansion of high impact technologies may be relatively more or less important as risk factors for specific population health problems; for example, population alone increases certain risks if population density becomes extremely high.

However, treating these factors independently for the purpose of simplifying foreign and domestic policy initiatives misses the point: the questions of which population where, what levels and types of consumption or monetary wealth accumulation and distribution, and which types of technology are being used, all implying the importance of context, are interdependent concerns. The I=PAT identity and the ongoing clarification of its components may be useful for framing discussions about, and initiatives to slow global ecological decline because it reminds us of the impropriety of singling out any one factor for attention over any other factor.

Environmental Kuznets curves

Environmental Kuznets Curves (EKCs), named for economist Simon Kuznets (see Kuznets 1955), have been used to help develop research hypotheses about the relationship between income growth and changes in industrial output and technology, public pressure for pollution reduction, and public policy on numerous indicators of environmental quality (Rayner and Bates 1997; Panayotou 1997). For epidemiologists concerned with the economic drivers of ecological changes, and with the impacts of those changes on human health, the construction of EKCs can be useful. EKCs can help in generating hypotheses, challenging beliefs about the relationship between aggregate income and indicators of environmental quality, and resolving relationships that may present differently at local, regional, national, and global levels.

Kuznets (1955) was interested in the relationship between national income and income inequality as countries become more industrialized and urban. Only later was the inverted "U"-shaped curve (which Kuznets hypothesized for the relationship between national income and income inequality in developed nations) used as a graphical description of how specific industrial pollutants would parallel rising national income until sufficient income was generated to implement pollution control measures. In the concluding section of his original article, Kuznets tempered his arguments by saying that "the paper is perhaps five percent empirical information, and 95 percent speculation, some of it possibly tainted by wishful thinking" (Kuznets 1955).

EKCs should likewise be treated with caution, and employed mainly to place implicit beliefs "out on the table" and generate hypotheses about how, and by which forces (e.g., market signals or government regulation), ecologically damaging activities (e.g., the emission of toxic gases) are reduced or halted. Improved understanding of these dynamics is valuable for addressing questions about the relationship between ecological integrity, human health, and confounding or modifying wealth variables.

For example, Harbaugh et al. (2002) concluded that the evidence was unconvincing that ambient levels of sulfur dioxide, total suspended particulates (TSP), and smoke declined (i.e., followed the classic inverted "U" pattern) as income rose well beyond the expected per capita income "turning point" identified by Grossman and Krueger (1995). Could it be that the slow pace at which the often externalized health costs of these environmental challenges are internalized hinders the adoption of control measures? If so, this is relevant information for eco-epidemiology. To use DPSEEA language, it helps place, within the realm of (D)riving forces, elements such as private or public sector accounting practices and specific types of market failures. These factors are recognized occasionally for their contribution to ecological data gaps (e.g. Anielski and Wilson 2007), but less so for their contribution to downstream population health impacts.

Hypothetical EKCs force investigators to clearly define the scale of analysis and the ways in which terms are operationalized—critical tasks in research dealing with potentially ambiguous concepts such as "ecological integrity" and "sustainability." Some research, for example, suggests that while the classic EKC inverted-"U" shape may hold true for some environmental pollutants at the local or regional level, a quite different relationship may characterize compounds such as CO_2.

Carbon dioxide is emitted at multiple discrete points, but has impacts on ecological conditions (and human health) through its effects on the total global climate system—effects which can result in local or regional ecological impacts at great distance from the original generators. Possibly because of the lack of, or greatly lagged evidence of any kind of "problem" at local or even national scales, CO_2 emissions appear to rise monotonically with income (Arrow et al. 1995). Finally, as relationships between economic and political systems and ecological health are explored (e.g., Rainham et al. 2008; Franco et al. 2004), EKCs may help generate hypotheses about how specific practical features of these different systems (in contrast to broad ideological categories) affect the production of specific ecosystem-affecting agents (such as CO_2 or mercury) over time.

CONCLUSIONS

There is a growing need to better understand the multi-faceted and complex linkages between global ecological change and human health. The methodological approaches and tools discussed in this paper provide an overview of those available and conceivable in order to advance eco-epidemiological research.

Eco-epidemiology requires a system-based research approach. Such an approach is at the heart of the Integrated Assessment paradigm. Integrated Assessment provides an integrated systems-based research approach for combining knowledge to enhance our understanding of cross-linkages and pathways under complexity. It provides a structured process for dealing with complex issues, using knowledge from various scientific disciplines and/or stakeholders, such that integrated insights are made available to decision-makers. Integrated Assessment models provide structured representations of complex systems, more amenable to a real-world understanding of the dynamics in a causal pathway. Integrated Scenario Analysis permits understanding of where current and anticipated trends will lead; only when we see likely futures can we act to prevent harms by steering away from them. Participatory Methods provide a mechanism for broadening our understanding of complex issues. An extended peer community provides a superior form of quality control under complexity. Only by exploring futures with explicit assumptions can we then identify those structures amenable to interventions that would increase the probability of arriving at more favourable futures.

We have also reviewed several conceptual and analytical tools that also can support system-based research into ecology-health effects and their interactions. We argue that each of these tools offers practical application in the growing field of eco-epidemiology research under global ecological change. Conventional Ecological Footprint Analysis prompts macro-level sustainability and associated population health questions. Disaggregating the Ecological Footprints of consuming units such as households, corporations, or countries enables more focused investigation of the human health implications of specific ecosystem impacts. Product Life-Cycle Analysis can assist in the disaggregation of the Ecological Footprint and ensure that ecological impacts associated with post-consumer deposition (e.g., landfills, incineration, recycling) are not neglected. The DPSEEA framework aids understanding of the relationships among larger forces leading to the development of human health risks, and prompts researchers to make explicit the roles of sociological, economic, and political forces in human systems. The I=PAT functional identity provides an important reminder to be context-sensitive and systems-oriented, and to be clear about definitions and dimensions when researching and interpreting relationships among human drivers of ecologically-mediated human health impacts. Finally, Environmental Kuznets Curves can point to testable hypotheses about wealth, ecology, and health relationships, and serve as prompts for questions about the scale of analysis, the function of different chemical actors in the environment and in the economy, and the effects of policy interventions at different levels, and among different types of governance. As tools, they need testing and refinement in actual eco-epidemiological investigations. Moreover, to avoid further fragmentation of knowledge relevant to social/ecological sustainability, these tools need application within a larger analytical structure that includes, for example, modeling and scenario methods better suited than multivariate regression for dealing with complex relationships (see Greenland and Brumback (2002), for a discussion of four such approaches, including causal and structural equation modeling).

These research methods and tools should be tested further because they could be effective for the improved exploration and modeling of human health under global ecological change. Their application in problem-oriented transdisciplinary research encourages the adaptation and adoption of formerly discipline-specific methods into other disciplines, and the development of new conceptual frames. Their continued employment and evaluation are encouraged.

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Table 1. Overview of the contrasts between the (traditional) Newtonian and Complexity paradigms

Newtonian paradigm	**Complexity paradigm**
Reductionism	Holism
Predictability	Unpredictability
Linear	Non-linear
Uncertainties implicit	Uncertainties acknowledged
Deterministic	Non-deterministic
System equilibrium	System instability