

2000 Presidential Address: Grand Challenges in Earth and Environmental Sciences: Science, Stewardship, and Service for the Twenty-First Century

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INTRODUCTION

A measure of our future success as earth scientists will depend on our ability to help our global society find and implement effective solutions to environmental problems. In its most inclusive sense, environmental science could be considered to be “the” earth science. As used here, environmental science is defined to be a broadly integrative study of processes occurring at or near the surface of Earth and involving interactions between the uppermost lithosphere, the atmosphere, the hydrosphere, and the biosphere (which includes mankind). It encompasses a broad range of traditional disciplines including biology, ecology, meteorology, atmospheric sciences, hydrology, oceanography, geology, and geophysics.

Broad agreement exists within the scientific community that we must employ an integrated systems approach to solving complex environmental problems. Our long-term goal for environmental science should be to understand natural and perturbed systems well enough to predict outcomes, consequences, and impacts.

The effects of a number of important drivers of environmental science must be factored into our approaches to solving environmental problems: population growth, concentration of population into huge urban centers (many of which are situated in areas subject to natural hazards), an accelerating need for resources, mankind as a significant agent of change in the earth system, and unrealistic expectations for absolute guarantees from science. This final driver is a purely sociopolitical factor, but a critical one in seeking societally acceptable solutions to environmental problems.

Rapid technological developments in information science, telecommunications, and sensor development in the past few decades have greatly increased our ability to tackle complex environmental problems. In the earth sciences, we are only beginning to harness the power of broad bandwidth observational systems and real-time data delivery to probe active natural systems and processes on spatial scales and time scales never before possible. For example, we now have the capability to globally monitor physical properties daily (e.g., see www.ssec.wisc.edu/data/sst.html for daily sea surface temperature maps). Fifty years ago, the concept of having daily global snapshots of direct measurements of a variety of earth properties freely available on home computers was unthinkable. These advances will enable increasingly sophisticated numerical modeling of natural systems, but in many cases our scientific understanding of the interconnected physics, geology, chemistry, and biology of these natural systems is still at the infancy stage.

GRAND CHALLENGES IN EARTH AND ENVIRONMENTAL SCIENCE

So what are the big environmental problems, the grand challenges of the coming decades? Here are six, characterized on a process level rather than a discipline or theme basis:

- ▲ Recognizing the signal within the natural variability
- ▲ Defining mass flux and energy balance in natural systems
- ▲ Identifying feedback between natural and perturbed systems
- ▲ Determining proxies for biodiversity and ecosystem health
- ▲ Quantifying consequences, impacts, and effects
- ▲ Effectively communicating uncertainty and relative risk

Each of these challenges will require creative attacks involving integration of efforts in all the disciplines mentioned above. For an alternative view of grand challenges in environmental science from a topical perspective, see National Research Council (2001).

Recognizing the Signal Within the Natural Variability

This first challenge is, of course, at the crux of the global warming conundrum. Are steady increases in global temperature (and accompanying climate changes) in the past 150 years simply an expression of natural variability, or are they a direct result of mankind’s activities that have resulted in an increase in greenhouse gases? The weight of the scientific evidence suggests the latter, however the debate on global warming has turned into a high-stakes, international issue with potentially multibillion-dollar implications.

Documenting and understanding natural variability is a vexing topic in almost every environmental problem: How do we recognize and understand changes in natural systems if we don’t understand the range of baseline levels? Our geologic perspective allows us to view the short interval of historical records with a healthy skepticism. Figure 1 shows a 350 year record of precipitation in California (1600–1950), determined using 52 tree-ring chronologies as proxies for precipitation (Fritts, 1984). I have added two important historical dates to this chronology: 1769, the founding of the first of the Spanish missions in California and the inception of written records; and 1849, the beginning of the California gold rush that within years increased the number and

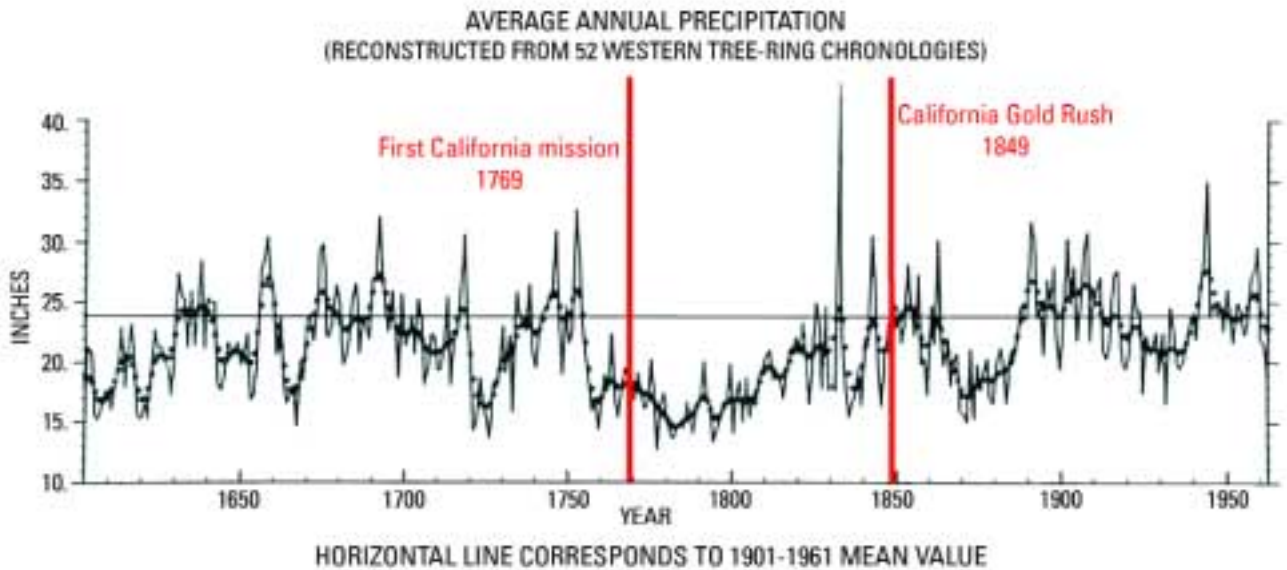


Figure 1. Average annual precipitation in California for 1600–1950 as determined using tree-ring chronology from 52 trees as a proxy for precipitation (Fritts, 1984). Horizontal line represents 1901–1961 average precipitation value from instrumental records.

distribution of population manifold throughout the state. These two dates roughly bracket a significant 80–90 year interval of apparent drought relative to the 1901–1961 average precipitation value. While this extended dry period occurred during a period of historical records, it was probably not noteworthy since the mission padres had no baseline against which to judge the climate. Clearly, a repeat of a similar extended dry period in California today due to natural variability would be devastating to the vast agricultural enterprise that provides ~50% of the vegetables, fruits, and nuts for the entire nation (California Agriculture Statistics Service, 1999) and feeds a thirsty population with one of the fastest growth rates in the country.

Natural variability is important on both spatial and temporal scales. In an attempt to establish natural geochemical background baselines to monitor environmental change, Davenport et al. (1993) analyzed samples of organic sediment in more than 40,000 lakes in Newfoundland and Labrador. They concluded that compared to the regional background, there was no evidence of enrichment of arsenic levels in the vicinity of the major urban center of St. John's. In contrast, the lead levels they measured near St. John's were above the ninety-ninth percentile of values found in all Newfoundland, including areas of lead mineralization, suggesting an anthropogenic source near St. John's. The regional baseline data thus provide the range of natural variability to assess the geochemical signals within the urban areas.

Defining Mass Flux and Energy Balance in Natural Systems

This second challenge requires a thorough quantitative understanding of the physics, chemistry, geology, and biology of natural systems. Understanding biogeochemical cycles such as the carbon or nitrogen cycle is fundamental to

understanding how larger natural systems, such as the global climate system, function. The name itself—biogeochemical cycles—implies complex, interconnected processes, which involve water, air, soil, biological, and sometimes human pathways (Fig. 2).

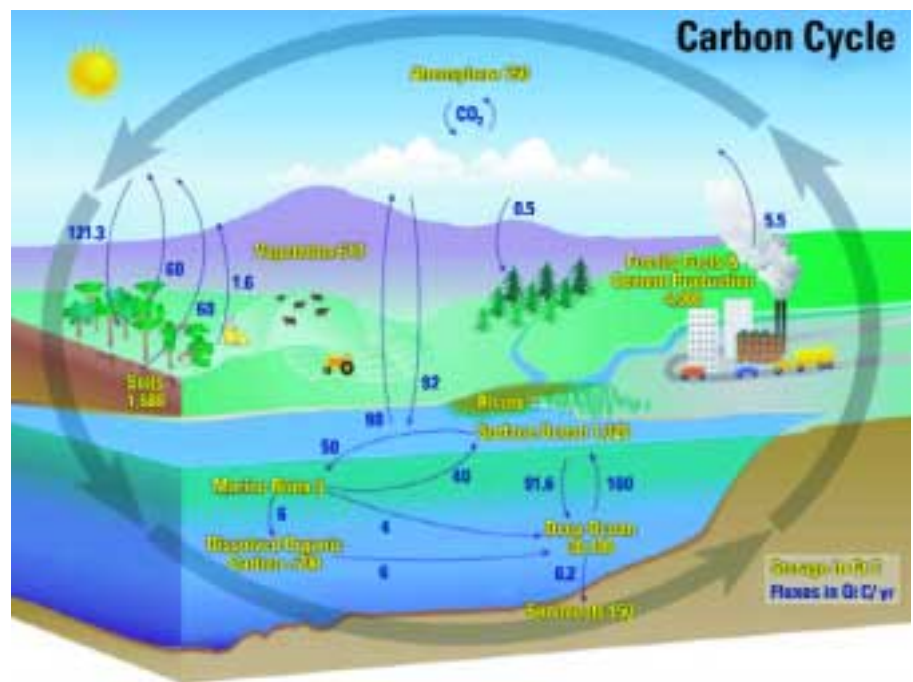


Figure 2. Major fluxes and storage associated with carbon cycle. Image courtesy of NASA Ecology Program. Fluxes and storages from Intergovernmental Panel on Climate Change, 1995 Special Assessment Report on Climate Change. See www.unep.ch/ipcc/pub/sarsum1.htm.

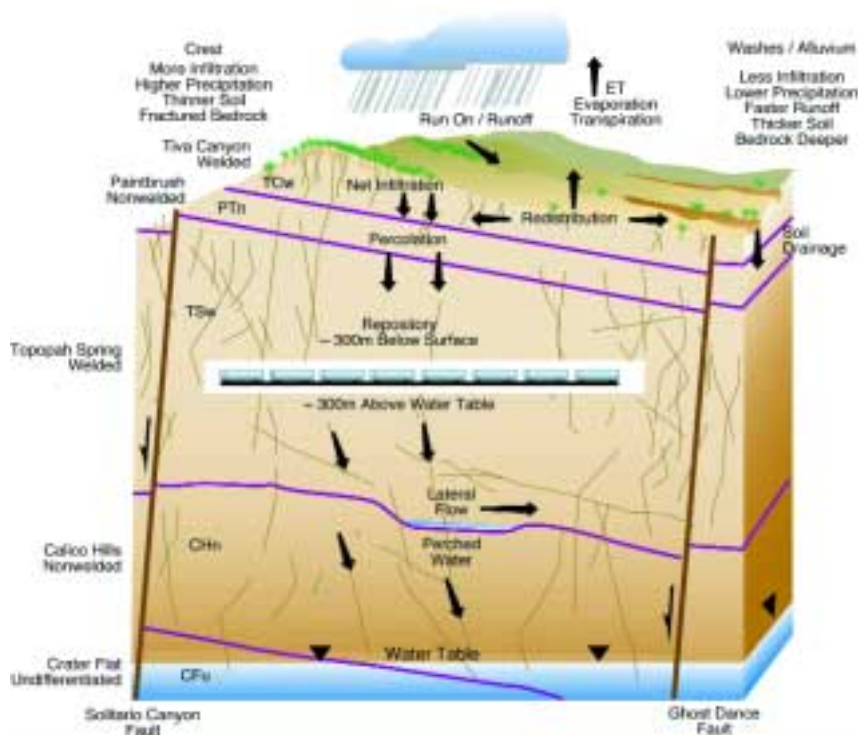


Figure 3. Block diagram showing processes acting within proposed vadose (unsaturated) zone repository at Yucca Mountain (Office of Civilian Radioactive Waste Management, 1998).

A practical example of a natural system that we have a critical need to understand is the vadose or unsaturated zone: the near-surface zone in Earth where water exists but does not fill interconnected pore space. As indicated in Figure 3, interaction of climate, rock properties, hydrology, and biology through evapotranspiration are essential in producing the net upward flux of moisture within the near surface to assure that the zone remains unsaturated. The vadose zone in fractured rock in the arid west is where we plan to store (and in fact are already inadvertently storing) high-level radioactive waste (e.g., the proposed repository at Yucca Mountain, Nevada, and the Hanford Reserve, a former nuclear weapons facility located along the Columbia River in southeastern Washington). However, quantitative understanding of the myriad of critical interconnected atmospheric, hydrologic, geochemical, and biological processes acting on and within this zone remains elusive. As indicated by former under-secretary of energy, Ernest Moniz, in a *New York Times* article on the myriad of problems with tanks leaking high-level waste at the Hanford Reserve (“Admitting Error at a Weapons Plant,” March 23, 1998), “There has not been enough science for vadose zone assessment. ...The vadose zone is intellectually virgin territory.”

Moniz, a former chair of the Physics Department at the Massachusetts Institute of Technology, recognized the need to understand the entire system in order to be able to assess human impacts upon it.

A lack of understanding of this natural system has led to solutions that could exacerbate existing environmental problems at the Hanford Reserve, which is currently under U.S. Department of Energy (DOE) control for maintenance and cleanup. On the central plateau of the Hanford site, ~55 million gallons of liquid, high-level radioactive waste is stored in 177 below-ground tanks. The tanks, 148 of which are single walled, were filled with the waste beginning in the 1940s. Not surprisingly, at least one-third of the tanks are believed to have leaked, and more than one million gallons of the liquid waste (with an estimated more than 1.8 million curies) is now in the subsurface (National Research Council, 2000). DOE engineers initially believed that the unsaturated zone would act as a barrier to contaminant migration, and that transit times to deep aquifers below the vadose zone would be on the order of tens of thousands of years. However, large plumes of radioactive and chemical contaminants have already been detected in the aquifer underlying Hanford and indicate transit times

through the vadose zone of some contaminants of tens of years, not tens of thousands of years (National Research Council, 2000).

To protect workers from possible hazards associated with the leaking tanks, site engineers decided to cover the ground surface above the tanks with gravel to prevent the spread of contamination by wind, rooting vegetation, and burrowing animals. This solution, of course, reduced the risk of surface contaminant transport as well as fire hazards, but may have increased infiltration, thereby providing a potential driving force to carry already leaked contamination to the groundwater. In addition, by destroying the vegetation, a critical biological pathway for upward flux of water through evapotranspiration in the vadose zone was destroyed.

Identifying Feedback Between Natural and Perturbed Systems

As the vadose zone example demonstrates, this third challenge is linked to the previous challenge but includes the recognition that actions of man have deliberately or inadvertently perturbed natural systems. A dramatic example of such feedback affecting local urban weather has been suggested near Atlanta, Georgia. A comparison of satellite infrared imagery taken over a 19 year period indicates the extensive urban sprawl in the vicinity of that city over the past two decades (Fig. 4). The imagery indicates the ground is actually hotter and emitting more heat at night even though evening air temperatures are cooler (Quattrochi et al., 2000). Bornstein and Lin (2000) have suggested that evening thunderstorms southwest of Atlanta are caused by the effects of an urban heat island created by the urban sprawl.

Probably nowhere has mankind had a bigger impact than on the water cycle. In addition to the natural components of this cycle, we must also understand the effects of irrigation, flood control, pollution, reclamation, urban use, and agricultural use, among others. For millennia, mankind has been a victim of the water cycle. Today, while we fundamentally control a great deal of the water cycle, we have only a nascent understanding of the full impact of our control on this system. The water cycle is, of course, just one component of the global climate cycle, the one natural system for which we are furthest along in developing complex computer models that incorporate not only the significant physics and chemistry

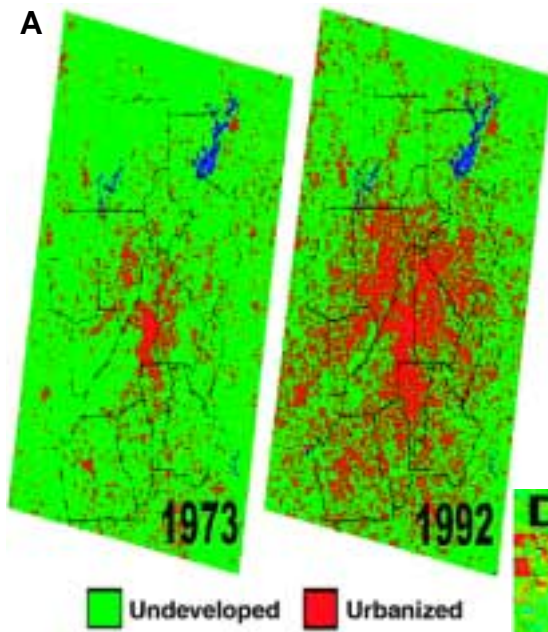
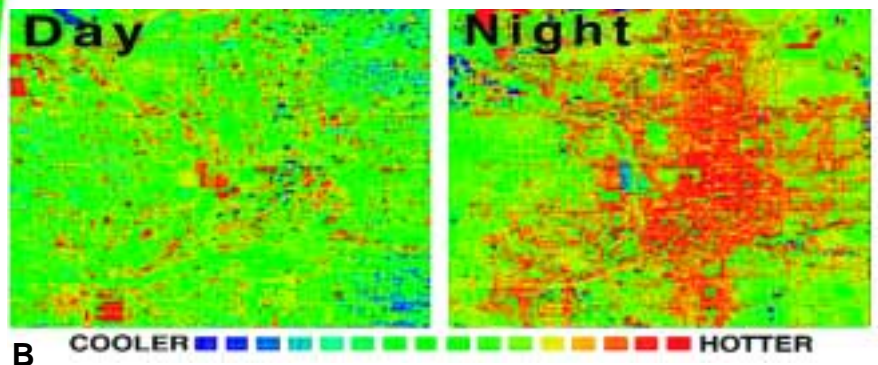


Figure 4. Urban heat island created by urban sprawl in vicinity of Atlanta, Georgia. **A:** Comparison of infrared images taken in 1973 and 1992 indicating extensive growth of development in this 20 year period. **B:** Comparison of daytime (left) and nighttime (right) surface temperatures around Atlanta inferred from thermal infrared data. Images courtesy of Dale Quattrochi, Project ATLANTA (ATLanta Land use ANalysis: Temperature and Air quality), at NASA Marshall Space Flight Center. See www.ghcc.msfc.nasa.gov/urban/urban_news.html.



of the system but also attempt to incorporate some of the complex feedbacks induced by the activities of man.

Identifying Proxies for Biodiversity or Ecosystem Health

Identifying geologic, chemical, or biologic parameters or a suite of parameters that can indicate the health or biodiversity of an ecosystem represents a substantial challenge for all practitioners of environmental science. This challenge gets at the crux of solving environmental problems. Once we think we have found solutions for environmental problems, how do we monitor or measure (one hopes remotely) parameters that indicate the effectiveness of our corrective actions or efforts at restoration or remediation?

Some tools for remote monitoring of ecosystem health already exist. A National Aeronautics and Space Administration (NASA) sensor currently being tested, the Vegetation Canopy LIDAR (light detection and ranging), or VCL tool, can measure the density and structure of forest vegetation (NASA, no date). By analyzing multiple bounces within the reflecting radar signal, this sensor is able to map the areal distribution of tree height, the vertical structure within the forest, and the subcanopy topography at very high resolution. NASA plans to launch a satellite-based VCL system to do forest biomass monitoring on a global scale in 2003. Interestingly, geologists in the U.S. Geological Survey (USGS) Earthquake Program have used LIDAR obtained from aircraft to map the topography under the dense tree cover and discover young thrust fault scarps in the Seattle, Washington, region (Haugerud et al., 2001; Blakely et al., 2002). In this case, the vegetation canopy information is simply noise!

We also need to explore new types of land-based monitoring techniques and capabilities to measure the health of natural or perturbed systems. Restoration of wetlands is an issue currently receiving a great deal of political and economic attention. Ecologically, wetlands provide numerous critical functions, including: filtering sediments and chemicals from water washed through them, providing flood control, helping regulate atmospheric gases, and providing habitat and food that attract

and support abundant fish and wildlife (Constanza et al., 1997). The state of California alone has lost 90%–95% of its wetlands since the middle of the nineteenth century (Natural Resources Conservation Service, 1999; California Habitat Protection Division, Wetlands, no date). Louisiana has requested federal funding for a \$14 billion plan to restore its coastal wetlands, which are disappearing at a record pace (Bourne, 2000). How can we monitor the progress of such a massive restoration effort? Perhaps by deploying millions of low-cost, low-power sensors to monitor and report back in real-time critical parameters such as temperature, humidity, salinity, and water chemistry, which are then continuously processed and analyzed. Of course, to do useful monitoring, we need to understand the system being monitored. Maybe it is time for a grand experiment to make a big step forward.

Quantifying Consequences, Impacts, and Effects

This fifth challenge is directly related to the long-term goal of understanding natural systems well enough to quantify their consequences and impacts in response to changes in natural or anthropogenic forcings. We need to build complex computer models of natural systems that can forecast impending disasters and predict their likely effects or can predict the consequences of a given societal decision or the trend or change in a natural system.

Figure 5 illustrates such a prediction for the change in Douglas fir growth range corresponding to a doubling in CO_2 over pre-industrial levels, a level we might experience sometime this century if current emission rates of greenhouse gases continue. Thompson et al. (1998) used knowledge of the factors controlling Douglas fir growth and the results of climate modeling to predict a significant contraction of the range of Douglas fir in western North America in a $2 \times \text{CO}_2$ climate.

For most systems, however, we will not be able to predict absolutely, but must forecast probabilistically. We can predict the most likely outcome and assign a level of certainty to that prediction—or give a range of the most likely outcomes at a given confidence level. Probabilistic forecasting is widely applied in my own field, the study of earthquakes and earthquake hazards. We are currently unable to scientifically predict earthquakes, and even if we could, that would not prevent the damage to buildings and infrastructure. A recent study led by the USGS in the San Francisco Bay area assigned a 70% likelihood of a damaging earthquake (≥ 6.7 M) striking the region during the next 30 years (Working Group for Northern California Earthquake Probabilities, 1999). The 30 year time frame of this forecast was selected as large enough to represent a significant fraction of the earthquake cycle for major events on any given fault (typically several hundreds of years) and short enough to have some societal reference (e.g., the length of a typical home mortgage). The high likelihood indicates mitigation measures might be cost effective.

This forecast gives only a likelihood of the occurrence of a future earthquake and not its likely effects. The forecast information can be combined with theoretical models of earthquake ruptures and seismic wave propagation to give annual likelihoods of exceeding a given level of ground motion. The USGS National Seismic Hazards maps (<http://geohazards.cr.usgs.gov/eq/>) are probabilistic maps of annual exceedance of ground-motion levels over different time periods. Exceedance maps are used to develop and upgrade seismic design criteria in the Unified Building Codes.

Effectively Communicating Uncertainty and Relative Risk

Perhaps our biggest challenge as earth scientists is to refocus society's desire for absolute guarantees from science and replace it with an acceptance that most solutions are uncertain and will carry some level of risk and also some level of environmental consequences. We must frame the questions and explain the choices so that decision makers can make better-informed decisions. Forcing one correct, "ultimate" solution will rarely be socially acceptable.

Safe, long-term containment of high-level radioactive waste is an excellent

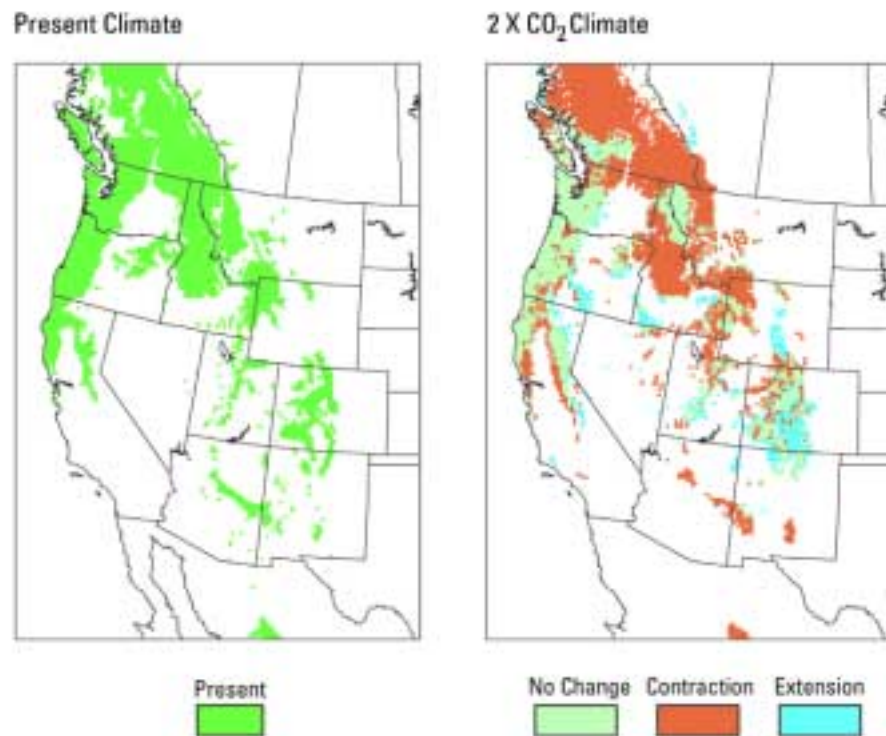


Figure 5. Distribution of Douglas fir in western North America at present and anticipated changes in range in $2 \times \text{CO}_2$ environment (from Thompson et al., 1998).

example of the dilemmas faced in finding acceptable solutions to environmental problems. Spent nuclear fuel and other high-level radioactive waste is currently stored at 72 commercial reactors in 33 U.S. states as well as at an additional 86 government sites around the country (Office of Civilian Radioactive Waste Management, 1998; Fig. 6). Many of the nuclear reactors are along coastlines or in river valleys. Typically, the spent fuel rods are stored in cooling ponds located at the surface of these sites. If we don't come up with a long-term solution for radioactive waste storage, we are opting for the default solution of continued storage at the widely dispersed sites, many of which were never designed for very long-term storage (>100 years, 30–50 years of which have already passed) and are exposed to multiple hazards.

The nation is near the end of site characterization for a potential high-level radioactive waste underground storage repository at Yucca Mountain, Nevada. Many of the geologic, geochemical, and hydrologic processes affecting the site have been carefully examined and quantified. However, the long-term suitability of this site for a geologic repository cannot be guaranteed absolutely; only statements about the likelihood of migration of radioactive contaminants away from the site and

traveling through the aquifer can be made. The "default" solution I mentioned and the risks associated with it have not been factored into our public discussion and dialogue on the suitability of Yucca Mountain or any other site as the nation's geologic repository for high-level radioactive waste, nor have the policy choices between Yucca Mountain and continued existing storage been properly framed for decision makers.

WHAT CAN WE DO TO MEET THESE CHALLENGES?

We, as earth scientists, can do a great deal to meet these grand challenges in environmental science. First, we need to learn some biology and ecology. We need to aggressively exploit technological advances in the area of monitoring active processes, both in situ and remotely from space or aircraft. We need to work with information technology experts to develop the means to process huge amounts of data generated by these monitoring sensors in real time and assimilate this information into self-learning complex numerical models of

natural systems that incorporate feedback and evolve in real time.

However, finding workable solutions to large-scale environmental problems will require more than first-rate integrative physical and biological science. Implicit in its definition, environmental science has a human and social aspect. Environmental scientists must work with social scientists and economists to gain societal acceptance of proposed solutions that utilize the best scientific and engineering judgment, but that will undeniably be associated with considerable uncertainty. Solutions for environmental problems will represent a delicate balancing act in which society must weigh the level of risk they are willing to live with as well as the level of environmental consequences.

WHAT SHOULD WE DO?

We should begin now to design grand, bold, process-level experiments that fully exploit modern technology to tackle these

challenges. We should acknowledge that solving these problems is every bit as difficult and complex as building the atomic bomb that started the radioactive waste problem.

For example, we should tackle safe, long-term isolation of high-level radioactive waste as one of the grandest scientific, technological experiments of the twenty-first century. Globally, our lack of solutions to this problem will continue to affect our world's energy future. DOE is now considering a staged approach to repository design, development, and operation that recognizes that we do not yet understand many of the important processes involved. In a 1999 letter to the National Research Council, DOE requested a study on such an option, stating that they were interested in an approach in which "decisions must be made in a step-wise and reversible fashion." This is exactly the approach the scientific community has been advocating for more than a decade (National Research Council, 1990). We, the earth science community, should become active

participants in such a grand experiment.

The challenges I've outlined are daunting, but I think earth scientists are extremely well equipped and positioned to address them. I'm proud to be part of a science and a scientific society that can help the nation and the world address these challenges.

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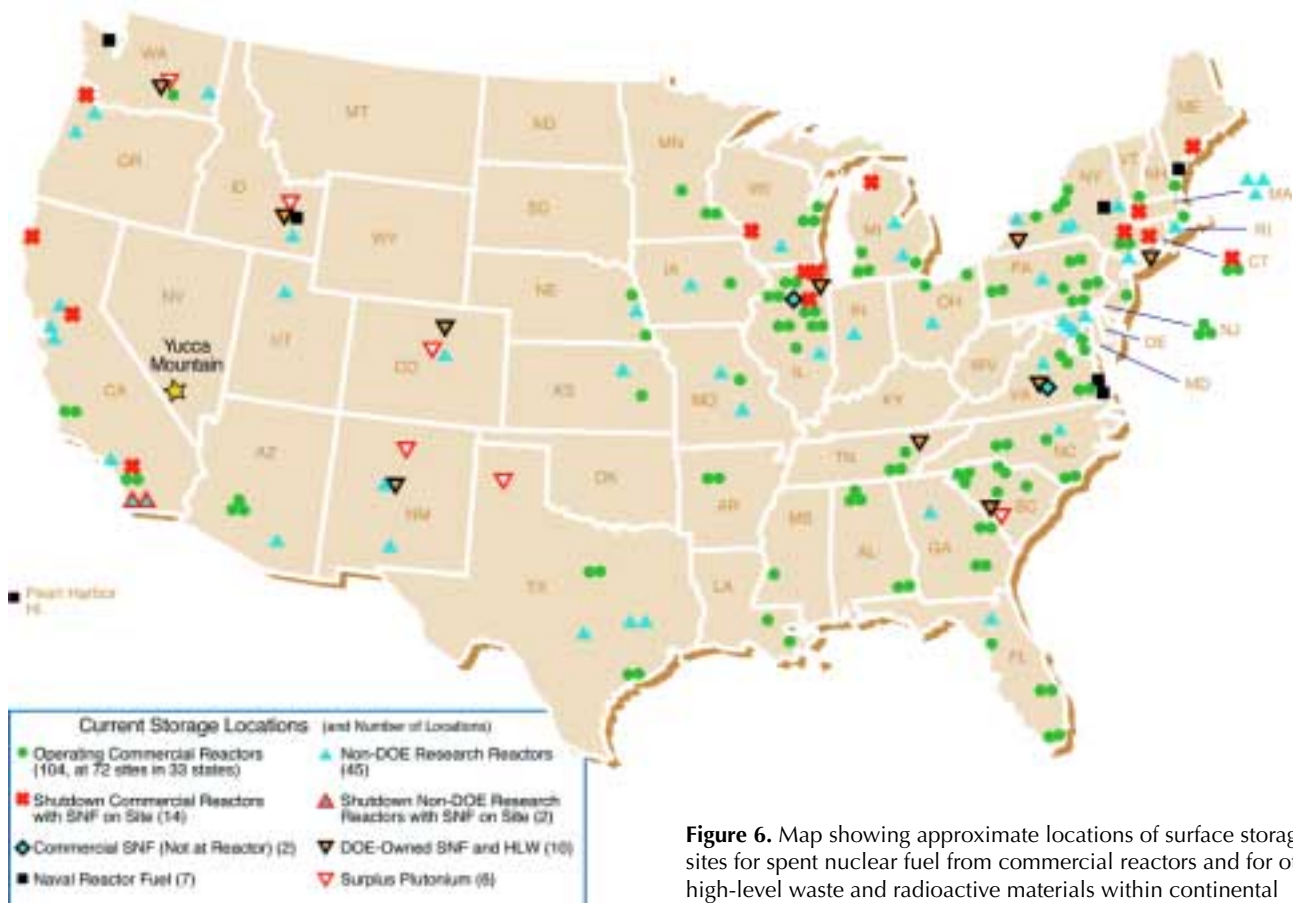


Figure 6. Map showing approximate locations of surface storage sites for spent nuclear fuel from commercial reactors and for other high-level waste and radioactive materials within continental United States. Illustration courtesy of U.S. Department of Energy.

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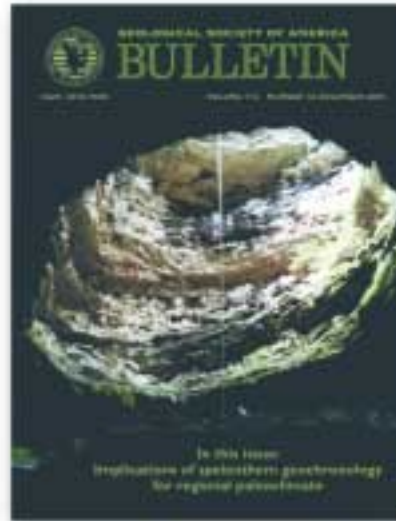
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