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FOOD, WATER, HEALTH, AND INFECTIOUS DISEASES: FOCUS ON GLOBAL CHANGE

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1. Introduction

In spite of numerous international commitments made over the last three decades to improve food, water, and health security in the developing world, some 840 million people remain undernourished, over 1.2 billion lack access to safe water, and more than 2.5 billion are at risk of infectious diseases, of which just six account for over 90% of the 13 million deaths a year. The world population is projected to increase by some 50% to reach 9 billion over the next five decades. This growth, combined with economic growth and increasing consumption and pollution, will result in substantial ecological pressures on land, water, the atmosphere, and biological resources. Global environmental change, particularly climate change, will lead to ecological changes that will likely cause higher levels of disease-causing pathogens and parasites.

There is a critical need for integrated climate, ecology, economy, and demographic (CEED) assessments to identify those ecosystems and populations that will be most at risk under conditions of global environmental change. These assessments require spatial analyses by differential vulnerability of ecosystems and populations (Lutz and Shah, 2002; Lutz, 2006) to target policies that may respond to and mitigate the threats of food, water, and health insecurity.

This paper presents an integrated CEED methodology and a policy-modeling framework for the assessment of the evolution of the world food system in the 21st century, under various future scenarios of population growth, economic growth, and environmental change. A global ecological database, comprising spatial data on land, water, forests, population, and habitation for all countries, is combined with national and regional general equilibrium models that are embedded in the global agricultural economy. This CEED systems analytic approach, particularly the spatial global ecological database and methodology, is also suited to the assessment of the extent, intensity, and location, as well as to the analysis of policy options, for future water insecurity and infectious disease distribution and risks.

2. Food and Hunger

Adequate nourishment is universally recognized as a fundamental human right. At the global level, there is enough food to meet everyone's need, and yet a fifth of the world's population continues to be chronically undernourished. Every year some 15 million people die from hunger alone, and over 200 million suffer health consequences due to nutritional deficiencies including those of proteins, micronutrients, and essential amino acids. Balanced nutrition is the foundation of good health, and healthy people are less susceptible to many infections and diseases.

In 1974, world political leaders set the goal of eradicating hunger within a decade. A quarter of a century later, at the Millennium Summit in 2000 and the World Food Summit in 2002, world leaders endorsed the less ambitious goal of reducing hunger by half by 2015, even though the rate of progress over the previous ten years indicated that it would take more than 60 years to reach this target. Political goals have a role and relevance in this effort, but in the face of continued shortfalls there is a limit to the hope and trust of the hundreds of millions who spend their lifetimes in debilitating hunger.

In addition to the intractable problem of world hunger, there is also an emerging problem of over-consumption, which is resulting in obesity and related health disorders such as diabetes and cardiovascular disease. More than 800 million people worldwide are estimated to be obese. The globalization of the world food system and the increasing influence of large food corporations – processors, distributors, and retailers – are affecting food consumption patterns through the increased marketing of processed foods that contain unhealthy levels of fat, salt, and sugar.

The next world food crisis will no doubt be a human health crisis, with conditions of too little food or too much unhealthy food affecting people differently in all countries, developing and developed. The scientific community, civil society, national governments, and the international development community bear the fundamental responsibility to achieve nutritionally sound, productive, and sustainable food agriculture. The key challenge will be in linking food sciences, agricultural technology, land, water, biodiversity management, and national and international policies and actions through all stages of the food chain, from production to marketing to consumption.

Agriculture must be given the highest political commitment and attention, because producing food is the predominant use for environmental and natural resources, and it has the greatest impact on the sustainability of ecosystems and their services. The trend in reduced allocation of national development budgets to agriculture – for example, in extension services and training, marketing, and infrastructure – together with declining multilateral lending and bilateral aid for this sector exemplifies the fact that agriculture is not given the attention and commitment it requires. There can be no progress toward reducing hunger and poverty without sustainable resource management and a science-based policy commitment to agriculture (Shah, 2001).

2.1. *The Challenge for Agricultural Science*

The promise of science to improve societies and human well-being cannot be delivered unless science is relevant to real, practical, and people-centered issues. The scientific community and the development policy community at the national and international levels must work expeditiously towards the goal of achieving health-enhancing food systems that are socially, economically, and environmentally viable and sustainable. This will require a systemic combination of the relevant sciences, including biology and biochemistry, agro-ecology and environmental science, social and economic science, as well as the fields of informatics and knowledge communication.

The challenge to the biological sciences is to combine the best of conventional breeding technology with biochemistry and safe, ethical molecular and cellular genetic research to develop nutritionally enhanced and productive germplasm (Shah and Strong, 2000). The specific food crops used by the poor, including coarse grains, roots and tubers, and plantains and bananas, should be given the highest priority. There is considerable scope for the development or improvement of environmentally sound fish farming and intensive livestock production, with due consideration of potential health hazards and animal welfare.

Targeted research, including biotechnology, has the potential to overcome many environmental constraints such as soil toxicity, water limitations, and pests and diseases, as well as to increase the nutritional content of crop plants. Vitamin A and iron fortification of rice can reduce the risk of blindness that affects 8 million people annually, prevent the death of 2 million infants disposed annually to diarrhea and measles, and lower the prevalence of anemia that affects 30% of the world's population.

Agro-ecological sciences, together with recent developments in geographical information systems, including remote sensing and the increasing quality and spatial coverage of sub-national, national, and global resource databases – of soils, water resources, land cover, thermal regimes and rainfall patterns, population distribution, etc. – has enabled productivity assessment tools to identify the potential of and environmental constraints to crop production at regional and national levels. The integration of this information into assessments of the global food economy, together with projections of future climate change and variability, enables evaluation of the possible impacts of climate change on agriculture and provides a basis for prioritizing regional and commodity-specific agricultural research for adaptation to and mitigation of the agricultural effects of climate change.

Climate change and variability will result in irreparable damage to arable land and water resources, with serious consequences for food production. Most of these losses will occur in developing countries where the capacity to cope and adapt is limited. Although the international community has focused on climate change mitigation, adaptation to climate change is an equally pressing issue and must be put on the international agenda. Adaptation is of critical importance to the many developing countries that have contributed little to greenhouse gas emissions thus far, yet will bear the brunt of the negative impacts of climate change and variability.

The challenge in the social sciences and economics is to ensure an environment that enables and empowers farmers and consumers to benefit from advances in science. In developing countries, health services, food aid, education and training, extension services, marketing, and infrastructure development are priority areas. The information and communication revolution has a significant role to play in developing global agricultural systems by combining the best of science with traditional knowledge. However, the fact that less than 1% of the population in Africa and developing Asia have access to the Internet, in comparison to about half of the population in the developed world, will further inhibit progress towards sustainable agriculture. This digital divide must be overcome because otherwise, global disparities will widen further.

2.2. *Integrated CEED Assessment of the World Food System*

Sustainability of land and water resources is significant to many central themes and issues in the study of global environmental change. Alterations in the earth's surface have major implications for the global radiation balance and energy fluxes, contribute to changes in biogeochemical cycles, alter hydrological cycles, and influence ecological balances and complexity. These environmental impacts at local, regional, and global levels, driven by human activity, have the potential to significantly affect food and water security and the sustainability of agro-ecological systems.

Food production systems interact with land and water resources, forest ecosystems, and biodiversity, and are susceptible to the effects of climate change. Ensuring soil fertility, genetic diversity, agricultural water resource management, and adapting to the impacts of climate change is critical to enhancing production.

The Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) have over the last two decades developed integrated CEED analytical tools and global databases. The focus of these efforts has been on multi-disciplinary scientific research that analyzes the current and future availability and use of regional and global land and water resources, in the face of local, national, and super-national demographic and socioeconomic change, international trade and globalization, technological development, and environmental changes including climate change and climate variability.

We assess the sensitivity of agro-ecosystems to climate change, as determined by the FAO/IIASA Agro-ecological Zones (AEZ) model (Figure 1, see page 413) within the socio-economic scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions (SRES). For this purpose, IIASA's global linked model of the world food system is used. This modeling framework, referred to as the Basic Linked System (BLS), comprises a representation of all major economic sectors and views national agricultural systems as embedded in national economies, which in turn interact at the international level. The combination of AEZ and BLS provides an integrated ecological-economic framework for the assessment of the impact of climate change. We consider climate scenarios based on experiments with four General Circulation Models (GCM) and assess the four basic socioeconomic development pathways and emission scenarios formulated by the IPCC in its Third Assessment Report.

The AEZ methodology for land productivity assessments follows an environmental approach; it provides a framework for establishing a spatial inventory and database of land resources and crop production potentials. This land-resources inventory is used to assess, for specified management conditions and levels of inputs, the suitability of crops/Land Utilization Types in relation to both rain-fed and irrigated conditions, and to quantify expected production of cropping activities relevant in the specific agro-ecological context. The characterization of land resources includes components of climate, soils, landform, and present land cover. Crop modeling and environmental matching procedures are used to identify crop-specific environmental limitations, under various levels of inputs and management conditions. The framework contains the following basic elements:

– Geo-referenced climate, soil, and terrain data, which are combined into a land-resources database. The computerized global AEZ database comprises some 2.2 million grid-cells;

– Selected agricultural production systems, with defined input and management relationships, and crop-specific environmental requirements and adaptability characteristics. AEZ distinguishes more than 180 crop, fodder, and pasture land-use types, each at three generically defined levels of inputs and management;

– Accounting of spatial land use and land cover, including forests, protected areas, population distribution and density, and land required for habitation and infrastructure;

– Multi-criteria analysis of agricultural production options.

The BLS (Figure 2) is a global general equilibrium model system for analyzing agricultural policies and food system prospects in an international setting. BLS views national agricultural systems as embedded in national economies, which interact through financial flows and trade at the international level. The BLS consists of 18 single-country national models, two models for regions with close economic co-operation (one for the European Union and one for the countries of Eastern Europe and the former Soviet Union), and a further 14 regional models for the rest of the world's countries. The BLS national and regional models simulate the behavior of producers, consumers, and the government. They distinguish two broad sectors, agriculture and non-agriculture, and the agriculture sector produces nine aggregate commodities.

The individual national and regional models are linked together by means of a world market. The model is formulated as a recursively dynam-

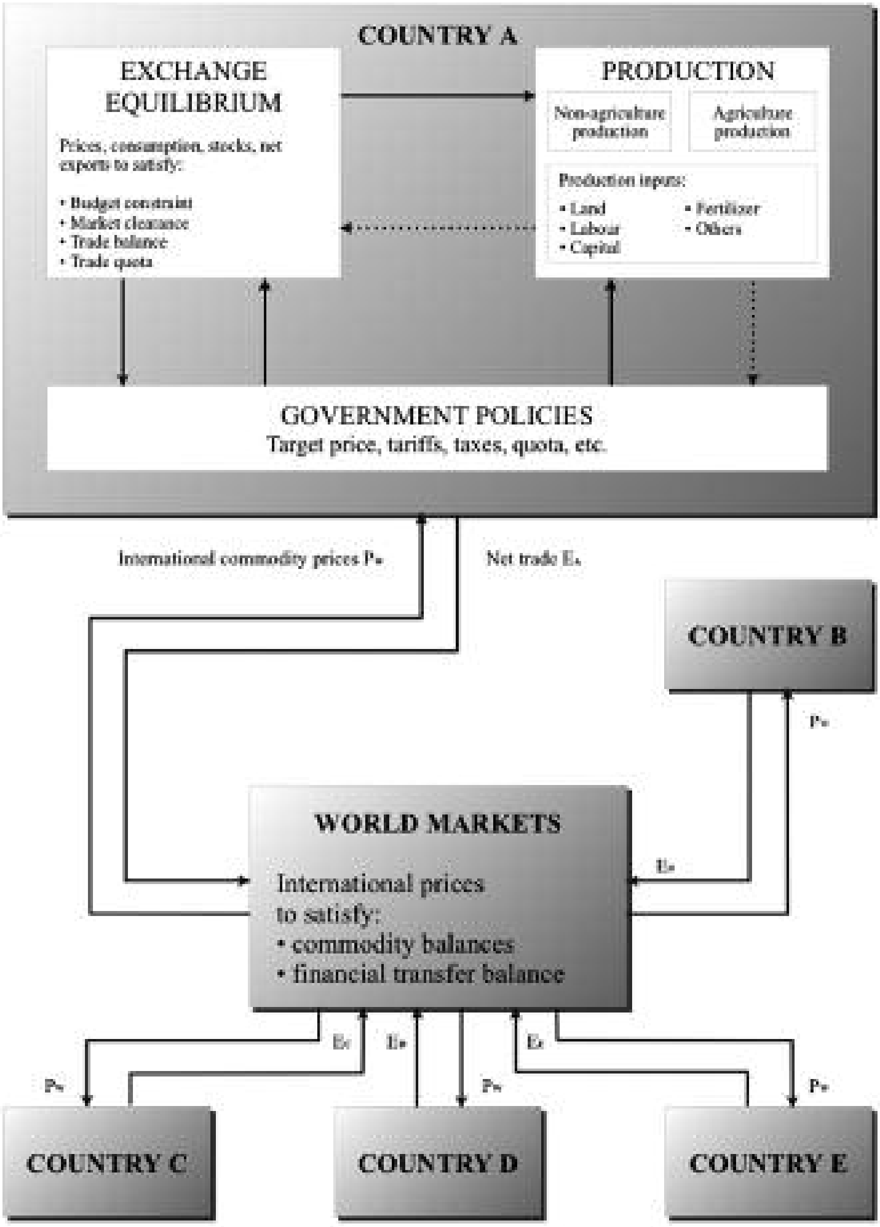

Figure 2. The International Linkage in the BLS (Fischer *et al.*, 2002b).

ic system, working in annual steps, where the outcome of each step is affected by the outcomes of earlier ones. Each individual model covers the whole economy of the respective geographical area. For the purpose of international linkage, production, consumption, and trade are aggregated to nine agricultural sectors and one non-agricultural sector. All physical and financial accounts are balanced and mutually consistent, including the production, consumption, and financial accounts at the national level, and the trade and financial flows at the global level.

The integrated CEED methodology and database (Figure 3, see page 414) provide a foundation for detailed country studies. The main results of the IIASA study include climate-change effects on the prevalence of environmental constraints to crop agriculture; climate variability and the variability of rain-fed cereal production; changes in potential agricultural land; changes in crop production patterns; and the impact of climate change on cereal production potential. Results of the AEZ-BLS integrated ecological-economic analysis of climate change on the world food system includes quantification of the scale and location of hunger, international agricultural trade, prices, production, land use, etc. The analysis assesses trends in food production, trade, and consumption, and the impact on poverty and hunger of alternative development pathways and varying levels of climate change. Some highlights of results are summarized below:

Environmental Constraints to Crop Cultivation: Two-thirds of global land surface – some 8.9 billion hectares – suffers severe constraints for rain-fed crop cultivation: 13.2% is too cold, 26.5% is too dry, 4.6% is too steep, 2.0% is too wet, and 19.8% has poor soils. Climate change will have positive and negative impacts, as some constraints may be alleviated while others may increase. The results for the Hadley HadCM3 climate model and the IPCC A1F1 scenario indicate that the constraints listed above will change respectively to 5.2%, 29.0%, 1.1%, 5.7%, and 24.5%. The agro-ecological changes due to climate change will result in water deficits in some areas and surpluses in others, and will alter the levels of infestation of disease pathogens and parasites.

Land with Cultivation Potential: In Asia and Europe, the rain-fed land currently under cultivation amounts to 90% of the land that is potentially suitable or very suitable for agricultural production. In North America, some 75% of the potentially suitable or very suitable land is currently under cultivation. By contrast, Africa and South and Central America are estimated to have some 1 billion hectares of potentially suitable or very suitable land in excess of the some 350 million hectares of currently cultivated land. However, most of this additional cultivable land is concentrated in just seven countries – Angola, Congo, Sudan, Argentina, Bolivia, Brazil, and Colombia.

Cultivation Potential in Forest Ecosystems: About a fifth of the world's land surface – some 3 billion hectares – is forest ecosystems. Sixty percent of the world's forestland is located in eight countries – Russia, Brazil, Canada, the United States, China, Australia, Congo, and Indonesia. During the past decade, some 127 million hectares of forests were cleared, while some 36 million hectares were replanted. Africa lost some 53 million hectares of forest during this period, primarily from the expansion of crop cultivation. The study results show that some 470 million hectares of land in forest ecosystems have crop cultivation potential. However, cultivating this land would have serious environmental implications, as forests play a critical role in watershed management and flood control and the protection of biodiversity, and serve as carbon sinks.

Climate Change and Fragile Ecosystems: The world's boreal and arctic ecosystems are likely to decline by 60% due to a northward shift of thermal regimes. The semi-arid and arid land areas in developing countries may increase by about 5 to 8%. Over a fifth of Africa's population, some 180 million people, currently live in these areas, where they derive their livelihoods from agriculture.

Climate Change Impact on Food Production: Although strong gains in crop production potential occur in North America and the Russian Federation, significant losses are projected for Africa, particularly North and Southern Africa. Currently there are some 78 food insecure countries. The current population of these countries is 4.2 billion, of which 18% are undernourished, and their total population in the 2080s is projected at 6.8 billion. Of particular concern are some 40 developing countries, many of them in the least developed country group, which as a whole may lose some 10 to 20% of their cereal production potential by the 2080s due to climate change.

Climate Change and Agricultural GDP and Trade: By 2080s, climate change will reduce Asia's agricultural GDP by 4%, Africa's by around 8%; meanwhile, North America's agricultural GDP will increase by up to 13%. The results also reveal a growing dependence of developing countries on net annual cereal imports – between 170 and 430 million tons. Climate change will add to this dependence, increasing imports of developing countries by up to 40%.

Climate Change and Number of People at Risk of Hunger: Some fairly robust conclusions emerge from the analysis of climate-change impacts on the number of people at risk of hunger. First, climate change will most likely increase the number of people at risk of hunger. Second, the importance and significance of the climate-change impact on the level of undernourishment depends entirely on the level of economic development assumed in the SRES scenarios. For the wealthy societies of IPCC development path scenario A1 – where even the currently poor regions are assumed to reach economic levels exceeding in per capita terms the current average OECD income – hunger is a marginal issue and remains so even with climate change. This is a desirable vision, but perhaps overly optimistic in view of the actual achievements of the last 30 years. Figure 4 summarizes the simulation results, showing the additional number of people at risk of hunger in 2080 plotted against different levels of atmospheric CO_2 concentrations and associated climate changes and Figure 5 (see page 415) shows the additional number of undernourished people by selected regions, climate modes, and IPCC future development scenarios.

Global environmental change raises the issue of fairness and equity. Developing countries have thus far contributed relatively little to the causes of climate change. Yet many of the poorest countries and those in food deficit will suffer substantial losses in domestic food production, which will increase food insecurity and hunger. The climate-change-induced ecological changes will also further exacerbate the water, health, and infectious disease challenges in many of the same countries.

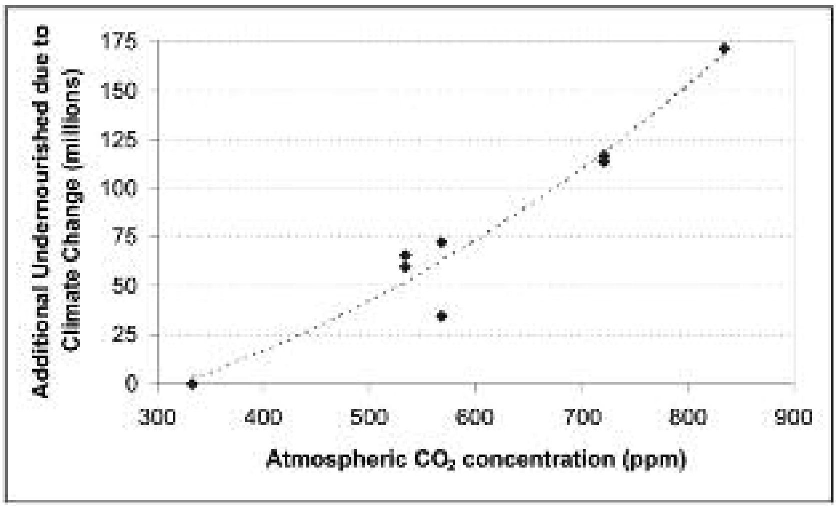

Figure 4. Increase in undernourished population due to climate change (Fisher *et al.*, 2002b).

2.3. *Food and Hunger: Examples of Spatial Extensions of CEED Methodology and Resource Database*

– Incorporation of regional and global climate change models;
– Formulation of CEED future agricultural path scenarios;
– Assessment of surface and groundwater resources and irrigation potentials;
– Assessment of bio-energy crop cultivation and production potentials;
– Assessment of natural vegetation and analysis of interaction with crop agriculture;
– Assessment of livestock production potential – pastoral and intensive;
– Assessment of sustainable marine fisheries and potentials for aquaculture;
– Analysis of national and international trade, subsidies, tariffs, and quotas;
– Assessment of nutrition, hunger, rural poverty, and livelihood options;
– Assessment of food security and food safety;
– Analysis of differential vulnerability of ecosystems and populations;
– Risk and uncertainty analysis;
– Initiation of detailed CEED national and regional food system studies.

3. Water and Health

The 1972 United Nations Conference on the Human Environment and Development in Stockholm endorsed the statement 'that all people have the right to have access to drinking water'. Some twenty years later the United Nations General Assembly declared the International Drinking Water and Sanitation Decade to achieve universal access to water supply and sanitation.

In 2002 the United Nations Committee on Economic, Social, and Cultural rights, interpreting the provision of the International Covenant on Economic, Social, and cultural rights, proclaimed, 'Water is fundamental for life and health. The human right to water is indispensable for leading a healthy life in human dignity. It is pre-requisite to the realization of all other human rights'. Some 145 countries that have ratified the covenant are now compelled to progressively ensure that everyone has access to safe and secure drinking water, equitably and without discrimination.

Only 2.5% of the world's water is fresh water. Present global water consumption accounts for 5% of total renewable water resources and this use is projected to double in the next two decades. The worldwide inequity in water consumption – an average of 20 liters per capita per day in the developing countries compared to over 400 liters in the developed countries – is an example of the global disparity between the rich and the poor.

Globally, some 170 million people in urban areas and about 1 billion in rural areas currently lack access to safe water. On average about 80% of the global population has access to safe water; however, there are significant regional differences. For example, in Africa only 60% of the population has access to safe water. To achieve the Millennium Development Goals (UN, 2005) of halving the number of people without access to water by 2015, over 1.5 billion additional people will need to be provided access to safe drinking water. This task, which will involve increasing water access capacity by over 30% of current water infrastructure, will require substantial investments. It will also require the local availability of water resources, as the transport of water over long distances is prohibitively expensive.

Although there are sufficient water supplies at the global level, these do not coincide with regional distribution of the global population. Water conflicts within countries and across countries are increasing. Water-stressed and water-scarce countries are defined, respectively, as those with less than 1700 and 1000 cubic meters of water available per capita. Currently, more than 30 countries with a total population of over 500 million are regarded as water scarce (Meinzen-Dick and Rosengrant, 2001). By 2025, some 50 countries with a total population of about 3 billion may be in this category. The arid and semi-arid zones of the world, which constitute 40 percent of the global landmass, have only 2 percent of global run-off.

Pollution and inefficient use of water resources have resulted in dropping water tables, drying rivers, the extinction of aquatic species, and the disappearance of invaluable wetland ecosystems. In many countries water supplies are drawn from underground aquifers faster than they are recharged with rainfall. The result is shrinking ground water tables, which has serious consequences for the rural poor who often cannot afford the cost of deeper drilling. Some of most populous countries, such as China, India, Pakistan, and Mexico, have substantially depleted their groundwater resources during the last three decades. The proximate causes of groundwater depletion, as well as groundwater pollution, are rooted in population growth, economic expansion, the distorting impacts of subsidies and financial incentives, and the spread of energized pumping technologies.

The pollution and depletion of aquatic ecosystems has serious consequences for biodiversity. During the last fifty years, half the world's wetlands have been destroyed, and pollution in coastal areas has resulted in declining fisheries and the destruction of biologically diverse habitats. Aquatic ecosystems, both freshwater and marine, are sensitive to pollution from agriculture, human waste, and industry.

In many tropical regions, annual rainfall occurs during a short rainy season, and most of this rainfall, unless it can be stored, is lost in runoff and river flows to oceans. The large majority of the 45,000 dams in the world were built between 1960 and 1990, but this construction has slowed with increasing awareness of the environmental disruption, displacement of populations, loss of agricultural lands, silting, and impacts on downstream areas created by these dams.

About 70% of the world's freshwater goes to agriculture. It is expected that over the next two decades the world will need 17 percent more water to grow food for increasing populations in developing countries, and that total water use will increase by 40 percent. This is projected to result in more than half of the world population facing moderate to high water scarcity (FAO, 2002).

With increasing water stress on the one hand and the increasing demand for water to meet the food needs and industrial and municipal needs of a growing population on the other, the challenge of water policy lies in finding integrated water resource management solutions that take into account multiple development needs while also protecting the environment. At the levels of watersheds, basins, and nations, water productivity must be understood from multi-stakeholder perspective in the broadest sense. For example, water productivity at the basin level must be defined to include: crop, livestock, and fishery yields; wider ecosystem services and social impacts, such as health; and the systems of resource governance that ensure equitable and cost effective distribution of benefits.

Irrigated agriculture with the heavy use of chemicals is a major cause of agricultural runoff of fertilizers and pesticides. This runoff in turn contaminates rivers, lakes, and underground aquifers, polluting drinking water supplies. These chemicals, even in low concentrations, can build up over time and eventually lead to chronic diseases. Agricultural pesticides such as DDT and heptachlor often wash off in irrigation water and as a result are found in water and food products. This has implications for human health because they are known carcinogens and also may cause low sperm counts and neurological disease.

Health problems caused by nitrates in water supplies are becoming a serious problem; in over 150 countries, nitrates from fertilizers have seeped into water wells. Excessive concentrations of nitrates cause 'blue baby syndrome', an acute and life-threatening disease among infants and young children. High levels of nitrates and phosphates in water also encourage the growth of blue-green algae, which leads to eutrophication.

It is estimated that more then a third of the global burden of disease is attributable to environmental factors. Inadequate water and sanitation are the primary causes of diseases such as diarrhea (4 billion episodes annually resulting in over 2 million deaths per year), malaria (400 million episodes with 1.5 million deaths annually), schistosomiasis (200 million episodes with 200,000 deaths and 20 million suffering severe consequences a year), intestinal helminthes (1.5 billion infections a year with 100,000 deaths annually), and trachoma (500 million people at risk and 6 million blinded every year) (WHO, 2001). Some 60% of all infant mortality is linked to infectious and parasitic diseases, most of them due to consumption of contaminated water.

Population growth combined the with impact of climate change in the 21st century will significantly affect the availability of water resources as well risks of waterborne diseases (Vörösmarty, 2000). Climate change affecting temperature, precipitation, and variability is likely to affect the geographic distribution of vector borne diseases, especially malaria, cholera, dengue, and schistomiasis. For example, higher temperatures would result in an increased prevalence of malaria in higher altitudes and latitudes. Heavier rainfall would cause the increased transport of microbial agents from soil leaching, such as cryptosporidiosis, giariasis, amsebiasis, typhoid, and promote the growth of mucilaginous blue-green algae and coastal/marine copepod zooplankton that provides hosts for cholera pathogens.

Climate variability events such as El Niño have been found to extend malaria and dengue epidemics and increase incidences of diarrhea. The frequency and intensity of extreme climate events is likely to increase as climate changes. In poor and vulnerable countries lacking early warning systems and security support, such events already result in significant losses of life, population displacement, the destruction of individual assets, physical infrastructure, and services, and outbreaks of infectious diseases in the aftermath of the event.

3.1. *Water and Health: Examples of Spatial Extensions of CEED Methodology and Resource Database*

– Compilation of geographical distribution of water bodies, waterborne vectors and diseases, and populations at risk;

– Analysis of CEED driving forces and cofactors of water borne diseases;

– Analysis of capacity of health care systems, including prevention, detection, and treatment;

– Analysis of safe water supplies, access, and affordability;

– Assessment of pollution and contamination of surface and groundwater resources;

– Identification of water stress and scarcity areas and evaluation of water policy options;

– Spatial differential vulnerability of ecosystems and populations to waterborne diseases;

– Risk and uncertainty analysis;

– Initiation of detailed CEED national and regional water and health studies.

4. Ecology and Infectious Diseases

The biological diversity of nature lies in the variety of life and its processes. It includes the vast array of organisms, the genetic differences among them, the communities and ecosystems in which they occur, and the ecological and evolutionary processes that keep them functioning yet ever changing and adapting. The organisms that constitute the world's biodiversity, a major share of which are parasitic and infectious organisms, live interdependently in complex ecological networks, where each relies for nutrients and energy on those that share its habitat (Shah, 2004).

Healthy Ecosystems support the energy needs of all species and also perform essential services such as purification of air and water, binding of toxins, decomposition of wastes, watershed and flood management, stabilization of landscapes, and regulation of parasites and pathogens.

Biological species live and evolve in environments and biotic cycles that encompass physical, chemical, and behavioral relationships that promote continued evolution. The symbiotic relationships between species are not only invaluable for the future well-being of the human race but also ensure the sustainability of the Earth's life-supporting capacity. More than half of the world's biodiversity is found in tropical rainforests, which cover just 7% of the earth's land area. It is well documented (Stevens, 1992; Chown and Gaston, 2000) that marine and terrestrial biodiversity decline as one moves farther from the equator, a phenomenon known as the latitudinal species diversity gradient. A number of studies have analyzed the diversity gradient and possible causal factors such as area, water, energy, geographical patterns, and habitat diversity (Rhode, 1992; Hawkins, 2003). However, parasitic and infectious organisms that account for a major share of the world's biodiversity have not been considered in most previous studies (Guernier *et al.*, 2004)

Infectious agents include viruses, bacteria, protozoa, and multi-cellular parasites. The microbes that cause 'anthroponoses' have adapted, via evolution, to the human species as their primary host. In contrast, non-human species are the natural reservoir for those infectious diseases agents that cause 'zoonoses'. Zoonotic pathogens are the most significant cause of emerging infectious diseases, and account for over 70% of pathogens. Vectors, pathogens, and hosts survive and reproduce within a range of climatic and ecological conditions. It is important to identify geographically how hosts, vectors, and parasites interact with each other and with the environment. The key questions in this identification relate to the potential carrying capacity, extent, and transmission of parasites and pathogens, as well as insects and other intermediate hosts. Particular ecological systems are associated, to a large extent, with particular infectious diseases; the exception is malaria, which is found in dry land areas, forests, and wetlands. Ecological change plays an important role in the emergence or resurgence of infectious diseases. Hence understanding the relationship between ecological changes and the nature of epidemic and endemic diseases and emerging pathogens is critical.

Guernier *et al.* (2004) have investigated the influence of temperature and moisture, as well as certain demographic and economic characteristics, on the latitudinal diversity and distribution of parasitic and infectious diseases. The analysis was based on compilations of epidemiological data on 332 different human pathogens across 224 countries and allowed for cofactors such as size of country, demography, economy, and environment. The results showed that a large number of parasitic and infectious disease (PID) species follow the same diversity latitudinal gradient as other biological species. This study also found significant positive correlations between pathogen species richness and the maximum range of precipitation, but little significant relationship between pathogen species richness and monthly and annual mean temperatures.

A number of previous studies have analyzed the influence of climate on specific infectious diseases:

– Regional cholera epidemics occur seasonally and are associated with periods of excessive rainfall, warm temperatures, and increases in plankton populations (Lipp *et al.*, 2002). Monthly and annual cholera deaths have been found to be positively correlated with sea surface temperature (an ENSO correlate) and air temperature (Speelmon *et al.*, 2000);

– Malaria outbreaks often occur following periods of increased rainfall and temperature, due to positive effects on vector breeding (Kilian *et al.*, 1999), development rates, parasite sporogony, and, ultimately, entomological inoculation rates;

– Meningococcal meningitis, an airborne bacterial disease, shows a highly seasonal and epidemic pattern in sub-Saharan Africa where outbreaks occur during the hot, dry season and decline when the rainy season begins (Molesworth *et al.*, 2002);

– Dengue epidemics are characteristically associated with high rainfall as well as elevated temperatures and humidity due to direct and indirect effects on pathogen and vector biology (Gubler *et al.*, 2001);

– Yellow fever, a zoonotic viral disease, has been found to be dependent on temperature but the importance of temperature fluctuations in the inter-annual variation of disease is unclear (Reiter, 2001);

– Rhodesiense African trypanosomiasis studies have suggested a link between temperature and vegetation and the distribution of tsetse in Africa (Fischer *et al.*, 1985; Robinson *et al.*, 1997);

– Japanese encephalitis epidemics are highly seasonal, occurring during the monsoon season when temperatures reach 30°C or above (Mellor and Leake, 2000);

– Rift Valley fever outbreaks are positively associated with warm ENSO events and above-normal precipitation (Anyamba *et al.*, 2002);

– West Nile virus epidemics occur during unusually hot and dry periods (Epstein, 2001);

– Schistosomiasis is related to environmental factors such as rainfall, temperature, and water body composition (Brooker and Michael, 2000);

– Lymphatic filariasis epidemics are related to temperature and precipitation (Lindsay and Thomas, 2000);

– Chagas disease is associated with high temperatures and low humidity (Carcavallo, 1999) as well as particular types of vegetation (Dumonteil *et al.*, 2002);

– Lyme disease incidences peak during high temperature summer months (Estrada-Peña, 2002).

Many of the disease-causing parasites and pathogen populations have flourished as environmental changes impact predator species. The wealth of biodiversity and its intricate connections are increasingly threatened as growing human populations and their ever-increasing consumption ravage the environment. The damage is evident: partial loss of the ozone layer; global warming and climate change; air, water, and land pollution; land degradation and erosion; salinity and desertification; wetland destruction; disappearing forests; extinction of species; and depletion of mineral resources. The cumulative consequences of unsustainable human activities will, in the long run, threaten nature's life-supporting capacity and resources.

Over the past half century, more than a quarter of the world's 8.7 billion hectares of crop-lands, pastures, forests, and woodlands have been degraded through misuse or overuse. Agriculture is by far the largest use of land and has the greatest impact on the environment and its biodiversity. Agricultural expansion has already resulted in the loss and fragmentation of the world's forests, modification of wetlands, streams, estuaries, lakes, and coastal and marine ecosystems. Many ecosystems are also threatened by unchecked expansion of urban areas and road infrastructure (Patz *et al.*, 2004).

Evolutionary ecologists are trying to identify the drivers that regulate species diversity. Among various hypotheses, factors such as area and energy, geographic constraints, and habitat diversity have been considered. Intuitively, one can hypothesize that plant species diversity results from an interaction between temperature, precipitation, topography, and soils. In turn, the herbivore species diversity results from the diversity of vegetation, and carnivore species diversity depending on the herbivores. The diversity of domesticated livestock has evolved in tandem with the variability and range of food supplies and in the context of social and economic development around the world. Next in this chain, the evolution and spread of parasite and pathogen diversity depends on the availability of habitat and breeding environments and hosts, including wildlife, livestock, and humans.

In recent years there has been a growing emphasis on Integrated Vector Management (IVM) strategies, as they combine the most effective epidemiological and ecological chrematistics. IVM, which integrates environmental management, biological control methods, and chemical control methods, aims to 'improve the efficacy, cost-effectiveness, ecological soundness and sustainability of disease vector control'. Furthermore IVM encourages a multi-disease control approach, integration with other disease control measures and the considered and systematic application of a range of interventions, often in combination and synergistically (WHO, 2004).

All biological species need access to dispersal areas as climatic and environmental conditions, and food and water supplies undergo seasonal changes. The movement of zoonotic and wildlife hosts combined with the existence of areas of urban population concentration further add to risks and prevalence of infectious diseases.

The Earth's latitudinal diversity of biological species including parasites and pathogens, and the relevance of and inter-relationships with cofactors such as mean and variability of climate parameters, environmental degradation and pollution, vegetation changes (crops, pastures, natural vegetation), and water resources remain to be analyzed. These factors, as well as economic and demographic development, are relevant to assessing the risk and prevalence of infectious diseases.

4.1. *Ecology and Infectious Diseases: Examples of Spatial Extensions of the CEED Methodology and Resource Data Base*

– Compilation of geographical distribution of parasites, pathogens and infectious diseases and populations at risk;

– Analysis of CEED driving forces and cofactors of infectious diseases;

– Analysis of capacity of health care systems: prevention, detection, and treatment;

– Spatial differential vulnerability of ecosystems and populations to infectious diseases;

– Risk and uncertainty analysis;

– Initiation of detailed CEED national and regional ecology and infectious diseases studies.

5. Concluding Remarks

Climate change is global, long term, and involves complex interactions among demographic, climatic, environmental, economic, health, political, institutional, social, and technological processes. It has significant international and intergenerational implications in the context of equity and sustainable development (UN, 1992). Climate change will impact social, economic, and environmental systems, and it will shape prospects for food, water, and health security. Quantitative information for geographically specific areas provides important knowledge that can underpin sub-national, national, and regional adaptive policies to mitigate the consequences of global environmental change. It may also facilitate international negotiations on climate change and sustainable development that take into account global inequities.

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