Infrastructure and the Environment

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Abstract

Infrastructure is the foundation on which industrialized economies are built. As global population has grown and as economies of many regions have expanded, the quantity and scale of infrastructure has increased dramatically. Although some infrastructure is used to move people and commodities, much infrastructure is also used to control natural processes or to extract natural resources. Thus, understanding environmental change necessitates understanding the role of infrastructure in the environment. We review available inventories of infrastructure and current understanding of environmental impacts for different types of infrastructure. We also examine the current status of aging infrastructure and the potential environmental impacts and benefits of infrastructure decommissioning. Finally, we briefly review policies that have facilitated or inhibited infrastructure decommissioning or environmentally oriented modifications of infrastructure operation.

Contents

1. INTRODUCTION

To understand the current status of the environment and the distribution and use of natural resources worldwide, it is first necessary to understand infrastructure. The building of infrastructure is a response to societal demands, primarily developmental and economic. Thus, we begin with a brief review of the motivators of global infrastructure expansion.

1.1. Political Economy of Infrastructure

Infrastructure is at the core of any industrialized economy, necessary for day-to-day operations and in forming the sinews of society (1). Here, infrastructure includes elements that provide crucial physical (public or private) services for an industrial society: transportation, water and sewage, power, and military. Economically, infrastructure plays a central role in decisions of where to locate industries (2) and provides an impetus for economic development and growth (3). With global population and economic growth, infrastructure has also grown worldwide (**Figure 1**) (4). Infrastructure is used to move people and commodities (e.g., roads, railroads), but also to constrain the effects of natural processes and thus allows people to move into areas that would not otherwise be usable (e.g., dams, levees). Moreover, infrastructure is used broadly to extract natural resources. Thus, understanding large-scale environmental change requires an understanding of infrastructure.

Infrastructure generally takes on two scales. We consider fine-scale infrastructure to be that which is developed by private landowners, local municipalities, and at times by private industry. The second scale of infrastructure is made possible by a large concentration of capital, often triggered by external funding or subsidies, particularly via national government or international organizations (e.g., World Bank), often making up infrastructure systems that span regions. For example, construction of dams in the United States increased dramatically in the mid-twentieth century through a federal desire to facilitate development in the arid western United States and to revitalize the southern U.S. economy, which was based on riverine transport (5). Infrastructure expansion, and the associated environmental change, is driven by the economic demand for the services the infrastructure provides and is combined with the political will and ability to facilitate the implementation of the infrastructure construction and operation programs (6). Infrastructure is not permanent and is expected to go through a life cycle of expansion and, eventually, contraction (**Figure 1**). Internationally, the stage of this life cycle is quite variable, with developing countries seeking to drastically expand their infrastructure, and many developed countries face difficult end-of-life decisions for infrastructure that is no longer used or functional. A complete life cycle of infrastructure is driven by (*a*) expansion of infrastructure owing to changing technologies and economic or political demand, (*b*) reliance on infrastructure by society or specific economic sector, and (*c*) decline in demand through a shift in technology or economy. Whether private or public, infrastructure should be viewed as temporary on the landscape, and the question of what to do with infrastructure as it ages and/or becomes obsolete is increasingly of concern in developed nations (7) and ought to be considered proactively in developing nations.

As an example of infrastructure discussions in a developed nation, infrastructure is currently at the heart of many current policy discussions in the United States (8), and part of the driver for this is timing: The population and the economy of the United States expanded dramatically during the mid-twentieth century, and during this time, there was an accompanying expansion of infrastructure (9). As economies and technologies have shifted, the demand for some of this infrastructure has changed as well—with some demand increasing, such as roads; some demand decreasing, such as railroads; and some demand transitioning, such as the movement away from many small coal mines to fewer but larger coal mines. In all, many structures in the United States have been in place for >50 years, and this is similar to infrastructure in other developed nations, and for a number of large structures in the developing world where outside interests played key roles (e.g., Aswan High Dam, Panama Canal). Public works engineers often approximate infrastructure lifetimes on the order of several decades to a century (10), and thus an increasing portion of U.S. infrastructure is approaching or exceeding its originally intended design life. Infrastructure conditions in the United States have consistently declined and will require more than $1.6 trillion to reach acceptable levels of safety and function (11).

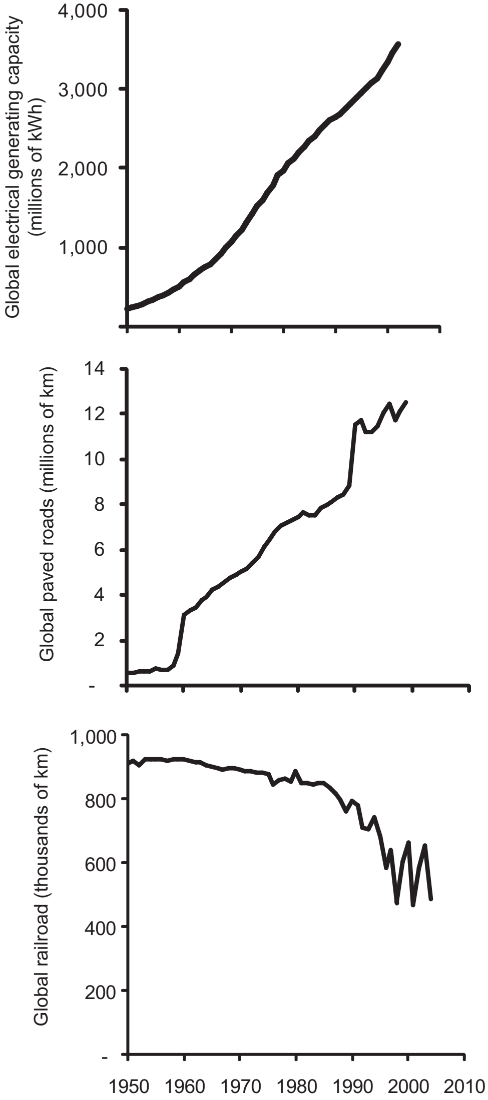


Figure 1

Expansion and contraction of global infrastructure systems. Oscillations in the length of railroads are likely from closures and reopenings of different lines worldwide. Data from Reference 4.

In contrast, many developing nations are faced with a lack of infrastructure, and so discussions and policy formulations are quite different. However, because of the finite life span of all infrastructure, the nations that are currently expanding their infrastructure systems, such as India and China, will inevitably face issues similar to those faced by the United States in the coming decades. As such, the lessons regarding environmental degradation associated with infrastructure, as well as decisions surrounding decommissioning or adapting infrastructure, will become critically important for these nations in the future.

1.2. Environmental Impacts of Infrastructure and Decommissioning

The earth's ecosystems are increasingly dominated by land-use change, altered biogeochemical cycles, invasive species, and a globally manipulated water budget (12). The increase in scale of these activities from local to global during the twentieth century was facilitated by infrastructure expansion: Road construction precedes deforestation; port construction precedes ballast tank releases of aquatic invasive species (13); and cement production, the backbone of global infrastructure, itself contributes 5% to global anthropogenic CO_2 emissions (14) without even considering the vast environmental impacts of the roads and dams built with the concrete.

In response to this environmental degradation, there is an increasing call for restoration. Restoration, as used here in the context of infrastructure decisions, is considered as deliberate and purposeful decisions to assist the recovery of damaged, degraded, or destroyed ecosystems (15). We generally do not consider restoring ecosystems precisely to preinfrastructure conditions possible; rather, we consider an appropriate goal is to modify the operation or presence of infrastructure in a way that repairs some ecosystem functions and associated biotic communities, without necessarily returning to historic conditions. Although restoration has become a burgeoning industry in some developed countries (16), the scale of most restoration projects is relatively minor, particularly in comparison with the continued rate and scale of global environmental degradation.

The combination of infrastructure decay and the demand for environmental restoration has raised infrastructure decommissioning as a key issue in environmental policy development in some developed nations, particularly in the United States and western Europe. Decommissioning can include complete removal or abandonment, partial removal or modification, or altering operations of the structure or system of structures. The potential scale of decommissioning, and its environmental impacts/benefits remain relatively unknown, particularly when considered across infrastructure types. Nevertheless, infrastructure decommissioning may provide unprecedented opportunities for restoration at scales larger than have previously been pursued or even contemplated.

1.3. Purpose and Structure of This Article

Here, several types of infrastructure are reviewed as examples of the scale of infrastructure-driven environmental change, the number and relative age of different infrastructure systems, and relevant science and policies that constrain decommissioning decisions and alternatives for operations and management. Although the scope of the analysis here is global, we draw on examples from the United States because of the availability of data and because of the position of the United States as a dominant—and aging—industrial society. We then draw on the lessons from these U.S. databases and, where appropriate and possible, make recommendations for issues that are likely to emerge in other countries and regions of the world. Different types of infrastructure are first reviewed individually, and then lessons are synthesized to point toward needs in research, management, and policies.

2. ROADS AND RAILROADS

Roads and railroads have fundamentally altered the earth's ecosystems through their direct and indirect impacts, their facilitating future development of an area, and the sheer scale of road and railroad networks worldwide. The bulk of the road construction in the United States that occurred during the nineteenth century was minor roads and paths, but the road network expanded rapidly in the mid-twentieth century (**Figure 2*a***) (17–19), as did road construction

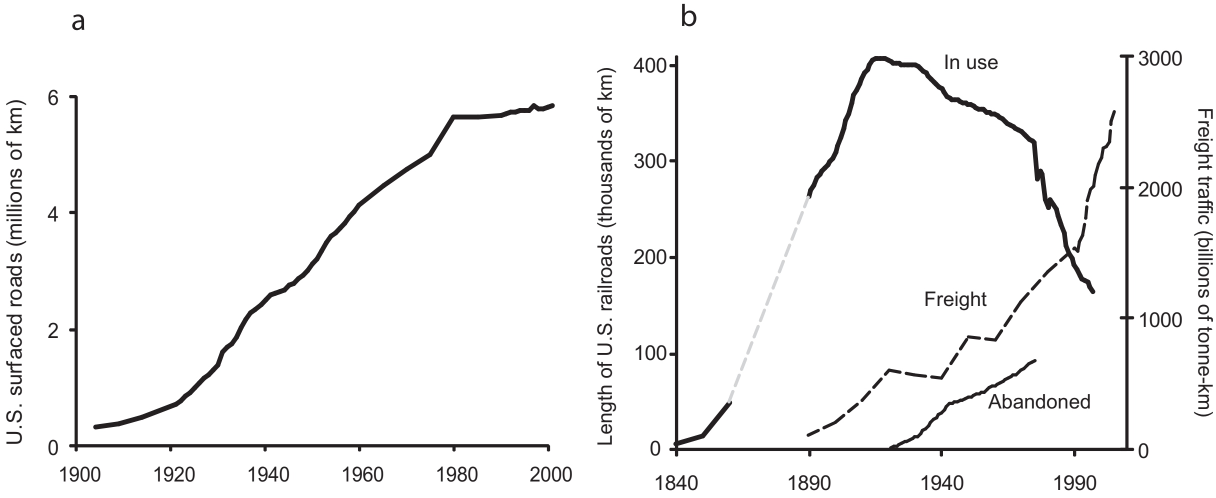


Figure 2

Road and railroad infrastructure in the United States. (*a*) Length of U.S. surfaced roads (17–19). Surfaced roads include soil surfaced with slag, gravel or stone, asphalt, and concrete. (*b*) U.S. railroad inventory (19, 21). The dashed line portion of the "in use" series is estimated.

internationally (**Figure 1**). In 1900, there were 328,000 km of surfaced roads in the United States, but through the expansion of the federal government role in national infrastructure activities, the road network expanded to the current 6 million km of surfaced roads, handling about 12 billion vehicle kilometers per day (20). However, since 1980, the road infrastructure in the United States has been expanding slowly (<0.2% per year), as greater emphasis is on lane addition and maintenance rather than new length construction. The epicenter of paved road expansion has shifted to South and East Asia.

Railroads developed rapidly during the nineteenth century, but unlike paved roads, railroads have been in decline in the United States and globally over the past few decades (**Figures 1** and **2*b***) (21). In the United States, railroads expanded rapidly in the late 1800s, reached a peak length in 1919 at 407,000 km, and then gradually declined to 164,000 km by 1997. Similarly in Britain, by the end of the 1960s, the British railroad network was about half of its 1914 peak length of 32,000 km (22). While the length of railroads has decreased, freight on U.S. railroads has continued to increase. The impetus behind these contrasting trends is the abandonment of peripheral lines, channeling railroad traffic instead on high-volume lines for particular commodities; coal alone made up >42% of freight transported by rail in 2005, and this traffic is focused on relatively few, high-volume routes (**Figure 2*b***).

This vast network of roads and railroads has profound ecological impacts, generally grouped into seven effects: mortality from road construction, mortality from collision with vehicles, modification of animal behavior, alteration of the physical environment, alteration of the chemical environment, spread of exotics, and increased use of areas by humans (23). Even unsurfaced roads, such as forest access roads and other unpaved surfaces prevalent throughout developing regions, fragment ecosystems and introduce large quantities of sediment to streams and rivers (24). Although roads, railroads, and roadsides directly cover only a small portion of the landscape (e.g., roads and roadsides cover 0.9% of Britain and 1.0% of the United States), the area over which roads extend significant ecological effects—the road-effect zone—covers an estimated 15% to 20% of the U.S. land area (25). Expansion of road

Priority pollutants: the U.S. Environmental Protection Agency must establish ambient environmental quality criteria and emissions or effluent limitations for these pollutants

networks is often the necessary precursor for other types of environmental degradation: Deforestation rates in tropical rainforests are driven by road density, and road density of neighboring counties (26), as access to roads is a necessary factor for the expansion of rural economies. In addition, and particularly for paved roads, road construction uses approximately 260 Mg of concrete annually for U.S. highway construction alone (27).

Environmental impacts specific to railroads are also widespread. Railroad ties have been treated with creosote for over 130 years, and creosote contains up to 85% polycyclic aromatic hydrocarbons (PAHs), considered a priority pollutant by the U.S. Environmental Protection Agency. There are over 9 million railroad ties in Switzerland, and over 19 million ties are produced each year in the United States, the majority of which are treated with creosote (28). During the average 20- to 30-year lifetime of a railroad tie, roughly 5 kg of creosote are emitted, 0.5 kg of PAHs are emitted, with 10 g emitted as phenolic compounds, which, accumulated over the tens of millions of railroad ties, may have an enormous influence on photochemical ozone creation and human health (29). Against these impacts, railroads use about half as much energy as cars for passenger transport, and they emit far fewer atmospheric pollutants than cars for freight transport—generally an order of magnitude less grams/tonne-kilometer for CO_2, NO_x, SO_2, and volatile organic compounds (22).

Although much road infrastructure remains critical and is continuing to expand in developing regions, there are some road networks and railways that have been decommissioned, and many more are being considered for decommissioning in developed countries. In the United States, road decommissioning is increasingly common on lands managed by the U.S. Forest Service (USFS) and other federal agencies. From 1980 to 1995, there was a large increase in the number of forest development roads, as the total USFS roads increased almost 50%, from 362,000 to 563,000 km. Most of these roads are not multilane, and many are no longer even passable by high-clearance automobiles. The USFS estimated in 2000 that its maintenance backlog on system roads was \$8 billion to \$10 billion and that maintenance costs of its entire road system would be >\$500 million per year (30). Beginning in the 1990s, the USFS acknowledged an excess of roads on its lands in its annual reports. Similarly, the U.S. Fish and Wildlife Service (also in 2000) estimated it would spend \$100 million on road maintenance alone within the National Wildlife Refuge System. In 1998, the USFS inventoried 3400 km of road decommissioning, and between 2002–2005, more than 7800 km of roads were decommissioned at a cost of approximately \$45 million. The USFS is anticipating decommissioning between 161,000 and 300,000 km of roads during the next 20–40 years (31).

Forest road decommissioning ranges from abandoning a road and treating stream crossings to fully recontouring the roadbed (32). Road decommissioning via “ripping” (essentially plowing the former roadbed) increases precipitation infiltration and decreases landslide erosion (33). Restoring stream crossings has shown mixed success in the geomorphic stability and reduced sediment loads at restored crossings (34). Unfortunately, there is very limited research on the ecological effects of road removal, although some research has shown wildlife benefits and stream habitat benefits of road decommissioning in the western United States (35–38). Also, modeling studies indicate that wildlife habitat could be increased by 24% in the western United States through the annual removal of only 1% of USFS roads for 25 years (39) and that a modified road network could be used to decrease road length by 75% while still accessing the same points in the forest (40). Sediment loads can increase immediately following road recontouring, but within 12 months, erosion from decommissioned roads typically drops below levels of untreated roads (32). Road removal also requires the clearing of vegetation on roadbed surfaces, which may take several growing seasons to regenerate.

3. DAMS AND LEVEES

River infrastructure has accumulated to staggering numbers and scales, utilizing essentially the same technology for centuries (41). There are >48,000 large dams worldwide (i.e., >15 m tall) (7), which are capable of retaining about 15% of the global water runoff (42), and perhaps as many as 800,000 known impoundments worldwide (43). In the United States, there are ∼78,000 dams >3 m tall (**Figure 3**) (44, 45), and as many as 3 to 8 million detention reservoirs and small man-made impoundment ponds (46). Inventories of levees are less clear, but current estimates approach 40,000 km in the United States (47). Whereas dams are spread relatively constantly throughout the United States, levees are more heavily concentrated in specific areas or regions: the state of California controls 2600 km of levees in the Central Valley, and there are over 1600 km of locally managed levees in the Sacramento-San Joaquin Delta. Also, there are over 17,000 km of levees in the Upper Mississippi Valley and over 3,700 km of mainline levees along the Lower Mississippi, resulting in over 90% of the Mississippi River floodplain being leveed (48).

Globally, the rate of dam construction has remained relatively constant, although dam construction has shifted from western Europe and North America toward Asia, particularly China, and South America. Both dams and levees experienced a substantial construction boom in the twentieth century; the age of most dams in the world is now >35 years, and >85% of U.S. dams will be >50 years old by 2020 (11, 35). Because of their age, an estimated $36 billion is needed to bring U.S. dams into safe working conditions and to remove those no longer needed (11). The age and structural stability of levees is mostly unknown (49), although some estimates can be made. For instance, 10% of the 1800 km of inventoried Sacramento River Project levees are in need of significant repairs at an estimated cost of $145 million (about $15,000 per linear meter of levee). Moreover, historical flood-control effects (upstream dams, higher engineering) have not reduced the occurrence or frequency of levee breaks in California, which are still dominated by relatively frequent, El Niño-Southern Oscillation–driven floods (50).

Although dams and levees have made significant contributions to human development worldwide, they have come at a staggering financial, social, and environmental cost. There is now a preponderance of research illustrating deleterious environmental impacts of dams, including extinction of native species, spread of exotic species, and disruption of normal riverine hydrologic and nutrient cycles (51, 52). As well, construction costs more often than not exceed expectations, and performance revenues often fall short, meaning that many dams do not live up to their financial promises (7). These economic shortfalls and environmental impacts are in addition to the 40–80 million people worldwide who have been physically displaced by dam construction and operation (7).

Globally, dams intercept 4–5 Gt of sediment per year, or about 25% to 30% of the global riverine sediment load (43). Such scales of water and sediment storage increase coastal erosion, increase salinization of groundwater, and drive the collapse of coastal fisheries through the loss of riverine nutrients (53, 54). Similarly, levees have come at an extreme cost in terms of increasing downstream flood elevations (55), increasing populations in hazardous areas (56), and widespread environmental damage. Levees affect riverine ecosystems by disrupting natural flood pulses (57), which are critical for seed dispersal, plant establishment, nutrient cycling, sediment deposition, and maintenance of species richness. Levees also affect vegetation distribution and recruitment (58), as well as the cycling of nitrogen, and cumulatively can lead to increased nutrient loading to downstream ecosystems (59).

Over the past 20 years, there has been a growing interest in dam and levee decommissioning and also in a growing industry of dam removal with ∼600 dams intentionally removed in the United States alone. However, this interest is worldwide, and even gained the attention of the World Commission on Dams (7).

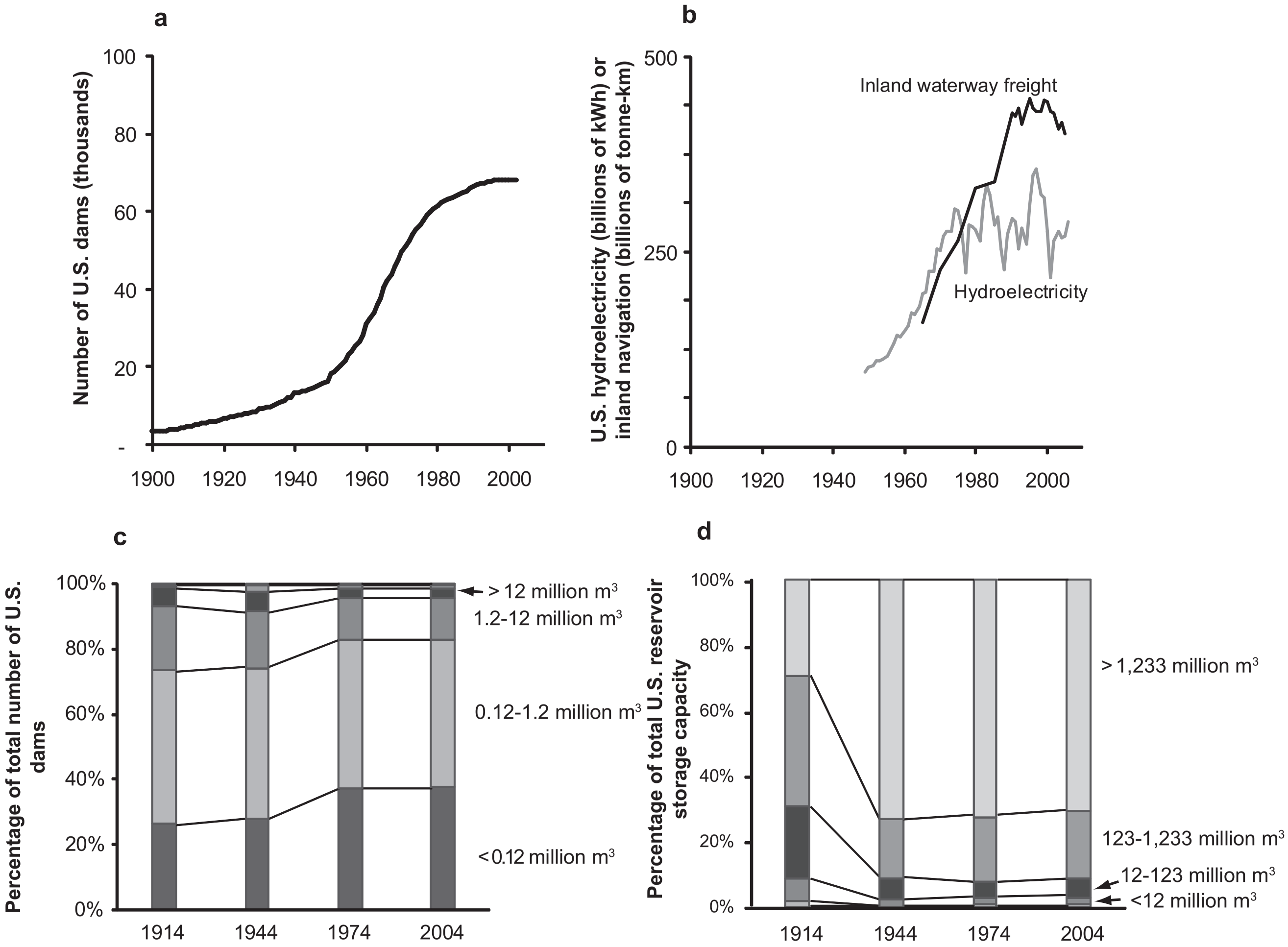


Figure 3

Inventory of dam-related infrastructure in the United States. (*a*) Dam construction in the United States (44, 45), (*b*) U.S. inland waterway freight and hydroelectricity (45), (*c*) percentage of dams in the United States by size and (*d*) by storage capacity (44).

The primary questions associated with dam removal in any setting or nation revolve around the fate of released sediment, nutrients, and any pollutants stored in the reservoir, as well as if and when the river will recover to predam conditions (60). River response to dam removal varies widely, and in many cases, the removal of a dam causes only minor sediment and nutrient elevation downstream, whereas in others, downstream sedimentation and nutrient loading can be substantial (61). Of particular concern has been the mobilization of contaminated sediments from reservoirs, although very few studies have been conducted that document the downstream extent, timing, and impacts of such transport. Also, the ecological recovery following removal can be rapid or slow: Invertebrates and fish have shown recovery within months or years of a dam removal, whereas unionid mussels and riparian vegetation may require decades (62). In most of these cases, the key concerns are how to stabilize the reservoir sediment, and if the sediment cannot be stabilized, how to estimate the amount that will be mobilized.

For levees, full removal is rare in comparison to simply abandoning a breached levee or breaching the levee intentionally. In 1993, several levees in the United States failed along the Missouri River, leading to widespread crop damage and also to the creation of substantial restoration projects through creative policies. Following the floods, owners of flood-damaged cropland could sell their land for permanent easements if the cost of levee restoration and cropland renovation exceeded the value of the land; the levee and associated farmland was abandoned and converted to wetlands (63). In one instance, 1050 hectares (ha) of floodplain along the Iowa River was purchased after a 1993 flood broke the levee in two sites and resulted in \$2.7 million in damage. These sites were converted into the Port Louisa National Wildlife Refuge, which created substantial quantities of floodplain wetland restoration as well as removing the need to reconstruct or repair levees. However, empirical evidence of the ecological benefits of levee decommissionings is completely lacking. Modeling studies, mesocosm studies, and flooding experiments (64, 65) have suggested that levee removal and associated channel-floodplain reconnection could substantially improve downstream water quality as well as enhance trophic interactions in food webs (66). Empirical studies documenting such ecosystem improvement at the river reach or segment scale have not been undertaken.

4. COAL MINES

Mining activities vary widely, ranging from underground mines, to surface strip mines, to dredging operations. In the United States, nearly 3.2 million ha are currently permitted for mining, including 2063 coal mines, 263 metal mines, 739 nonmetal mines, and 4490 stone mines (**Figure 4*a***) (67, 68). With the exception of stone, the number of mines in the United States has decreased over the past few decades, most dramatically for coal and metal mines. Here, we focus on coal mines, as the United States has a long history of coal mining and its regulation and reclamation, and because coal is a critically important global energy source.

The environmental impacts of coal mining include removal of vegetation, movement and erosion of sediment, and potentially large-scale pollution of soil, water, and the atmosphere (69). Globally, the sediment moved as part of mining greatly exceeds the sediment moved by natural geomorphic processes (70). The chemical pollution associated with coal mining is often the result of oxidation of minerals when the ore is exposed to air. Acid mine drainage (AMD) is widely considered the most serious environmental problem caused by mining of sulfide ore deposits and has well-documented effects on fish populations and invertebrate communities, and can precipitate fundamental changes in downstream aqueous geochemistry (71). Between 8,000 and 16,000 km of streams in the United States are affected by AMD, and mining has contaminated the headwater reaches of

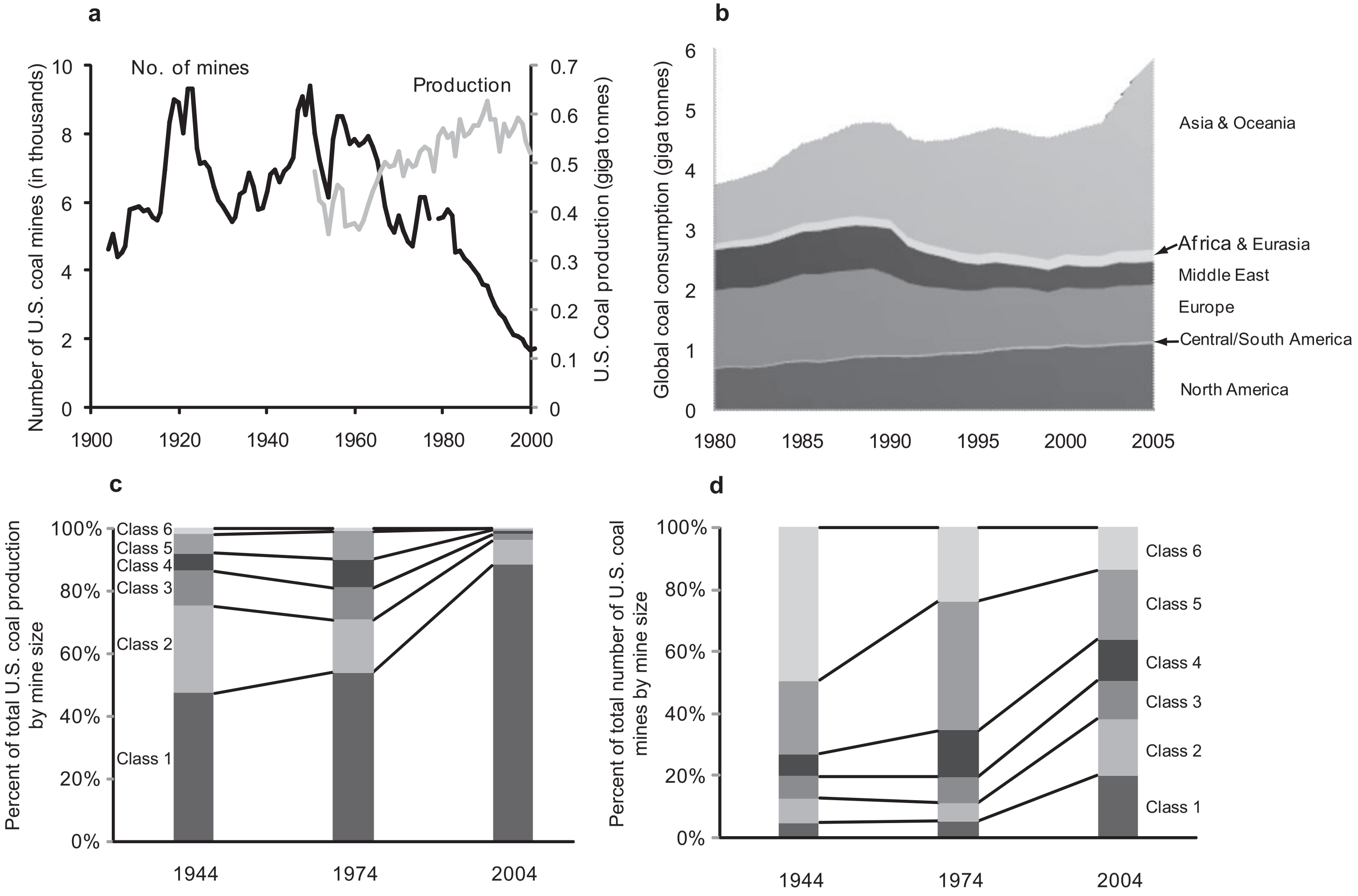


Figure 4

Temporal distribution of coal mining in the United States and globally. (*a*) Number of active coal mines and the production of coal mines in the United States (67), (*b*) global consumption of coal by region (45), (*c*) and (*d*) distribution by production and size (67, 68). For panels *c* and *d*, the classes of mines are class 1, >454,000 tonnes/year (>500,000 tons/year); class 2, 181,400–454,000 tonnes/year (200,000–500,000 tons/year); class 3, 90,720–181,440 tonnes/year (100,000–200,000 tons/year); class 4, 45,360–90,720 tonnes/year (50,000–100,000 tons/year); class 5, 9,070–45,360 tonnes/year (10,000–50,000 tons/year); class 6, <9,070 tonnes/year (<10,000 tons/year).

more than 40% of the watersheds in the western United States (72).

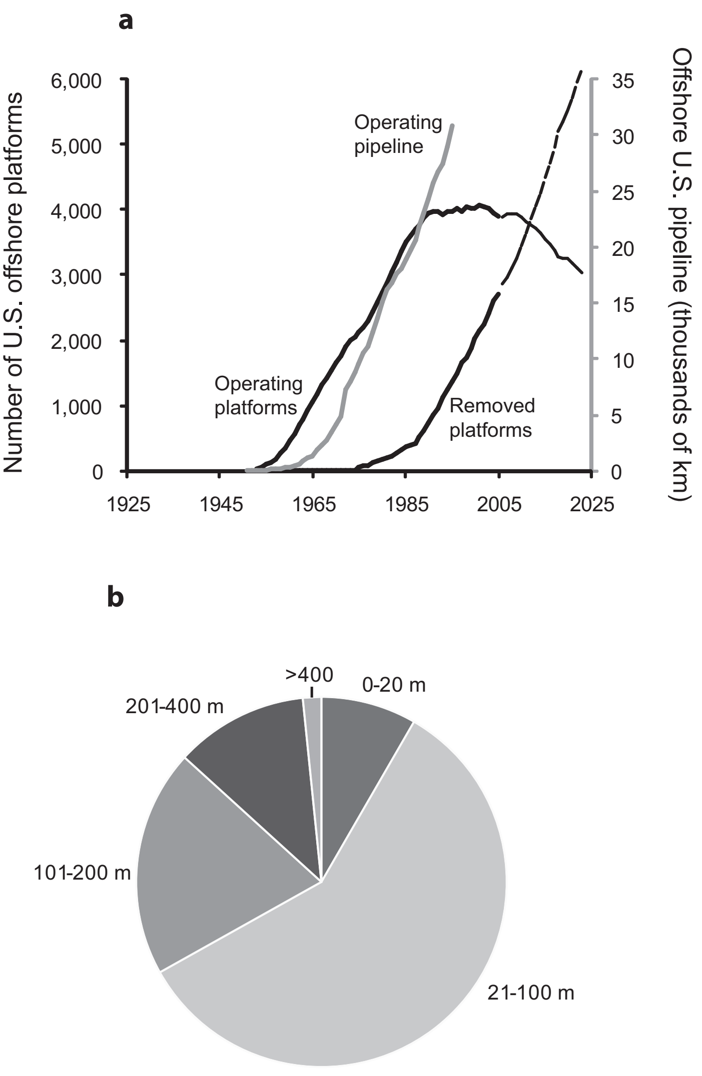
Coal produces about 25% of the world's energy and is likely to increase because of the rising cost of petroleum and the relatively large sources of coal still available in the United States, China, and India. U.S. coal mines remain a primary energy source in the United States, and production is expected to continue to expand (73). The number of coal mines peaked at approximately 9400 mines in 1923 and in 1950 (**Figure 4*a***). Since 1950, the number of coal mines decreased to 1600 in 2005. Although the number of mines has decreased over the past five decades, actual coal production has increased slightly over the same time period, indicating that fewer mines are producing a greater amount of coal. In 1944, class 1 mines—those that produced >500,000 tons/year (454,000 tonnes/year)—made up only 5% of the mines but produced 47% of all coal; class 6 mines—those that produced <10,000 tons/year (9,070 tonnes/year)—made up 50% of all mines but only produced 2% of all coal. By 2004, class 1 mines made up 20% of all mines and produced 88% of U.S. coal, whereas class 6 mines had decreased to only 14% of all mines and produced only 0.1% of U.S. coal. Thus, there has been a consistent movement toward fewer, larger mines (74), and increasingly, these are surface mines. An important by-product of this movement has been the abandonment of thousands of small mines.

What to do with decommissioned and abandoned coal mines has become a profoundly important question over the past few decades. Until the mid-1960s, there were essentially no efforts made to reclaim surface-mined areas. However, this changed in the United States with the passage of the Surface Mining Control and Reclamation Act (SMCRA) in 1977. The SMCRA requires mine operators in the United States to post a bond to fund reclamation and to develop a reclamation plan for a site after mining (75). Reclamation involves restoring mined lands to a postmining land use, and this is most often forestry or pastures, which requires restoring the original topography of the landscape and reestablishing vegetative cover within five years. Establishing vegetation on previously mined lands can be quite difficult owing to soil pH, soil compaction, high surface temperatures, and lack of soil nutrients. Yet reclaimed sites can develop flora similar to surrounding undisturbed sites (76), although a number of years are needed before reclaimed sites approach the vegetation communities of surrounding areas, meaning that longer monitoring periods are likely needed to evaluate the success of reclamation programs (77). Moreover, recovery of ecosystem functions, such as nutrient cycling, may take decades to centuries as different nutrients take different amounts of time to recover predisturbance rates of cycling.

5. OFFSHORE OIL AND GAS PLATFORMS

U.S. oil production is dominated by >500,000 onshore oil wells, but offshore platforms make up an increasing portion of U.S. oil production, increasing from <5% in 1960 to >35% in 2005 (78). Since the first offshore platform was built in the Gulf of Mexico (GOM) in 1947, over 6600 offshore structures have been constructed in the United States as well as over 19,000 km of oil and gas pipelines (**Figure 5**) (79). Globally, there are >7500 offshore platforms (80) located in the continental shelves of 53 countries, predominantly located in the GOM (4500 current installations), 950 in East Asia, 550 in West Africa, and 490 in the North Atlantic and North Sea.

All phases of offshore platform construction and operation can have environmental impacts. During the exploration and development phase, tens of thousands of tonnes of drilling mud are produced, and these most often go overboard at the offshore well site (81). Once in operation, a major source of concern is the potential for accidental spills. There are an estimated 6.5 oil spills (spills >1000 barrels) per billion barrels of extracted oil in the GOM during the extraction,



Portion of platforms by depth of water

Figure 5

(*a*) Inventory of offshore oil and gas platform construction, operation, and removal, and (*b*) location of offshore platforms with respect to depth of water (78, 79).

pipeline transportation, and tanker transportation phases combined (82).

The effect of offshore platforms on coastal ecosystem resources, like fisheries, is somewhat ambiguous. Platforms clearly compete for space with commercial fishing through their limitations for navigation safety; their unburied pipelines; and the various structures, materials, and fragments that are often associated with platform construction. However, offshore platforms also create unique habitats, and act as artificial reefs. Observations in the GOM suggested a positive relationship between offshore platforms and fish populations (83), although other studies have questioned whether these structures increased fish production or simply attracted fish (84). More recent studies in offshore California showed that the number of the rockfish bocaccio living around offshore platforms constituted 40% of the median value for the entire range of the species (85). They concluded that some of the platforms offshore California were producing bocaccio and not just attracting. In the GOM, total coral abundance was found to be related with platform age (86), suggesting that offshore platforms may facilitate the expansion of coral populations overall in the GOM.

Platform decommissionings are increasing as aging fields reach the end of their productive and economic limits. As such, there is growing interest in the economic and environmental implications of aging offshore infrastructure as well as the options available for decommissioning: An estimated $29 to $40 billion is likely needed for decommissioning over the next 30 years (87), which may become the major issue facing the global offshore industry in the near future. Federal laws in the United States require that all offshore structures on a lease be removed within one year after the lease is terminated. Typically a lease is terminated when production on the lease ceases. Structures that exist on a lease that have not produced in the last year or have not served a useful economic function are called "idle iron" or "dead steel," and of the U.S. offshore structures, approximately one-third are idle (88). It should be noted that as oil prices rise, the economic productivity of offshore installations increases, and there will be a decrease in interest in decommissioning when oil prices are high.

To date >2700 shallow water platforms have been decommissioned (**Figure 5**), most of which were completely removed then disposed onshore. Platforms can also be partially removed, toppled, or left in place. The limitation for offshore platform removal is the availability and expense of heavy-lift equipment needed for removing platforms, particularly those in deepwater, as there are very few vessels in the world capable of removing deepwater platforms. For instance, to remove the Harmony platform offshore California (365 m water depth, 59,000 tonnes), which is comparable in size to New York City's Empire State Building (381 m tall, 54,000 tonnes of steel), requires a derrick barge that is not available on the West Coast (89). Although costs for removing relatively small platforms in shallow waters of the GOM are in the hundreds of thousands of U.S. dollars (88), cost estimates for removing deepwater platforms are in the tens to hundreds of millions; cost estimates for removing the Harmony platform exceed \$123 million (89). This problem escalates globally as >50% of Brazilian offshore platforms are located in depths >400 m; Norway has only 7% of the world's offshore installations, but it accounts for >35% of the projected global decommissioning expenditure because of the high weight, depth, and complexity of Norwegian installations (80).

Because of the costs associated with full removal and the potential ecological value of platforms as reefs, in the United States the Minerals Management Service may waive the requirement to remove a platform to accommodate conversion of a platform structure to an artificial reef, following the National Artificial Reef Plan. States have developed innovative mechanisms of facilitating platform reefing, converting a decommissioned platform into an artificial reef. In Louisiana and Texas, the state assumes responsibility for the reefs, but the oil and gas companies must contribute half of the disposal savings to a state environmental trust fund. Through 2004, >190 retired platforms were permanently dedicated for fisheries enhancement in federal waters offshore Louisiana and Texas, which facilitated lower platform decommissioning costs and >\$20 million in industry donations to state environmental trust funds.

6. DEPARTMENT OF DEFENSE AND ENERGY FACILITIES

U.S. Department of Defense (DOD) and Department of Energy (DOE) facilities pose unusual challenges and opportunities. Of the 257 million ha of U.S. federal lands, >10 million ha belong to the DOD as military bases, bombing ranges, and other installations (90), and >1 million ha belong to the DOE (91). These levels of landholding are not unique internationally: The Ministry of Defense in the United Kingdom holds over 1% of the entire U.K. landmass, and many other developed countries dedicate a comparable portion of their land to military purposes (92).

In the United States, DOD and DOE facilities have almost bimodal ecologies. First, many sites contain chemical and radiological wastes generated by the production and testing of weapons, including nuclear weapons, as well as contamination and ecological disturbances associated with continued military operations. The remediation task at these sites is monumental, representing >20% of the world's environmental remediation market (93). Second, along with hazardous wastes, most of the larger DOD and DOE facilities have extensive natural ecosystems that have been relatively undisturbed for >50 years (91, 94), containing some of the richest ecological reserves of any of the nation's public lands. DOD facilities harbor >200 threatened and endangered species (95). DOE buffer lands (∼810,000 ha) are relatively uncontaminated and require little remediation, and the ecological value of DOE lands led to its preservation through the creation of the National Environmental Research Parks.

The status of DOD and DOE facilities, however, is changing (**Figure 6**). For DOD, five rounds of Base Realignment and Closure (BRAC) have closed or reclassified more than 400 military sites since 1988 (96). For the DOE, the need for large security buffer areas has become less important as the DOE mission shifted away from the production of nuclear weapons components (97). As such, there have been

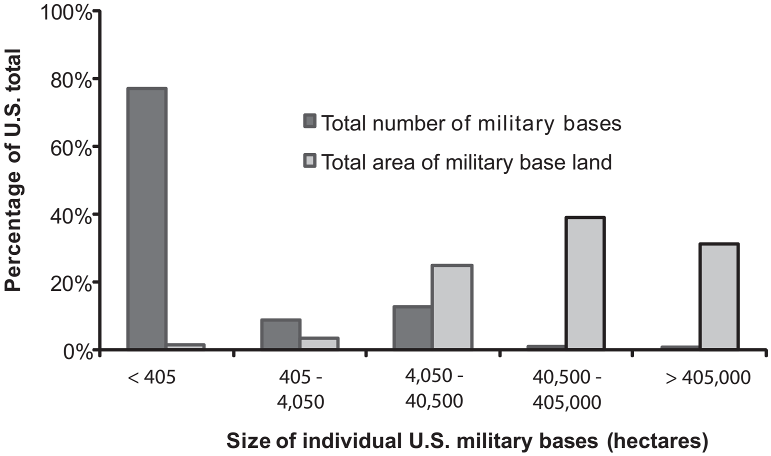


Figure 6

Distribution of U.S. military bases by size of installations (90, 96). While the majority of military bases are small, the majority of total area in military holdings lies within a few very large bases.

increasing questions about what to do with decommissioned DOD and DOE lands. With changes in military technologies and geopolitics, similar land-use questions are emerging across Europe, in the former Soviet Union, on the Korean Peninsula, former nuclear testing sites in Oceania, and elsewhere (98).

Conversions of both DOD and DOE lands for development often requires substantial remediation, which has become problematic not just because of the expense and technical difficulties of such projects, but also because contaminant removal can disrupt unique ecosystems that have developed during decades of restrictive military management. An alternative strategy has been to reduce or avoid remediation efforts and instead allow the sites to remain contaminated and operating as natural reserves (99). Although this approach avoids the disruption of surface conditions and can preserve ecological communities that have developed on site, it also leaves many military hazards or toxins in situ and requires a shift in cleanup standards that typically precludes human residency. To date, management of 21 DOD bases on >445,000 ha has been transferred from the DOD to the U.S. Fish and Wildlife Service to become part of the National Wildlife Refuge System (e.g., Jefferson Proving Grounds, Indiana, became the Big Oaks National Wildlife Refuge). DOE sites, such as Hanford and Rocky Flats, have met similar conservation-oriented redesignations. In DOD and DOE cases, decision criteria are dominated by strategic, economic and logistical concerns, specifically, not to remediate DOD and DOE facilities, and thus conversion to natural refuges makes an attractive end condition.

7. DRINKING WATER AND WATERSHED MANAGEMENT

Drinking water supply systems are critical to global health. Globally, over 1 billion people do not have access to improved water supply, and over 2.4 billion are not served by improved sanitation infrastructure. Nearly 82 million additional people in Africa, 418 million in Asia, and 79 million in Latin America gained access to a water supply through a house connection during the 1990s. Yet the population increase over this same period of time was even greater. Moreover, between 1990–2000, while the number of people in rural areas with access to a water supply and sanitation increased, the coverage of people with access to drinking water in urban areas decreased (100).

The United States has over 54,000 community water systems, which provide water for human consumption to at least 15 service connections year-round. The infrastructure for these systems includes collection devices, drinking water treatment plants, wells, pumps, and transmission and distribution lines, including an estimated >960,000 km of publicly owned pipe in the United States (101). The U.S. Environmental Protection Agency has estimated that building new, and upgrading existing, drinking water systems from 2000 to 2019 would require \$263 billion, including \$102 billion in capital investment and \$161 billion in operating and maintenance funds. Over the same 20-year period, building new and upgrading existing wastewater treatment facilities will require \$271 billion, including \$122 billion in capital investment and \$148 billion in operating and maintenance funds (102). As population continues to grow, opportunities for decommissioning water infrastructure are likely extremely limited.

However, there may be opportunities for ecologically based replacement of some types of water infrastructure. Although traditional water and wastewater treatment facilities are critical to human health, there are many natural ecosystem services that can replace some of these services traditionally performed by water treatment (103). Thus, ecological restoration and conservation may be a potentially useful tool in reducing the costs of some water and wastewater treatment infrastructure.

Even though this ecological approach to providing drinking water may seem difficult at best, the approach is being put to the test in the most severe of trials, in New York City (NYC) (104). Approximately 90% of NYC drinking water is derived from the Catskill/Delaware watershed system. This, along with a smaller system in the Croton basin, provides an average of 4.9 billion liters (1.3 billion gallons) of drinking water per day. NYC drinking water is not filtered, but during the 1990s, federal regulations mandated filtration for public surface drinking water supplies unless the water supplier could demonstrate a sufficient watershed control program, which minimized potential contamination. Costs for a filtration system on the Catskill/Delaware system were estimated at almost \$6 billion, with over \$300 million in annual operating expenses. However, if a watershed management program was developed and maintained sufficiently to meet specific water quality standards, NYC could avoid the filtration system. Not surprisingly, this was the option chosen.

The NYC watershed management program contains many elements consistent with ecological conservation and restoration. For instance, within the watershed program is a Land Acquisition Program, which purchases land from willing sellers to be set aside as conservation easements. This is occurring at a substantial scale: 144,000 hectares are targeted for purchase over the next 10 years at an estimated cost of \$250 million. Similarly, as part of the watershed management program, the City has initiated a Watershed Agriculture Plan, which seeks to improve environmental practices by farmers within the watershed. Buffer strips bordering reservoirs and the stream network are a core part of the watershed plan, as natural floodplain areas have been shown to be important to sustaining water quality, as well as natural stable stream ecosystems.

NYC is not unique in its approach of using watershed conservation and restoration for drinking water, as approximately one-third of the world's largest cities obtain a significant proportion of their drinking water directly from protected areas (105). Furthermore, smaller efforts are also underway: The City of Seattle has committed to a \$90 million road decommissioning effort in order to improve water quality in one of its principal watersheds and to avoid building a filtration plant or search for more pristine alternative watersheds (30). As water treatment infrastructure continues to age, particularly for larger cities, ensuring drinking water quality at the source in this way through ecological management and restoration will likely increase.

8. OPPORTUNISTIC CONSERVATION AND RESTORATION

The world has a substantial system of infrastructure that spans continents and spans economies. These infrastructure systems have greatly impacted the environment. Yet many of these systems are aging, and a surprising number of them are changing in their importance. We now shift toward examining how the changing demand for infrastructure can present unusual opportunities for environmental restoration.

8.1. Lessons from Previous Cases

The cases examined here are wide ranging, but there are several lessons that can be drawn from them for effective policies in managing infrastructure and, in particular, in approaches that facilitate infrastructure decommissioning and removal. Infrastructure is rarely if ever decommissioned for purely environmental reasons. For dams, oil platforms, and DOD closures, all decommissioning decisions were driven primarily by economic concerns, with environmental restoration as a supporting, but clearly secondary, influence. In the observed cases, environmental restoration was one of the more important driving factors in structure decommissioning, but it is both rare and difficult to decommission infrastructure—even those that are extraordinarily damaging ecologically—if it is ably providing the service for which it was built.

One combination of legal and policy elements that facilitates restoration of aging infrastructure relates to ownership and certification: Clear definitions for safety and economic liability, and/or a timeline for relicensing the infrastructure can often catalyze restoration or decommissioning activities. At times this is prompted by litigation, as in levee failure liability re-evaluation in California (106). Also, infrastructure relicensing (such as the process managed by the Federal Energy Regulatory Commission for dams) or federal lease renewals (for offshore oil platforms) can trigger decommissioning discussions. This is likely the most common cause of intentional infrastructure removal to date in the United States, although comprehensive data and analysis are lacking.

A third framework for removal is emergency response, which is a form of economic and safety mitigation, but it is also often associated with removal of a structure following some event that damaged the structure. For example, in the mid-1990s, major winter storms in the Clearwater National Forest in Idaho triggered more than 900 landslides amid a dense network of logging roads. Starting with an $8 million program of emergency repairs, Clearwater Forest officials now integrate ecological planning with road removal to reduce the risk of additional road failures and improve aquatic and terrestrial wildlife habitat (30). Similarly, the decommissioning of levees following the 1993 Missouri and Mississippi River flooding (described above) illustrates how such safety and economic mitigation can facilitate infrastructure decommissioning. In such cases, the decision to remove infrastructure is often enhanced by the potential for ecological restoration, and indeed, local landowners or structure owners may be compensated for removing the structure because of the ecological benefits associated with structure removal (e.g., U.S. Emergency Watershed Protection Program).

A final and emerging framework is compensatory mitigation, in which environmental impacts associated with land development or road building are mitigated (or offset) by environmental restoration elsewhere (107). This approach is perhaps the most proactively environmental approach in that it is the ecological benefits of restoration that are being specifically sought in order to mitigate the ecological damages done elsewhere. At present, this type of approach is only emerging, and its potential remains unknown. It is worth noting that dam removal in the southeastern United States is being used as a mechanism of environmental restoration in order to generate stream restoration credits as part of state compensatory mitigation programs for streams and wetlands. A critical question that emerges under this type of approach is whether the negative consequences of infrastructure decommissioning, such as the sediment loading to downstream ecosystems, is itself offset by the long-term restoration potential. Unfortunately, the availability of long-term data on dam removals is rare, but preliminary studies indicate that, in some cases, the environmental impacts of removal may not be as severe as expected (61), and the ecological recovery can be substantial (62). In the compensatory mitigation framework, these types of studies must eventually be directly compared with more traditional restoration approaches to decide whether such divergent mitigation approaches are comparable or even preferable.

Military and defense bases fit into these other frameworks in several ways. As the BRAC process has highlighted, many military installations are functionally obsolete as new weapons systems present new technological and testing demands, encroaching development limits training activities, and geopolitical changes affect military strategy and tactics. Consolidating scattered small bases into a reduced number of large and increasingly remote installations addresses many of these issues simultaneously and also provides economic advantages of scale. At sites such as the Rocky Mountain Arsenal in Colorado, liability issues and litigation also played a key role in the ultimate redesignation of the site for conservation purposes (it is now managed as a national wildlife refuge). The presence of a protected endangered species—in this case, the bald eagle (*Haliaeetus leucocephalus*)—also expedited the shift from military to habitat use. We should note that development and financial pressures often still trump goals of environmental restoration. In the case of the Arsenal and many other DOD and DOE sites, the degree of contamination is severe enough to preclude residential or commercial development. Nevertheless, the BRAC program appears to present the only proactive avenue for infrastructure decommissioning that takes a systematic approach rather than considering infrastructure futures on a case-by-case basis.

Finally, there are questions about how relevant the decommissioning and restoration lessons are for developing regions. The most important lesson for future infrastructure development is that no infrastructure is permanent, and the costs of structure removal can be quite substantial. As such, future financial planning of infrastructure must consider the costs of not only construction, operation, and management, but also the costs of decommissioning, removal, and if relevant remediation and restoration. Unfortunately, because of the limited finances available for many of these projects, the likelihood of setting aside such funds in advance is likely quite small, and thus, we expect that many developing countries will face large costs for infrastructure maintenance and removal in the decades to come. Even as significant financial costs may remain unresolved in these settings, integrating ecological planning into infrastructure developments from the outset can reduce long-term environmental costs.

8.2. Coupling Restoration with Ongoing Rehabilitation

On the basis of the number of limited cases in which decommissioning was chosen, it appears that the future of infrastructure will include larger consideration of environmental impacts and, when and where possible, environmental restoration. To facilitate such approaches, emphasis should be placed on programs that couple infrastructure retirement with ecological restoration, particularly policy programs that leverage economic incentives for retiring infrastructure. These programs are critical to reducing economic and safety liabilities by removing social reliability on aging and obsolete infrastructure, and ecological restoration is often a side effect. Unfortunately, programs for reevaluating infrastructure systems and considering decommissioning are often only funded immediately following disasters, and then the need for restoration is perceived to have passed. For instance, farmers or homeowners in urban areas who sell easements to their land or sell their houses following floods as part of levee decommissionings might later consider the program as a "federal land grab" and regret their decision once the disaster has passed (49, 56). This can be the case even though such federal and state programs are completely voluntary.

Decisions for coupling environmental restoration and infrastructure do not need to be reactionary but can be planned opportunistically when ecological planning is integrated into routine maintenance of infrastructure. Biologists working with the Florida Department of Transportation, for example, have mapped ecological hot spots in order to create transportation networks that are more sensitive to habitat conditions (108). As a result, bridge and highway repairs can often accommodate wildlife crossings or improved habitat connectivity with only modest alterations in design or reconstruction plans.

It is interesting to note that one of the primary issues that emerges in infrastructure decommissioning and removal is that of prioritization. As management agencies grapple with the number and scale of the issue of aging infrastructure, there is often the need to prioritize which structures should first be considered for either repair or removal. With limited budgets and hundreds of thousands of kilometers of roads, tens of thousands of dams, and thousands of kilometers of levees alone, it becomes a conundrum of funds allocation. Infrastructure management, and particularly aging infrastructure management worldwide, will eventually require careful consideration of what priorities should be placed on maintaining versus decommissioning.

In addition, and perhaps most difficult to deal with from a policy initiative, is the social attachment that can play an important (and in fact decisive) role in decisions about aging infrastructure. For instance, dams are often identified as a natural feature of the landscape: LaValle Wisconsin described itself as the "best Dam town in Wisconsin" with the LaValle Dam (removed in 2000) featured on local postcards. Similarly, large protests are often an expected part of meetings in which road removal is considered, even though such resistance is more commonly a response to the general idea of restricting access than it is to the closure of a particular stretch of road (30). This issue is especially salient in the issue of military base closures, as entire economies and town personalities can be based on such military bases, and there is often a perception that communities will vanish in the absence of longstanding military economies. In fact, by many measures, base closures can generate long-term economic benefits for a majority of affected communities (109), and the BRAC process itself emerged as a result of the severe political pressures against closing bases in light of these localized economic concerns (110).

Regardless, decisions to renew or remove infrastructure will occur within a complex, and often contentious setting of contrasting economic and ecological drivers, coupled with uncertain social and political settings. Greater considerations of the potential advantages of decommissioning infrastructure may provide unusual economic and ecological opportunities, but often these opportunities will only occur in short windows of time, constrained by policies, politics, and personalities.

8.3. Recommendations and Conclusions

Earth's ecosystems are increasingly dominated by processes controlled or created by infrastructure. Yet the role of infrastructure is changing, as critical components of infrastructure worldwide are often at or beyond their intended service lives (111). This raises important issues in environmental and resource policy as well as the economics of what to do with these aging infrastructure systems. A first alternative is to simply repair the infrastructure of concern. This would allow the continued provision of services. However, this is a financially significant option, and in a surprising number of cases, the original purpose for the infrastructure may no longer be present or be pressing enough to justify the expense. The second alternative is to remove the infrastructure. We have suggested that this is an often overlooked but, nevertheless, a viable and potentially preferable option. Most importantly, it does provide an alternative that reduces long-term costs and has the additional benefit of providing real, lasting environmental benefits. The final option, and the one most often chosen, is simply to ignore the problem of aging infrastructure. However, "no decision" is in reality a significant decision, as eventually the infrastructure will age to the point that it will fail. The question is really not whether the infrastructure will be dealt with but when the infrastructure will be dealt with. We suggest that deliberate consideration of the infrastructure's future is a more economically and environmentally viable path to take. For industrializing countries currently expanding their infrastructures, such long-term planning is particularly opportune and can reduce both economic and environmental costs.

One of the more important steps needed in the development of all infrastructure systems is to incorporate the costs of decommissioning and removal into the costs of construction of new projects. The costs associated with removal of many structures can be tremendous, and it is often the case that no financial provisions have been made for funding the removal of these structures. Thus, bonding funds at the time of new construction should be mandated such that trusts mature at the end of the projected (and realistic) design lives of the projects. If the project then exceeds its design life, a portion of the funds can be used for repair or maintenance, but the funds for removal must remain in place. Unfortunately, such preparatory financing is the exception rather than the rule. Surface mines in the United States are among the few types of infrastructure bonded in this way, following the passage of the Surface Mining Control and Reclamation Act in 1977, but the law only applies to coal mines, and bonding requirements are often inadequate for genuine restoration. Below the federal level, some states such as Montana have bonding requirements for hard-rock or metal mines, but these too have proven difficult to administer and are often underfunded. Decommissioning and removing offshore oil platforms provides another example of how such funding is developed, although there are few cases where these funds are actually in place for very large platform decommissioning projects.

Ecologically, infrastructure decommissioning represents a tremendous opportunity for ecological restoration at scales not previously considered possible. If infrastructure aging and decommissioning can be anticipated, funded, and planned for systematically, the liability of obsolescence can be turned into important opportunities not just for ecological gain, but also for economic revitalization and longer planning horizons for built and natural environments. Road removal programs to restore watersheds are already bringing high-wage restoration jobs to rural communities left vulnerable to diminishing economies, which were previously based upon resource extraction. There are numerous pathways where ecological restoration can be incorporated into infrastructure decisions, but in all cases, the potential for success increases with proactive planning. Regardless of whether these recommendations are taken, or if other better options subsequently emerge, the status quo is not a viable option for either the infrastructure or the environment. Deliberate decisions must become the norm in deciding whether to maintain and repair a structure or to decommission a structure. Infrastructure planning and decommissioning must also be responsive to evolving environmental concerns, such as reducing carbon emissions in the face of climate change, and incorporate new technologies that reduce the systemic impacts of power production, water treatment, transportation, and military operations. We expect that when faced with the economic and safety liability realities of infrastructure, more agencies, communities, and private landowners will increasingly remove structures and that the potential for restoration will increase. Broad-scale ecologically designed programs that link infrastructure maintenance, upgrade, and repair with decommissioning and removal promise to provide the greatest benefit across categories of economy, environment, and safety over the long term.

SUMMARY POINTS

1. Infrastructure construction and operation is one of the primary drivers of environmental change.
2. Infrastructure is not permanent, and in many areas of the world, infrastructure expansion occurred more than 50 years ago, placing some infrastructure systems near the end of their projected design lives.
3. Although much infrastructure remains critical to national and global economies, some infrastructure can be decommissioned or removed without economic or safety concerns.
4. Infrastructure decommissioning and removal, when used with appropriate caution, offers unusual opportunities to remove safety hazards and reduce economic liability while providing substantial opportunities for ecosystem restoration and economic revitalization.
5. Proactive policy and economic planning is needed to ensure that sufficient funds are available to deal effectively with aging and obsolete infrastructure.
6. There is substantial inconsistency in how infrastructure is managed within an environmental context.

FUTURE ISSUES

1. Although the environmental impacts of infrastructure are increasingly known, the economics and policies of cumulative infrastructure systems are mostly unknown, as is who (i.e., what agencies or industries) will be responsible for end-of-life or abandoned infrastructure.
2. Environmental consequences of and ecosystem response to infrastructure removal are in some cases unknown. Basic information on the magnitude and rate of change is needed to inform infrastructure management decisions.
3. Many agencies responsible for infrastructure management have not fully contemplated how to manage aging or obsolete infrastructure. Greater policy and economic considerations and research are needed to determine how to finance the treatment of aging structures.
4. Impacts on local communities must be a core part of infrastructure management decisions, but many communities lack finances to maintain infrastructure.

DISCLOSURE STATEMENT

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