by Brian J. Skinner

Resources in the 21st century: Can supplies meet needs?

As in the past, we are concerned today with the magnitudes of mineral resources and the adequacy of these resources to meet future needs. In looking at global resource issues, we should consider the need for the resource, its supply, and the environmental consequences of using it.

The need for a resource can become a resource dependency, especially as the global population expands and each of us becomes increasingly dependent upon hundreds of natural materials. Therefore, our great mineral consumption makes the human population a true geologic force, which will be even more significant in the future when the global population is projected to reach alarming proportions.

Although our supplies of mineral resources probably will be sufficient for the next century, the uneven distribution of minerals in the Earth's crust almost certainly will continue to be a major problem. The most likely result will be major shifts in both prices and sources of supply of many mineral resources. As for energy resources, we must avoid an obsessive dependency on one fuel and expand instead to other energy resources.

Finally, because the use of resources affects the environment, we need to focus on resource exploitation and global pollution, particularly in regard to ground water and arable land. We must manage our resources so as to be in balance with our environment. (Ed.)

Introduction

Almost a century ago, the fifth International Geological Congress (IGC) was held in Washington, D.C., USA. The world was a smaller place in 1891. The pace of life was more leisurely, and changes came slowly. The number of geologists who attended the Congress was tiny by comparison with the nearly 6,000 geologists registered for the 28th Congress, which was held at the same location. The few hundred who attended the fifth Congress probably all knew one another, and the group was small enough to be photographed on the steps of one of the smaller government buildings in Washington.

The world and the pace of life have changed so greatly over the past century that one can be forgiven for assuming that the issues discussed by our forebears at the fifth IGC must have differed greatly from the issues of today. Nothing could be farther from the truth. Geologists of the late 19th century already were concerned about the magnitudes of key mineral resources, even though automobiles, aircraft, plastics, electricity in every home, and myriad other resource-hungry industrial marvels were as yet unknown. Coal and iron were of particular concern—known deposits were huge, but so were rates of exploitation. Little more than a decade after the fifth Congress, the issue of resource depletion had become a matter of national and international politics. Concern in the USA reached a pinnacle in 1908. At a conference held in the White House that year, Andrew Carnegie (1909) stated, "I have for many years been impressed with the steady depletion of our iron ore supply. It is staggering to learn that our once-supposed ample supply of rich ores can hardly outlast the generation now appearing, leaving only the leaner ores for the later years of the century. It is my judgment, as a practical man accustomed to dealing with those material factors on which our national prosperity is based, that it is time to take thought for the morrow."

The subject of the magnitudes of mineral resources, as well as the adequacy of these resources to meet future needs, has been addressed again and again by speakers and writers at all of the International Geological Congresses. Over the past century, geologists have been optimistic, for the most part, concerning the magnitudes of resources. Perhaps we should not wonder at this. Think of the extraordinary discoveries that geologists have made. Consider all the oil and gas that has been discovered in the USA, Canada, Mexico, Venezuela, the Middle East, the USSR, and elsewhere. Think too of all the porphyry coppers, the giant lead-zinc deposits, the bauxite deposits, and the great new iron districts such as Serra dos Carajás in Brazil, the Krivoy Rog basin in the USSR, and the Hamersley basin in Western Australia. These were all discovered and developed during the century past. Some of the kinds of new deposits would have been familiar to geologists who attended the fifth Congress, but others would have seemed very strange. For example, porphyry coppers were not defined as a class of deposit until the middle years of the 20th century, and the first commercial production of aluminum only commenced in 1888, so knowledge of bauxite deposits in 1891 was sparse indeed. In fact, one of the bauxite minerals, boehmite, was not even defined until the 1920s. A further example is present in the use of metals such as niobium, tantalum, germanium, and indium, all of which postdate 1891, so at the time of the fifth IGC, practically nothing was known about deposits containing them.

The concerns expressed by Andrew Carnegie and his fellow conferees of 1908 have not yet come to pass for two important reasons. The first reason is one in which geologists can justly take pride—we, together with our colleagues in the mining and petroleum industries, have been very successful as a profession in finding new deposits over the past century. The second reason is technology and the way it has opened the world. Economies of scale, such as low-cost bulk-transportation systems, have changed the way the world operates. Resources of all kinds are sought now around the globe

and are shipped to the places where they are needed. In 1891 resource issues had national dimensions; today they have global dimensions, and so they are likely to remain. The remarks in this paper are directed, therefore, to questions of global resources.

Resource issues

All resource issues have three underlying aspects. The first is need or, as economists have taught us to say, demand. Embodied in the term "demand" is a host of questions that are social, technical, political, and financial in nature. We hear these words all the time, but all too often we geologists tend to minimize them because the issues are far removed from geological thinking. Nevertheless, they are questions that we must face eventually. The finding, mining, movement, processing, and use of resources always involve social, technical, political, and financial problems, and we cannot avoid these problems forever.

The second aspect of resource issues is supply. How much of a given resource is there? How accessible are the deposits, and how are they distributed geographically? Here geologists have made their greatest contributions over the past century. Supply questions surely will continue to occupy our attention, but I argue in this paper that they will probably not be the most important questions we and our children will have to face in the century ahead.

The third aspect of resource issues is one that has been ever present, but for which the magnitude only recently has been widely appreciated. That aspect is the consequence, large or small, that the use of a given resource has on the environment. No resource is totally free of environmental consequences. Geologists have a vital role to play in assessing these consequences, and this is where I believe our greatest challenge lies. I conclude that the consequences of use, not the magnitudes of supply, probably will determine the use of resources during the century ahead.

I will discuss briefly each of these issues—need, supply, and consequence, in that order—and I will focus on the aspects that I believe are most important.

Need

Without need, a commodity would not become a resource. Rightfully, need stands first. Need can be complex or simple, but if fulfillment makes performance of the daily tasks more efficient or makes life safer and easier, a resource need quickly can become a resource dependency. Such dependencies cannot be corrected and cured in the same way as medical dependencies just because history reveals a difficult consequence. Increased efficiency in the workplace and safer living conditions lead to an expanded population. No law of nature says that this has to be so, but the history of population since the industrial revolution tells us that the human response tends to make it so, at least up to a population size that greatly exceeds the prerevolutionary starting point.

The global population is now vastly in excess of the population that lived basically an agrarian life a few hundred years ago, as most of our ancestors did. The world's population today is totally dependent on the maintenance of an enormous and complex supply chain of resources. If we break links in that chain, the population must shrink. Each of us, no matter where we live, has become dependent, directly or indirectly, on hundreds of natural materials. The extent of our global dependency grows larger year by year. More than 70 chemical elements and dozens of specific minerals are processed into needed products. On the basis of the heterogeneity of mineral distribution in the Earth's crust, it is hardly surprising that no country in the world today is completely self-sufficient with respect to re-

Figure 1.—Import data of mineral resources for the USA, Japan, and the USSR in the early 1980s. The data are from the U.S. Bureau of Mines and are presented in Craig and others (1988, fig. 2.10).

sources. Even the USSR, having a mighty land area available for resource exploration, chooses to import some needed materials (fig. 1), but times change. The USA had the same choice as the USSR only 50 years ago.

Let us stop for a moment and consider the magnitude of the present per capita consumption of mineral resources in the USA (fig. 2). Here, the total mass of mineral resources consumed is about 17 metric tons (t) per person per annum. The 245 million people in the USA consume almost 4.2 billion t of resources each year. For the world population, the per capita numbers are much lower, but the total consumption is huge because the global population is huge. On a global basis, individual consumption is about 10 t per person per

Stone.....	4900 kg
Sand and gravel.....	3770 kg
Cement.....	383 kg
Clays.....	195 kg
Salt.....	170 kg
Phosphate.....	145 kg
Iron and steel.....	562 kg
Aluminum.....	22 kg
Copper.....	9 kg
Lead.....	5 kg
Zinc.....	6 kg
Petroleum.....	3100 kg
Coal.....	2600 kg
Natural gas.....	1950 kg
Uranium.....	0.1 kg

Figure 2.—Per capita consumption of mineral resources in the USA, 1987. The data are the annual consumption numbers published by the U.S. Bureau of Mines (1987) divided by the population at the end of that year. About 17 metric tons of new mineral materials are required annually by each citizen.

annum. In contrast, the per capita consumption of mineral resources on a global basis in 1891 is estimated to have been about 2 t per annum. Remember that per capita consumption has increased in all societies and excessive consumption is a problem for everyone, not just the industrial countries.

Per capita consumption is growing, and so is the global population. The world's population today exceeds 5 billion. In 1988 the total mass of mineral products consumed by those 5 billion people was 50 billion t. This is the material that is actually used. It does not include all of the material moved in order to facilitate mining, the soil disturbed during house building and parking lot construction, or any of the other disruptions to the Earth's crust. It is material dug out and used directly or indirectly to feed us, clothe us, transport us, heat us, cool us, and entertain us.

We should contrast the world's annual mineral consumption with the mass of sediment that is transported yearly to the sea by all the rivers of the world. Suspended sediment is estimated to be about 14 billion t a year, and the dissolved load is estimated to be about 2.5×10^9 t a year for a total of 16.5 t a year (Milliman and Meade, 1983). This is only one-third of the total mass of mineral resources that is consumed. Indeed, the human population is a geological entity to be reckoned with. Therefore, even small leakages from the resource chain can affect the composition of the world ocean, the atmosphere, streams, and lakes—pollution, as we have come to call it.

The drive behind need is people, so it is instructive to take a brief look at the question of population, which is an exceedingly complex question. The complexity results because it is difficult not to draw simplistic judgments and because many aspects of these judgments tug at questions of private rights, religion, societal preferences, and bodies of law that are the very fabric of our society. However, numbers speak for themselves.

When the fifth International Geological Congress was held, the world population was about 1.7 billion people. Today the global population has passed 5 billion and is nearing 6 billion. The rate of increase is so great that as each minute passes, the world population increases by 170, even when the deaths occurring in each minute are taken into account. When I presented this paper at the 28th Congress, I spoke for 30 minutes, during which 5,100 people were added to the Earth. While people were away from home for 10 days attending the 28th IGC, 2.5 million people were added to the human race, and remember, we are counting not just births, but 2.5 million births in excess of deaths. By the year 2000, this growth rate will mean that the world population will be nearing 7 billion. These projections of population are made by demographers working for institutions such as the World Bank, the United Nations, and the Population Council. The projections presume that some human-engendered catastrophe does not wipe out the breeding population, and they are based in large part on the age structures of societies (fig. 3). From

Figure 3.—Demographics by age and sex for the years 1975 and 2000. A, A typical developed region. In these regions, the population is distributed reasonably evenly by age. Such a population structure tends to maintain itself at the same size; that is, it approximates zero population growth. B, A typical developing region. In these regions, a preponderance of younger people (many still below breeding age) means that a large population expansion must occur before a stable population size is reached, even if people do no more than replace themselves. The diagrams are taken from Craig and others (1988, figs. 1.4a, b). The primary data in these two examples came from the "Global 2000 Report to the President" of the USA in 1980 (Council on Environmental Quality, 1980).

Figure 4.—Population projections to the year 2100. Note that the two countries that rank high in the list of populations today, the USA and the USSR, are projected to fall far behind in the future as countries such as Bangladesh, Nigeria, and Pakistan pass them in numbers. Modified from Demeny (1984).

population structures, population trends can be projected even beyond the year 2000. The optimistic presumption is that all populations eventually will approach a distribution that is more or less even by age, so that the population will maintain itself but not grow.

The projected population numbers reach alarming proportions. A thoughtful and conservative discussion of the projections was presented in a paper by Dr. Paul Demeny (1984) of the Population Council. In that discussion Demeny suggests, perhaps optimistically, that the world's human population will level off eventually at about 12 billion people (fig. 4). Note in figure 4 that two countries ranking high in the list of populations today, the USA and the USSR, are projected to fall far behind in the future, as countries such as Bangladesh, Nigeria, and Pakistan pass them in numbers. Discussions concerning the populations of individual countries can become very heated. Someone may consider a projected number to be too high or another too low. Some objections are correct and some are probably incorrect, but over the past 50 years, demographers have been rea-

sonably good with their projections of global population numbers. There seems little reason to say that they have erred badly in future projections.

I find it easier to think of the global population issue in terms of population density rather than total numbers. The world's land area is 153 million square kilometers (km^2). If we exclude the areas covered by permanent ice and the places above 5,000 meters (m) in altitude, this leaves about 133 million km^2 of dry land on which we can conceivably live and from which we can produce or recover resources in one way or another. Some land, of course, is pretty mean and some climates are very inhospitable, but even so, each square kilometer can supply some resources.

In 1891 the global population density was 11 people per km^2 . This equates to a square block of land 300 m on an edge for each person alive then. I think of this block of land as one's support square. Today the support square is 160 m on an edge, no larger than one city block in Washington, D.C. The square can be thought of as the amount of land that must supply not only all of the resources that an individual will use throughout a lifetime, but also all resources to fulfill the same purposes for others who follow. Somehow, that space also must consume most of the solid wastes left over. By the year 2000, the square will be 140 m on an edge, and by 2088, it will shrink to 100 m on an edge (fig. 5).

Population densities in a few regions or countries are of interest because they indicate just how tightly packed we humans can live. In Japan and Korea, each person has a support square 57 m on an edge; in China, 68 m; in India, 71 m; and in Europe, 100 m. The USA by comparison seems sparsely populated, as each person has a support square 198 m on an edge, and hardly anyone seems to live in Canada, where each person enjoys a support square 1,000 m on an edge.

You may protest that these numbers are unrealistic and that a vast world ocean also must be taken into account. Do not place your hopes too high. For today's 5 billion people, each has an oceanic support square 265 m on an edge. When we are 12 billion, that square will be only 175 m on an edge.

The land support square in Europe today, 100 m on an edge, is what the land support square will be for the entire world when the population reaches 12 billion. Obviously, such a densely packed herd of large mammals—the human herd—inevitably must cause massive changes in the environment by simply being alive.

Supplies of mineral resources

Where minerals are concerned, the economy is engaged continuously in a struggle between two forces: advances in technology that enhance the productivity of labor and the exhaustion of resources that diminish productivity. Over the last two centuries, technology has been the clear victor, but will that pattern hold true for the century ahead?

Year	Global Population Density		
	# $\times 10^9$	# / km^2	Support square, meters on edge
1888	1.7	11	300
1988	5.0	38	160
2000	7.0	52	140
2088	12.0	90	100

Figure 5.—Population density of the world in 1888, 1988, 2000, and 2088. The figures are derived from the population numbers (#) of Demeny (1984) and 133 million km^2 of conceivably inhabitable land.

Figure 6.—Price and production curves for zinc (A) and lead (B) over the past 150 years. Note the steady rise in production but approximately level prices of both metals. Data are normalized to the value of the pound sterling at the end of 1983. The figures are taken from Skinner (1987, figs. 4, 6). Basic data came from an article in *Mining Annual Review* (1985).

In 1986 I joined with Digby McLaren to organize two Dahlem Conferences. Present were geologists, engineers, technologists, economists, and other scientists of various disciplines. Some of my remarks here are derived from concepts discussed at those conferences and published in the conference volume, titled "Resources and World Development" (McLaren and Skinner, 1987).

The experts struggled with the problem of resource magnitudes at the Dahlem Conferences, as they have at other conferences. They reached the conclusion that the magnitudes of the global resources of minerals mined for purposes other than energy resources are such that physical exhaustion need not be a problem a century hence. Sufficiency in a global sense is not likely to be a limiting issue, but heterogeneities of geographic distribution almost certainly will continue to be the major problems, just as they are today. What seems most likely is that major shifts will occur in both prices and sources of supply of many mineral resources. These changes probably will have major impacts on the geological profession.

First, we will consider the question of prices. Over the past century and a half, the real prices of many mineral commodities have stayed approximately level (fig. 6). The reasons for a possible change in this 150-year pattern differ from commodity to commodity, but there are two underlying causes. (1) Over the century ahead, we will have to exploit less attractive, more expensive ores, and we will have to do so in the face of level or rising costs for energy. And (2) so far we have not had to pay the environmental costs of using mineral resources. Already there are indications that the costs of recovery have been reduced as much as possible through large volumes. And surely everyone must see now that environmental costs are going to have to be paid.

Second, what of the questions of changes in the sources of mineral supplies? Over the past 50 years, a slow but steady movement has shifted the sources of metallic mineral supplies from today's industrial countries to the developing countries. That trend is likely to continue for some years into the future. However, I think that over the next century, there will be a slow reversal and that when geologists gather to celebrate the 53rd IGC in 2088, mining will still be alive and strong in North America and Europe. The reasons behind this statement are straightforward. Prospecting for new deposits is most active in countries that have histories of political stability. That is unlikely to change. A certain amount of favorable land remains to be prospected by conventional means in these favored areas, but in both favored and unfavored areas, the hunt eventually will be for blind deposits that are buried beneath thick blankets of surface rocks. That search will become intense over the next century.

In some favorable places, blind ore bodies have been found beneath 0.5 km of cover. We have every reason to believe that prospecting will be possible eventually to depths of many kilometers, if the needed background work has been done. That background work involves mapping in the third dimension by using techniques such as deep-seismic sounding and deep continental drilling. COCORP, Lithoprobe, and similar programs are just a hint of the work that lies ahead. Exploration geologists of the future will tend to work in the countries that have made the long-term investment needed to measure and map the Earth's crust to depths of 15 to 20 km. The countries that are starting to make that needed investment are today's industrial countries, such as the countries of North America, Europe, and Australasia. North America provides an example of the potential for such deep exploration (fig. 7).

Figure 7.—Likely areas for deep prospecting in North America. Precambrian rocks are exposed in Canada but are largely covered in the USA. In Canada the rocks are richly mineralized. Phanerozoic cover is less than 1.5 km thick inside the patterned areas, and in this region, the basement is readily accessible by today's drilling technology. The area is huge and the prospects are excellent. The dashed line marks the tectonic boundary of the shield, and most of it is no deeper than 5 km. Taken from an article by Skinner (1989, fig. 6).

Supplies of energy resources

What about energy resources? No resource issue receives more attention than the issue of energy resources, especially fossil fuel. Considering John Bookout's elegant paper in this issue, I have little specific to add. However, on a general level, some additional remarks are warranted.

The current pattern of energy use is weighted heavily toward fossil fuel. Today, about 40 percent of the world's fuel is oil and about 30 percent is natural gas. What seems clear on both a global scale and a local scale is simply this: by drawing on all fuel sources, we need not face energy shortages over the next century. We may have to pay more for energy, but it will be worth the cost if it avoids the big danger that lies ahead. The big danger is an obsessive dependency on one fuel and a lack of flexibility to expand other energy sources.

The case against obsessive dependency is stated nicely by Bent Elbek (1988, p. 100) of the Niels Bohr Institute who wrote:

The specter of the energy crisis has faded away. But it could reappear, because nothing fundamental has changed in the energy outlook. Oil is still the world's most important fuel. Its share of the primary energy supply has been reduced only slightly from 44 percent in 1975 to 40 percent today. The world now consumes more oil than in 1973 drawing on the same limited resources. The main change since then is that the OPEC countries produce less

and the non-OPEC countries more. The United Kingdom, Mexico and the Soviet Union are the major new suppliers which, for the time being, have forced the OPEC countries to produce less than they can and want to. But the OPEC countries still possess 75 percent of the proven oil reserves. It seems inevitable that sometime in the not too distant future the scene will be set for another oil crisis.

One might argue about the percentages stated by Elbek, but the numbers do not change sufficiently to negate the conclusions he draws.

The most important energy questions for the 21st century, so far as I see them, are the following. First, how much energy is used, and second, what are the likely patterns for energy use in the future?

So far as energy use is concerned, consider this. In 1988 the human population used about 4×10^{20} joules (J) of energy. This is equivalent to burning 2.2 t of coal or nearly 12 barrels of oil that year for every living man, woman, and child. Few would argue that this consumption rate could be changed quickly without massive social disruption—not in 2 years, 5 years, or probably even 10 years. We are just starting to become aware of our massive dependency and the consequences of such a high rate of energy use. One of the consequences is that an enormous amount of CO_2 is pumped into the atmosphere, about 1.2 t for each person every year (fig. 8). Reducing our dependency on fossil fuels clearly has many positive aspects, but realistically, one has to conclude that the dependency probably will grow even larger before it declines.

Now for the question of future patterns of energy use. In 1929 a famous geologist, Foster Hewett, demonstrated that the record of mineral exploration and exploitation in Europe revealed patterns that were applicable in a wider sense to all mineral resources (fig. 9). King Hubbert used Hewett curves to great effect in his analysis of onland oil production and its future potential in the USA. Now Hewett curves are being projected far beyond the limits that Hewett himself might have imagined. Considering historic energy sources, Joel Darmstadter (1986) used Hewett curves to suggest that the pattern shown in figure 10 forecasts the future. A lot more fossil fuel will be burned, apparently, before other energy sources start to dominate.

Let me summarize my thoughts on mineral and energy supplies. The magnitudes of undiscovered mineral resources of all kinds are such that demand probably could be satisfied for the next century if

Figure 8.—Increasing amount of CO_2 released to the atmosphere. Taken from Clark (1986, fig. 1.14).

Figure 9.—Hewett curves demonstrating stages in mining and metal production in industrial countries. The arrows indicate my estimates of four industrial countries at the present time. Note that as time passes a country moves from left to right. The source of the figure is Skinner (1977) based on Hewett (1929).

Figure 10.—Predictions by Darmstadter (1986, fig. 5.10) for future energy sources. Note the close tracking of Hewett curves for several energy sources. Wood and coal appear to have peaked and now are declining. Oil is close to peaking, and gas is still rising, as is nuclear power. Solfus (solar and fusion) has yet to be achieved.

(and, of course, it is a big if) geologists, geophysicists, geochemists, and others continue to find ways to push the exploration potential for blind ore deposits ever deeper. The historic record of our expanding scientific and technical expertise suggests that probably we will be able to do so. Of energy, there is no shortage. The issue here is the need to develop flexibility of source. Not all of the potential energy sources will require the skills of geologists to identify resources—solar energy, for example—but other sources will call on geological skills. Geologists have an enormous challenge ahead in the geothermal energy area. The natural successor to fossil fuels, in a geological sense, is geothermal power: energy from the Earth's great store of heat. The technical challenge to use this energy source is vast but so is the magnitude of the resource. A simplistic example serves to

illustrate this point. If a person lives for 75 years and throughout this lifetime uses energy at a rate of 10,000 watts (approximately the per capita consumption rate in the USA), that person will use 240×10^{11} J. If we take the heat capacity of rock in the upper crust as 20 J/g, the density of rock as 3 g/cm³, and the average geothermal gradient as 40 °C/km, the heat energy above 25 °C in a column of rock 1 m square and 6 km deep is 250×10^{11} J.

Consequences of use

Finally, we must consider the third aspect to resources: the consequences of their use through their influence on the environment. The use of resources has been recognized for a long time to affect the environment, and this recognition often has been articulated very clearly. One of the first of our profession to do so, and one of the best, was Vernadsky, the great Russian geochemist, who wrote in 1929: "... for the first time man has become a large-scale geologic force. ... Chemically, the face of our planet, the biosphere, is being sharply changed by man consciously, and even more so, unconsciously." Vernadsky's concern is now the concern of every living soul, and that concern is starting to influence our professional and scientific thinking.

In 1988 Raymond Price, then Assistant Deputy Minister of the Geological Survey of Canada (G.S.C.), wrote in a letter to me that "resource exploitation and global pollution are high in the consciousness of the Canadian public. Public opinion polls indicate that Canadians are concerned enough to pay the price to correct the situation." He continued, "At G.S.C. we think that matters relating to global change, environmental geology and (natural) hazard analysis will occupy us increasingly." But which matters are really the most pressing? We hear a lot about the CO₂ problem, the methane issue, the ozone question, contaminants in the ocean, and so forth. We are probably going to hear more and more about them. However, we hear too little about two issues that have strong geologic affinities—issues that I suggest may be far more serious in the long run.

The first issue concerns water. More and more of the world's ground-water supplies are being withdrawn for irrigation (fig. 11) and for household and industrial use in densely populated cities. Ground water is cheap to use because pumps and their fuel are less expensive than the costs of damming rivers and building distribution systems. As a result, withdrawal rates in many places around the world equal or exceed recharge rates. To a certain extent, the situation is reversible—simply stop pumping. The problems with this solution are that food raised by irrigation is needed for the growing population and that cities relying on pumped water cannot afford new dam systems.

The second issue concerns arable land. The area of land around the world given over to grain production has peaked apparently and is starting to decline (fig. 12A). The main reason for the decline seems to be soil erosion. Intensive cropping on marginal lands has caused very large areas to be stripped of soil so severely that they can no longer be used. To compensate for reduced acreage, the growing population is fed by increasing yields per hectare on the better farming land (fig. 12B). This increase is achieved through continual cropping and the intensive application of fertilizers (fig. 13). Soil degradation and increased rates of erosion result.

How severe is the erosion problem? The data for stressed countries speak for themselves (fig. 14). Approximately 40 percent of the once-arable land in India is reported to have been degraded through overly intense agricultural uses. Topsoil there is said to continue to be lost at a rate estimated at 4.7 billion t a year. However, India is not alone. Severe erosion occurs in North America too. Estimates of the rate of topsoil loss in excess of soil regeneration in the USA indicate that 1.7 billion t are being lost each year. Data bearing on

Figure 11.—A, World acreage under irrigation, and B, acreage under irrigation in the USA. Note that over the past century the trends in both cases have been strongly upward. Both figures are from Brown (1988, figs. 4 and 5).

global erosion rates were gathered first by a geologist, Sheldon Judson (1968). More recent work is summarized by Lester R. Brown (1984). Around the world, soil loss amounts to an estimated 25 billion t a year, or 5 t for each person a year. To put this another way, the average food consumption is about three-quarters of a metric ton for each person a year, and to produce that food, 5 t of soil—seven times the food mass—is lost. The redistribution by wind and water of such an enormous quantity of material is a geologic problem and, if continued unchecked, eventually must have massive consequences both for the environment and for food production.

The manifold concerns about the consequences of resource use have led to a great new initiative of the International Council of Scientific Unions (ICSU): the International Geosphere/Biosphere Programme (IGBP) called "A Study of Global Change." According to the program description, the focus is: "To describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions."

Many geologists have expressed concern that the IGBP will focus only on climate and the atmosphere, that other aspects of re

Figure 12.—A, Area of the world that is producing grain. The area peaked about 1980 and has been declining slowly since then. B, World grain yield per hectare. Despite the decline of areas growing grain, production has been increased through intensive cropping and increased fertilizer use. Both figures are from Brown (1988, figs. 3, 6). The primary sources of data used by Brown in both cases came from the U.S. Department of Agriculture (USDA).

Figure 13.—Grain-producing area compared to fertilizer use on a per capita basis. Taken from Brown (1988, fig. 7). The primary data used by Brown concerning fertilizers came from the Food and Agriculture Organization (FAO), and data concerning grain areas came from USDA.

source production and use will be ignored, and that geology will have only a minor role in the program. I do not agree. The focus of IGBP is the focus that much of our science will have in the century ahead, and we geologists will have to fill many roles. Real-time monitoring of geologic processes will lead to an understanding of our Earth that is hard to imagine today. In the process, I predict that our thinking will change dramatically. We cannot stop the human herd from changing the environment, but we can learn which stresses cause the greatest rates of change, and a century hence, perhaps even less, we will have learned to modulate the rates. Insightful management is the way ahead. In short, once again we must move to be in balance with our environment, as the handful of hunter-gatherers, our ancestors, were a hundred-thousand years ago. If we fail to do so, it will not be due to limitations of geologic resources but rather to limitations of the greatest resource of all, human intelligence.

References

- Brown, L.R., 1984, Conserving soils, in Brown, L.R., Chandler, William, Flavin, Christopher, Postel, Sandra, Starke, Linda, and Wolf, Edward, eds., *State of the World—1984*: New York, W.W. Norton and Company, p. 53–73.
- 1988, *The changing world food prospect: The nineties and beyond*: Worldwatch Paper 85, 58 p.
- Carnegie, Andrew, 1909, Address on The conservation of ores and related minerals, in Conference of Governors, Conference of Governors in the White House, Washington, D.C., May 13–15, 1908, Proceedings: Washington, D.C., U.S. Government Printing Office, p. 14–25.
- Clark, W.C., 1986, Sustainable development of the biosphere: Themes for a research program, in Clark, W.C., and Munn, R.E., eds., *Sustainable development of the biosphere*: New York, Cambridge University Press, p. 5–48.
- Council on Environmental Quality (U.S.), 1980, *The global 2000 report to the President: Entering the 21st century*: Washington, D.C., U.S. Government Printing Office, v. 1, 47 p.; v. 2, 766 p.
- Craig, J.R., Vaughan, D.J., and Skinner, B.J., 1988, *Resources of the earth*: Englewood Cliffs, N.J., Prentice-Hall Inc., 395 p.
- Darmstadter, Joel, 1986, Energy patterns—In retrospect and prospect, in Clark, W.C., and Munn, R.E., eds., *Sustainable development of the biosphere*: New York, Cambridge University Press, p. 140–170.
- Demeny, Paul, 1984, A perspective on long-term population growth: *Population and Development Review*, v. 10, no. 1, p. 103–126.
- Elbek, Bent, 1988, What happened to the energy crisis? A commentary on the global commentary papers, in Kristensen, T., and Paludan, J.P., eds., *The Earth's fragile systems: Perspective on global change*: Boulder, Colo., Westview Press, Inc., p. 100–102.
- Hewett, D.F., 1929, *Cycles in metal production*: American Institute of Mining and Metallurgical Engineers Year Book 1929, p. 65–93.
- Judson, Sheldon, 1968, Erosion of the land, or what's happening to our continents?: *American Scientist*, v. 56, no. 4, p. 356–374.
- McLaren, D.J., and Skinner, B.J., eds., 1987, *Resources and world development*, Dahlem workshop reports: New York, John Wiley, 940 p.
- Milliman, J.D., and Meade, R.H., 1983, World-wide delivery of river sediment to the oceans: *Journal of Geology*, v. 91, no. 1, p. 1–21.
- Mining Annual Review, 1985, *Metals output and prices—A historical review*: London, London Mining Journal Books Ltd., p. 22–25.
- Skinner, B.J., 1977, Cycles in mining and the magnitude of mineral production: *Transactions of the Royal Society of Canada*, 4th series, v. 15, p. 13–27.
- 1987, Supplies of geochemically scarce metals, in McLaren, D.J., and Skinner, B.J., eds., *Resources and world development*, Dahlem workshop reports: New York, John Wiley, p. 305–325.
- 1989, Mineral resources of North America, in Bally, A.W., and Palmer, A.R., eds., *The geology of North America—An overview*, v. A of *Geology of North America*: Boulder, Colo., Geological Society of America, p. 575–583.
- U.S. Bureau of Mines, various years, *Minerals yearbook*: Washington, D.C., U.S. Government Printing Office.
- Vernadsky, V.I., 1929, *The biosphere*: Oxford, Synergetic Press, Inc., 82 p. [English language edition published in 1986 based on the 1929 edition in French]. □

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Land Type	Area (million hectares)
Degraded nonforested land	94
Saline and alkaline land	7
Wind-eroded land	13
Water-eroded land	74
Degraded forested land	35
Total degraded land	129
National land area	329

Source: D.R. Bhumba and Arvind Khare, *Estimate of Wastelands in India*, Society for Promotion of Wastelands Development, New Delhi, undated.

Figure 14.—Degraded land in India. The data are quoted by Brown (1988, table 3) from the source given in the figure.

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