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Using System Dynamics Models of the Environment to Teach Sustainability Science: The Border+20 Model as a Pedagogical Device

Edward Sadalla, Susan Ledlow, and
Subhrajit Guhathakurta

ABSTRACT

The Southwest Consortium for Environmental Research and Policy (SCERP) system dynamics model was originally developed as a tool that would allow stakeholders to explore the future environmental and quality of life implications of policy decisions in the U.S.-Mexican border region. As the model took shape, it became apparent that it could also be useful in classroom settings to illustrate principles that apply to a wide variety of urban environments. This chapter argues that this model is uniquely suited for teaching concepts from the emerging field of sustainability science and for teaching systems thinking in relation to environmental issues. Use of the Border Plus Twenty Years (B+20) model fosters an appreciation of the widespread consequences of changing one part of a dynamic system and promotes an active learning approach to education that has been shown to enhance student involvement, interest, and retention of content.

The importance of introducing concepts concerning sustainability and human-environment interactions into educational curricula and the new field of sustainability science is herein discussed. Also reviewed are the educational problems that occur when the concept of sustainability is approached from the vantage point of a single academic discipline. System dynamics models are recommended as devices for teaching systems thinking about human-environment interactions. The pedagogical advantages of the B+20 model are also described using specific examples. Finally, the technical literature on the concepts of active learning and discovery learning is discussed, thus supporting the use of manipulable systems models in educational contexts.

La Enseñanza de la Ciencia Sustentable Utilizando Modelos de Sistemas de Dinámicas del Medio Ambiente: El Modelo Frontera+20 como un Mecanismo Pedagógico

Edward Sadalla, Susan Ledlow, y
Subhrajit Guhathakurta

RESUMEN

El modelo de sistema de dinámicas del Consorcio de Investigación y Política Ambiental del Suroeste (CIPAS), fue desarrollado originalmente para funcionar como una herramienta que permitiera a las personas interesadas explorar implicaciones futuras de decisiones de políticas del medio ambiente y de la calidad de vida en la región fronteriza México-Estados Unidos. Cuando se fue conformando el modelo, fue aparente que también podría ser útil en los salones de clase para ilustrar principios aplicables a una amplia gama de ambientes urbanos. Este capítulo discute que este modelo es adecuado para la enseñanza de conceptos del área emergente de la ciencia sustentable así como para enseñar sistemas de pensamiento en relación a temas ambientales. El uso del modelo Frontera+20 (F+20) acoge una apreciación de las consecuencias extendidas de cambiar una parte de un sistema de dinámica y promueve un enfoque activo de enseñanza de la educación que ha demostrado realzar la participación de los estudiantes, su interés, y la retención del contenido.

La importancia de introducir conceptos relacionados con la sustentabilidad y las interacciones humano-ambientales en la curricula educativa así como la nueva área de ciencia sustentable son discutidas de aquí en adelante. De igual manera son revisados los problemas educativos que ocurren cuando el concepto de sustentabilidad es aplicado desde una posición ventajosa de una sola disciplina académica. Los modelos de sistema dinámicos son recomendados como mecanismos para la enseñanza de sistemas relacionados con interacciones humano-ambientales. Las ventajas pedagógicas del modelo F+20 son descritas a su vez utilizando ejemplos específicos. Finalmente, la literatura técnica de los conceptos de enseñanza activa y exploratoria es discutida apoyando el uso de modelos de sistemas de manipulación en un contexto educativo.

THE EDUCATIONAL PROBLEM

Given the trajectory of current environmental problems, there is a need for educated citizens who are aware of the dynamic relationships between elements in the environment, between human behavior and environmental systems, and between environmental systems and human quality of life. According to Peter Raven, chair of the American Association for the Advancement of Science board, “We must find new ways to provide for a human society that presently has outstripped the limits of global sustainability. New ways of thinking—an integrated multidimensional approach to the problems of global sustainability—have long been needed, and it is now up to us to decide whether the especially difficult challenges that we are facing today will jolt us into finding and accepting them” (Raven

2002). There are specific contributions science education can make to the development of a sustainable society. The National Research Council's study "Our Common Journey: A Transition Toward Sustainability" (NAS 1999) concludes that citizen education is a key component for societies moving in the direction of sustainability. The report stressed that advances in basic knowledge about environmental systems must be combined with the social capacity and the political will to turn this knowledge into action. Long-term sustainable development is primarily an applied problem rather than a theoretical one; if sustainability is to be achieved, new knowledge will have to be both generated and used for planning. Both citizens and decision-makers will need to be aware of long-term goals and the consequences of different courses of action.

The educational problem is how to foster such knowledge and new ways of thinking. Science education has traditionally focused on within-discipline problems and has not fostered the broad-based, multidisciplinary perspective required to make sound long-term decisions about environmental problems. One proposed remedy is the creation of a new scientific discipline and educational curriculum concerning the interaction between humans and the global environment.

Sustainability Science

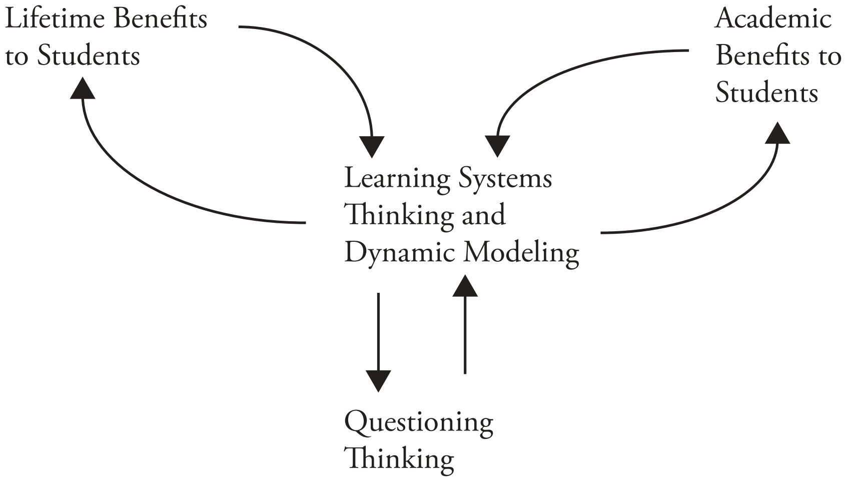
Recently, the U.S. National Academy of Sciences organized a group of professionals to examine the question of whether basic human needs over the next two generations could be met while sustaining the planet's life support systems (National Research Council, Board on Sustainable Development 1999). The report suggested that the achievement of sustainable human-environment interactions would require the development of a new intellectual discipline called sustainability science. This new field, discussed in a seminal article by Kates, et al. (2001) would use knowledge of industrial, social, and environmental processes to address applied questions about the sustainability of human-environment systems. As outlined by Kates, et al., sustainability science involves the use of scientific knowledge and methods in support of a transition to sustainable environments. It is responsive to concerns for environmental stability and human quality of life rather than to current scientific agendas. It is integrative across disciplines and based on concerns about specific places and specific human groups. Multidisciplinary skills will be required for this endeavor; practitioners will be required to combine information from diverse sources with the goal of balancing economic, environmental, and societal objectives (Milhicec, et al. 2003).

The field of sustainability science would break with the historical tradition of western science that has organized knowledge into discrete scientific fields or content disciplines. Traditional scientific disciplines, from anthropology to zoology, provide a conceptual structure for the organization of theory and research. Their disadvantage is that they do not necessarily match the way the world works, and they promote specialization in both knowledge and methods among their respective practitioners.

Over the past decade, the environmental movement and the accompanying interest in sustainable development have provided a major impetus for interaction among disciplines in social sciences, engineering, planning, construction, and environmental science. A number of international agreements, such as Agenda 21, the Rio Declaration on Environment and Development in 1992, the Earth Summit in 1995, and the World Summit on Sustainable Development at Johannesburg in 2002 pushed the cause of sustainable development across the world. Several nations followed with specific policy directives to implement an agenda for sustainable environments.

In response to problems of sustainability, natural and social scientists have begun to emphasize the importance of developing an integrated framework for modeling ecological and socioeconomic processes (Figure 1). Measuring and analyzing the dynamic interaction among economic, social, and environmental sustainability is critical because what gets measured can be managed, and possibly improved.

Figure 1. Pedagogical Implications of Systems Thinking and Dynamic Modeling



Source: Waters Foundation 2003

Sustainability science addresses applied issues of human-environment interactions. Although work in this area has been based on information gleaned from established scientific disciplines, the problems addressed underscore the limitations of such traditional scientific disciplines in dealing with the complex reality of social institutions interacting with natural phenomena. Core questions of sustainability science include:

- How are long-term trends in human population and consumption reshaping nature?
- Can scientifically meaningful limits or boundaries be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?
- What systems of incentive structures—including markets, rules, norms, and scientific information—can most effectively promote sustainable trajectories?

Answers to questions such as those posed above require models of interrelationships between complex systems and approaches that work backward from undesirable consequences to identify pathways that might avoid such outcomes. The problems of system complexity, complex interactions between system components, and long time lags between actions and their consequences make traditional methods of hypothesis testing problematic.

The type of education required is substantially different than the single-discipline and single-major approach that currently dominates higher education. Environmental problems are intrinsically multidisciplinary, and more importantly, are the result of the interrelationship between such diverse elements as economic variables, social variables, population growth, water use, air quality, and quality of life. The emerging discipline of sustainability science is based in part on the premise that systems thinking is necessary to understand the dynamic relationships that occur between environmental components.

SYSTEMS THINKING AND THE NATURE OF DYNAMIC MODELS

Across many diverse intellectual disciplines, system dynamics models are beginning to replace simple, one-way, causal chains as explanatory devices. Current thinking in the environmental sciences recognizes that simple cause-effect models do not allow students or researchers to grasp the complexity of the phenomena studied (Schellnhuber and Wenzel 1998). System dynamics models are based on the concept that modifying one component in a system has wide-ranging, and sometimes unforeseen, consequences that may in turn feed back and influence the component originally modified.

For example, during the past decade the harvesting of timber from forests in the Pacific northwest region of the United States has created jobs and supported economic development. Timber harvesting has, however, produced some unforeseen consequences. Logging has increased soil erosion during the rainy season, which has in turn increased the turbidity of water in rivers and streams. Because of increased water turbidity, salmon migrating upstream from the ocean have more difficulty mating and spawning. The soil runoff has thus reduced the harvest of salmon from rivers in this region and adversely affected the economic well-being of a network of employees and businesses that depend on the salmon harvest. Political pressure from the fishing industry is being brought to bear on the logging industry.

In the example above, timber, forest ecosystems, soil, salmon, economics, the social organizations involved in the lumber and fishing industries, and the quality of life of the residents of the region can be seen as part of a complex dynamic system. Understanding the impact of changing any part of the system requires the ability to model and think about the system as a whole.

What does the term "systems thinking" actually mean? As Forster and Cleveland discuss in Chapter I-1 of this volume, the phrase can refer to a set of tools—such as causal loop diagrams and simulation models—that help a student map and explore dynamic complexity. It can also mean a unique perspective on reality, a perspective that sharpens awareness of a whole system and of how the parts within that system interrelate. Finally, systems thinking can refer to a special vocabulary that expresses understanding of dynamic complexity. For example, systems thinkers may describe the world in terms of reinforcing and balancing processes, limits, delays, and patterns of behavior over time.

In this context, system dynamics models become important as pedagogical tools (Figure 1) that not only inform students about specific problem areas, but also teach a way of thinking about environmental issues in general.

Some type of model-building is central to understanding and the educational process. Everyone creates mental models of the world around them. With the advent of personal computers and graphical programming, more complex models of the phenomena in the surrounding world can be formally represented and displayed. As Heinz Pagels (1988) has noted, the system dynamics computer model is to the mind what the telescope and the microscope are to the eye. It is possible to model the macroscopic results of micro-phenomena, and vice versa. Possible futures of a dynamic process can be displayed. A key feature of system dynamics models is that such programs produce results that could not be predicted by the programmer.

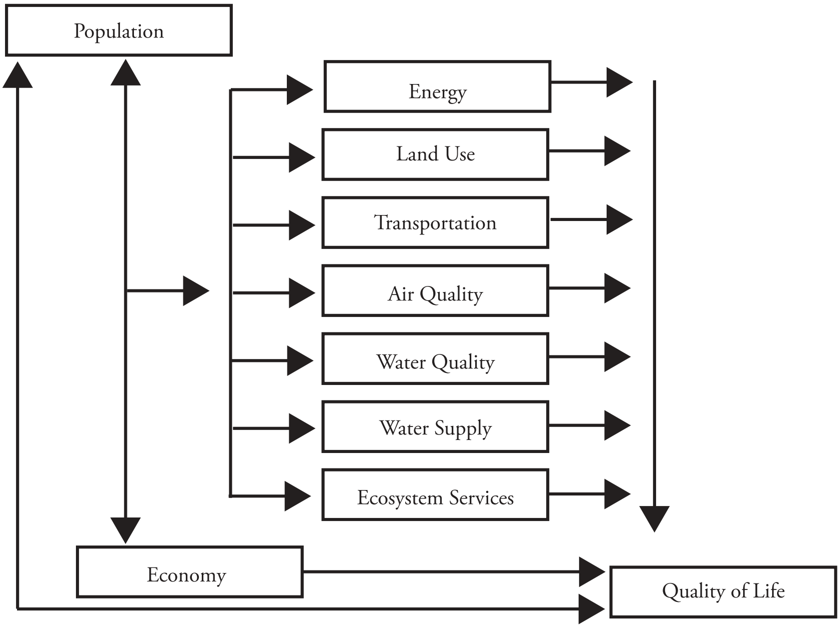
Manipulation of the models allows students to experience surprise and discovery—processes that engage their attention and facilitate long-term memory.

The system dynamics approach allows the student to manipulate and thereby explore the consequences and interrelationships between both hard (scientific/technical) and soft (social science/behavioral) variables. This combination of hard and soft variables and relationships is necessary to thoroughly understand any environmental system. Underpinning this approach is the assumption that policies related to migration, economy, air quality, or water supply have wide-ranging, long-term, and frequently surprising impacts on other environmental elements, as well as on human quality of life.

A useful aspect of system dynamics models is their ability to describe emergent phenomena that develop from micro-scale processes of individual behavior. Behavior in an urban environment is often derived from the interactions of many individual processes; simple aggregation of these micro-scale processes does not necessarily capture larger patterns of behavior. The products of interactive development may bear little resemblance to the original micro-scale patterns, and therefore require a synthetic approach to the study of the whole system.

For example, markets emerge from the dynamic interactions between consumers and producers and cannot be understood by examining one component in isolation. Similarly, urban phenomena such as traffic congestion, agglomeration of activities, and clustering of socioeconomic groups have to be seen in light of complex individual interactive processes (Nagel, Rassmussen, and Barrett 1996; Krugman 1996; Torrens 2000). The Border Plus Twenty Years (B+20) model (a computer-based system dynamics model of an urban environment) can be used to both foster systems thinking on the part of students and provide a novel and engaging way to teach key concepts in environmental sciences courses. The software tool represents the principal elements of an environmental system—such as population, economy, energy, air quality, water supply, land use/transportation, and quality of life sectors—and their interrelationships. A schema of the model is depicted in Figure 2.

Figure 2. SCERP System Dynamics Model



Source: Authors

Because the model captures the dynamics of any urban environmental system, it can be used as a pedagogical tool in a variety of environmental science courses. Although environmental attributes vary from region to region, the modeling framework attempts to capture underlying interrelationships common to all urban regions (such as relationships among population growth, economic development, transportation systems, air quality, and human health).

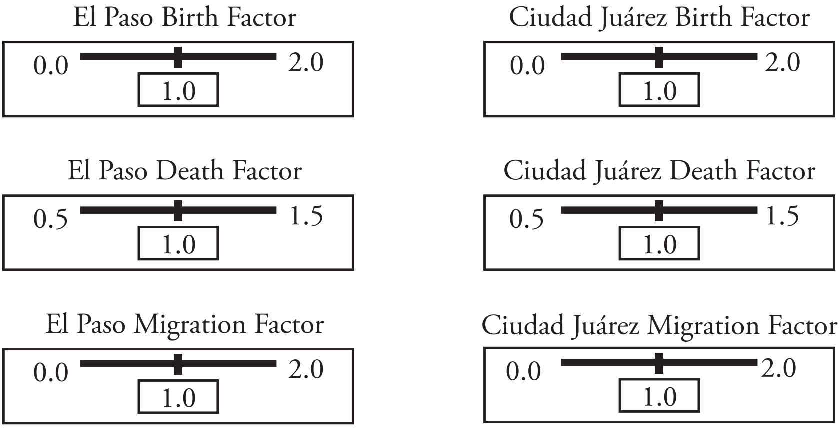
Decision-maker/stakeholder participation was gathered throughout the modeling process to ensure all potential users of the model have confidence in their ability to use it. The resultant user-friendly modeling environment also allows the user to change key system variables and observe the trends and consequences over different spans of time.

Manipulating the Model

One aspect of the model is the incorporation of "sliders" in each component of it. Sliders allow the user to manipulate particular parameters of one component of the system, then run the model and observe the consequences in other parts of the system. For example, Figure 3 depicts some of the sliders that can be manipulated in the demographic sector of the model.

Users can vary the birth rates, death rates, and migration rates in El Paso, Tex., and Ciudad Juárez, Chih., and observe the consequences of such variations on other demographic variables such as population size. More interestingly, the model will depict the impact of such variation on other components of the system. For example, increasing the size of the population in Ciudad Juárez will affect the air quality of both Ciudad Juárez and El Paso, and will have diverse impacts on water use, water availability, land use, and per capita income, as well as on quality of life variables such as health. Some of these consequences are capable of "feedbacks," that is, they may in turn affect birth rates, death rates, and migration rates.

Figure 3. Sliders in the Model Demographic Sector



Source: Authors

Through the manipulation of sliders, the model can also be used to teach the consequences of specific interventions. Consider the issues that surround environmental regulatory agencies. What are the trade-offs between environmental regulation and economic development? This general question can be explored by manipulating a slider in the economic sector that allows the user to adjust the level of "regulatory enforcement." The student can run the model for the base case, which assumes little regulatory enforcement. Questions such as the following may be explored: What happens to economic production? What happens to pollution per capita? What happens to pollution per dollar of gross domestic product (GDP)? What happens to air quality as the economy grows?

The impact of regulatory policies can be explored by moving the enforcement slider. With regulatory enforcement increased by 25% or 50%, the model can be run again to explore the impact of such manipulations on economic production, pollution, health, and health costs, among other sectors. This process leads students to general questions about goals. For example, should economic growth be sacrificed to achieve better air quality? What would be the anticipated total cost (including health costs) of improving air quality?

Pedagogical Rationale

Use of the model as a pedagogical tool exemplifies what is known about best practices in teaching and learning. In working with the model, students are automatically integrating knowledge from diverse areas and are actively engaged in posing problems and discovering their solutions.

Integrating Knowledge from Diverse Subject Areas

As discussed above, sustainability science involves knowledge from various scientific disciplines, including both the physical and social sciences. In current university settings, these disciplines are taught independently and students are rarely given the opportunity to integrate knowledge learned in different classrooms. The Boyer Commission on Educating Undergraduates in the Research

University (1998) notes that "[m]any students graduate having accumulated whatever number of courses is required, but still lacking a coherent body of knowledge or any inkling as to how one sort of information might relate to others."

Sustainability science requires conceptual frameworks that allow students to integrate previously learned material. Current research reviewed by the National Research Council and documented in the book *How People Learn* by Bransford, et al. (2000) indicates that to develop competence in an area of inquiry, students must have a deep foundation of factual knowledge, understand facts and ideas in the context of a conceptual framework, and organize knowledge in ways that facilitate retrieval and application.

The B+20 model lends itself perfectly to the integration of knowledge from different sources. The model draws upon knowledge gained in diverse disciplines and allows students to explore the relationship between economics, population, water use, air quality, land use, and quality of life variables. The model is itself a conceptual framework that promotes the ability to think systemically about environmental and quality of life variables.

Active v. Passive Learning

While evidence for the advantage of active engagement in learning continues to accrue, most college and university professors teach as they were taught—by the lecture method. While traditional lectures are an effective means of integrating information from diverse sources and for demonstrating disciplinary reasoning and habits of mind, they are not as effective for improving students' critical thinking or for promoting long-term retention of information. As Thorndike (1912) noted long ago, "The commonest error of the gifted scholar, inexperienced in teaching, is to expect pupils to know what they have been told. But telling is not teaching."

As a means of overcoming this limitation, a number of additional instructional strategies are currently being practiced and promoted in higher education. These include cooperative learning (Johnson, Johnson, and Smith 1991; Ledlow 2002; Millis and Cottell 1998), case teaching/Socratic dialogues (Christensen and Hansen 1987), classroom assessment techniques (Angelo and Cross 1993), writing across the curriculum/writing to learn (Bean 1996), and discovery or problem-based learning (Jonassen 2004; Starfield, Smith, and Bleloch 1994; Bruner 1960; Bruner 1966). These strategies fall under the general rubric of active learning. Bonwell and Eison (1991) note that while definitions of the term vary, most agree that when actively engaged, "students are involved in more than listening." The research literature indicates that when students are actively engaged in writing, discussing, and problem-solving, retention of information and critical understanding is enhanced (McKeachie, et al. 1986; Chickering and Gamson 1991; Boyer Commission 1998; Bransford, Brown, and Cocking 2000; Light 2001).

A representative study of the consequences of active learning methods was conducted by Felder, et al. (1998). In this project, a cohort of chemical engineering students took five courses taught by the same instructor in five consecutive semesters. Active and passive instructional techniques were systematically varied in an experimental design. Comparisons showed that students engaged in active learning classes outperformed students taught using traditional (passive) lecture methods. Experimental group students outperformed the comparison group on a number of measures, including content retention and graduation in chemical engineering; further, more of the graduates in this group chose to pursue advanced study in the field.

Most apropos of using the B+20 model in the classroom is discovery learning, originally discussed and advocated by Bruner (1960; 1966). Discovery learning is "an approach to instruction through which students interact with their environment by exploring and manipulating objects, wrestling with questions and controversies, or performing experiments" (Ormrod 1995). Discovery learning requires the student to make decisions about what, how, and when something is to be learned. Instead of being told the content by the teacher, it is expected that the student will have to explore examples and from them discover the principles or concepts to be learned (Snelbecker 1974).

Bruner suggested that students are more likely to understand and retain information that they discover on their own. He also indicated that students engaged in discovery learning are likely to develop higher-order thinking skills:

> Mastery of the fundamental ideas of a field involves not only the grasping of general principles, but also the development of an attitude toward learning and inquiry, toward guessing and hunches, toward the possibility of solving problems on one's own ... For if we do nothing else we should somehow give to children (students) a respect for their own powers of thinking, for their power to generate good questions, to come up with interesting informed guesses ... to make ... study more rational, more amenable to the use of mind in the large rather than memorizing (Bruner 1960; 1966).

A focus on problem-solving also teaches scientific reasoning because "the natural as well as the social sciences always start from problems" (Popper 1999). A 1996 report to the National Science Foundation reviewing the state of undergraduate education in science, math, engineering, and technology concluded that:

> On the basis of all that we have heard and learned during this review process, we urgently wish for, and urge decisive action to achieve, an America in which: All students have access to supportive, excellent undergraduate education in science, mathematics, engineering and technology, and all students learn these subjects by direct experience with the methods and processes of inquiry (George, et al. 1996).

The B+20 model is an ideal instrument for use in active learning and discovery learning contexts. Students literally discover concepts and outcomes by manipulating the model—programmers of the model do not themselves know the outcome of the program until it has run. Instructors may pose questions and ask students to try to answer them by manipulating sliders and then running the model. Alternatively, students may pose their own questions and run the model to answer them. Used in these ways, the model supports active engagement of the learner in the learning process and promotes the development of higher-order thinking skills (Bloom, et al. 1956).

CONCLUSION

The B+20 model represents a class of system dynamics models that are well-suited to teaching concepts related to sustainable development. This particular model is unique in that it includes environmental, demographic, economic, and quality of life components. Sustainable development means different things to different people, but the most frequently quoted definition is from the report "Our Common Future" (also known as the Brundtland Report): "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The issue at hand is whether the present trajectory of human-environment interactions can be maintained for the foreseeable future.

It is becoming increasingly apparent that human actions are producing increasing impacts on the environmental conditions that support life on Earth. Major threats to Earth's environment, including global warming, ozone layer destruction, exhaustion of fisheries, erosion of agricultural land, loss of biodiversity, and air and water pollution have been documented. Unless the environmental consequences of human activity are understood and overcome, such changes could substantially decrease the quality of life for both present and future generations. Opportunities for mitigating environmental problems exist because the majority of current problems result from environmental policy, political decisions, and from patterns of human behavior such as overpopulation and overconsumption.

The magnitude of the problem is formidable. Raven (2002) suggests:

> ... the world has been converted in an instant of time from a wild natural one to one in which humans, one of an estimated 10 million or more species, are consuming, wasting, or diverting an estimated 45% of the total net biological productivity on land and using more than half

> of the renewable fresh water. The scale of changes in Earth's systems, well documented from the primary literature ... is so different from before that we cannot predict the future, much less chart a course of action, on the basis of what has happened in the past.

During the past several decades, much of the human impact on environmental systems has been related to the growth of the urban population. Within a few years, a majority of the world's people will, for the first time, be living in cities (Lash 2001). The world's urban population is currently growing at four times the rate of the rural population. Between 1990 and 2025, the number of people living in urban areas is projected to double to more than 5 billion; if it does, then nearly two-thirds of the world's population will be living in towns and cities.

The growth of urban areas has historically been associated with environmental degradation. Emissions from transportation systems and industrial sources degrade air quality. Farmland and open space is converted to factories, commercial, and residential use. As a result of obsolescence, industrial sites are abandoned or move, often leaving contaminated land in the urban core. Water quality is degraded through increased runoff volume, decreased infiltration, poor runoff quality, and increased discharge from point sources. The manner in which development or redevelopment takes place can significantly increase or decrease these impacts.

There is an emerging consensus that because environmental problems are the result of human behavior, education will play a key role in promoting sustainable environmental trajectories. Education should encourage thinking about the environment as a complex system, with humans as part of that system. Models such as the B+20 model can be used as pedagogical devices that facilitate the achievement of such educational goals.

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