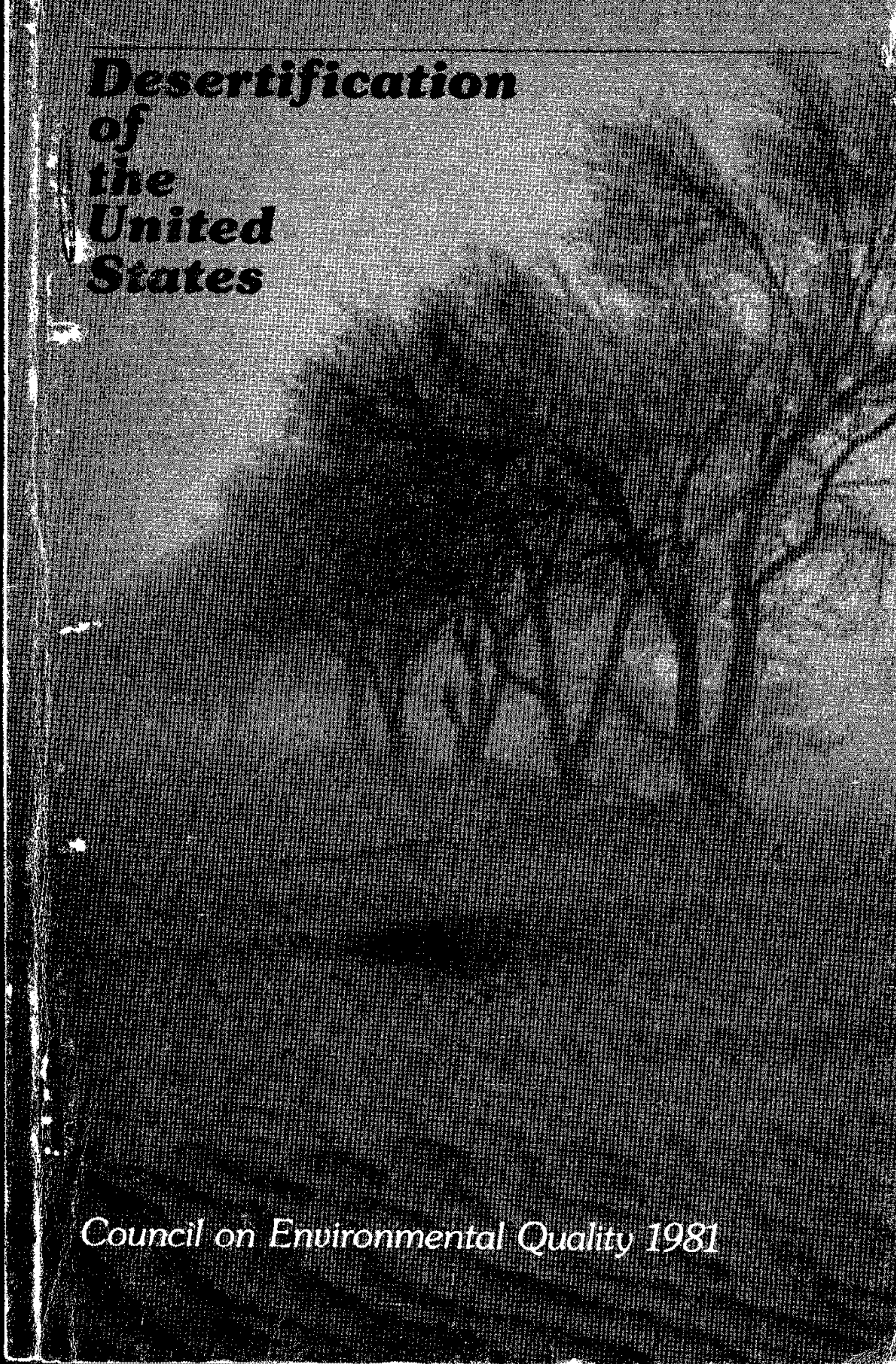
Desertification of the United States



Council on Environmental Quality 1981

Desertification of the United States

Written by David Sheridan

Council on Environmental Quality 1981

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

FOREWORD

[T]he desert lies in wait for arable land and never lets go.

—Fernand Braudel
The Mediterranean[1]

There is an extensive and growing body of scientific literature on desertification. Indeed, the computer printout of one bibliography of sources on the subject measures over 30 yards long.[2] Most of this material, however, discusses desertification in Africa or on the Indian subcontinent.

The purposes of this report, therefore, are:

- To synthesize the available scientific information on desertification *in the United States* and
- To identify federal policies that promote or discourage desertification.

This report uses Australian geographer J.A. Mabbutt's definition of desertification, that is, a "change in the character of land to a more desertic condition" involving "the impoverishment of ecosystems as evidenced in reduced biological productivity and accelerated deterioration of soils and in an associated impoverishment of dependent human livelihood systems."[3]

CONTENTS

DESERTIFICATION OF THE UNITED STATES

INTRODUCTION

> Based on climatic data, more than a third of the earth's surface is desert or semi-desert. If we go by data on the nature of soil and vegetation, the total area is some 43 percent of the earth's land surface. The difference is accounted for by the estimated extent of manmade deserts (9.1 million square kilometers), an area larger than Brazil.
>
> —United Nations[4]

The term *desertification* sounds odd in an American context. A French scientist used it to describe the northward advance of the Sahara in Algeria and Tunisia;[5] it gained wide currency during the terrible drought in the Sahel (the southern rim of the Sahara) in 1968–73 and the Sahara's accelerated southward advance, which continues to this day. Desertification was the subject of a much publicized international conference convened by the United Nations in Nairobi in 1977.[6]

Desertification in the United States has attracted less attention for good reason—its impact on human life is far less severe. But in the Sahel or in western Rajasthan (India), desertification causes great human misery—starvation or malnutrition for untold millions of people.

Nonetheless, desertification in the United States has some very far-ranging implications in terms of the nation's food and energy supplies, balance of payments, and environment. It is an affliction that saps an arid land's ability to support life. Its major symptoms are:

- Declining groundwater tables;
- Salinization of topsoil and water;
- Reduction of surface waters;
- Unnaturally high soil erosion; and
- Desolation of native vegetation.

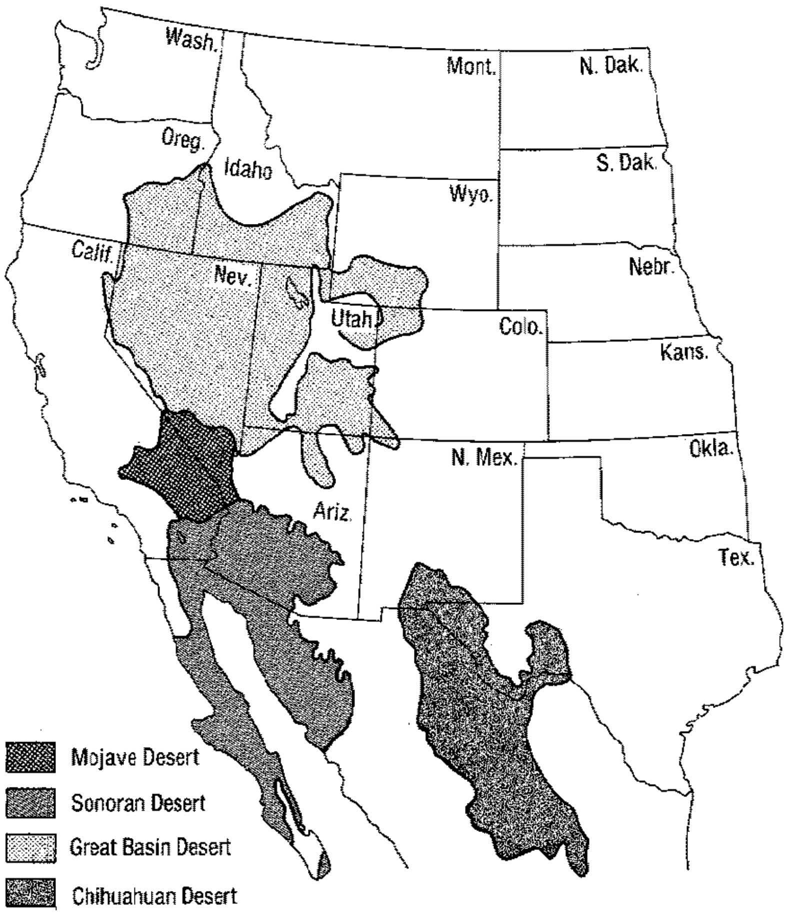
An arid area suffering from desertification can manifest all five symptoms, but the existence of any one can mean that it is undergoing desertification. Frequently, the symptoms are interconnected. For example, the destruction of native plants is quickly followed by excessive soil erosion.

Desertification is often thought of as the literal invasion of a desert, especially desert sand dunes, into nondesert areas. This analysis, for the most part, is a misconception. The process of desertification bears a closer resemblance to guerrilla warfare than to a conventional frontal war:

> Desertification breaks out, usually at times of drought stress, in areas of naturally vulnerable land subject to pressures of land use. These degraded patches, like a skin disease, link up to carry the process over extended areas. It is generally incorrect to envision the process as an advance of the desert frontier engulfing usable land on its perimeter: the advancing sand dune is in fact a very

Figure 1

North American Deserts



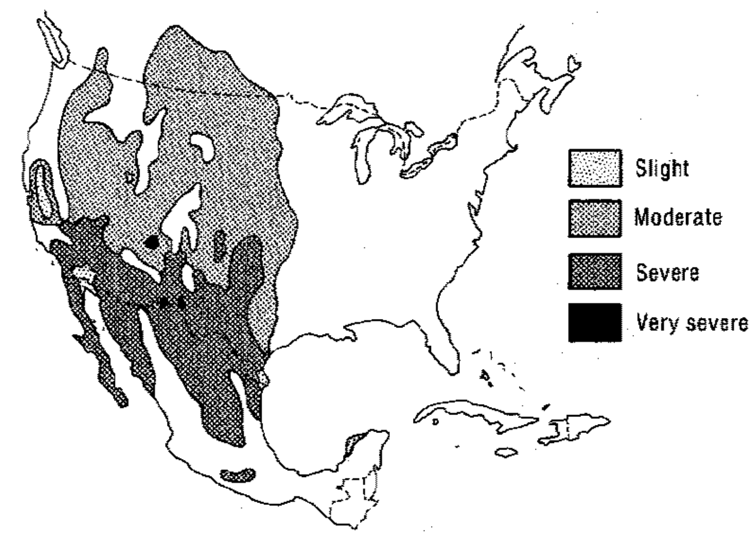
> special and localized case. Desertification, as a patchy destruction that may be far removed from any nebulous front line, is a more subtle and insidious process.[7]

Desertification also applies to the impoverishment of ecosystems *within* natural deserts. For example, the Sonoran and Chihuahuan

deserts of the American Southwest (see Figure 1) are probably a million years old as deserts, and yet they have become perceptibly more barren during the past 100 years. Their native wildlife populations have diminished greatly, with the exception perhaps of rodents. So have their native plants. Perennial grasses have declined and invader species such as tamarisk (*Tamarix pentandra*) and Russian thistle (*Salsola kali*) as well as natives such as burroweed (*Haplopappus tenuisectus*) and snakeweed (*Gutierrezia sarothrae*) have multiplied. The deserts' floodplain vegetation has changed almost beyond recognition in such areas as the Santa Cruz River Valley of Arizona. In short, these deserts have undergone desertification. (Of course, there are locales within these deserts where this generalization does not apply, e.g., where dense stands of mesquite have replaced sparse desert grasses.)[8]

Figure 2

Status of Desertification in North America



Source: Harold Dregne, "Desertification of Arid Lands," *Economic Geography* 53 (4):325 (1977) (copyright © by Clark University).

The overall land area affected by desertification in North America is surprisingly large. Harold Dregne, head of the International Center for Arid and Semi-Arid Land Studies at Texas Tech University, calculated that 1.1 million square miles, or 36.8 percent of the continent's arid lands, have undergone "severe" desertification[9] (see Figure 2). Some 10,500 square miles of the continent have undergone "very severe" desertification, according to Dregne. By contrast, Africa's "severe" desertification totals 4 million square miles, but its "very severe" desertification is less than North America's—5,500 square miles.*

The areas of "very severe" desertification in North America, which Dregne has mapped, are mostly in the United States. The northernmost one is on the Navajo Indian reservation in Arizona and New Mexico. The other two spots bracket El Paso, Texas—with the one to the west straddling the New Mexico-Mexico border and the other, the Texas-New Mexico border.

Dregne estimates that about 225 million acres of land *within* the United States have experienced severe or very severe desertification.[10] (A larger-scale map would show other "very severe" areas of desertification.) This estimate suggests that approximately 10 percent of the U.S. land mass is in a state of severe or very severe desertification. The actual acres *threatened* by severe desertification, however, are almost twice that amount.

THE ARID WEST: LIMITS OF NATURAL RESOURCES§

> Draw a line anywhere from the region's eastern boundary to the Pacific, stand on its mid-point and you will find yourself either in the desert or near it. If we do not understand the West it is because we perversely refuse to recognize this fact.... When the desert pokes a hot finger into the border regions, the people speak of a drought; when it pulls the finger back, they say "the country is getting more seasonable." At the heart of the desert there is no drought, there is only an occasional mitigation of dryness.
>
> —Walter Prescott Webb
> Historian[11]

Just over a hundred years ago, John Wesley Powell wrote *Report on the Land of the Arid Region of the United States*.[12] Historian Bernard Devoto describes it as "one of the most remarkable books ever written by an American." He adds: "It is a scientific prophecy and it has been fulfilled—experimentally proved. Unhappily the experimental proof has consisted of human and social failure and the destruction of the land."[13]

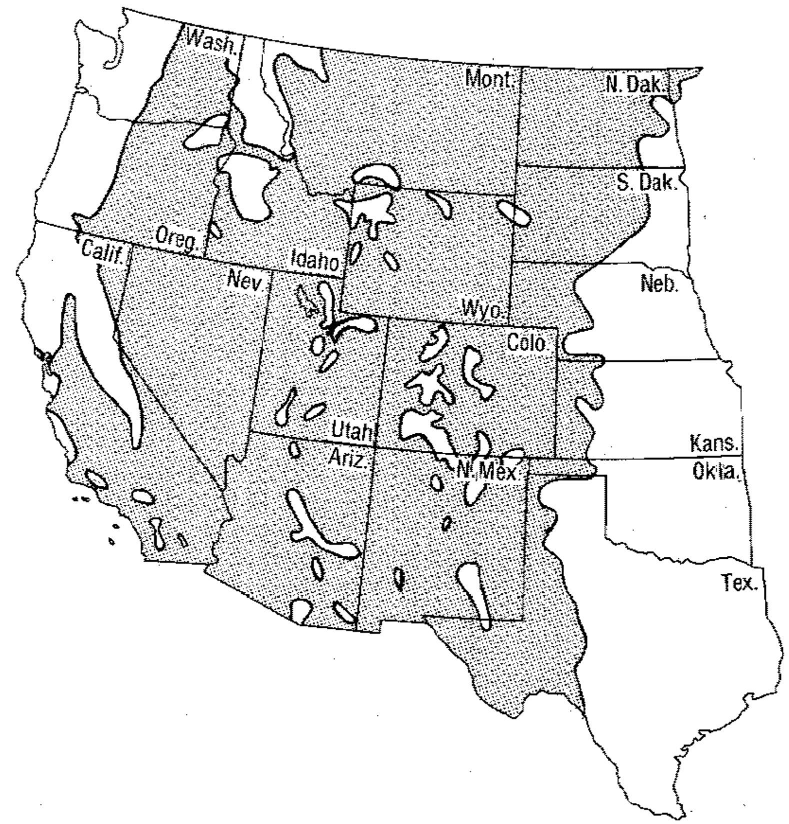
What Powell proposed was truly radical: The arid West should live

*By "severe" desertification, Dregne means: (a) undesirable forbs and shrubs have replaced desirable grasses or have spread to such an extent that they dominate the flora; (b) sheet, wind, and water erosion have largely denuded the land of vegetation, or large gullies are present; or (c) salinity controllable by drainage and leaching has reduced crop yields more than 50 percent. Dregne's criteria for "very severe" desertification are: (a) large, shifting barren sand dunes have formed; (b) large, deep, and numerous gullies have occurred; or (c) salt crusts have developed on nearly impermeable irrigated soils.

§ For the purposes of this report, arid lands are those that receive 20 inches or less precipitation per year (Figure 3). On a year-to-year basis, the 20-inch precipitation line moves considerably. During the Dust Bowl days of the 1930s, it bulged eastward, and then it retreated far to the west in the 1940s. In addition, there are areas west of the line that average 20 inches or more per year. They are at higher elevations in the mountains and along the Pacific coast.

Figure 3

Areas with an Average Annual Precipitation of Less than 20 Inches



Source: James J. Geraghty et al., *Water Atlas of the United States* (Port Washington, N.Y.: Water Information Center, Inc., 1973) (copyright © by the Water Information Center, Inc., Syosset, N.Y.), Plate 2, based on U.S. Department of Agriculture data.

within its means. At a time when railroads, land speculators, and Chambers of Commerce were portraying the arid West as a "garden watered by ample streams and numerous artesian wells,"[14] Powell emphasized the natural *limits* of the arid West's water resources, of its grazing land, of its irrigable land, and of its moisture for dryland farming:

> [T]here . . . remain vast areas of valuable pasturage land bearing nutritious but scanty grass.[15]
>
> Within the Arid Region only a small portion of the country is irrigable. The irrigable tracts are lowlands lying along the streams.[16]

The limit of successful agriculture without irrigation has been set at 20 inches [annual rainfall].... Many droughts will occur; many seasons in a long series will be fruitless; and it may be doubted whether [dryland] agriculture will prove remunerative.[17]

These lands will maintain but a scanty population.[18]

As historian Henry Nash Smith observed: "He [Powell] was asking a great deal. He was demanding that the West should submit to rational and scientific revision of its central myth."[19] Powell, of course, lost. His recommendations to tailor the West's development to fit the limits of its natural resources were rejected by the Congress, with Senators and Congressmen from the region itself providing the stiffest opposition.[20]

In 1893, Powell addressed the boom-minded International Irrigation Congress in Los Angeles. He put aside his prepared speech and amid catcalls and boos said: "I tell you gentlemen you are piling up a heritage of conflict and litigation over water rights for *there is not sufficient water to supply the land.*"[21] (Emphasis added.)

Was Powell right?

When he wrote his report, roughly 1.5 million people lived in the *arid* West. Today, over 28 million live there. The population of the arid West has grown faster than that of the nation as a whole. In 1880, 3 out of every 100 Americans lived in the arid West. By 1970, it was 14 out of every 100. Between 1960 and 1970, the population of the arid West grew 27 percent, and apparently this growth accelerated between 1970 and 1980. According to the 1978 Census, the arid West contains many of the fastest growing metropolitan areas in the nation (see Table 1).

Table 1

Population of Selected Cities in the Arid West, 1978, and Percentage of Growth from 1970

Metropolitan area	Population 1978	Growth
Riverside-San Bernadino-Ontario, Calif.	1,385,400	22
Phoenix, Ariz.	1,293,200	33
Fresno, Calif.	479,000	16
Tucson, Ariz.	461,700	31
El Paso, Tex.	443,400	23
Albuquerque, N.M.	408,800	23
Las Vegas, Nev.	376,800	38
Bakersfield, Calif.	365,300	11
Colorado Springs, Colo.	291,400	22
Modesto, Calif.	246,100	27
Lubbock, Tex.	200,000	12
Reno, Nev.	163,200	35
Amarillo, Tex.	158,100	10

Source: U.S. Bureau of the Census, *Current Population Reports*, "*Population Estimates and Projections*," Series P-25, No. 873 (Washington, D.C.: U.S. Government Printing Office, 1980), Table 1.

The agricultural output of the arid West is equally impressive. In 1977 arid land crop marketings totaled $8.7 billion and livestock,

$7.9 billion.* The agricultural output of the arid West ($16.6 billion) accounted for more than *18 percent* of the nation's total agricultural output that year. Arid lands produced 66 percent of the nation's cotton, 39 percent of its barley, and 21 percent of its wheat.[22]

Clearly, the arid lands of the West are sustaining vastly more people than Powell ever envisioned and are producing far more food and fiber (although Powell's prediction about conflict and litigation over water rights has unfortunately come true). And yet Powell's assessment of the region's physical resources—water, soil, and vegetation—is essentially sound. How, therefore, have the region's agricultural output and its phenomenal population growth been possible? How has the region overcome its fundamental deficiency in the most essential climatic element—water?

Many factors, of course, played a part in the arid West's development, but none more important than:

- The "mining" of groundwater, that is, pumping more water out of the ground than nature is putting back in;
- The damming of the region's rivers to make water available on demand; and
- The transporting of water long distances, from where it is abundant to where it is scarce.

The mining of groundwater was made possible on a grand scale by the development (many years after Powell's report) of the centrifugal pump which, when coupled with an internal combustion engine or an electric motor, can suck water from underground in far greater volume, at greater speed, and from much greater depths than its predecessor, the windmill. As Figure 4 demonstrates, the mining or overdraft of groundwater is widespread throughout the arid West and adjacent semi-arid lands. Irrigated agriculture consumes much of the water in the overdraft areas shown in the figure.[23] In addition, however, municipal users are also drawing down groundwater reservoirs. Several of the fast growing metropolitan areas listed on the table rely heavily on groundwater, including Fresno, Tucson, Albuquerque, Las Vegas, El Paso, and Lubbock.[24]

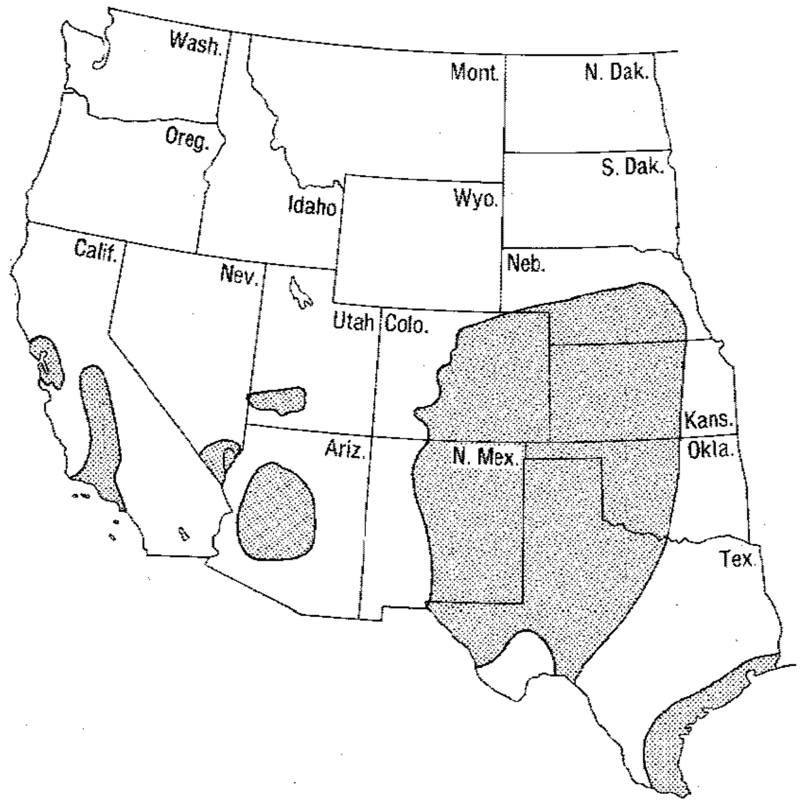
In west Texas, groundwater supplies 75 percent of the total water consumption for the area's billion-dollar-per-year agricultural economy as well as its supporting industries and municipalities. In Arizona it supplies 62 percent of all the water consumed and in California, about 40 percent. By contrast, groundwater accounts for about 20 percent of the water consumed nationwide.[25]

The damming of rivers and the transport of water over considerable distances require, more than anything else, enormous sums of capital. During Powell's lifetime and for many years thereafter, the

*These figures include the agricultural output from Arizona, New Mexico, Nevada, Colorado, Montana, Utah, Wyoming, and Idaho as well as from the arid portions of Texas, Nebraska, Kansas, and California. They do *not* include the arid portions of Washington, Oregon, North Dakota, and South Dakota, however, because the statistics are kept on a county-by-county basis, and in these states it is difficult to correlate the arid land output with county agricultural output figures.

Figure 4

Ground Water Overdraft Areas in the Arid West



Source: U.S. Water Resources Council, *The Nation's Water Resources: 1975-2000*, Vol. 1: *Summary* (Washington, D.C.: U.S. Government Printing Office, 1978), p. 59.

arid West did not have the capital for damming. Ultimately, it was federal dollars that financed the lion's share of the region's huge water projects. Ongoing federally funded projects include the Central Arizona Project ($1.5 billion) and the Central Valley Project of California ($3.5 billion).[26] "One out of every five persons in the [arid] western states is served by a water supply system that imports [water] from a source a hundred miles or more away. In total tonnage, the amount [of water moved] exceeds the freight carried by all the region's railroads, trucks, and barges combined."[27]

Impressive as these developments are, they have not succeeded in solving the region's essential deficiency—its scarcity of water. In addition, they have created troublesome new problems such as salinization.

OVERGRAZING

I don't care if you're talking about Arizona or if you are talking about sub-Saharan African.... There are very, very few arid lands today that are being grazed within their carrying capacity.

—Jack D. Johnson, Director
Office of Arid Land Studies,
University of Arizona[28]

The most widespread and cataclysmic change in the desert [of the United States] in modern times has resulted from unrestricted grazing.... The desert in many places is one-tenth as productive for livestock as it was when white men first came on the scene.

—David F. Costello
The Desert World[29]

At the time of Powell's report, there were approximately 14 million sheep and 5 million cattle grazing in the arid West, and as Powell predicted, their numbers grew rapidly. He warned:

> Though the grasses of the pasturage lands of the West are nutritious they are not abundant, as in the humid valleys of the East. Yet they have an important value. These grasses are easily destroyed by improvident pasturage, and they are replaced by noxious weeds. To be utilized they must be carefully protected, and grazed only in proper seasons and within prescribed limits. . . [T]hey must have protection or be ruined. . . .[30]

But the owners of western rangeland—government and cattle barons for the most part—were in no mood to heed talk of "prescribed limits" and "protection." This was a boom time for arid land ranching, a time of both expansive visions and profits. Within 10 years, the number of sheep grazing on western rangeland increased 28 percent; cattle increased 60 percent.

"Improvident pasturage," or "overgrazing" as it has come to be known, has been the most potent desertification force, in terms of total acreage affected, within the United States.

The three large areas of "very severe" desertification in North America that Dregne mapped (see Figure 2) have all been plagued by overgrazing.*

One is the 15-million-acre Navajo Agricultural Products Industry, described Navajo lands as "tremendously overgrazed." The result is a "badly eroded land base with little of its natural grasses and low shrubs still intact and vigorous."[31]

*Another desertification force in these areas and some other spots in the arid West has been the cutting of trees or bushes for fuel wood, a common practice in the last century and for the first 20 years or so of this century. However, the environmental effects of wood gathering in the arid United States have not been analyzed. Hence, it is not possible to specify the importance of wood gathering as a desertification force relative to overgrazing. In the Sahel, where its effects have been studied, it is thought to be the second major cause of desertification, second, that is, to overgrazing. The possibility that wood gathering may once again become a desertification force in the arid United States is discussed in the "New Stresses" section of this report.

Runoff from intermittent flooding causing bank erosion of overgrazed land on the Navajo Indian reservation in northern Arizona (W. G. McGinnies).

THE NAVAJO LAND CRISIS

Several factors have caused the "Navajo land crisis."[32] Most important, the Navajos have experienced a rapid growth in population—about 3 percent per year—and an anemic development of nongrazing economic opportunities. The Navajos have a birth rate comparable to India or Mexico—31.8 per 1,000 people per year, and unemployment is worse than in the nation's older inner cities—about 63 percent. As a result, the Navajos are reluctant to reduce the number of their sheep and cattle to the carrying capacity of the range. In addition, normal methods of livestock control such as fencing conflict with the Navajo communal tradition. Specifically, once grazing land is used by members of a given clan, it becomes the special preserve (a "customary use area") for their sheep or cattle, but it is not their private property. Other resources on the land such as water, timber, and firewood are considered communal property open to all who need them. Moreover, the Navajos have traditionally viewed the earth as abundant and boundless.[33]

The reality of the situation is that over the last century the Navajo

population has multiplied tenfold while the area of the Navajo reservation has increased only threefold.

In addition, the current Navajo land tenure system possesses inherent uncertainties that inhibit the raising of capital and hinder "rational decision making."[34] Under the treaty between the Navajos and the United States, some 3.3 million acres of reservation are held in trust by the federal government as long as the tribe exists. The land is not owned by individual Navajos; nor does it belong to the Navajo tribe. It is federal property held in trust for the tribe. Individual Navajos exercise control over use rights to the land. The larger portion of the reservation was created by Executive order of the President. In essence, certain lands were withdrawn from the public domain for Indian use. Although custom usually gave the Navajos title to such land, the legal title is still open to serious question.[35]

Federal efforts to control overgrazing on the Navajo reservation began in 1937. By that time the number of sheep on the reservation totaled 1.3 million. The carrying capacity at the time was estimated at about 600,000. The Commissioner of Indian Affairs gave the Navajo Tribal Council the responsibility of livestock reduction and enforcement of grazing regulation. The Bureau of Indian Affairs (BIA) surveyed the customary use areas of livestock owners, and the Council issued sheep permits on the basis of each area's carrying capacity. Livestock reduction met with bitter opposition and progressed slowly.[36]

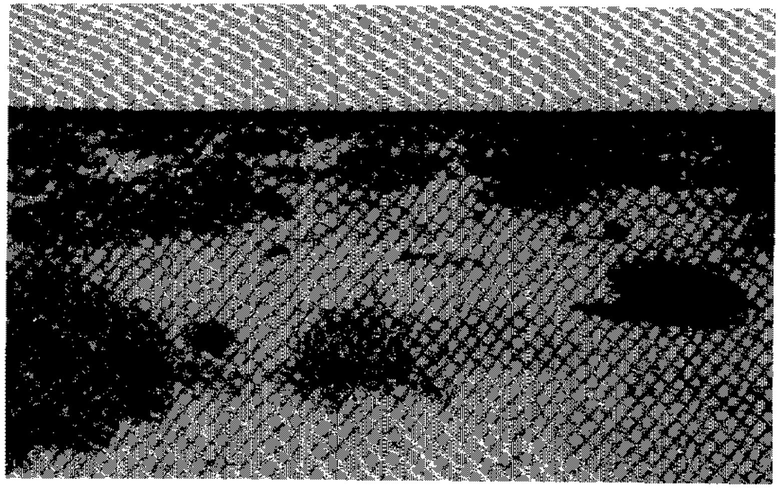
Measures adopted since the forced reduction in livestock in order to control overgrazing have been "ineffective," according to Bahe Billy. He describes the Tribal Council and BIA as "lax" and warns that "if control systems are not implemented soon, this overutilized land will blow or wash away."[37] Today there are reportedly 2,170,300 sheep on Navajo rangeland.[38]

Another factor that has contributed to the desertification of the Navajo reservation was the cutting of shrubs, especially the four-wing saltbush, for firewood. Bahe Billy reports:

> The exploitation was so complete in certain areas that it is now necessary to haul juniper trees from the Flagstaff, Arizona, area or from any place where there is a wood supply. . . . [T]he harvesting of bushes for cooking and for heat has not only reduced the natural resource (vegetation), but also has created a shortage of food for the livestock.[39]

BLM LANDS

The U.S. Bureau of Land Management (BLM) is responsible for a good portion of the land in the other two areas of "very severe" desertification in the United States. Reports from these areas speak of "very poor" range grass conditions, blowing dust, "invasion of mesquite," and formation of sand dunes because of overgrazing.[40]



Sand and mesquite dunes are signs of very severe desertification in the Jordona Desert, New Mexico (Harold Dregne, Office of Arid Lands, University of Arizona).

Throughout the arid West, the BLM manages some 170 million acres of rangeland. In January 1975, the agency reported to the Senate Committee on Appropriations that some 50 percent of this range (81.5 million acres) was in "fair condition," 28 percent (45.6 million acres) in "poor condition," and 5 percent (8.2 million acres) in "bad condition." The remaining 17 percent (27.6 million acres) was either in "excellent" or "good" condition.* The trend in range conditions was not much more encouraging. The BLM reported that the condition of some 105.9 million acres (65 percent) was "static," 31 million acres (19 percent) were "improving," and 25.7 million (16 percent) were "declining."[41] The agency concluded: "Public rangeland will continue to deteriorate; projections indicate that in 25 years productive capacity could decrease by as much as 25 percent. . . ."[42]

More recent analyses by the BLM and U.S. General Accounting Office (GAO) suggest that these figures understated the poor and deteriorating state of the public rangeland.[43]

In December 1974, the U.S. District Court for the District of Columbia found, in *Natural Resources Defense Council* v. *Morton,* that the BLM was in violation of the National Environmental Policy Act for failing to prepare sufficient environmental impact statements (EISs) on public grazing land under its care. Subsequently, under an amended court order, the BLM was required to prepare 144 individual EISs on its grazing plans. In the nine areas where the BLM has completed EISs, the grazing plans call for reduced livestock use on 44 percent of the allotments. At this writing, however, it is not at all clear whether any of these reductions in grazing have in fact been implemented.

*The BLM's assessment of whether a unit of rangeland was in excellent, good, fair, or poor condition was based primarily on a comparison of that unit's actual forage output with its estimated potential output. Some range ecologists have criticized this approach as too crude, believing that the quantity of soil-stabilizing nonforage plants and other criteria should also be considered. Future analyses of range conditions may well be more sophisticated. For the time being, how ever, the BLM report cited here is the best overall assessment of the condition of this public rangeland.

Two such areas for which the BLM has done EISs are the Challis area of central Idaho and the Rio Puerco Basin of New Mexico, 40 miles northwest of Albuquerque. Both are classic cases of the ill effects of long-term overgrazing on arid rangeland. Even before preparing EISs, the BLM had reduced the amount of grazing allowed in both these areas, although not enough. Massive overgrazing in the latter half of the 19th century and the first half of the 20th century left these rangelands in such poor shape that more drastic action was necessary to halt their further deterioration, that is, to stabilize the soils and allow perennial grasses to return so that the very slow recovery process could begin. Whether the new BLM grazing management plans for these areas will accomplish stabilization remains to be seen, but they do seem to be based on a more realistic assessment of soil and vegetation conditions than were previous management efforts.

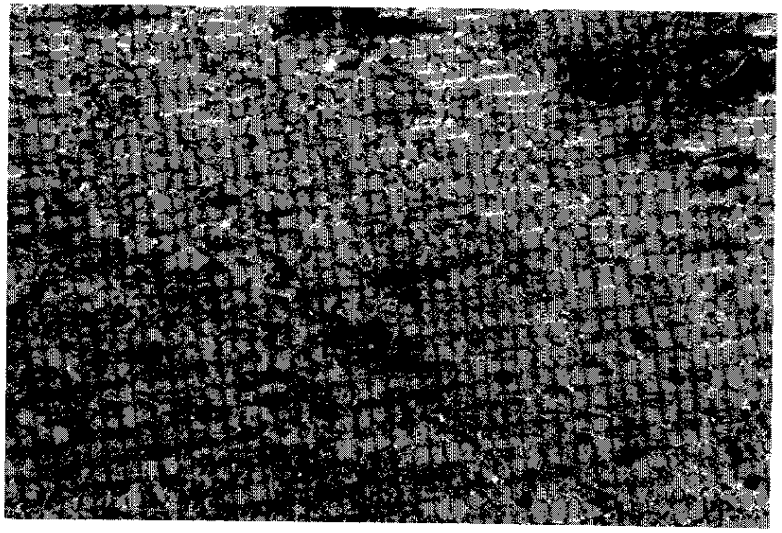
THE CHALLIS PLANNING UNIT, IDAHO

The Challis Planning Unit of the BLM comprises about 352,000 acres of land. In 1948, the BLM allowed some 24,388 animal unit months (AUM)* of grazing in the Challis area. By 1975, the allowance had been trimmed to 18,062. These reductions were insufficient, however, because in 1977 the BLM reported that 30 percent of the range was in "poor" condition and 64 percent, in "fair."[44]

Cattle grazing began here in a big way back in the fabled cattle boom of the 1880s, which James Michener described so vividly in *Centennial.*[45] Challis was then, as it is now, a mixed sagebrush and grass land, but today the grasses are far less abundant than they once were. Indeed, there is a notable "sparsity of grass between sagebrush plants" in many places, and invading plant species such as rabbitbrush and snakeweed proliferate. In the predominately grass areas that have survived, there are "few if any seedlings of bluebunch wheatgrass, Idaho fescue, or Indian ricegrass," and older plants of these species are in "very poor vigor."[46] (Livestock prefer to eat grass, which gives sagebrush, snakeweed, and rabbitbrush a competitive edge.)

Consequently, soil erosion is rampant here. The BLM reported: "In some areas, most of the topsoil has been lost and remaining soil is held only by pedestals of live plants; or dead and dying plants." Overall, about 187,000 acres, or 52 percent of the area, are undergoing "moderate" to "severe" soil erosion. Surface signs of soil erosion—pedestaling, rills, and gullies—are readily apparent in the Challis area. Particularly widespread is the absence of plant litter on the ground to help stabilize the soil and germinate seeds.[47]

*An AUM is the forage needed to support one cow or horse or five sheep or goats for 1 month.



Overgrazed rangeland in the area of Challis, Idaho. Note the absence of plant litter (Robert O. Buffington, Bureau of Land Management).

THE RIO PUERCO BASIN, NEW MEXICO

The soil erosion problems of the Rio Puerco Basin are even worse. The Rio Puerco is, indeed, one of the most eroded and overgrazed river basins in the arid West.

Livestock grazing began in the Rio Puerco Basin in the late 1700s, when impoverished Spanish families from the Albuquerque area settled there. Hostile Navajo Indians destroyed their settlements within 20 years, however. Resettlement of Spanish Americans began in the mid-1800s under U.S. government protection. By the 1870s, approximately 240,000 sheep and 9,000 cattle grazed in the 3.9-million-acre Rio Puerco Basin. Along the alluvial floodplain of the river itself, numerous small farms flourished using ditch irrigation. Prosperous agricultural villages grew up along the river, including San Fernando, Duran, San Francisco, Casa Salazar, Guadalupe, Cabezon, and San Luis[48] (see Figure 5).

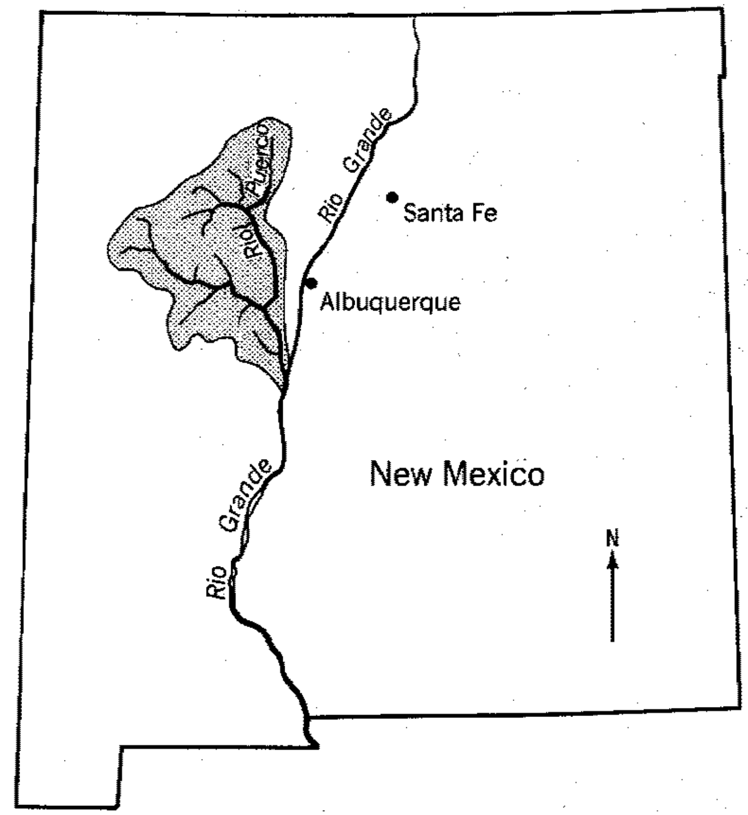
Near the turn of the century, the farms in the middle Rio Puerco Basin were sufficiently productive that the region was known as "the bread basket of New Mexico."[49] But by that time, a process of desiccation and erosion had already begun, a process from which the Rio Puerco has yet to recover.[50]

In the late 1880s in the Rio Puerco, water tables began to drop, arroyo cutting began, and large quantities of sediment began flowing out of the area. Between 1885 and 1962, an estimated 1.1–1.5 billion tons of soil washed from the Rio Puerco Basin into the Rio Grande.[51] As a result, the bed of the Rio Grande downstream of the Rio Puerco rose. Between 1931 and 1938, for instance, it rose 5 feet, and downriver irrigation systems experienced heavy siltation.[52]

The number of livestock grazed in the Rio Puerco Basin peaked in about 1910. Since then, the number has diminished steadily, except for the brief increase in sheep grazing during the 1930s.[53] Irrigated

Figure 5

The Rio Puerco Basin



Source: Based on U.S. Geological Survey, Hydrologic Unit Map-1974, State of New Mexico.

agriculture along the Rio Puerco fared even worse. As Edward J. Dortignac, Chief of the Forest Service's Branch of Water Resources, Division of Watershed Management in the late 1950s and early 1960s, noted, "[W]hat was good, deep, fertile irrigation alluvium has been largely replaced by deep fingering arroyos."[54] The agricultural villages along the Rio Puerco were abandoned one by one during the first half of this century. By 1950 all the settlements had become essentially ghost towns.[55]

Paleobotanist Vorsila Bohrer, who has studied the flora in the Rio Puerco Basin, explains why this area has unnaturally high water runoff and soil erosion: "Historic overgrazing has created extremely dry conditions for plants due to the removal of litter, loss of soil cover, and the trampling of the ground that prohibits rainfall from reaching the roots of plants."[56]

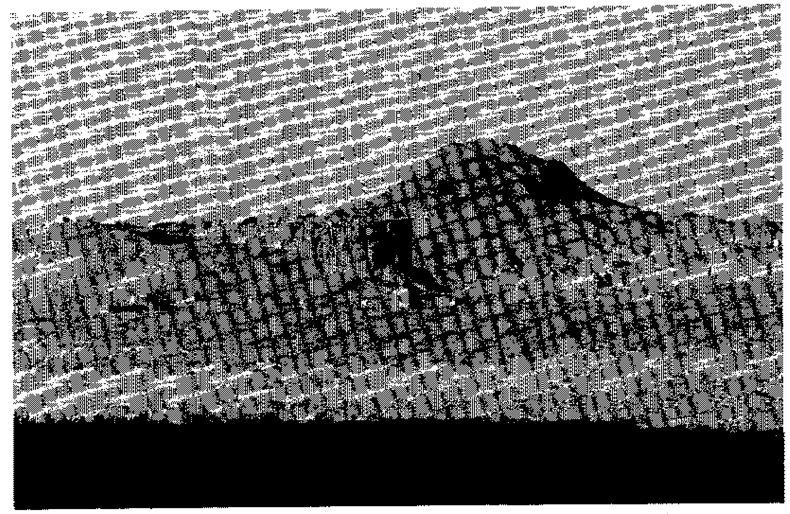
Can the great soil erosion and arroyo cutting that the Rio Puerco and other river basins in the southwestern United States have experienced since the 1880s be attributed entirely to livestock overgrazing of plant cover and trampling of the soil, or has "climatic deterioration" contributed? Scientists disagree.[57] (See "The Santa Cruz and San Pedro River Basins" section of the report for further discussion of this matter.) Some scientists suggest that a change in the seasonality of rainfall in the region—with more rain occurring in the late summer and fall when the vegetational cover is weakest rather than in the spring—contributed to the decline of perennial grasses and helped to trigger the arroyo cutting.[58] Other scientists, such as Bohrer, are skeptical that any such change in the weather actually occurred during this period.[59]

Analyses of tree rings (dendroclimatic data) and pollen deposits in alluvial sediments indicate that the Southwest underwent "high-frequency flunctuations" in climate, specifically in the amount of rainfall, during prehistoric time. Unusually wet or dry periods have dominated many a past century and spanned 20- to 50-year stretches at a time. And within these periods, even more extreme deviations from the average rainfall, such as 1- or 2-year droughts, occurred. Archeological evidence unearthed in the region shows that cultural and demographic changes among prehistoric peoples such as the Anasazi of Chaco Canyon or Mesa Verde coincided with the environmental stresses caused by the climate fluctuations. Furthermore, analyses of the region's hydrologic data indicate that arroyo-cutting episodes have occurred several times in prehistory.[60] Thus it is quite possible that climatic change did trigger the most recent arroyo-cutting episode, which began in the 1880s. It is still unclear, however, exactly what change in the climate touched off the arroyo cutting. Tracking changes in the seasonality of rainfall, for example, requires rather detailed meteorological records, and they simply do not exist for most of the Southwest, including the Rio Puerco, before about 1900-1910.

There is a plausible middle-of-the-road position in this dispute. That is, climatic change of some sort may have initiated the arroyo cutting, but the damage done by livestock made the land much more vulnerable to erosion once it had begun. Perhaps, therefore, the arroyo cutting has been more severe and longer lasting than it would have been in prelivestock times.

Edward Dortignac studied the Rio Puerco and reported that it is "riddled with huge gullies." He estimated that "recovery" would require "many years of prodigious effort." By "recovery," Dortignac meant revegetation.[61]

More recently, geologist Fred Nials has studied the Rio Puerco. He calls the soil erosion "ongoing and incredible—it must be seen to be believed." He reports that in the late 1930s the average arroyo here was 35 feet deep and 121 feet wide. Since then many of the arroyos have not cut appreciably deeper, but they are growing much wider—the average arroyo is now 300 feet wide. Nials notes: "The arroyos



Abandoned village of Guadalupe in the Rio Puerco Valley, Sandoval County, New Mexico (Peter B. George).

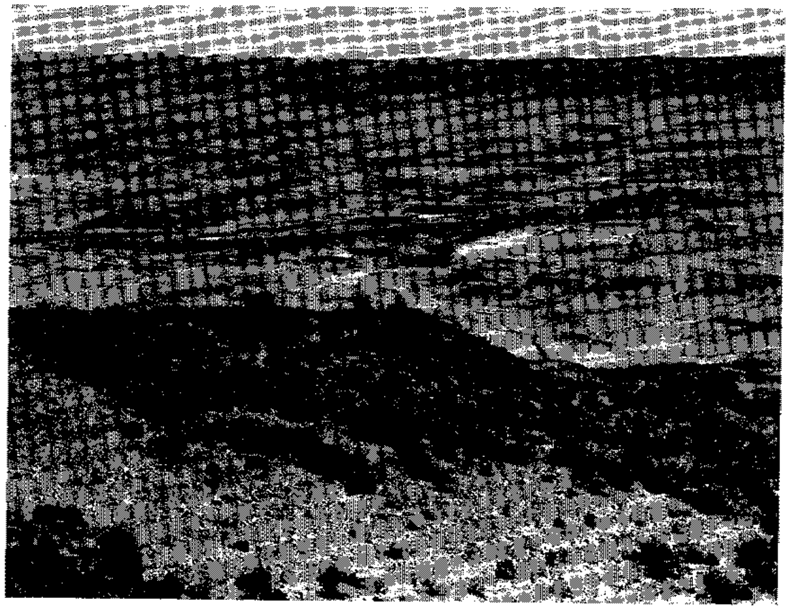
are now eroding laterally at an enormous rate. In 1972, for example, I measured one arroyo which was 38 feet across. A year later it had widened by 50 feet."[62]

Today the BLM manages some 492,063 acres in the Rio Puerco Basin, making it the area's major land manager, and 134 ranchers in the Rio Puerco Basin hold grazing permits for the public land. Of these ranchers, more than 90 percent have Spanish surnames, and 63 percent operate "subsistence" ranches, relying in part on other employment to support themselves.[63]

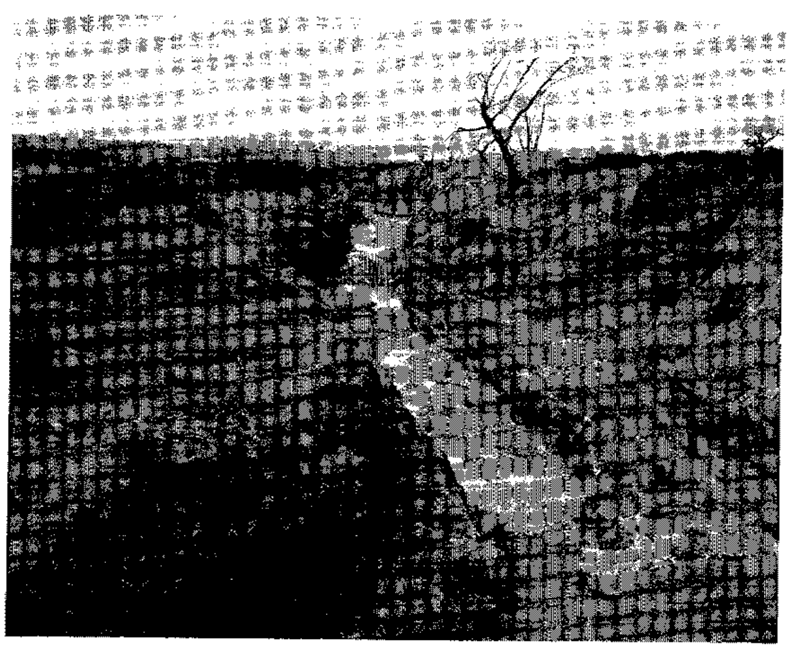
Even though livestock grazing in the Rio Puerco has been reduced significantly since earlier in the century, the land has not yet stabilized. In 1975 the BLM conducted a resource inventory of the public land in the Rio Puerco. It discovered "that forage capacity was inadequate to support overall livestock numbers permitted under the specified grazing privileges."[64] The BLM estimated that 55 percent of the area (270,170 acres) was undergoing "moderate" to "severe" soil erosion.[65] And judging from the observations of Nials, Bohrer, and others, the BLM estimates significantly understate the deteriorated condition of the Rio Puerco Basin.

Particularly unstable are the channels of the Rio Puerco and its tributaries. BLM's EIS on its grazing plan for the Rio Puerco Basin does take note of this phenomenon:

> In the main drainages, the channels have cut down to bedrock, or to a point where downcutting and resistive forces are offsetting. In places, the channel bottom has been lowered as much as 50 feet. Presently, the main channels are widening. As a steep, raw bank is undercut and falls into the channel, the flow is diverted and begins to undercut another bank, which falls in its turn. This process will continue until the channel is so wide that the water flows will lose the erosive forces needed to undercut the banks. Many of the smaller tributary



Arroyo cutting in the Rio Puerco Valley, Sandoval County, New Mexico (Peter B. George).



Rio Puerco drainage—youthful state of arroyo cutting in New Mexico (Bureau of Land Management).

channels are in a more youthful state of development. Here, channel downcutting is still occurring and deep undercuts are common.[66]

Studies by the U.S. Geological Survey and the Soil Conservation Service in various locations within the Rio Puerco Basin indicate that the water erosion of the area's soils ranges from 2 to 8.7 tons of soil per acre annually.[67] In an arid area such as the Rio Puerco, nature probably regenerates soil at a rate of less than 1 ton per acre per year. Suspended sediment concentrations at the mouth of the Rio Puerco are sometimes as high as 267,000 milligrams per liter.[68] (The upward limit for healthy fish life is about 80 milligrams per liter.) Although the Rio Puerco supplies less than 10 percent of the Rio Grande's water, it accounts for over one-half the Rio Grande's sediment load.[69]

Wind erosion of the Rio Puerco Basin, it should be noted, has not been measured, but it is "evident," according to the BLM.[70] Especially vulnerable to wind erosion are the fine sandy loam soils, which cover about 140,000 acres, or 27 percent of the public land.[71] Based on wind erosion rates calculated for comparable arid rangeland elsewhere, the Rio Puerco Basin, overall, is probably losing another 2-4 tons of soil per acre annually to wind erosion, with the especially susceptible soils eroding at upwards of 10 tons per acre per year.

Instability also characterizes the vegetation of the area. For example, broom snakeweed has invaded some 15,000 acres of deteriorated shortgrass and has become established as the dominant species.[72] In fact, of the nine major subtypes of vegetation* found in the area, shortgrass (blue grama, galleta, alkali sacaton) appears to be faring the worst.[73] Overall, the BLM projects that the vegetation in the Rio Puerco in "poor" condition will increase from today's 85,651 acres to 170,703 by the year 2000 under current grazing practices. Moreover, it projects that the land suffering "moderate" to "severe" soil erosion will increase to 360,554—73 percent of the public land here.[74]

Bohrer notes the absence of cool season perennial grasses like mutton bluegrass (*Poa fendleriana*), once quite widespread in the Rio Puerco Basin. Today such species do not reproduce in grazed areas and are found mostly in places inaccessible to sheep and cattle. She also observes that a species such as vine mesquite grass (*Panicum obtusum*), often found in areas recovering from overgrazing, occurs rarely in the Rio Puerco Basin—usually in ungrazed refuges. The diminished state of the once abundant Indian ricegrass (*Oryzopsis hymenoides*) also signals the continuing stress of overgrazing in the Rio Puerco Basin.[75]

To halt the downward spiral of Rio Puerco soils and vegetation, the BLM has proposed a new grazing management plan. In 1975-76, the BLM allowed 58,225 AUMs of grazing on the public land here—the equivalent of 4,852 animals. It would reduce the AUMs by 6,154 and

*The dominant species are: ponderosa pine, 8,638 acres; big sagebrush, 95,145 acres; four-wing saltbush, 18,428 acres; greasewood, 8,974 acres; shortgrass, 150,126 acres; broom snakeweed, 14,693 acres; pinyon-juniper, 181,716 acres; steep and rocky, 10,436 acres; and barren, 3,861 acres.

initiate a rest-rotation system on 370,182 acres of public land. Under this system, a schedule of resting and grazing the various pastures would be followed through the four seasons. About 29 percent of the public rangeland would receive a year's rest from grazing at a given time, with other acreage receiving briefer rests. The plan also calls for the construction of various "range improvements," for example, fences, wells, water catchments, cattleguards, and water tanks. In addition, some 2,525 acres of brush would be burned or cut and then seeded for grass.[76]

Whether the measures proposed by the BLM are in fact strong enough to stop the continuing deterioration of the land and plants in the Rio Puerco Basin is open to question. Geologist Nials thinks not. He suggests that in order for the areas on the public land with extremely fragile soils—about 98,000 acres, or 20 percent of the total—to stabilize, the BLM will have to close them entirely to grazing for a long period.[77] As noted earlier, the absence of plant litter across large portions of the Basin will make the germination of seeds difficult, even under reduced grazing.

If the land and plants here finally do stabilize, three factors militate *against* the swift return of the Rio Puerco to its pregrazing richness. First, of course, the Rio Puerco is a dry area with average annual precipitation ranging from 9 to 14 inches. Dry land recovers very slowly from abuse. Second, the massive soil erosion that has occurred here over the last 100 years has exposed soils that are less able to support plant life because of their lower organic content. And third, invader species such as broom snakeweed have already become well established because of the competitive edge grazing has given them over more palatable species. They will not disappear naturally. Massive intervention by humans will be necessary if they are to be rooted out and replaced by native species.

FEDERAL EFFORTS TO MANAGE GRAZING

Arid land experts such as Dregne are encouraged by the BLM's efforts in recent years to bring the grazing of public rangeland in the West in line with its carrying capacity.[78] Passage of the Federal Land Policy and Management Act of 1976 cleared away any lingering doubts concerning the BLM's mandate. This law makes the BLM responsible for the *long-term* productivity of the public rangeland under its management. BLM Director Frank Gregg states that the court-ordered EIS on grazing management plans for specific areas has provided the agency with "a special opportunity to gain a better understanding of the basic capability of the vegetation and soils of these lands and the needs and desires of the people who use them."[79]

In 1978, the Congress passed the Public Rangelands Improvement Act. This legislation recognized that public rangelands:

- Are still producing forage below their potential and
- Will remain in an unsatisfactory condition, or decline even further, under present levels of funding and management.

Range improvement in the Rio Puerco Valley, Sandoval County, New Mexico. Grass on the left is protected from overgrazing (Soil Conservation Service).

It also recognizes that to continue the current level of management of the land will mean further loss of soil, water, wildlife habitat, and forage. Under the law, the Congress authorized "an intensive public rangelands maintenance, management, and improvement program involving significant increases in levels of rangeland management and improvement funding for multiple use values." This mandate was backed with a commitment of $365 million over the next 20 years for a program of intensified rangeland management, but subject to annual appropriations over the next 2 decades.[81]

Do these encouraging signs spell the end of overgrazing of arid public land* in the United States? Alas, no. The issue is far from resolved. In 1934 the Congress passed the Taylor Grazing Act. It was intended to end overgrazing of the public rangeland but, in fact, did not. Why?

For one reason, the BLM, then known as the Grazing Service, was ill prepared to implement the law.[82] The BLM is better prepared today, but whether it has the expertise and personnel to manage grazing effectively on 170 million acres of land is still not clear. Of particular concern is the agency's failure to establish effective systems for monitoring ongoing soil erosion and vegetation stress in critical areas.[83] Without such systems, the BLM may continue to learn of potentially irreparable damage to the land *after* it has already occurred. For example, researchers studied the environmental effects of BLM-authorized sheep grazing on four sites in the western Mojave Desert in 1978. They found that the heavy grazing caused at least a 60 percent reduction in annual vegetation and decreased the cover of perennials 16-29 percent. The sheep also caused significant soil compaction, which could hinder the return of annuals. The researchers noted: "These changes indicate that the range quality of the Mojave Desert is deteriorating under sheep grazing pressures."[84] An adequate monitoring system could have alerted the agency to the problem that such severe impacts were occurring and allowed it to take timely remedial action.

A second reason why the Taylor Grazing Act failed to end overgrazing is that there is no painless means of accomplishing this task. Political scientists refer to a policy such as the reduction of grazing on the public land as "redistributive" and note that in our political system such policies are very difficult to implement because of the stiff political opposition of the group which has something to lose, in this case, the ranchers.[85] The way to stop overgrazing is to reduce the number of livestock on the land. But this reduction results, at least in the short term, in reduced income for the ranchers who own the livestock that graze on the public rangeland. Bitter opposition to the BLM's proposed grazing management plan for the Rio Puerco Basin, for example, is evident in the ranchers' comments on the plan, reprinted in the EIS.[86] As the BLM produces grazing management plans for more areas, political pressure from the ranchers will mount and coalesce into a strong political opposition to reduced grazing on the public rangeland. Indeed, the BLM's still very limited efforts to

*Although this report concentrates on public rangeland, private rangeland in the arid West is by no means immune to overgrazing. On the subject of the overgrazing of public land versus the overgrazing of private land, the author has heard the following statements:

- Private rangeland is every bit as overgrazed as public rangeland,
- Private rangeland is less overgrazed than public rangeland, and
- Private rangeland is more heavily overgrazed than public rangeland.

Unfortunately, there seem to be very few solid data to support any one of these generalizations, at least in terms of an overall assessment of the arid region of the United States. Any of the three may be correct, depending on the locale one is observing.

reduce grazing have already aroused considerable opposition. This opposition has partially fueled the so-called "sagebrush rebellion" in the arid West, which seeks to turn over large portions of the federally managed public land to the states or to private owners. Political pressure from the livestock industry from 1934 to 1976 effectively hamstrung the implementation of the Taylor Grazing Act.[87]

Additionally, ranchers do not necessarily see their current use of the public rangeland as exceeding its carrying capacity. The ranchers often differ with range scientists in the government or academia on what level of use actually constitutes overgrazing. Such differences were made abundantly clear in the *Range Condition Report* prepared for the Senate Committee on Appropriations by the BLM.[88] Ranchers who commented on the condition of a given area of public rangeland invariably said that it was in better condition than did the range scientists.[89] Anyone who has ever attended a conference at which both scientists and ranchers were present has observed this phenomenon in action. The ranchers argue, on the basis of their long working experience with the land, that it is not overgrazed; scientists, on the other hand, who have studied the current state of the land's plant and animal life and compared it to pregrazing conditions, argue the contrary. Both sides can be quite persuasive—the ranchers as practical men whose livelihood depends on understanding the range and the scientists as objective data gatherers. Sometimes, however, the scientists' understanding of pregrazing conditions is limited by the lack of a control (ungrazed) area.

Do ranchers really have so much to lose from reduced grazing of the public rangeland? Perhaps not in the long term, because reduced grazing now will allow the grasses and forbs to recover somewhat, and hence the range will produce more forage in the future. For example, the BLM calculates that, under its proposed grazing management plan for the Rio Puerco Basin, the public rangeland will produce 121,788 AUMs of forage by the year 2000, compared with 69,446 today.[90] In the short term, however, when a rancher's allotted AUMs on the public rangeland are cut, that rancher is faced with three alternatives:

- Reduce the size of his herd;
- Intensify grazing on his own land; or
- Purchase additional forage for his animals on the private land of others, that is, on the free market.

Under the first alternative, the rancher can incur a loss if beef or lamb prices are low at the time of sale in relation to costs. The second alternative can lead to lower productivity of private rangeland; the third increases the rancher's costs. Public forage is cheaper than private forage. In New Mexico in 1978, for example, the BLM grazing fee was $1.51 per AUM, or $18.12 to graze one cow each year. But private land grazing leases ran $5.20 per AUM, or $62.40 for one cow per year.[91]

OVERGRAZING ON INDIAN RESERVATIONS

A final consideration regarding overgrazing: The court-ordered EISs, the new law, and the BLM's new grazing management plans do not affect the millions of acres of rangeland on Indian reservations in the arid West. Under law, the federal government has a fiduciary responsibility for the Indians and their resources; yet this land is some of the most overgrazed in the arid West. The Navajo reservation is not the only example. There are numerous others; for example, the Papago reservation in southern Arizona and the Fort Hall Indian reservation in southeastern Idaho are in poorer condition than private, BLM, or Forest Service rangeland in their vicinity.[92]

The basic cause of the heavy overgrazing of Indian reservation rangeland is no mystery. These are poor people, not as poor as the people of the Sahel but among the poorest in the United States. Like the people of the Sahel, they overgraze the land because they have no choice.

CARRYING CAPACITY

From North Africa and Asia Minor to Greece and Spain, this planet is replete with examples of the catastrophic effect of imposing intensive land use for short-term gain on vulnerable landscapes.

—George V. Burger[93]

Developed initially as a concept for describing the growth and dynamics of species populations, "carry capacity" was defined as a limit on the number of species that could be maintained within an ecosystem or habitat. . . . [T]he concept of carrying capacity needs to be broadened to include interactions that occur between human and natural system.

—A. Berry Crawford and A. Bruce Bishop[94]

In the chapters that follow, five specific areas within the arid West are examined. They differ in many respects. The Wellton–Mohawk Irrigation District in southwestern Arizona, a green postage stamp on an expanse of brown desert, can be driven through in an hour. California's San Joaquin Basin, on the other hand, is a seemingly endless stretch of flat fields, belonging to what are still called "farms" but could be more accurately described as food and fiber factories. The Santa Cruz and San Pedro Basins in south central Arizona are creased with canyons and gullies and are uplifted at intervals by mountain ranges and mesas. Gaines, Crowley, and Kiowa Counties on the Great Plains resemble a gently swelling sea.

The one characteristic that binds them together (aside from an average of less than 20 inches of rainfall per year) is that, within each, humans are exceeding the carrying capacity of their natural life support systems.

In the Wellton–Mohawk District, for example, the ability of the land to absorb water and leach out salts is being exceeded, just as it is in the San Joaquin Basin. In Gaines County and the San Joaquin, the consumption of groundwater by agriculture is exceeding nature's ability to replenish it. In Crowley and Gaines Counties as well as in

the Santa Cruz Basin, groundwater is being mined by both agricultural and urban users. In the San Joaquin, Santa Cruz, and San Pedro Basins, livestock owned by humans are eating grasses and forbs faster than these plants can reproduce. In Gaines, Kiowa, and Crowley Counties as well as parts of the San Joaquin, cultivation of the soil is causing it to blow away faster than nature can regenerate it. In Crowley County and in the Santa Cruz and San Pedro Basins, cultivated fields have been abandoned for lack of irrigation water.

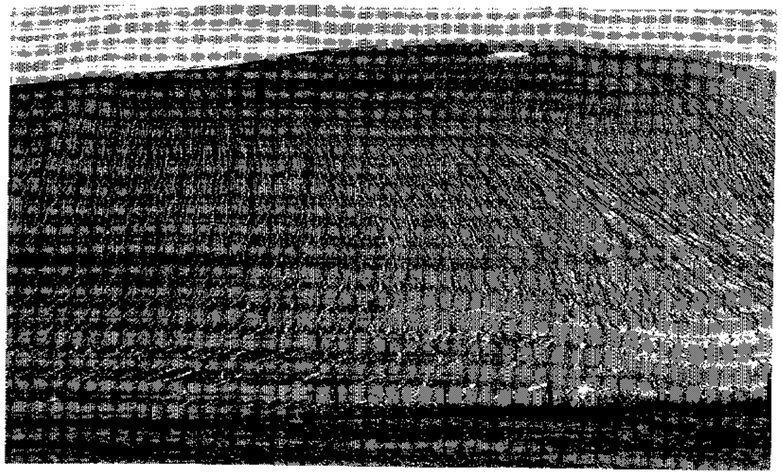
These are *not* isolated cases. In the arid West, there are many others. Natural life support systems are overtaxed throughout the region.

In western Nevada, for example, irrigation (the Newlands Irrigation Project) and urban (Reno-Sparks) diversion of water from the Truckee River and overdraft of Truckee Valley aquifers have decreased the flow of water into Pyramid Lake. Since 1906, the level of the Lake has dropped 70 feet, and in the past 2 decades, its turbidity and salinity have increased markedly. As a consequence, the Lake's population of cutthroat trout and other fishes, the primary source of income for the Pyramid Lake Paiute tribe, has diminished. Unless the Lake receives more water from the Truckee, it will die.[95]

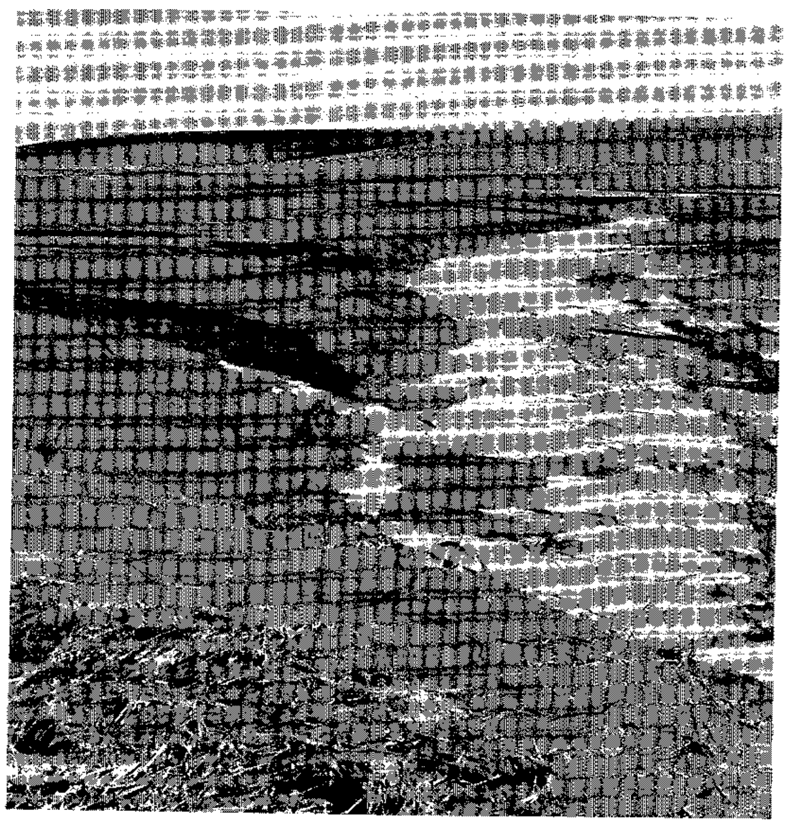
To the north, in the Palouse River Basin of eastern Washington, excessive tillage of silty loess soils on rolling terrain is causing severe soil erosion. Some 1.3 million tons of silt, much of it from cropland, is deposited in the Palouse River annually. A 4-year study by the U.S. Geological Survey (USGS) found that the loads of suspended sediment in the mouth of the Palouse average 2,850 milligrams per liter.[96] As noted earlier, 80 milligrams per liter is considered the upward limit for healthy fish life. In southeastern Idaho, in the Snake River Basin, increasing numbers of farmers are plowing foothills and high terraces above valley floors now that grain prices are rising. Soil erosion from these steeply sloping fields might exceed 20-40 tons per acre per year.[97]

In Arizona, southwest of Phoenix, in the Gila River Basin, huge tracts of desert have been plowed up in order to raise cotton. One such operation in this area—the Paloma Ranch at Theba, owned by the Northwestern Mutual Life Insurance Company—has approximately 20,000 acres of desert under cultivation for cotton. It is irrigated primarily with groundwater. A Soil Conservation Service expert there reports that "groundwater overdraft in the area is very bad." With the groundwater level dropping, irrigators are having to pump water from farther and farther down. Some wells in the area are now drawing water from 500 feet below the surface.[98]

In the Antelope Valley, California, a fast-growing area an hour north of Los Angeles, on the edge of the Mojave Desert, the groundwater is dropping about 3 feet per year because of increased urban demand for water.[99] To the north, the Owens Valley has been desiccated by the Los Angeles Aqueduct. The Valley's once large lake, which still appears as a splash of blue on many atlas maps, is now dry. During high winds, dust storms blow from the barren Owens Lake



Above, severe rill erosion on finely worked summer fallowed ground in the Palouse River Basin, Whitman County, eastern Washington (Verle G. Kaiser, Soil Conservation Service). Below, silt from eroded cropland filled a channel during a 2-hour cloudburst when 3 inches of rain fell in north Grant County, Washington, August 1976 (J. Pettibone, Soil Conservation Service).



Heavy deposits of silt created islands at the mouth of the Palouse River in eastern Washington (Earl R. Baker, Soil Conservation Service).

bed. Farther north, the whole process is being repeated at Mono Lake. Water is being siphoned off and transported nearly 300 miles south to Los Angeles. Consequently, the Lake's level is dropping precipitously, exposing ever broader expanses of bare, dry shoreline for wind storms to ravage.[100]

In western Kansas and Nebraska, many farms have converted to irrigation. Overdraft of the Ogallala Aquifer, which underlies this whole area, is now, in fact, epidemic.In west central Kansas, for example, irrigation wells numbered 250 in 1950. Today there are 2,850. Within the Aquifer there, the area saturated with water was 58 feet thick in 1930; today it is less than 8 feet thick. According to the USGS, present rates of irrigation in some parts of southwestern Nebraska will cause water level declines of almost 50 percent between 1978 and the year 2000. In Nebraska, an average of more than 300,000 acres of irrigated corn (for grain) has been established each year since 1973. Half of all the existing irrigation projects in the western part of the state are expected to experience water shortages in 20-25 years.[101] A recent report on farming in this area noted:

> When drought struck in the early 1970s, the Department of Agriculture and the machinery companies responded with "center-pivot" irrigation.... Huge, quarter-mile-long scaffoldings now "walk" around a farmer's field, spraying

Erosion on a cultivated foothill in southeastern Idaho (Frank M. Roadman, Soil Conservation Service).

> water from a central well. Although enormously expensive and already running up against groundwater limitations, central-pivot agriculture has created another quantum leap in production figures.[102]

In light of the wholesale overdraft of the Ogallala and other aquifers throughout the arid western states, it is noteworthy that hydrology once boasted a concept known as "safe yield." This meant that aquifers should be pumped no faster than they are naturally recharged. The concept was abandoned, and within the last 20 years or so, the USGS simply dropped the term "safe yield." The new rationale that replaced "safe yield" was explained by H.E. Thomas of the USGS in his influential article, "Water and the Southwest—What Is the Future?" in which he wrote:

> [W]holesale depletion (of groundwater) may be economically feasible in the long view if it results in building up an economy that can afford to pay for water from a more expensive source.[103]

Today the Ogallala Aquifer supports irrigated agriculture on more than 11 million acres of arid land.[104] As Charles Bowden observe: "Fossil water and fossil fuel made a billion dollar economy."[105]

At present, three federal agencies are engaged in major studies of the future of the Ogallala. The USGS is doing a 5-year study of the hydrologic impact of pumping on the whole aquifer. The U.S. Department of Commerce's Economic Development Administration is studying the impact of declining water levels on the region's economy. The U.S. Bureau of Reclamation is analyzing the High Plains' "water problems and needs."[106]

Yes, the farms, industries, and cities in the arid West are straining the region's life support systems—water, soil, and vegetation. The stress signs are obvious: dry streams and lake beds; gullies; sediment-choked and increasingly saline rivers; denuded slopes; and weed-infested or desiccated grasslands—the telltale symptoms of desertification.

Arid land experts Crawford and Bishop warn against the use of an overly simplistic carrying capacity concept when applied to "the interactions between human and natural systems." They point out that in most systems controlled by people, limits are subject to change. "Means exist for increasing water supply and for decreasing demand; the carrying capacity... is elastic."[107]

They are right, of course. The entire development of the arid West corroborates the point. Human ingenuity has stretched the capacity of natural resources. The question today is: *How much further can the natural resources of the arid West be stretched?* For instance, beneath the Ogallala Aquifer in parts of west Texas, there lies another water-bearing stratum. It contains hugh quantities of brackish water. To utilize it, humans will have to drill deep (more than 1,500 feet) through an impervious layer of clay that underlies the Ogallala, pump the water up, and purify it. Will technology exist in the future to make such drilling economical? More important, can we plan on this technology being available?

Questions such as these crop up repeatedly when the carrying capacity of the arid West's natural life support systems are examined—because these systems, as Crawford and Bishop observed, are breaking down with "increasing frequency."[108]

THE SAN JOAQUIN BASIN, CALIFORNIA

> The first recorded civilization, that of the Sumerians, was thriving in the southern Tigris-Euphrates Valley by the fourth millenium B.C. Over the course of two thousand years, Sumerian irrigation practices ruined the soil so completely that it has not yet recovered.... Vast areas of southern Iraq today glisten like fields of freshly fallen snow....
>
> —Erik P. Eckholm
> *Losing Ground*[109]

Only a few hundred acres of land in the San Joaquin as yet wear a glistening mantle of salt. But salinization of the top soil, one of the deadliest forms of desertification, could spread to large stretches of this rich valley during the next 30 years. And although salinization is the major threat to the San Joaquin's productivity, it is not the only one. In fact, of the several areas discussed in detail in this report, the San Joaquin is the one in which all the major forces of desertification are at work:

- Poor drainage of irrigated land;
- Overgrazing;
- Cultivation of highly erodible soils;
- Overdraft of groundwater; and
- Off-road vehicle damage to soil and vegetation.

The San Joaquin is the southern half of the great Central Valley of California, lying between the Coast Ranges and the Sierra Nevada (see Figure 6). The San Joaquin Basin encompasses 18.2 million acres—mountains, rolling foothills, and a flat valley floor. The valley floor and foothills total about 10 million acres.[110]

The San Joaquin is an arid land. Annual precipitation in the north averages about 14 inches per year and declines with movement southward, averaging about 5 inches in the southernmost Tulare sub-basin. Nonetheless, this Basin is one of the most productive agricultural areas of the world.[111]

The eight San Joaquin counties produced $4.76 billion worth of farm products in 1977, which is more than most states produce.[112] In fact, the San Joaquin outproduced all but three states—Iowa, Texas, and Illinois.[113] Major crops grown in the San Joaquin are cotton, grapes, tomatoes, barley, alfalfa, and sugar beets as well as a variety of tree crops—including walnuts, almonds, oranges, and apricots. It also has a sizable livestock industry.

Despite its aridity, the San Joaquin is so productive for several reasons. Material eroded over millennia from the mountains on either side have accumulated in the valley to form a thick, rich soil. The growing season is long—most of the valley is frost free for at least 8 months. It possesses a Mediterranean climate with hot, dry summers and mild, moist winters. Of the Basin's 4.8 million acres of cultivated cropland, 97 percent are irrigated.

Where does the water come from? Twenty percent is imported from outside the Basin, mostly from the northern part of California.[114] This water is stored in reservoirs behind government-built dams and is delivered by government-built aqueducts (state and federal). The cost to the irrigator varies, but it is relatively inexpensive—ranging from about $12 to $35 per acre-foot. The state charges more for water from its projects than does the federal government.

Forty percent of the irrigation water comes from aquifers within the Basin and 40 percent from streams. The San Joaquin's agricultural prosperity rests in part on the very shaky foundation of groundwater overdraft. About 1.5 million acre-feet more water is pumped from the basin's aquifers each year than is naturally replenished. This overdraft fills 12.5 percent of the San Joaquin's average annual water supply.[115]

Agriculture dominates the San Joaquin, particularly the 8.5 million acres of valley floor. Over the past 150 years, first cattle and sheep grazing and then crop production (especially wheat, at the beginning) transformed the valley's natural ecosystem beyond recognition. Desert shrubs occupied portions of the valley between the coastal ranges and the valley trough, although most of the San Joaquin was grassland dotted with oak trees; surprisingly, large marshes and shallow lakes once existed there. Today the native perennial grasses are gone, and the wetlands have almost disappeared. Gone also is most of the native wildlife. Major portions of the valley have become a crop-producing factory.[116] Except for livestock grazing,

Figure 6

The San Joaquin Basin and the Imperial Valley

Source: Based on U.S. Geological Survey, Hydrologic Unit Map–1974, State of California.

development of the San Joaquin foothills came mostly after World War II. The combination of cattle and sheep overgrazing and the introduction of European plant species such as filaree desolated the native perennial grasses of both the foothills and the valley floor. Later, orchards, vineyards, and subdivisions were planted in the foothills.[117]

SALINIZATION OF CROPLAND

Today about 400,000 acres of irrigated farmland in the San Joaquin are affected by high, brackish water tables. Ultimately, by the year 2080, *1.1 million acres* of San Joaquin farmland will become unproductive unless subsurface drainage systems are installed.[118]

As Figure 7 shows, the poorly drained area runs along the west side of the valley for almost its entire length. A few of the highly saline "perched" water tables occur naturally, but many are created by irrigation water percolating down from the surface. All water, including fresh irrigation water, contains some salt. When the water is applied to a field for irrigation, some of it evaporates, some is consumed by the plants, and the remainder trickles down into the ground. The difficulty is that the sun and plants extract almost pure water from any water supply, and the water that is left and that trickles downward has a higher content of dissolved salts than when it was first applied. Some irrigated areas, such as west Texas, are fortunate because underlying the fields is a thick stratum of permeable material that allows the salty unused irrigation water to drain deep, far below crop roots. Other irrigated areas, such as the Tigris-Euphrates Valley, the Imperial Valley, and the San Joaquin, are not so fortunate. Not too far beneath the surface of the fields is a tight layer of material that blocks the water's downward passage. Hence the salty water builds up, perhaps adding to a water deposit that has already collected naturally or creating a new underground water deposit. In either case, as the deposit's volume increases, of course, its level rises toward the surface—toward the roots of the crops. The salty perched water table need not actually rise to root level to hurt the plants. If it comes within 5 feet of the roots, it will cause damage because some of the water will continue to rise through capillary action. When the salty water does reach a crop's roots, it inhibits the plants' ability to absorb moisture and oxygen. As a result, the plants either become stunted or die, depending on how concentrated the salt is in the water. And if the salty groundwater reaches the surface of a field, it will evaporate and leave salt crystals behind. If enough salty water reaches the surface and evaporates, a salt crust will form over the soil, a crust that is relatively impermeable, thereby diminishing the natural leaching power of water falling on the field.

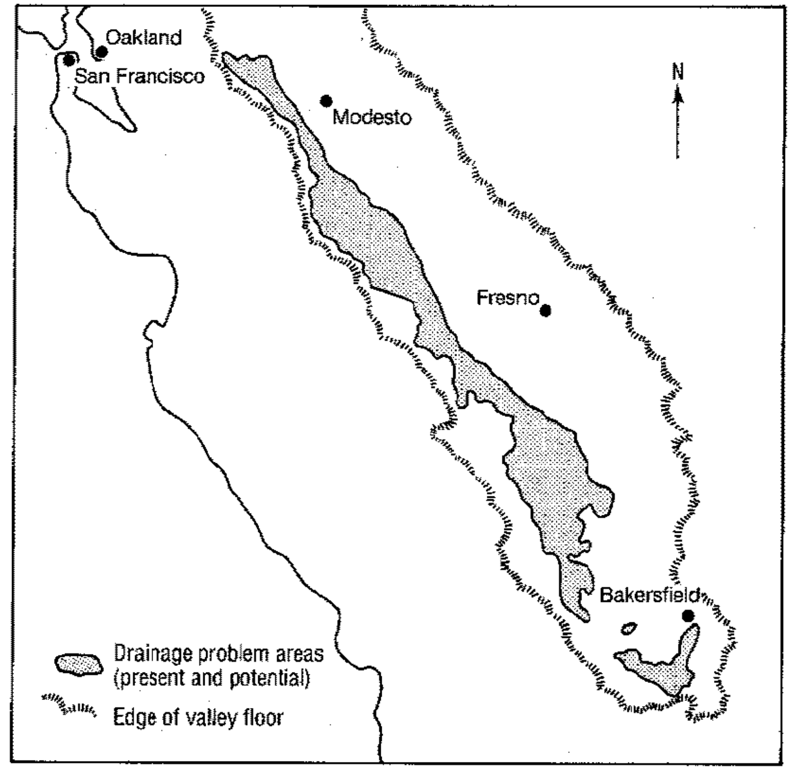
Figure 8 shows in profile a typical section of land in the poorly drained San Joaquin. Particularly telling is the lateral movement of the groundwater downslope. This movement makes the problem even more difficult because the upslope farmer who contributes to the problem may not suffer the consequences. Rather, the downslope neighbor may end up with a perched water table endangering his crops.

There is no technical mystery to solving the age-old irrigation problem of salinization. The solution is quite clear—drain off the excess groundwater. First, the irrigator needs to install an on-farm drainage system to collect the perched saline groundwater. To date, only about 40 percent of the San Joaquin's farms have on-farm drainage systems.

Next, the irrigator needs to dispose of the drained water. In some cases, on-farm drainage can be combined with on-farm disposal by a few vertical wells or deep ditches on the perimeter of the fields so that the unused irrigation water drains into a water-holding stratum far beneath root level and beneath the layer of material that has been blocking its downward flow. The big danger with this procedure is in draining the salty water into the aquifer system from which water is

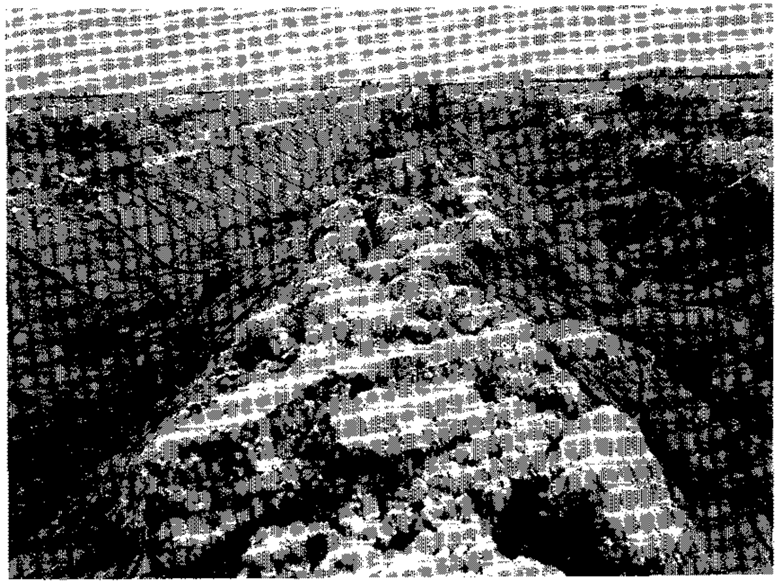
Figure 7

Drainage Problem Areas in the San Joaquin Valley



Source: U.S. Bureau of Reclamation and California Department of Water Resources, *Agricultural Drainage and Salt Management in the San Joaquin Valley, Preliminary Edition* (Fresno, Calif., 1979), p. 6.2.

being pumped for irrigation. The great advantage to this approach is that there is no off-farm drainage water disposal problem. An alternative, the one which is apparently most practical for farms in the San Joaquin's poorly drained areas, is to lay perforated pipes in parallel lines 6-10 feet beneath the fields. (Historically, such drains were made of clay tile, and today they are still referred to as "tile drains," although they are now usually made of concrete or plastic.) After collection in an on-farm sump, the saline water must then be pumped along a lined ditch to a master drain. From the master drain, the saline water can be dumped into a natural salt sink, a salt lake, or an ocean, for example, or into an evaporation pond created just for this purpose. In a large, shallow evaporation pond, the saline water evaporates, leaving a salt bed behind. Another option is to release irrigation drainage water into a naturally low-lying area to create a saltwater marsh and wildlife refuge.



Severe salinization threatens the agriculturally prosperous San Joaquin Valley (Bureau of Land Management).

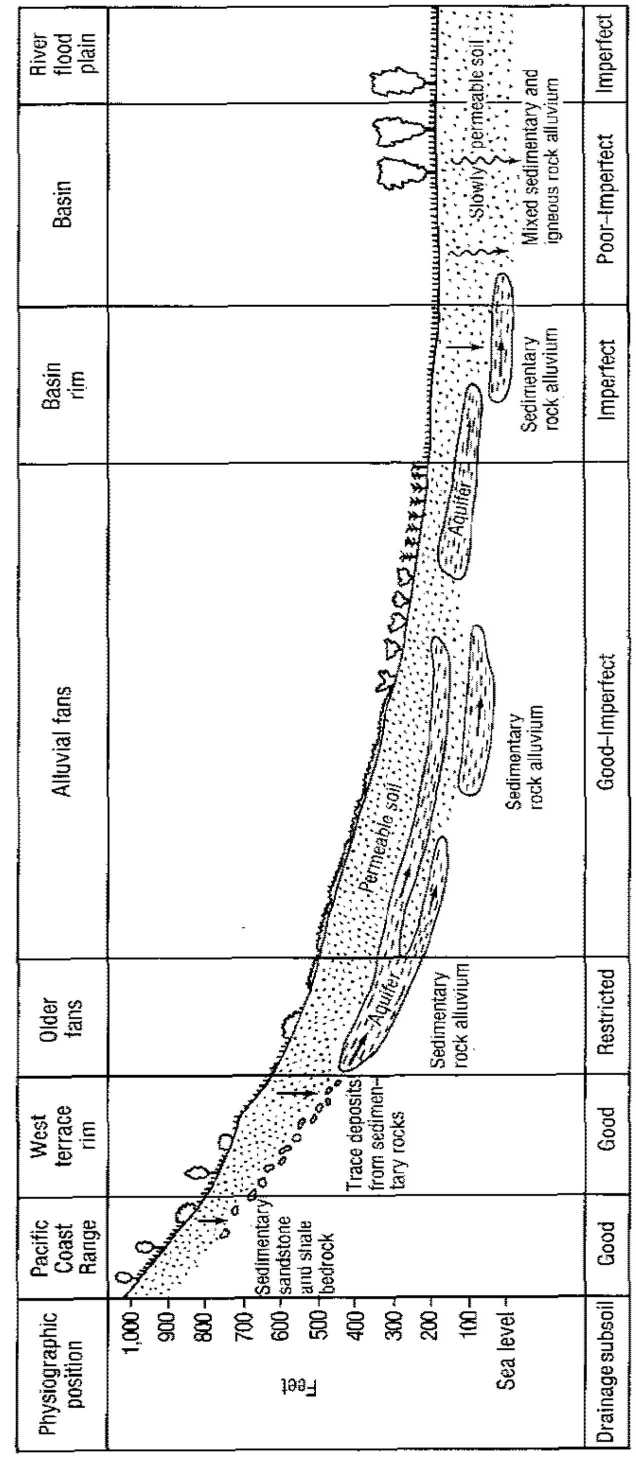
THE IMPERIAL VALLEY

The Imperial Valley, an area where highly intensive irrigation occurred before it did in the San Joaquin (see Figure 6), began tackling its irrigation drainage problem in 1922, when area voters authorized a $2.5 million bond issue to build a drainage project. At the time, many thousands of acres were already suffering reduced productivity because of highly saline groundwater, and several hundred acres had actually been taken out of production. After the drainage project was established, both the irrigated acreage and the acreage with subsurface tile drains grew steadily. Today the Imperial Valley is underlain with an intricate grid of drains. A map showing all the area's drains, on-farm to master, looks very much like a piece of graph paper. "By 1975, 395,000 acres of the Imperial Valley were served by 21,000 miles of tile drain, and [agricultural production] exceeded half a billion dollars."[119]

The Imperial Valley possesses one major advantage over the San Joaquin. Nearby it has a natural sink into which it can dump saline drainage water—the Salton Sea, a salt lake created from 1905 to 1907, when Colorado River floodwaters poured through an irrigation canal and settled in a prehistoric lake site (245 feet below sea level) between the Imperial and Coachella Valleys. On the other hand, the Imperial Valley's major disadvantage is that the irrigation water coming into it is far saltier than the San Joaquin's. The Imperial Valley diverts its irrigation water from the Colorado River, just below the Imperial Dam, and this water has become quite salty. Furthermore, using the Salton Sea to dispose of drainage water is not

Figure 8

Profile of a Drainage Problem Area in the Western San Joaquin Valley



Source: U.S. Department of Agriculture, Soil Conservation Service, *A Guide for Draining Agricultural Land along the Westside of the San Joaquin Valley* (Portland, Oreg., 1977), p. 4(b).

entirely without problems. Landowners around the Sea complain that, as it expands, adjacent water tables rise because of the increasing inflow of drainage water. Of course, without some influx of irrigation water, the Salton Sea would eventually disappear through evaporation.

DRAINAGE DISPOSAL IN THE SAN JOAQUIN

The San Joaquin's natural sink is the Pacific Ocean, and there is no way that a master drain from the San Joaquin can reach the Pacific without causing political, economic, or environmental problems. The San Joaquin's drainage problem is in essence a drainage *disposal* problem. The San Joaquin drains northward into the Pacific through the Delta, a 1,150-square-mile area northeast of the San Francisco–Oakland area, where the Sacramento and San Joaquin Rivers converge.* The freshwater from the Central Valley meets the salty ocean water in the area between the western Delta and the San Pablo Bay (see Figure 9).

One solution to the San Joaquin's drainage disposal problem would be to build a concrete-lined ditch some 290 miles along the valley's natural drainage course. This master drain would carry the salty groundwater drained off farms all the way north to the Delta area, discharging it into the Suisun Bay. An 82-mile segment of this drain, known as the San Luis Drain, has already been built.

Such a project has indeed been proposed by a task force comprised of the Bureau of Reclamation, the California Department of Water Resources, and the California State Water Resources Control Board.[120] But for their proposal to achieve a political consensus at both the state and federal levels, some very difficult questions will have to be resolved:

- Who will pay for the project? Should the farmers who will directly benefit pay? Should all farmers who use irrigation water in the San Joaquin pay? Should the state of California and the federal government subsidize some of the costs and, if so, to what extent?
- What impact will the annual discharge of some 250,000 acre-feet† of salty drainage water into the tidal waters of Suisun Bay have on the Delta environment? Will it endanger the drinking water supply of the people who live in the Delta area? Will the arsenic, boron, and mercury‡ present in the drainage water reach toxic levels? Will the salts in the drainage water alter the subtle salt–freshwater balance of the Delta's complex ecosys-

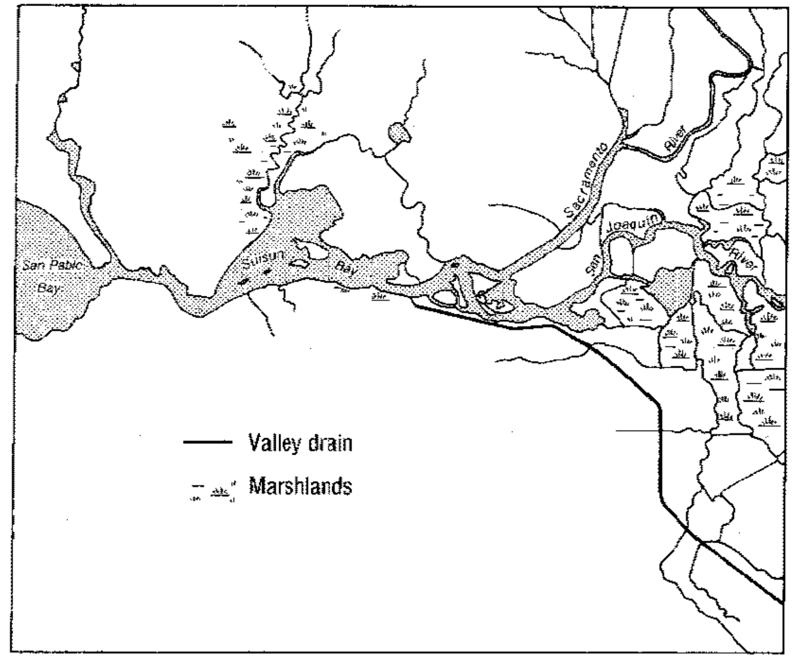
*The lower San Joaquin normally drains into the enclosed Tulare sub-basin, although in especially wet years it also drains northward.

†An acre-foot of water is enough to cover an acre of ground to a depth of 1 foot; it is 320,000 gallons, enough water to flush about 60,000 toilets.

‡Unusually high concentrations of boron and arsenic are found in the soils in certain parts of the western and southern San Joaquin. The mercury in the drainage water would come from pesticides used in the San Joaquin.

Figure 9

Proposed Alignment of the San Joaquin Valley Drain



Source: U.S. Bureau of Reclamation and California Department of Water Resources, *Agricultural Drainage and Salt Management in the San Joaquin Valley, Preliminary Edition* (Fresno, Calif., 1979), p. 11.5.

tem? In sum, will the project endanger one of California's last remaining great wetlands?

One alternative to discharging the drainage water into the Delta area would be to pipe it west over the Coast Range and discharge it directly into the Pacific Ocean. To do so, however, would be extremely costly both in dollars (capital and operating costs) and in energy. A tunnel through the mountains would reduce the operating costs but would greatly increase the initial capital and energy expenditures. The valley-long drain that has been proposed has the important advantage of letting gravity do a lot of the work of moving the drainage water.[121]

Another alternative would be to pump drainage water from the southern San Joaquin up into the Carrizo Plain, a valley within the Coast Range to the west of the Tulare sub-basin. There a huge (80,000 acres) evaporation pond could be formed, or the entire valley could be turned into a salt lake. The drainage water from the northern San Joaquin would go into local evaporation ponds (9,400 acres). A big advantage of this plan is that the Carrizo Plain is already a natural salt sink, and no agricultural land would be taken out of production. The big disadvantage is that the energy costs of pumping the drainage water up 2,000 feet to the Plain would be high, 10 times higher than in the master drain–Suisun Bay discharge alternative.[122]

There are other alternatives as well. For example, the drainage water could be run through strategically located desalinization plants and then reused for irrigation. The difficulty with this approach is that desalinization, even using the most up-to-date technology available, is costly and energy intensive. It currently costs about $300 per acre-foot to desalinate salty water, not including disposal of the brine.[123] Of course, radical improvements in the technology will lead to radically reduced costs, but these improvements may not occur in time to solve the San Joaquin's drainage problem. Will they ever occur?

DEVELOPING LOCAL DISPOSAL SYSTEMS

A strictly local solution to the drainage problem is also possible. Resource conservation districts cover about 75 percent of the drainage problem areas, and each one could develop its own disposal system. They could then dispose of the drainage water in local evaporation ponds or, in some instances, low-lying areas suitable for the development of saltwater marshes. There are two major difficulties with the localized approach, however. First, it is uncertain whether some of the resource conservation districts or whatever local entities take on the job can afford the initial capital investment needed to build drainage disposal systems. Second, because there is such an enormous quantity of salty water to dispose of over the coming years, the local evaporation ponds could eventually (by 2060) take over 150,000 acres of San Joaquin Valley farmland.[124] The advantages of the local alternative, on the other hand, are that it leaves the Delta wetlands alone, and it avoids the political hurdles that confront a big public works project in this era of tight budgets.

Unfortunately, the task force's cost-benefit analysis of the various alternative solutions to the San Joaquin's drainage disposal problem short-shrifts the local alternative. The task force assumes that local entities will serve only 25 percent of the drainage problem areas; hence the *net* benefits of this alternative are low—$2.1 million per year, compared with the *net* benefits of the recommended alternative (master drain–Suisun Bay discharge)—$34.5 million per year.[125] If, on the other hand, one assumes that 75 percent of the drainage problem areas will be served by local drainage disposal systems, an optimistic but not unrealistic assumption, then the *net* benefits of the local alternative come to about $25.3 million per year. And they would be higher still if drainage water was used to form solar salt ponds for generating electricity. In a solar salt pond, a layer of brine lies underneath a shallow layer of fresher, lighter water. Sun penetrates the top layer and heats the brine underneath to temperatures high enough to drive special turbines. The techonology was developed in Israel, and several applications are now being con-

sidered in the United States.[126] Unfortunately, the use of solar salt ponds as one of the solutions to the San Joaquin's irrigation drainage water disposal problem is not one of the alternatives currently under study.

The second major shortcoming of the task force's analysis is that it fails to calculate to what extent more *efficient use* of irrigation water will mitigate the San Joaquin's drainage water disposal problem. Logically, the less water farmers apply to their fields in the first place, the less drainage water there will be to dispose of. It appears that water usage per acre can be reduced without reducing agricultural productivity in the San Joaquin.

A recent interagency study found that the *basinwide* irrigation efficiency of the San Joaquin is high when compared with areas such as the Wellton-Mohawk in Arizona or the Imperial Valley.[127] In the northern half of the San Joaquin (1.4 million irrigated acres), irrigation efficiency is 73 percent. In the southern half (3.1 million irrigated acres), it is 96 percent. By contrast, the irrigation efficiency of the Imperial Valley (612,000 irrigated acres) is 66 percent. One reason for the San Joaquin's superiority is that some of the water that is imported to the basin and applied to fields percolates down into the ground and is pumped up again and reapplied.[128]

Nonetheless, there is room for improvement. The average *on-farm* irrigation efficiency in the northern San Joaquin is 64.8 percent. This figure is reached by estimating the evaporation-transpiration (ET) of each crop, adding the amount of water needed to leach (L) salts from the root zone, subtracting the rainfall (R), and dividing by the amount of water actually applied (WA):

$$\frac{ET + L - R}{WA} = \text{on-farm efficiency}$$

The on-farm efficiency figure differs from the basinwide figure because into the latter is factored tailwater recovery (TR), that is, water that percolates into the ground or runs off into ditches and is pumped back onto fields for reapplication:

$$\frac{ET + L - R}{WA - TR} = \text{basinwide efficiency}$$ [129]

The interagency study estimates that improved water management practices would increase on-farm efficiency in the northern San Joaquin to 79.4 percent, reducing water application by 1.5 million acre-feet—14.6 percent of the total on-farm water use for irrigation—and reducing water accumulation in perched water tables. In the southern San Joaquin, the reduction would be even more dramatic. The area's average on-farm irrigation efficiency, now 60.6 percent, would increase to 79.8 percent with more efficient water management practices, reducing on-farm water application 19.2 percent or 2.7 million acre-feet.[130]

WATER CONSERVATION EFFORTS

Incentives exist for San Joaquin farmers to use water more efficiently. If farmers are pumping groundwater for irrigation, more efficient water use will cut their energy costs. And, if they are buying imported water, more efficient use will cut their water costs as well. Of course, if the federal government raised its water rates to cover the full costs of its projects, the irrigator's incentive to conserve water would be even greater. There is, however, one drawback to more efficient water use—less tailwater is available for reapplication. So it is conceivable that some farmers may have to buy *more* imported water as a result of more efficient use. In other words, every acre-foot of consumption reduced through more efficient use is not necessarily an acre-foot saved. The great advantages of more efficient water use are decreased energy costs, now a significant factor in the overall cost of irrigated agriculture, and less buildup of salty groundwater.

Why, then, has not more efficient water use, sometimes termed water conservation, been achieved? Lack of technical information is probably one major reason. Irrigators need to know what the most efficient irrigation method—drip, sprinkler, or surface flooding—is for their particular crops and soils. They need to know the specific water requirements of each crop that they have cultivated and to have a water application system that can be controlled so as not to exceed those requirements. They need to know how to take an accurate reading of their root zone's moisture content so that they do not overirrigate. Irrigators also need to know the best time to irrigate so as to minimize evaporation. They need advice on field leveling for more even and efficient distribution of water during surface flooding. In short, they are not doing a better job of conserving water because their irrigation practices are scientifically imprecise.

Federal Water Conservation Efforts

The prime government agency for transmitting technical information and advice to the farmer about water conservation is the U.S. Soil Conservation Service (SCS). Gylan Dickey, water management engineer with the SCS' state office in Davis, California, reports, however, that "the water conservation job is not getting done because we don't have the staff or the money to do it."[131]

The Extension Service, which receives about 30 percent of its funding from the U.S. Department of Agriculture (USDA) and the rest from states and counties, is supposed to provide farmers with technical information on soil and water conservation. A recent study in California found, however, that in that state the Extension Service's administrative mandate for soil and water conservation "is incidental to an *over-arching concern for crop productivity*."[132] (Emphasis added.) It appears that conclusion describes accurately the Extension Service's role in other arid areas as well. In other words, the Extension Service does not seem to be a major force for soil or water conservation in the arid United States.

Cost Sharing

Water conservation often entails additional financial outlays by the farmer—whether it be for installing a drip irrigation system, for field leveling, or whatever. The main source of federal cost-sharing assistance for such improvements is the Agricultural Conservation Program (ACP), which is administered by the Agricultural Stabilization and Conservation Service (ASCS). Under the ACP, owners of farms may apply to their county ASCS committee for funding up to 80 percent of the cost of soil or water conservation measures and may receive up to $3,500 in a year. The problem is that the ACP funds available to any given county in a year are so paltry that many eligible farmers do not bother to apply. In fact, the ACP funds available to a county increase very little or not at all from year to year and have not kept pace with either inflation or groundwater salinization rates. In addition, because the county ASCS committees are elected by farmers, they mirror the farmers' preoccupation with immediate cash flow, so that measures promising a quick return, such as the installation of irrigation pipe or the drilling of a new well, receive the preponderance of the funds. One recent assessment concluded: "ASCS provides a funding function which is limited by available funds and priority biases."[133]

Any future analysis of the alternative solutions for the San Joaquin's salty water drainage disposal problem should include a calculation of the net benefits of a reinvigorated water conservation program by the SCS, ASCS, and Extension Service. It would be particularly interesting to see whether more efficient water use cuts the problem down to a size that makes the local alternative more practical than a valleywide public works project.

THE MASTER DRAIN PROJECT

The master drain project recommended by the task force would cost the federal government an estimated $258 million and the state, another $89.1 million.[134] These figures, however, do not include the cost of installing on-farm drainage systems, a must whether the ultimate disposal is local or valleywide. Various federal programs are available to help farmers finance these systems. Nor do the figures include the cost of facilities for collecting water from farms in a given area for injection into the master drain. These costs would be the responsibility of local entities such as the water districts, drainage districts, or resource conservation districts. Here again, however, a number of federal programs are available to assist on a cost-sharing basis.[135] Therefore, the total federal expenditure would be greater than $258 million, but how much greater has not been determined.[136]

Under the proposed plan, the cost of the master drain would be repaid, primarily by farmers in the drainage problem areas, over a 40- to 50-year period through a surcharge on each acre-foot of water applied and a charge as well on each acre-foot of water discharged. The annual cost to a farmer served by a federal water project would total about $44 per acre and for the farmer served by a state water project, $75 per acre.[137]

In calculating the costs for such a water project, the federal government uses a very low interest rate—6.62 percent. Hence the proposed master drain does represent a partially subsidized solution to the salinity problem of the San Joaquin.

At present, the task force proposal is stalled. Political opposition from environmentalists and residents of the Bay-Delta area exists, of course, but at this stage it is the lack of support from farmers in the San Joaquin valley that is the major political obstacle. The farmers have balked at paying $44 or $75 per acre per year—even though the task force estimates the benefits to farmers in the drainage problem areas of about $130 an acre per year.[138] Farmers with no drainage problem now, that is, in areas where the saline groundwater has not yet reached crop roots, are more concerned with their immediate cash flow problems. Rising costs, especially energy costs, are more of a priority than costs that will be incurred sometime in the future because of poor drainage. In addition, farmers who contribute to salinity problems downslope and do not suffer directly the consequences of poor drainage are reluctant to pay for the remedy.

The farmers experiencing salinity problems right now are employing a variety of very short-term remedies. Many, for example, are converting affected fields from deep-rooted, salt-sensitive crops to shallow-rooted, salt-tolerant crops or from crops to pasture. In either case, irrigation is still necessary, so the saline groundwater continues to rise. A few farmers are using already highly salinized fields as evaporation ponds for salty groundwater drained from elsewhere on their farms. A very few have simply taken salt-encrusted fields out of agricultural production entirely and are trying to recoup their losses through intensified cultivation and irrigation of other fields.[139]

If the master drain-Suisun Bay discharge alternative or one of the other alternatives is *not* adopted, that is, if no significant remedial action is taken either locally or valleywide, what will happen to the San Joaquin?

PROSPECTS FOR THE SAN JOAQUIN

For one thing, the agricultural yield from poorly drained land will drop precipitously. Today, on the 400,000 acres of San Joaquin farmland that already have a drainage problem, crop yields have declined 10 percent, or $31.2 million, annually since 1970. With no action, the amount of poorly drained land will increase to about 700,000 acres by the year 2000, and the annual crop yield loss will climb to $321.3 million.[140]

A certain percentage of these 700,000 acres will be taken out of agricultural production entirely—it is impossible to tell exactly how much from current data. If the land taken out of production was once desert, it will slowly revert to desert shrubs unless it has become a salt

flat. The process will take hundreds of years, and in the meantime, the lack of vegetation and desert pavement (a thin layer of rocks of various sizes) will make this land very vulnerable to wind erosion, especially during drought. If the land taken out of production was once grassland, then vegetation will return to it more swiftly but in a much debased form—with invader weed species such as Russian thistle (tumbleweed) and filaree dominating. This land too will be vulnerable to wind erosion during times of drought and, if it slopes, to water erosion during rains.

The task force estimated that about 1 million acres of agricultural land in the San Joaquin will undergo desertification during the next hundred years if the groundwater salinization problem is not treated. Francis Lum, head of the SCS in California, calls the 1-million-acre estimate "very conservative" and thinks that "at least twice this amount" of land could be lost to desertfication.[141]

OVERGRAZING IN THE SAN JOAQUIN

In terms of acres affected today, overgrazing is the second most serious land degradation force at work in the San Joaquin. The major interagency study done of the entire San Joaquin concluded: "A *significant portion* of the Basin's rangeland has problems."[142] (Emphasis added.) An all too familiar chain of events is outlined here: Overgrazing reduces forage plant covers; this reduction, in turn, leads to both increased soil erosion, which means lower soil fertility, and the invasion of weeds and bushes. The result is a land that produces still less forage *and* that is especially vulnerable to the big erosion events—windstorm and flood. Of the 4 million acres of private rangeland, 3.2 million acres, or 80 percent, have problems. Of the public rangeland managed by the Forest Service, 102,000 acres, or 17 percent, were found to have problems.[143] The rangeland in the Basin managed by the Bureau of Land Management—about 400,000 acres, was not assessed by this study, but it is thought to be in roughly the same condition as the private land.[144]

The study observed that "many of the range problems in the Basin can be traced to ineffective management techniques."[145] James Clawson, Extension Service range specialist at the University of California at Davis, suggests that absentee ownership of private grazing land—a condition encouraged by federal, state, and local tax laws—contributes to rangeland abuse. This condition is a problem, he suggests, equal in proportion to the mismanagement of public rangelands.[146] W.O. Beatty, area conservationist for the SCS in Fresno, voices a similar view and adds that rangeland along the western rim of the San Joaquin "is still deteriorating."[147]

The interagency study found that on some 338,000 acres of Basin rangeland, the forage vegetation was so badly overgrazed that it could not revegetate; on some of this land, woody and noxious plants were replacing forage vegetation.[148] The land is, in other words, undergoing desertification.

SOIL EROSION

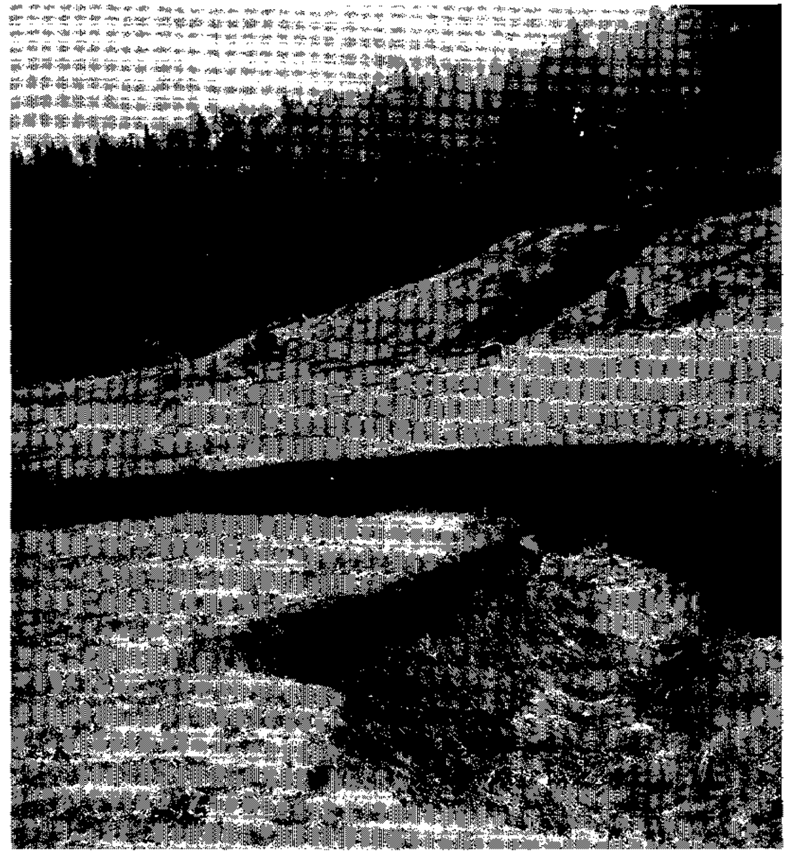
Some 2.2 million acres in the foothills and mountains of the San Joaquin Basin are undergoing moderate to severe water (sheet and gully) erosion of the soil. (Water erosion of the flat valley floor is low.) Rangeland is a prime victim of erosion. According to estimates of the USDA, erosion causes an annual loss of about $1.2 million of forage in the San Joaquin.[149] Erosion is also costly because of the sediment that it deposits in watersheds. The San Joaquin Basin study explains:

> Sedimentation has a number of repercussions. The capacity of streams, channels and reservoirs is reduced which causes flooding. Floods destroy cropland and deposit sediments and other debris which are expensive to remove. Sediment also destroys fish spawning by covering gravel beds.[150]

Overgrazing also plays a major role in the loss of soil by wind erosion. Such soil loss was dramatically demonstrated on December 20, 1977, in the Bakersfield vicinity of the southern San Joaquin. Early that day a windstorm struck the crescent of foothills and canyons that form the southern border of the valley. Within a 24-hour period, that windstorm moved more than 25 million tons of soil in a 373-square-mile rangeland area. As much as 23 inches of soil was stripped from some foothills. And as the wind moved down onto the valley floor, it scoured the recently plowed fields, and millions more tons of soil were displaced. A gigantic plume of dust, that is, soil, formed over the San Joaquin and extended northward to at least the far end of the Sacramento Valley, some 360 miles away.[151]

The wind removed 167 tons of soil *per acre* from the affected rangeland.[152] That such huge soil losses occurred in so short a time was because of both the terrific velocity of the wind—up to 186 miles per hour—and the poor condition of the land. To quote the USGS study of the windstorm's impact, "This land was particularly vulnerable to wind erosion because the vegetative cover had deteriorated seriously under the combined stresses of drought and grazing and because of low soil moisture due to drought."[153] When the scientists who were studying the storm's impact came upon grazed and nongrazed areas separated by only a fence, they beheld tangible and indisputable evidence of the causal relationship between grazing and wind erosion of soil. The *grazed* sides of the fencelines were conspicuously balder, wearing a much thinner cover of vegetation, and they bore far more serious scars of the wind's soil stripping.[154] All of the severely eroded land in the storm-affected zone lies within an area that the California Department of Forestry mapped in 1972 as "consistently overgrazed."[155]

The December 1977 windstorm was enormously costly. The soil that it stripped from rangeland represented a loss of nutrients valued at about $24 million. It blasted crops growing on the valley floor. Immature crops such as potatoes, onions, and carrots sustained sandblasting and root exposure. Perennial crops such as alfalfa, as well as vineyards and orchards, were sandblasted too, or were buried in sand.[156] In an average year, the San Joaquin valley crops suffer about $8.6 million in damage from wind erosion.[157] This single windstorm

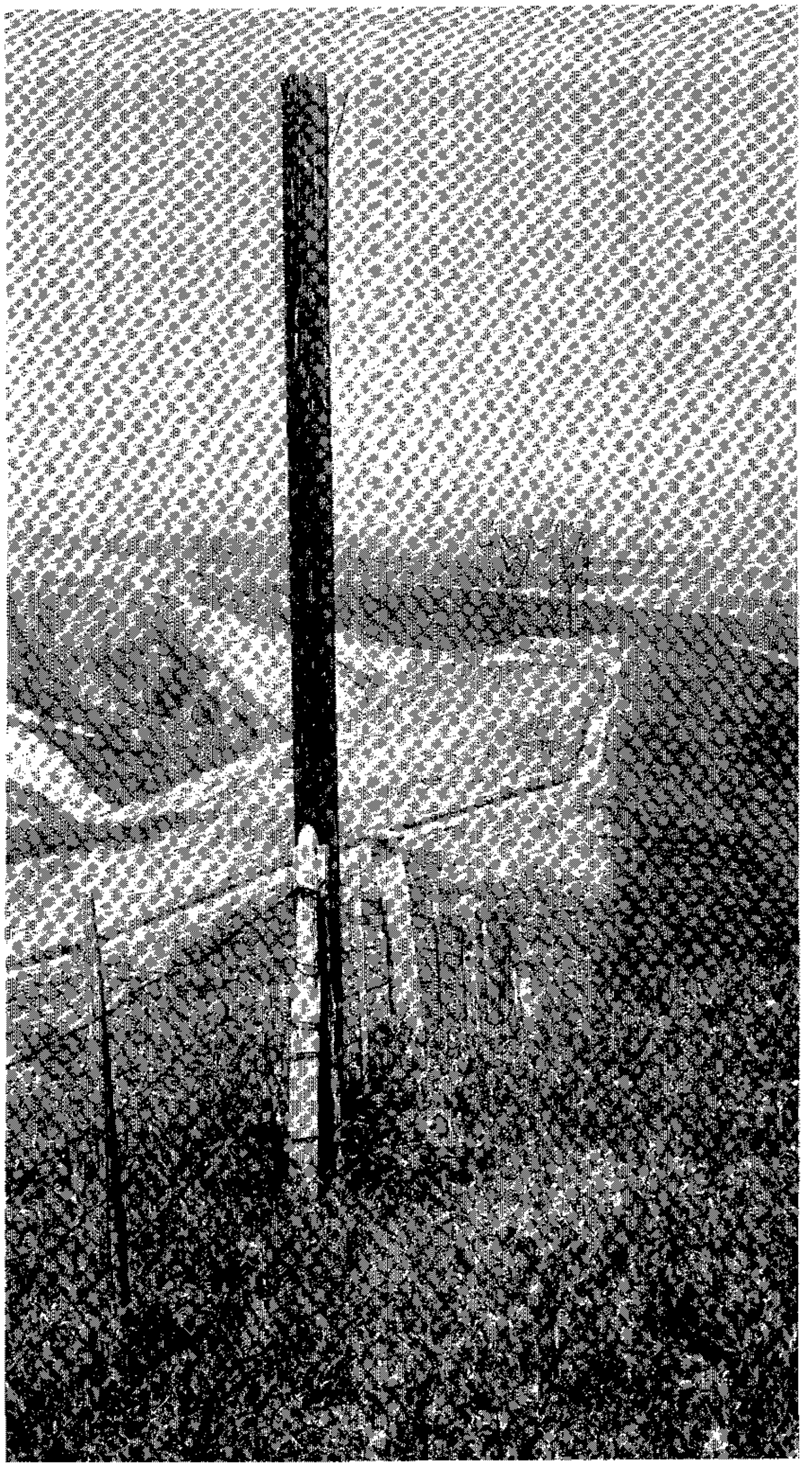


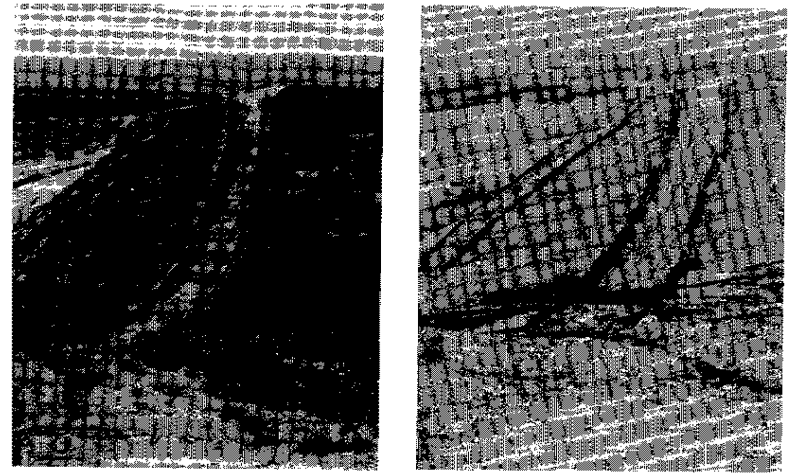
Above, gully erosion caused by overgrazing in Mariposa County, California (B. Peavy, Bureau of Land Management). Following page, the effects of fenceline control of grazing on erosion in the San Joaquin Valley after a 1977 windstorm (J. K. Nakata, U.S. Geological Survey–Stanford University).

did appreciably more damage in 24 hours. It also damaged other kinds of property, for example, toppling powerline pylons and sandblasting windshields. In addition, the windstorm carried spores of the so-called valley fever disease (coccidioidomycosis), endemic to parts of the southern San Joaquin Basin and the Mojave Desert, into the populated San Francisco Bay and Sacramento areas, both of which registered dramatically increased incidence of the disease.[158] A person contracts the disease by breathing in dust-borne coccidioidomycosis spores. The victim experiences unusually high fever for a protracted period. The disease is occasionally fatal.*

One reason this storm was so damaging was the sheer force of its winds. But the storm's destructive force was greatly enhanced by the

*Humans are not the only ones affected by valley fever. Soon after the above mentioned windstorm, a gorilla and an orangutan in the Fresno zoo died from coccidioidomycosis.[159]





Overgrazed land before and after the December 1977 windstorm (J. K. Nakata, U.S. Geological Survey–Stanford University).

sand that it carried. Indeed, according to the USGS study team, wind-driven sand was "the principal cause of vegetative and soil stripping"; the wind had scooped the sand from recently plowed fields, road cuts and shoulders, channelized stream beds, construction sites, oil fields, and areas denuded of vegetation by off-road vehicle use.[160]

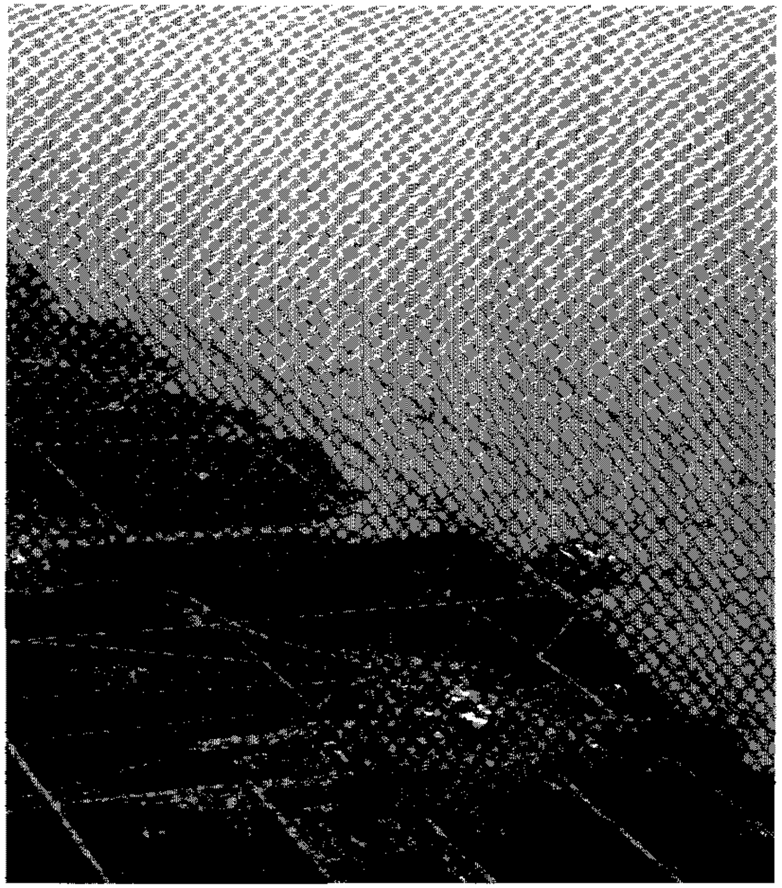
Windstorms of this intensity, although rare, have occurred before in this part of the San Joaquin Basin and will no doubt occur again. Moreover, prolonged droughts periodically strike the San Joaquin. In other words, the combination of factors that made this so damaging a storm could certainly come together again sometime in the future.

For 3 months after the windstorm, there came a period of unusually heavy rainfall. Floods caused severe damage to the southern San Joaquin. The USGS study observed that "slopes laid bare by the windstorm" contributed greatly to the severity of the flooding—increasing water and mud runoff. The study added: "On steep slopes and in tributaries to main drainages, gullies formed where none existed before."[161]

The previously mentioned San Joaquin Basin study also cites "off-road vehicles and other recreational pursuits" as another major cause of rangeland deterioration because they "destroy vegetative cover and accelerate erosion." Some 521,000 acres of San Joaquin rangeland have suffered reduced productivity from recreational "overuse" of the land, the study reported.[162]

URBANIZATION

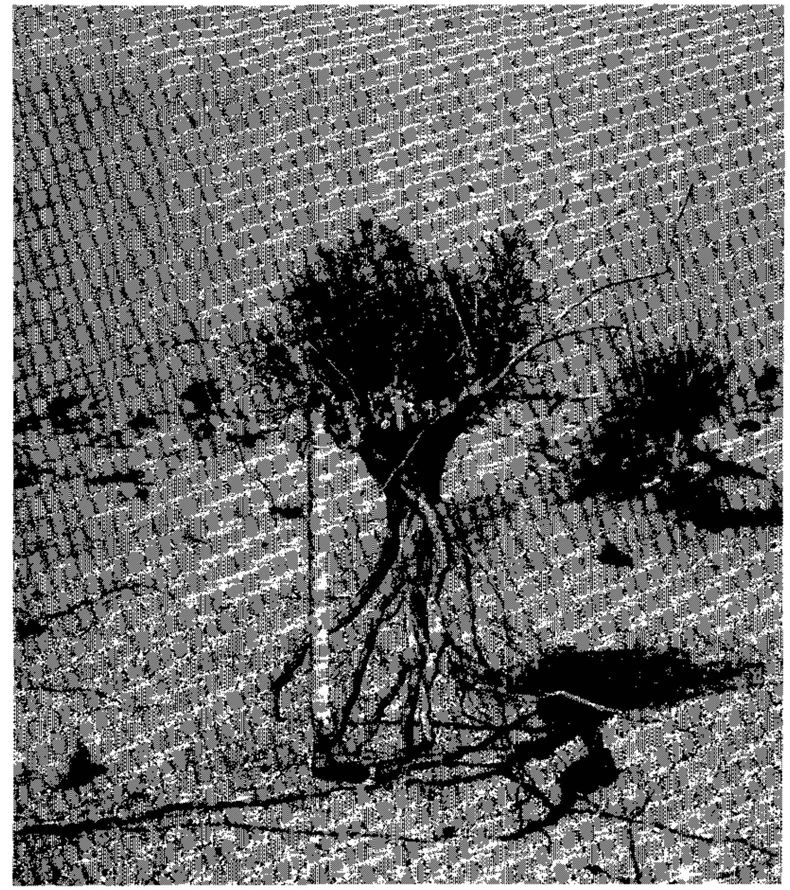
Soil experts also worry about the effect of urban sprawl on the San Joaquin. "Urbanization is a terrible thing to see as it takes over the best farmland and the best soils," says Morris A. Martin, district



The south end of the San Joaquin Valley. Before the storm, all the land was grassland; the land on the right of the fence was overgrazed (J. K. Nakata, U.S. Geological Survey–Stanford University).

conservationist, SCS Fresno field office.[163] It also causes severe erosion problems when the bulldozers move into the foothills, stripping away the natural vegetation and exposing unstable soils to sheet and gully erosion. Martin noted: "In the past several years, I have spent almost as much time working with developers, builders, and homeowners to control soil erosion as I have with farmers."[164]

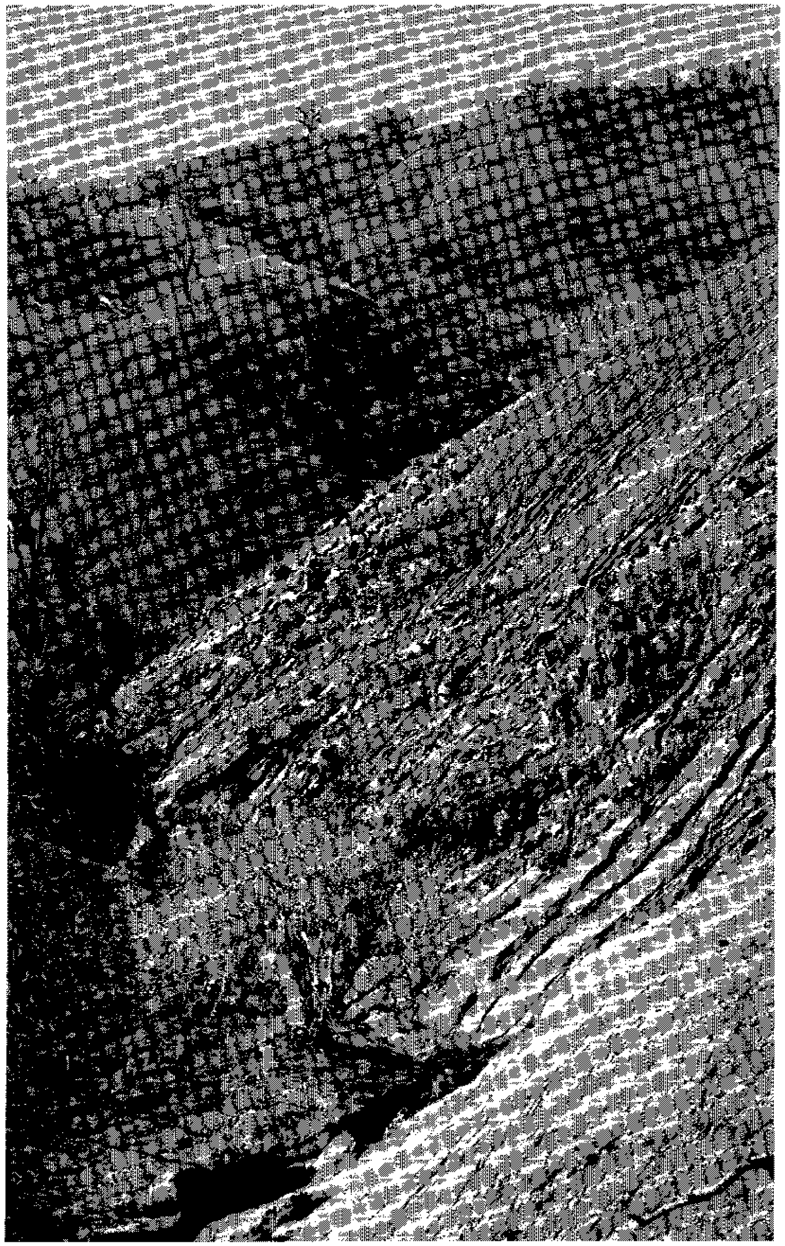
The San Joaquin has three major, fast-growing urban areas: Modesto, Fresno, and Bakersfield. Urbanization is projected to take over some 407,100 acres of irrigable farmland in the San Joaquin between 1972 and the year 2000.[165] A byproduct of the loss of farmland to urbanization is that poorer quality land is pressed into cultivation. Over the past 5 years, California has lost approximately 55,000 acres per year of "prime agricultural land" to urban development; during the same period, 75 percent of the newly irrigated acres brought into production have been on "medium and low potential land," that is,



An 11.7-inch loss of loosely consolidated sand and soil is indicated by exposed root systems (J. K. Nakata, U.S. Geological Survey–Stanford University).

Class III and IV land under the SCS' land classification system.[166]

The loss of productive farmland to urbanization in areas such as the San Joaquin was the reason that the California Land Conservation Act of 1965 (the Williamson Act) was enacted. This law allows local governments—cities and counties—to contract with landowners to keep land in agricultural production. Under such contracts, the localities assess the land according to its use value rather than its market value, thereby lowering the property taxes that the landowner will have to pay.[167] But the Act has been ineffective. The use-value assessment has not been a strong enough incentive to landowners in urban fringe areas—tomorrow's shopping center and housing development sites. Most of the contracts have been with large landowners in areas quite remote from urbanization who are simply taking advantage of a tax break.[168]



Fluvial erosion of wind-denuded slopes above I-5 southwest of Grapevine, California, after the December 1977 storm (J. K. Nakata, U.S. Geological Survey–Stanford University).

DEPLETION OF GROUNDWATER RESOURCES

The depletion of groundwater resources (another desertification force) could also lead to the abandonment of irrigable farmland in the

San Joaquin. Whether this, in fact, will occur depends ultimately on a number of factors, including the ability of the San Joaquin to import still more water from other basins through new federal or state water projects. When the Bureau of Reclamation sought authorization for a project to serve the Westlands Water District, one of the San Joaquin's more recent water import projects, the agency stated that the groundwater level in the area was declining an average 10 feet per year and, in some spots, 20 feet per year. Advocates of the project claimed that without the imported water this 72,000-acre area would soon be fit for growing only sagebrush.[169]

Before an aquifer is totally depleted of water, the energy costs of pumping water from it become prohibitive. These steeply rising costs can lead to the abandonment of irrigated cropland. As yet, however, there is no record of farmers in the San Joaquin abandoning cropland because of increased groundwater pumping costs, but it certainly is a distinct possibility in the future.

The deeper the well, of course, the higher the energy costs per acre-foot of water become. In the western San Joaquin today, some farmers are pumping water for irrigation from 3,500 feet beneath the surface.[170] Dropping groundwater levels and rising energy prices will certainly make the pumping of groundwater an increasingly significant cost item in San Joaquin agriculture.

The major physical effect on the San Joaquin of groundwater overdraft has been land subsidence. When water is mined from an aquifer system of fine-grained, unconsolidated sediments, the aquifer system compacts. As a result, the land surface above it sinks. The city of Venice is probably the most widely publicized case of subsidence from overdraft of groundwater. Mexico City also is experiencing subsidence.[171]

In the San Joaquin, about 5,200 square miles of land have subsided as of 1972, with about 4,200 subsiding more than 1 foot. In the western San Joaquin, some areas have sunk as much as 29 feet.[172]

The major cost of subsidence is the damage that it does to irrigation and drainage facilities, particularly canals and underground pipes. For example, between June 1975 and September 1976, the Bureau of Reclamation spent about $3.7 million to rehabilitate federal irrigation projects damaged by subsidence.[173] On-farm costs can also be high. In some cases in the San Joaquin, tilting of the land surface has changed the flow pattern on farms, and irrigators have had to realign entire irrigation systems. In addition, land subsidence damages homes and other buildings. South of Fresno, there is a small community that had to be entirely abandoned because of land subsidence.[174]

One of the long-term consequences of groundwater overdraft and subsidence that has not received much attention is the loss of water storage capacity. As an aquifer system compresses with the mining of its water, the amount of pore space within it shrinks. Because it is this very pore space that enables the system to store water, its storage capacity is therefore greatly diminished.

Water storage is vital to areas subject to periodic droughts, that is, the arid West, and aquifier systems are by far the most efficient means of storing water. Reservoirs lose tremendous quantities of water to evaporation. For example, the San Luis Reservoir in the western San Joaquin loses about 120,000 acre-feet of water per year to evaporation.[175]

Aquifer systems that have subsided because of overdraft will never again be able to hold as much water as they did before overdraft began.[176] In such cases, in other words, overuse results in the partial loss of a valuable nonrenewable resource.

THE WELLTON-MOHAWK IRRIGATION DISTRICT, ARIZONA

Let's face it, the Wellton-Mohawk is heavily subsidized agriculture.

—Herb Guenther
Senior Biologist,
U.S. Bureau of Reclamation[177]

For its size, the Colorado is probably the most utilized, controlled, and fought over river in the world.

—A. Berry Crawford and A. Bruce Bishop[178]

In 1947 Congress authorized the Wellton-Mohawk Project (see Figure 10). Built by the Bureau of Reclamation and completed in 1952, the project diverts water from the Colorado River, northeast of Yuma, Arizona, and pumps it about 30 miles east to irrigate 60,000 acres of desert.[179]

Situated on the floodplain and mesas along the lower Gila River, the Wellton-Mohawk receives only about 4 inches of rainfall a year, but the sun shines more than 90 percent of the time during daylight hours, and killing frosts are short lived. The area's soil is naturally fertile except for a lack of organic matter, and it is provided by crop residues.[180]

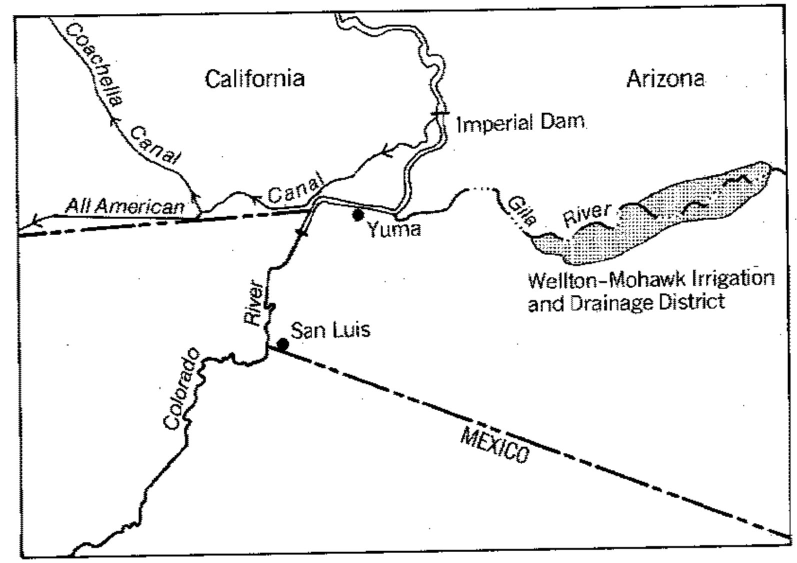
With a steady supply of cheap water from the federal government, Wellton-Mohawk has prospered. The area now produces $1,082 worth of crops per acre, up from $145 per acre in 1955.[181] Iowa crop production, by comparison, is about $125 per acre.[182]

Farm net income figures are not available for Wellton-Mohawk, but they are thought to be comparable, if not somewhat higher, than for Arizona as a whole. From 1970 to 1976, net income per farm in Arizona averaged $39,679, compared with $10,102 for Iowa and $7,589 for the entire nation.[183]

The key to Arizona agriculture's high profits, aside from the long growing season, has been cheap water. For example, Wellton-Mohawk farmers pay the federal government between $6.25 and $21.50 per acre-foot of water, depending on the amount used.[184] These prices reflect only the operating costs of delivering the water to Wellton-Mohawk, and not the capital costs of the project. If there were a free market in water, the water might sell for $100 to $500 per acre-foot.[185]

Figure 10

The Wellton-Mohawk Irrigation District



Source: Based on U.S. Geological Survey, Hydrologic Unit Map—1974, State of California.

Wellton-Mohawk's chief money crops are lettuce, cotton, alfalfa, wheat, cantaloupes, grass, and oranges. Its yields are impressive. Wellton-Mohawk produces 1,142 pounds of cotton per acre, compared with the national yield of 420 pounds of cotton per acre. It produces 87 bushels of wheat per acre, compared with 32 for the nation, and 8.8 tons of alfalfa per acre, compared with 3.1 tons for the nation.[186]

And yet, political uncertainty and controversy cloud Wellton-Mohawk's future. The Wellton-Mohawk's problem, as in the San Joaquin, is saline groundwater and what to do with it. In the Wellton-Mohawk, however, subsurface conditions are even worse than in the San Joaquin; that is, the substratum that effectively blocks further downward drainage of water is closer to the surface and underlies a large percentage of the irrigated land. Hence, irrigation water that does not evaporate or transpire soaks into the ground and rises rapidly into the root zone. The occasional spring floods of the Gila River compound the problem. In other words, Wellton-Mohawk's drainage problem is more immediate, and the amount of drainage water per acre that needs to be disposed of is greater. The solution to Wellton-Mohawk's drainage problem is made infinitely more complicated by the fact that the Colorado River, its natural sink, is "perhaps the most overdeveloped river in the world."[187]

Lettuce is one of the chief money crops in the Wellton-Mohawk Irrigation District (C. W. Siegel, Water and Power Resources Service).

INCREASED SALINITY OF THE COLORADO RIVER

In 1961, the Wellton-Mohawk Irrigation District began to operate a system of drainage wells that discharged into the Colorado River. At that time the Wellton-Mohawk's drainage water had a salinity of about 6,000 parts per million (ppm), and the Colorado River water taken in by Wellton-Mohawk was about 800 ppm.[188]

The salinity of the Colorado River water flowing into Mexico increased sharply. In 1960, it averaged 800 ppm. By 1962, it had increased to over 1,500 ppm. Wellton-Mohawk drainage water was the primary cause. It was not, however the only cause of the dramatic rise in the lower Colorado's salinity. Beginning in 1961, the flow of Colorado River water into Mexico was sharply reduced by the United States in anticipation of storage in Lake Powell behind the newly constructed Glen Canyon Dam. This loss of dilution water is illustrated by two statistics: "[F]rom 1951 to 1960, the average delivery to Mexico at the northerly International Boundary was 4.2 million acre-feet per year while . . . from 1961 to 1970, it was 1.5 million arcre-feet per year."[189]

Mexico raised strenuous objections to the Colorado's increased salinity and charged that the saline water was damaging crops and soils in the Mexicali Valley, a major agricultural area. The salt tolerance of crops cannot be defined in any absolute sense, but the U.S. Salinity Laboratory established a general classification of the *salinity hazard* to crops of irrigation water in parts per million:

Low: 100-250
Medium: 250-750
High: 750-2,250
Very high: > 2,250[190]

In 1962, the United States and Mexico entered into negotiations over the problem. A 5-year agreement, known as Minute No. 218, was signed in 1965. Under the terms of this agreement, the United States undertook mitigative measures that cost $12 million, but only a marginal improvement in the quality of water delivered to Mexico—from 1,500 ppm in 1962 to 1,240 ppm in 1971—resulted. Minute No. 218 expired in 1970, and the two nations negotiated a new agreement. Minute No. 241 was signed in July 1972. The United States agreed to undertake additional mitigative measures, but again only marginal improvement in water quality resulted—the average annual salinity of water delivered to Mexico dropped from 1,240 ppm in 1971 to 1,140 ppm in 1973.[191]

In 1973, the two nations signed Minute No. 242, "The Permanent and Definitive Solution to the International Problem of the Salinity of the Colorado River." Under this agreement, the United States for the first time committed itself to a specific level of water quality for the Colorado River water that it releases into Mexico. The United States agreed to release to Mexico water that has an average annual salinity of not more than 115 ppm over the salinity at the Imperial Dam in the United States.[192] The salinity of the water at the Imperial Dam was about 809 ppm in 1979, a year in which the Colorado's was unusually high.[193]

To implement this agreement, Congress passed the Colorado River Salinity Control Act of 1974. It is currently estimated that a $333 million federal effort will be required under Title I of the law, with much of the money allocated to solving the Wellton-Mohawk drainage problem.[194] In other words, Wellton-Mohawk's groundwater salinity problem has become a very expensive one.

A STRUCTURAL SOLUTION

The most expensive item in the "permanent and definitive solution" to the Colorado River's salinity problem is a desalinization plant near Yuma, Arizona. Under current Bureau of Reclamation plans, the plant will cost $178 million to construct and $12 million per year to operate; it will desalinate about 120,000 acre-feet of water per year drained from the Wellton-Mohawk.[195] The U.S. Department of the Interior reportedly expects to award the main construction contract in the mid-1980s if Congress appropriates the money.[196] Before completion, however, inflation might result in the plant costing as much as $300 million. This cost, in turn, would drive up the total cost to the taxpayer to over $500 million for Colorado River salinity control. In addition, as energy costs continue to climb, so will the plant's annual operating costs, because desalinization is energy intensive.

Are there alternatives to this capital-intensive, energy-intensive solution to the Wellton-Mohawk's drainage problem? At present, a

U.S.-built, concrete-lined drainage ditch is siphoning all the Wellton-Mohawk's drainage water directly into the Santa Clara Slough in Mexico on the Gulf of California, about 70 miles south of Wellton-Mohawk.[197]

Why not simply continue with this arrangement? The drainage water moves along the concrete-lined drainage ditch primarily by means of gravity, and its emptying into the already salty Santa Clara Slough has created a splendid wetlands wildlife habitat.[198] The difficulty is that none of this water is credited to the United States as part of the U.S. treaty commitment to release 1.5 million acre-feet per year of Colorado River water to Mexico. If the drainage water is desalinated, however, before being sent to Mexico, then it can be used for irrigation, and the United States would get credit for it.

To implement a no-desalinization-plant alternative, therefore, the United States would either have to (a) stop supplying water to the Wellton-Mohawk District to increase the flow of water to Mexico or (b) reduce the water allotments of one or more states along the Colorado by the amount that is drained into the Santa Clara Slough, sending that amount to Mexico. Any attempt to do the latter would stir strong opposition. Indeed, it would be somewhat like trying to take food away from a nest of angry rattlesnakes. Water is too precious in the arid Colorado River Basin for any state to accept willingly a reduction, even a relatively modest reduction, in its allotment.

The only reason that the federal government has been able to continue to meet its commitment to Mexico while still draining water into the Santa Clara Slough is that the River's flow in recent years has been higher than normal. For the years ahead, however, the Colorado River is already "overbooked," and excess supply may not exist (Table 2).

Table 2

Current Users of and Demand for Water from the Colorado River

Users	Demand (million acre-feet)
Upper Basin states (Wyoming, Utah, Colorado, New Mexico)	7.5
Lower Basin states (California, Nevada, Arizona)	7.5
Mexico	1.5
Evaporation	1.0
Total Basin diversions	17.5
Total supply – average annual flow	14.8[a]

[a]Edward M. Hallenbeck, Bureau of Reclamation, Yuma, Ariz., interview with author, April 14, 1979.

The U.S. government cannot simply stop supplying the Wellton-Mohawk with water; it has a contractual obligation to the farmers. The government could, however, buy out the farmers and then close down the Wellton-Mohawk District. Referring to the Colorado River Salinity Control Act of 1974, Rafael Mosses, counsel to the Colorado Water and Conservation Board of the Colorado River Commission, commented:

> We could have bought up the Wellton-Mohawk Project and retired the whole thing for a lot less than this is going to cost, but politically, of course, it is not feasible.[199]

In fact, the government has purchased and retired from production 5,000 acres of land in the Wellton-Mohawk where water use was particularly high—citrus trees grown on sandy soils—in an effort to reduce the District's drainage water outflow, although no District-wide purchase plan is underway.

The people who farm the Wellton-Mohawk do not want to sell. They insist that they will fight in the court any federal effort to buy them out and retire the project. Many years of litigation are threatened.[200] Land in the District currently sells for about $3,000 per acre.[201] At that price, it would cost the federal government about $180 million to buy the land under irrigation. However, even if the farmers finally agreed to sell, it would not be at the current market price. Clyde Gould, manager of the District, estimates it would cost the federal government $550 million and take 10 to 15 years to buy out the Wellton-Mohawk.[202] Farmer Jim Naquin, whose father cultivated this desert land before him, sums up the feelings of many Wellton-Mohawk farmers:

> We've invested our lives in this land. It is unimaginable that we would sell out. We did not sign Minute No. 242 with Mexico—the United States government did. Why should we have to pay for it?[203]

GREATER IRRIGATION EFFICIENCY

Another alternative is suggested by Jan van Schilfgaarde, director of the U.S. Salinity Laboratory: "The time has come to realize we can't continue to use huge capital and energy intensive solutions where management and social solutions will work." Van Schilfgaarde suggests that a desalting plant may not be necessary if Wellton-Mohawk farmers used irrigation water more efficiently and reused some of the drainage water to grow salt-tolerant crops.[204]

Efficiency in irrigation, that is, using less water without reducing crop yields, is important for two reasons. It reduces demand for a scarce resource—water, and it means less buildup of salty water in the ground and therefore less to be drained. The federal government is working with the District and individual farmers to reduce their water losses. It is subsidizing irrigation efficiency—providing capital on a cost-share basis for lining of irrigation ditches, leveling fields, and installing water control and measurement devices as well as low-pressure drip irrigation systems.[205]

Everyone concerned with the Wellton-Mohawk agrees that greater efficiencies can be achieved through better water management. Experts such as Van Schilfgaarde and Sol Resnick of the University of Arizona's Water Resource Center think that the potential is great. Resnick points to Israeli irrigation projects as a model of efficiency for Wellton-Mohawk and other subsidized irrigation projects in the United States. "At Wellton-Mohawk, they are using 13 feet of water per acre in some places to grow citrus crops. In the Negev Desert, the Israelis are using 2.5 feet, and the citrus yields per acre are higher," he reports. "The Israelis have much more sophisticated water control systems."[206] The Soil Conservation Service (SCS), the Bureau of Reclamation, and the farmers in the District see more modest gains in irrigation efficiency being achieved, but they do not agree on how much.[207]

In 1973, when Minute No. 242 was signed, on-farm irrigation efficiency in Wellton-Mohawk was about 56 percent—that is, 56 percent of the water applied to the land was consumed by crops, and the rest was lost to the sun or the ground. The current federal program has set a goal of 72 percent efficiency as the goal.[208] But there is strong disagreement among the federal agencies involved whether 72 percent can be achieved. The U.S. Environmental Protection Agency (EPA) and the USDA believe that on-farm efficiency in excess of 72 percent can be achieved within 10 years. The Bureau of Reclamation questions whether an overall efficiency greater than 64 percent can be achieved.[209] In 1977, on-farm irrigation efficiency in Wellton-Mohawk was 57 percent.[210]

These differing projections are important because the government is trying to figure out what size desalting plant it needs to build. At 64 percent efficiency, the District's drainage outflow would total about 167,000 acre-feet per year; at 72 percent, it would be 136,000 acre-feet and at 82 percent, 94,000 acre-feet. An interagency Technical Field Committee has recommended that the government delay "a final decision on sizing the desalting plant, while additional experience is gained with the effect of the ongoing programs."[211]

Even if 72 percent efficiency is achieved, it still leaves the government with a big problem—what to do with 136,000 acre-feet of saline drainage water. The government agencies involved in the problem see no alternative to a desalting plant of some size. What they have not considered seriously is whether there is some alternative that would *not* require building a desalting plant at all: something less drastic than buying out the entire District and more politically realistic than draining all the water outflow from the District into the Santa Clara Slough. Would, for example, a continuation of the current program to increase irrigation efficiency combined with a limited reduction in the irrigated acreage and with the development of solar salt ponds eliminate the need for a desalting plant?

The Wellton-Mohawk salinity problem is complicated by two additional factors. As noted earlier, the usually dry Gila River sometimes floods, as it did in the spring of 1979. Some of the overflow sinks into the Wellton-Mohawk groundwater, raising it even closer to the surface and requiring increased drainage outflow. Moreover, the Colorado River water that is diverted into the District is growing increasingly saline. There are irrigation projects upriver of Wellton-Mohawk whose drainage aggravates the River's natural salinity. In its pristine state, the Colorado River (at Lee's Ferry) had a salinity of about 380 ppm. A study of the Colorado River Basin Water Quality Control Project predicted that the salinity of the River water at the Imperial Dam would rise to 1,223 ppm by the year 2010. The study assumed a Colorado River Basin population of 8.5 million, a very conservative assumption given the area's current growth rate; construction of the Central Arizona Project; and no augmentation of the Basin's water supply with water transferred from other basins. It did not take into account Title II of the Salinity Control Act of 1974, which authorizes the Secretary of Interior to construct, operate, and maintain four salinity control projects in the basin in Colorado, Utah, and Nevada and to expedite completion of planning reports on 12 other such projects. These developments are estimated to cost $125.1 million, of which 75 percent will be paid by the federal government. It is not clear how much these measures will reduce the River's salinity levels in the future. Today, the lower Colorado River remains highly saline.[212] Increased future withdrawals—for energy production, for example—or a drought-induced shrinkage in the River's flow would make it extremely difficult to keep the Colorado's salinity under the *not* very stringent federal ceiling of 879 ppm below the Imperial Dam.

The Colorado River's salinity problem will not vanish if the entire Wellton-Mohawk Irrigation District is retired. Water for the Wellton-Mohawk is diverted from the Colorado River just below the Imperial Dam where water for the Imperial Valley, California, is also diverted. The Imperial Valley is one of the nation's most productive irrigated areas. If one buys a head of lettuce in January in Washington, D.C., New York City, or Boston, there is an excellent chance that it was grown in the Imperial Valley. The projections for Colorado River salinity bode as ill for this important agricultural area as for the much smaller Wellton-Mohawk.

PROSPECTS FOR IRRIGATED AGRICULTURE

Despite its relatively insignificant size, Wellton-Mohawk bears scrutiny because it exemplifies the issues involved in the future of irrigated agriculture in the Colorado River Basin.

First, high-yield, federally subsidized irrigated agriculture is already straining the basin's water supply. Under the circumstances, it will be difficult to justify subsidies for new projects. In other words, federally supported reclamation of additional desert land in the basin may be over. A more realistic prospect might be increased desertification of land now under cultivation. The 5,000 acres in Wellton-Mohawk that the federal government purchased and retired are reverting to desert; this fate awaits other acreage in this land of scant rainfall and poor irrigation.

Second, "a permanent and definitive" solution to the River's salinity problem does not yet exist. Salinity is one of the major external costs of irrigated agriculture. Bringing it under control will require federal outlays as well as the resolution of a number of technical issues.

Third, economic logic plays little or no role in the resolution of the Basin's central problem—a scarcity of water. For example, the U.S. government has sunk a series of wells in the Yuma Mesa, 5 miles from the Mexican border and will soon begin pumping water from this aquifer for delivery to Mexico. This action will give the United States credit for water as part of its 1.5 million acre-feet delivery requirement per year. Meanwhile, the Mexicans in the San Luis area immediately across the border continue to pump water from the very same aquifer. They are already overdrafting the aquifer, that is, pumping out water faster than it is being replenished by nature and irrigation runoff.[213] Pumping by the United States will, of course, hasten the aquifer's depletion and eventual exhaustion. For another example, the resolution of the Wellton-Mohawk salinity problem could end up costing the U.S. taxpayer more than $9,000 per acre of irrigated land, and yet, the net benefits to the general public of the crop production from those acres has never been assessed.

And as the authors of one recent study noted:

> It appears that salinity control, like water resource development in general, prefers structural solutions—desalinization facilities. Non-structural remedies, such as modification of development plans in the Basin or the elimination of the Wellton-Mohawk Project, would have invoked conflict and delayed the implementation of Minute No. 242 and the Basin-wide salinity control program.[214]

But their conclusion raises a further question: How long will the other regions of the country, especially those such as the upper Midwest and Northeast that have experienced a net outflow of dollars to the federal government, agree to underwrite the arid West's phenomenal growth by supporting structural remedies to the region's essential problems—water scarcity and salinity?

THE SANTA CRUZ AND SAN PEDRO RIVER BASINS, ARIZONA

> We are consuming water like there is no tomorrow.
>
> —Sol Resnick
> Water Resources Center,
> University of Arizona,
> Tucson[215]

Standing today atop the bank of the Santa Cruz River (see Figure 11) a few miles northwest of Tucson, it is almost impossible to imagine what this floodplain looked like a hundred years ago. Water flowed through an unchanneled river that wound sluggishly across a flat, marshy area. Trout were abundant. Beavers built dams. There were giant cottonwood, mesquite, willow, sycamore, and paloverde, and grass—grass tall enough to "brush a horse's belly," to shelter wild turkeys. Meandering, ungullied tributary creeks fed the river.[216]

Today the river channel is dry, a broad trench filled with nothing but gravel and sand. The River's bank is a bare dirt wall. Mesquite trees, 4 to 6 feet tall, grow along the trench. Some of the mesquite clumps are so thick they are impassable. Where the mesquite have not taken hold, the ground is bare except for a rare patch of grass. Farther back from the trench, the mesquite give way to desert shrubs, especially white-thorn (*Acacia* sp.) and creosote as well as cacti such as ocotillo. At irregular intervals, dry gullies—the River's tributaries—intersect the trench walls.

Arizona's San Pedro floodplain to the east has undergone a similar

metamorphosis.[217] Although the changes in these two floodplains' natural vegetation, hydrologic regimes, and topography in less than a hundred years are the most drastic, these definitely are not the only physical changes that have occurred in the Santa Cruz and San Pedro Basins. All the life zones of this region have, if fact, changed significantly.

Plant life in the region generally varies with the elevation. Beginning at the lower elevations and working upward are found desert shrub and cacti, desert grassland, oak woodland, pine forest, Douglas fir, and spruce-fir forests. Comparative analysis of old and new photographs of many different specific locations in the basins reveals that (a) the desert shrub and cactus communities in the lower elevations have become sparser; (b) in the higher elevations, the desert grasslands have receded, giving way to an invasion by desert shrubs and cacti and mesquite; (c) what was formerly oak woodlands is now dominated by mesquite; and (d) the timberline has moved upward. The major study on the subject describes the pattern of change as an upward migration by plant species away from hotter or drier conditions at the lower elevations toward "the old, favorable conditions" to which they are genetically suited. According to the study, it "is certainly surprising" that changes in the natural vegetation have taken place "on a scale so large over a period of time as short as eighty years."[218] The study adds:

> Taken as a whole, the changes constitute a shift in the regional vegetation of an order so striking that it might better be associated with the oscillations of Pleistocene time than with the "stable" present.[219]

What caused these changes? Like the Rio Puerco Basin in New Mexico, climatic variation and livestock overgrazing may have united here to impose unusual stresses on the land and vegetation of this region.

The essential facts appear to be these. Although pre-1900 weather records are extremely spotty, two important climate trends may have occurred in Arizona and New Mexico sometime after 1900: (a) there has been a downward trend in rainfall of about 1 inch every 30 years, with winter precipitation dropping markedly and summer precipitation only slightly and (b) the mean annual temperature seems to have risen by 3 or 3.5 degrees Fahrenheit.[220] As for livestock, the record indicates that in 1870 there were only 5,000 cattle in all of the Arizona Territory. By 1890, there were 1,095,000 cattle on Arizona rangeland! Photographs taken during the 1892-93 drought show the range's condition—"[t]housands of square miles of grassland, denuded of their cover, lay bared to the elements."[221]

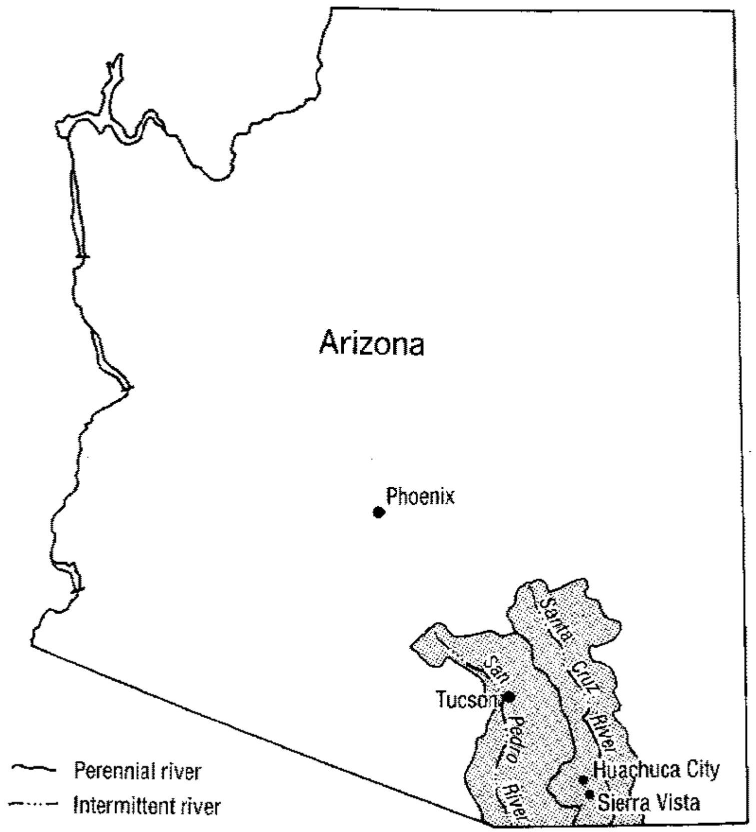
As the above-quoted study concludes:

> By weakening the grass cover, domestic grazing animals have reinforced the general tendency toward aridity. They have contributed to an imbalance between infiltration and runoff in favor of the latter. This imbalance, in turn, may have been the event that triggered arroyo cutting.[222]

In terms of the arroyo cutting and trenching that struck the Santa

Figure 11

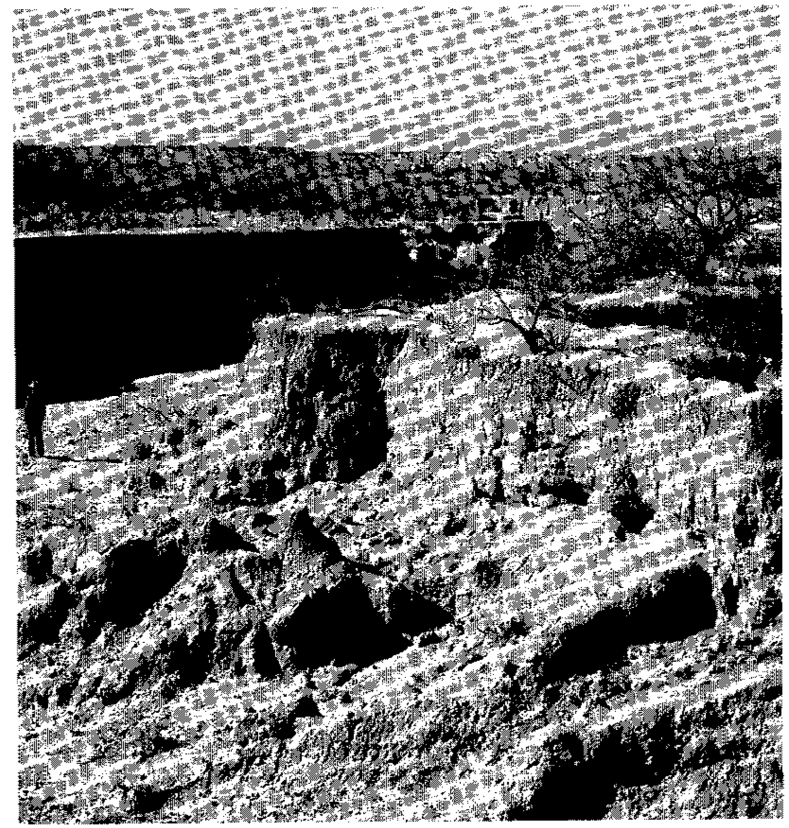
The Santa Cruz and San Pedro River Basins



Source: Based on U.S. Geological Survey, Hydrologic Unit Map—1974, State of Arizona.

Cruz, San Pedro, and other river basins of this region about 1890, hyrodologist Luna Leopold suggests two additional contributing factors. To begin with, the alluvial deposits of the region were ripe for arroyo cutting and trenching because during the period 1400–1860 "[t]he climate was not quite humid enough to cause further alluviation, nor was it sufficiently arid to cause degradation." Leopold adds: "On such a stage, postsettlement grazing could play a quick-acting and decisive role." He also suggests that a significant decrease in the number of small rains compared to the number of large rains after about 1850 unleashed another important cause of erosion in the region.[223]

What is the condition of the 16,501-square-mile Santa Cruz-San Pedro Basin today? The current available evidence indicates:



Arroyo cutting near Tombstone, Arizona (Bureau of Land Management).

- Overgrazing is no longer the area's major desertification force, but the land still suffers the aftereffects of the 1870–91 cattle orgy;
- The upward migration of plant species from drier, hotter conditions to moister, cooler ones continues, and there is no sign that the pace has slackened;
- The invasion of mesquite and tamarisk into riparian habitats, at the expense of grasses and traditional tree species, has accelerated;
- Human overdraft of groundwater is now the major desertification force at work in this area, and one of its chief consequences—the abandonment of irrigated cropland—is spreading.

The 8.1 million acres of rangeland in the Santa Cruz and San Pedro Basins produce less native forage today than in 1870.[224] On the other hand, comparative analysis of old and new photographs of the Basins' grasslands strongly suggests that they are less denuded today than 80 to 90 years ago. Mesquite, acacias, burroweed and other shrubs have filled in some of the areas that overgrazing had laid bare. Unfortunately, they have also muscled into grassy areas that had not been denuded. It is grazing that gives these intruders a competitive edge over grass in grazed areas. Cattle prefer grass to burroweed and acacia, and with mesquite (*Prosopis juliflora*), cattle act as disseminators. Cattle browse on mesquite beans, and many of them pass unharmed through their alimentary tracts and are deposited in their droppings—an ideal medium for the mesquite seed's germination. As many as 1,617 undigested mesquite seeds have been found in a single cow dropping.[225] The question is whether the invasion of mesquite into arid grasslands, as has occurred in the Santa Cruz–San Pedro Basins, constitutes desertification. The mesquite, it seems, is both villain and hero. When mesquite grows in an area that has been stripped of vegetation, it helps stabilize some soils, not as effectively as grass but better than nothing. Hence, mesquite does, under certain circumstances, impede desertification. However, when mesquite replaces existing forage grasses, it does contribute to the impoverishment of the ecosystem in terms of the major human use of that ecosystem—livestock grazing. And, as Dregne notes, a mesquite invasion into an area with sandy soils "leads to accelerated wind erosion . . . with hummocks around mesquite and blowouts between." The result, in this case, "is very severe desertification."[226]

OVERGRAZING

About 12 percent of the Santa Cruz–San Pedro's rangeland—970,000 acres—is undergoing critical soil erosion.[227] How much of this erosion can be attributed to current overgrazing and how much to overgrazing in the past has not been calculated. The USDA estimates that overall the Santa Cruz–San Pedro Basins are *undergrazed*. Presently grazing totals approximately 1.4 million AUMs, and the USDA calculates that the rangeland has the "potential" of 3.6 million AUMs.

This estimate is far from convincing. Indeed, it may well represent a classic example of the over-optimism about arid rangeland carrying capacity that invariably leads to inflated estimates (public and private) of grazing "potential." First, the USDA does not make clear whether the estimate hinges on "the improvement in forage production" through "protection of land from erosion and other deterioration."[228] If the estimate *is* based on the assumption of increased forage production, how will these improvements be implemented, and who is going to pay for them—especially on the private, state, and Indian rangelands that account for over half the land in question? If no such increase in forage production is assumed, the report leaves unexplained how the existing forage grasses that are losing ground to invading brush and weeds and are stressed by the region's increasing aridity can accommodate a 61 percent increase in grazing without further deterioration resulting. Second, the USDA estimate does not seem to take into account a very unpleasant fact of life—drought. As one agricultural analyst states:

> Drought must be recognized as a frequently occurring phenomenon with Arizona. Its patterns of occurrence are complex and can vary significantly in intensity, frequency, and duration from year to year. . . .[229]

In this regard, the USDA estimate that the extensive Indian land within the Basins has the "potential" for much more grazing is particularly suspect. At about the time the USDA was issuing its report, the government was airdropping bales of hay onto the Papago Indian reservation in the Santa Cruz Basin because the cattle there could not find enough native forage on the drought-ravaged rangeland.[230]

Studies conducted on the U.S. Forest Service's 50,000-acre Santa Rita Experimental Range, south of Tucson, reveal that perennial grass production fluctuates wildly from year to year depending on the amount of June-through-August rainfall. During a 10-year period, production (pounds of grass per acre) in the highest rainfall year was three to five times as great as in the driest year.[231] Moreover, other studies show that this area's droughts are so frequent and variable in their intensity that stocking a range on the basis of its average carrying capacity results in *overstocking* almost half the time. And as Forest Service range expert S. Clark Martin reports:

> Such overstocking would occur during the summer growing season in dry years when the perennial grasses are most susceptible to damage from repeated close grazing.[232]

State lands comprise about 26 percent of the Basins' grazing land. According to the USDA, many of the "critically eroded" rangeland areas are found on this land. The State Land Department does not have funds for erosion control measures and relies on its lessees to care for the land.[233]

Furthermore, unstable alluvium fill in valleys, which Leopold discussed in the context of arroyo cutting, remains unstable to this day. About 312 square miles of valley alluvium in the Santa Cruz and San Pedro Basins is undergoing severe erosion, that is, eroding at an annual rate greater than 40 tons per acre per year. Gully erosion dominates the "incised valley alluvium" in areas such as the San Pedro Valley and Altar Wash, but sheet and rill erosion are also occurring. In addition, the USDA estimates that some 190 miles of streambanks in the Basins are unstable and need protection.[234]

Regarding the upward migration of plant species, little more need be said except to reiterate that not all vegetation change in an arid land necessarily constitutes desertification. If, for example, mesquite takes over what was once an oak area, that is not desertification. If, on the other hand, the vegetation in a desert shrub zone (grass, brush, cacti) is becoming perceptibly sparser, then desertification is occurring. This phenomenon is, in fact, happening today in parts of the Sonoran Desert because of grazing, woodcutting, and a more arid climate.[235]

GROUNDWATER DEPLETION

The same holds true for the incredible ongoing vegetation changes occurring along the San Pedro River. It is significant that mesquite and tamarisk (*Tamarix pentandra*) are crowding out grasses, especially sacaton and sedges as well as cottonwoods, willows, and sycamores, but it is not desertification, except in terms of diminished grazing opportunities.*[236] Mesquite puts down a very deep taproot—50 to 100 feet deep—so its success at the expense of shallow-rooted species such as the cottonwood may signal a declining groundwater table because of overdrafting. However, the pumping of groundwater can cause such a precipitous drop in the water table that even mesquite cannot survive. In the Santa Cruz Valley, south of Tucson, for example, about 2,000 acres of mesquite forest have died because of a declining water table.[237]

There is no question that groundwater overdraft in the Santa Cruz Basin is as severe as anywhere in the United States. In the lower Santa Cruz, where some 552,000 acre-feet of groundwater are overdrafted every year, agriculture is the prime water consumer. The federally subsidized Central Arizona Project, now under construction, will deliver a yet to be determined amount of Colorado River water to this desert sometime in the 1980s (see Figure 12). But even this imported water may only temporarily decrease the level of groundwater overdraft. If present water use patterns continue, the annual overdraft will again exceed half a million acre-feet per year by the year 2020.[238]

GROUNDWATER OVERDRAFT IN TUCSON

The groundwater situation in the upper Santa Cruz Basin is, if anything, even more tenuous because the booming city of Tucson competes with agriculture and the copper industry, and the amount of water available for pumping is less. Tucson draws its water from the upper Santa Cruz and Avra Valley Basins to the west of the city. At present rates of consumption, the upper Santa Cruz's aquifers will be, for practical purposes, exhausted within a hundred years.[239] The annual groundwater overdraft totals about 236,000 acre-feet of water.[240] The Avra Valley aquifers will also be exhausted within a hundred years at current rates of consumption.[241]

Tucson, which averages about 11 inches of rain per year, is the largest city in the United States to rely entirely on groundwater.[242] There are wells in the Tucson area in which the water level has dropped 110 feet in the last 10 years.[243] Tucson currently pumps water out of the ground at five times the rate nature puts it back in.[244] The city also consumes some water that was deposited more than 5,000 years ago, so-called "fossil water."[245] And yet, Tucson continues to grow and attract new industry—most recently, a new IBM plant. In 1977, the voters of Tucson recalled the then-existing city council, which favored controlling growth through increased city water rates.[246] At its current growth rate, the population of the Tucson metropolitan area, now almost 450,000, will rise to about 652,000 by 1990.

The city of Tucson has purchased numerous irrigated farms in the

*The effect that these riparian vegetation changes have on native wildlife populations is not clear. Some mesquite and tamarisk thickets are so dense that they may provide poor habitat for wildlife. Conversely, mesquite and tamarisk stands may provide food and shelter for wildlife where none existed since the destruction of the original riparian habitat.

Figure 12

The Central Arizona Project

Source: Based on U.S. Bureau of Reclamation, General Location Map No. 344-314-944, 1968.

upper Santa Cruz Basin and Avra Valley in order to gain control of their wells. To date, the city has retired about 12,000 acres of farmland, and mining companies have bought up and retired another 8,000 acres.[247] Tucson officials anticipate the need to purchase about 36,000 acres by 1985 and have budgeted about $20 million for that purpose.[248] This purchase will effectively end irrigated agriculture, mostly pecan trees and cotton, in the Avra Valley and the upper Santa Cruz Valley.[249] Agriculture, notes an Arizona geographer, is "dispensable" in this area.[250] As a consequence, the acres of once-plowed fields that are "retired," that is, abandoned to wind and weeds, will grow right along with Tucson.

Water conservation, that is, more efficient use of water, has *not* been pursued as a major policy alternative by Tucson in dealing with its groundwater overdraft problem. The city's voluntary water conservation effort is geared toward keeping water consumption in the peak summer months within the water system's capacity—151 million gallons per day—rather than effecting long-term and fundamental changes in water consuming habits.[251]

Tucson has begun to recycle water. Effluent from one of the city's three water treatment plants is now used to water a municipal golf course. But the area's 16 other golf courses still use groundwater to keep the desert green.[252] Apparently Tucson sees the acquisition of additional groundwater sources through displacement of agriculture and the importation of Colorado River water through the Central Arizona Project as the solution to its long-term water supply problem.

Uncertainties loom ahead, however. Legal problems have arisen. Tucson relies, in part, on water pumped from wells south of the city on the edge of the Papago Indian San Xavier Reservation. The Papagoes are now suing the city of Tucson and other non-Indian interests (including a mining company), claiming that pumping has caused some wells on the reservation to dry up and the water levels in others to drop precipitously. They are seeking to restrain all groundwater withdrawals off the Reservation that affect groundwater levels on the Reservation.[253] The case could have far-ranging implications for Tucson's future water supply. In addition, whether Tucson will actually get Colorado River water remains open to question. A recent National Science Foundation-sponsored report observes that "it is neither certain that the Central Arizona Project will ever reach Tucson nor that the requested allocations will or can be granted or delivered."[254]

Even assuming that Tucson gets the Colorado River water that it has requested, the city's and the upper Santa Cruz Basin's long-term water problems are far from over. The University of Arizona's Water Resources Research Center made the following assessment of the area's water prospects:

> Central Arizona Project water will counter urban and mining depletions of groundwater and for a brief period of time there will be a dependable water supply in the basin. However, by the year 2005, an estimated dependable supply of 191,000 acre-feet will be exceeded by non-agricultural demands for 237,000 acre-feet.
>
> The Basin supply-use picture could be further clouded if the Department of Justice and Indian residents on the San Xavier Reservation are successful in their lawsuit . . . .[255]

One may ask, so what? Why should the water problems of the upper Santa Cruz Basin trouble anyone but the residents of that area? The agricultural output that will be lost is insignificant in national terms.

Two reasons come to mind. In the first place, the United States depends on the upper Santa Cruz Basin for roughly one-fourth of its supply of copper, an essential metal. There are five major open pit copper mines in the basin and another under development. These

mines produce an estimated 200,000 tons of sulfide-copper ore daily. It takes roughly 210 gallons of water per ton to mine and concentrate this ore. The concentration of the ore through a flotation process is especially water intensive and is becoming more so because it takes more water to recover copper from the increasingly lower grade ores being mined. In 1960, the ore mined here contained, on average, 1 percent copper. Today, it contains 0.5 percent. At present production, the copper industry in the upper Santa Cruz Basin consumes about 50,735 acre-feet of water per year.[256] To date, water scarcity has caused only minor disruptions in copper production. The worry is that as groundwater supplies become further depleted, a time will come when water scarcity will prevent the copper industry here from responding to the nation's copper demand, particularly if political events interfere in the export of copper from Chile, Zambia, or Zaire or if there is a surge in domestic demand like that which occurred during the Korean and Vietnam wars.

At present, mining accounts for 27 percent of the groundwater depletion in the upper Santa Cruz Basin, while urban uses account for 29 percent and agriculture, 41 percent.[257] Mineral industry officials see agriculture as the chief culprit in the area's water plight. For example, Tom Chandler, attorney for Anamax (a mining partnership between Anaconda and Amax), is quoted as saying:

> The farmer leases land from the state at a cheap rate, plus he gets power breaks, a cheap tax rate, government subsidies. He's pumping the copper mining industry dry; he's pumping the state dry; he's pumping the Indian people dry; and when he's got that done, he's going to move to La Jolla and raise martinis.[258]

A second reason for concern about this arid area's massive groundwater overdraft problem is that the U.S. taxpayers are being called on to finance its solution. Currently under construction, the Central Arizona Project will divert 1.2 million acre-feet of water per year from the Colorado River near Havasu, Arizona. The water will be lifted 2,000 feet and transported to metropolitan areas and irrigators in the middle of the state by means of a 250-mile-long pipe. About $270 million has been spent to date. And it will take $1.5 billion to complete the project, according to current estimates. But the cost to the U.S. taxpayer may eventually run much higher. A recent study, sponsored by the Andrew Mellon Foundation under the auspices of the National Audubon Society, reportedly estimates that the Central Arizona Project will, over the next 50 years, cost U.S. taxpayers $5.4 billion.[259]

As Kenneth E. Foster of the University of Arizona's Office of Arid Lands Studies concludes: "The Santa Cruz Basin is obviously a case where short-term objectives were given major priority. Now as groundwater levels fall, expensive alternatives must be considered to salvage the local economy."[260]

The pattern is a familiar one in the arid West. A local economy is built and thrives on the depletion of groundwater; then when it becomes apparent that the resource will not last, an expensive water import project is launched. Los Angeles is probably the classic example of this pattern. As Carey McWilliams has noted, Los Angeles exhausted its groundwater supply "as a young spendthrift might dissipate a legacy, in a single generation."[261]

In his book, *Killing the Hidden Waters*, Charles Bowden put the water problem of areas such as the Santa Cruz Basin into an illuminating perspective:

> Water is energy, and in arid lands it rearranges humans and human ways and human appetites around its flow. Groundwater is a nonrenewable source of such energy.... Humans build their societies around consumption of fossil water long buried in the earth, and these societies, being based on a temporary resource, face the problem of being temporary themselves.[262]

Although irrigated agriculture and urban development in the San Pedro Basin are still relatively modest, the Basin's annual groundwater overdraft already totals 246,000 acre-feet. Irrigation accounts for most of this. The Basin's 148,400 acres of irrigated cropland consume some 434,900 acre-feet of water per year.[263] Groundwater in the Fort Huachuca-Sierra Vista area, the Basin's major urban area, has dropped 30 feet in the past 25 years.[264] Four wells operated by the Bella Vista Water Company, which serves part of Sierra Vista, have experienced declines ranging from 30 to 46 feet since 1973.[265] The area faces "potentially severe water supply problems." The overdraft situation "could effectively exhaust the nearby aquifer by the year 2020."[266]

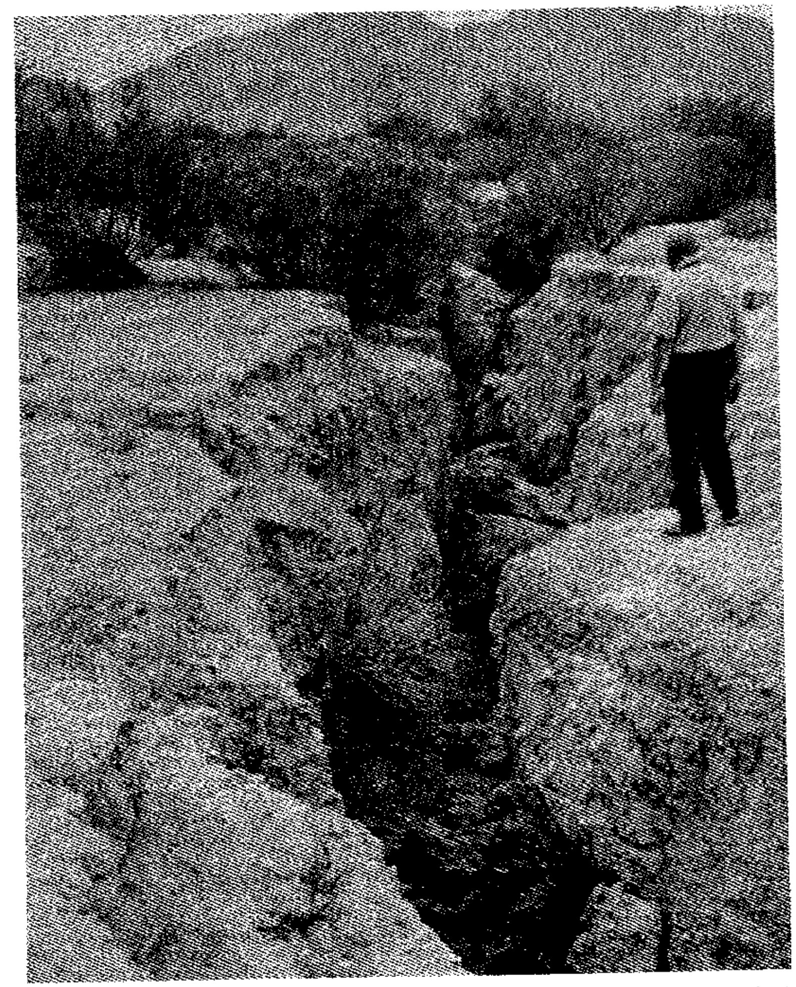
The environmental consequences of groundwater overdraft, though not so dramatic as the economic consequences, are also worth noting. Scientist Susan Jo Keith, who has studied the problem in Arizona, observes that "the innocuous-looking modern well, particularly found in large numbers, is a very effective agent of both surface and subsurface environmental change in arid lands."[267]

One of the most obvious consequences is the drying up of once perennial streams and rivers where they are in "hydraulic contact" with the groundwater that is being overdrafted.[268] For example, the Santa Cruz River ran dry in the 1930s because of "the advent of deep-well turbines which are capable of pumping water in excess of the recharge rate."[269] The upper San Pedro River could run dry—just as the Santa Cruz did—in the years ahead if massive groundwater overdrafting continues.[270]

SUBSIDENCE

Land subsidence caused by groundwater overdraft, mentioned earlier in the San Joaquin discussion, is occurring in various parts of central Arizona. Land near Eloy, Arizona, for example, has subsided as much as 10 feet in the last 30 years. Cities such as Casa Grande and Tucson have also experienced subsidence, although not dramatic.[271]

Accompanying subsidence in central Arizona are earth fissures and faults. They vary in size, but some fissures measure as much as 25 feet wide and 60 feet deep.[272] More than 75 cracks in the earth have



An earthcrack on the boundary between Maricopa and Pinal Counties, Arizona; it is at least 50 feet deep (Troy Pewe, Tempe, Arizona, July 25, 1972).

been found in central Arizona.[273] A USDA report describes the fissures in this area (the lower Santa Cruz and Willcox Basins) as ruptures of valley alluvium that have "disrupted local drainage and irrigation water application, damaged wells and canals, caused misalignment of highways and endangered homes."[274] They have also caused gullying. Researchers from the University of Arizona observed in this area, for example, "the creation overnight of a gully five feet deep, six feet wide, and 25 feet long where an existing drainage was breached by the surface opening of a fissure after (or during) a [rain]storm."[275]

Keith concludes: "The amount of land lost to the use of man by fissuring, faulting, and subsequent gullying can only be speculated on."[276] One thing does seem certain, however—the fissuring and

Homes endangered by a mile-long earth fissure. Perpendicular gullies are occurring by piping and erosion (E. E. Hertzog, Bureau of Reclamation).

faulting of the earth are expected to continue as long as the groundwater overdraft continues.[277]

Perhaps the most serious environmental consequence of groundwater overdraft in the Santa Cruz-San Pedro Basins is the abandonment of irrigated cropland. A recent analysis of Arizona agriculture observed:

> Long-term intensive pumping in this area has lowered water tables to a point at which production of some crops is now marginal. Minor fluctuations in fuel or power costs of pumping and commodity prices are sufficient to cause financial losses and have forced some abandonment of fields or shifts to high value crops. Farmers throughout southern Arizona who use groundwater face similar situations.[278]

Of the 549,100 acres of irrigated land in the Santa Cruz-San Pedro

Basins, 369,800 acres are in production, and 157,800 are "idle" but may be returned to production. Some 53,000 acres of formerly irrigated land have been abandoned.[279]

Lacking any natural cover, these abandoned fields and the "idle" fields with sandy and loamy soils fall quickly prey to wind erosion. Blowing dust from abandoned or "idle" fields in the lower Santa Cruz Basin, where they are most extensive, has been so severe at times that nearby interstate highways have had to be closed.[280]

The amount of irrigated acreage in this area is expected to decline in the years ahead, but by how much remains uncertain. A 15 to 20 percent decrease by the year 2000, as projected by some economists, could mean that an additional 82,000 to 110,000 acres of cropland ends up abandoned, that is, producing dust and tumbleweed.[281]

To see one of the abandoned fields in the lower Santa Cruz Basin of Arizona, its desiccated surface scoured by the wind, its irrigation ditches choked with sand, is to be reminded that arid land can be a merciless place for those who try to domesticate it.

ARIZONA'S EFFORTS TO CONTROL GROUNDWATER DEPLETION

Given the long-term economic and environmental consequences of massive depletion of groundwater, it is remarkable that the state of Arizona has done so little to manage and conserve this resource. Until very recently, the state's water code treated groundwater as essentially a property right rather than a public resource. Aside from designating basins where the withdrawal rate exceeded the replenishment as "critical groundwater areas," the state had done nothing substantive to control its use. Secretary of Interior Cecil D. Andrus warned Arizona that, unless the state took effective action, the Central Arizona Project would be delayed. This threat apparently provided the impetus for the competing water interests in the state—agriculture, the mining industry, and the cities—to negotiate an agreement on how groundwater should be allocated and conserved. A consensus was hammered out, and the state enacted a comprehensive water management and conservative law in June 1980. Aimed at achieving a "safe yield" in groundwater use by the year 2225, the new law requires a statewide registration of all wells; mandatory water conservation in the state's three major urban areas (Phoenix, Tucson, and Prescott) and its major agricultural area (Pinal County), a large portion of which comprises the lower Santa Cruz Basin; and empowers the director of a new Department of Water Resources to set per capita consumption limits for cities and to purchase and retire the water rights of irrigated farmes in this area after the year 2006. The law prohibits both new growth in areas where the developer cannot assure that a water supply will exist for at least 100 years and new irrigated agriculture in groundwater problem areas.[282]

Arizona Governor Bruce Babbitt, who signed the law, states:

> In the old West, we're going overnight from a laissez-faire system, a system where everybody used whatever they wanted wherever they wanted, to the

most comprehensive groundwater management system of any state in the American West.[283]

Obviously, many questions remain unanswered about Arizona's new law. It is too soon to tell whether the state will be able to accomplish the exceptionally difficult task that it has undertaken—the allocation and conservation of its most important scarce resource, groundwater. Buy by passing such a law, Arizona has acknowledged that groundwater is a finite resource and should be managed accordingly. This realization alone is historic.

As of now, it appears that irrigated agriculture in Arizona, specifically in the Santa Cruz Basin, will be hardest hit by the new law. Dale Pontius, executive assistance to Governor Babbitt, reports: "Agriculture uses 90 percent of the water. It was inevitable that they had to give up the most."[284]

KIOWA AND CROWLEY COUNTIES, COLORADO

Apparently, neither the hard-bought and soon-forgotten lesson of the Dust Bowl, nor the unregulated forces of the free market, is sufficient to safequard the soil.

—Erick P. Eckholm
Losing Ground[285]

On the morning of February 23, 1977, high-velocity winds struck the western rim of the Great Plains. Within 7 hours, millions of tons of soil from the region were in the atmosphere and a full-fledged dust storm was moving eastward. Within 27 hours, the dust storm cast a pall over 248,000 square miles of the south central United States, and within 48 hours it had reached the Atlantic Ocean. By the afternoon of February 26, the dust pall, that is, soil from the Great Plains, was still visible over the mid-Atlantic.[286]

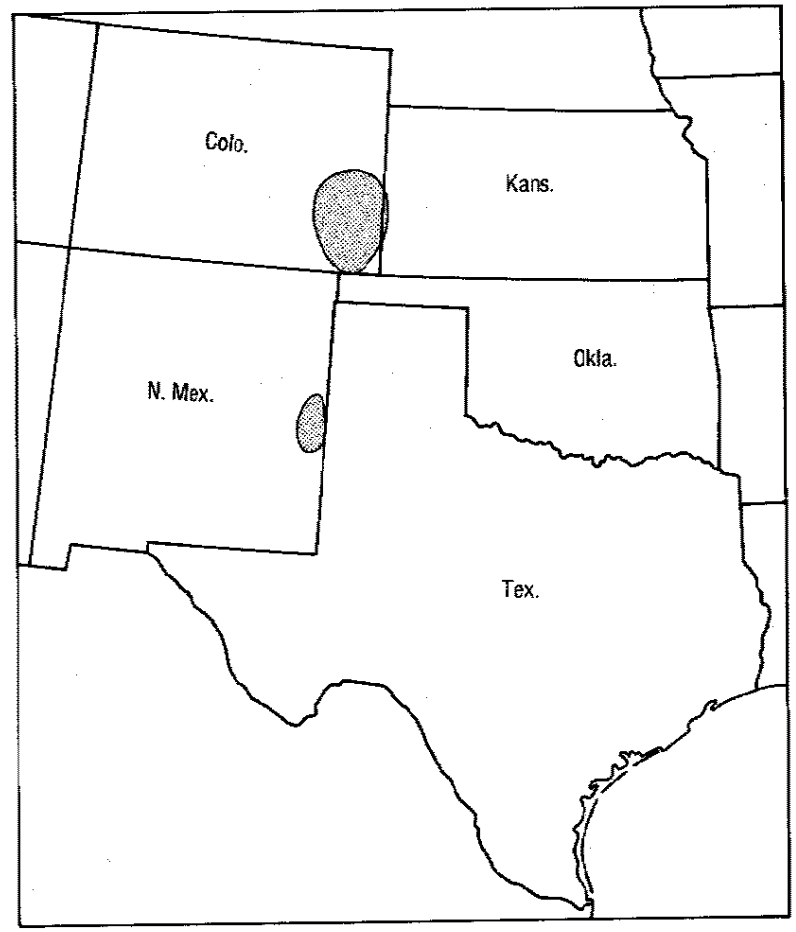
Analysis of photographs taken from geostationary satellites (GOES-1 and SMS-2) enabled scientists not only to track the dust storm but also to locate its origins. Most of the eroded soil for this dust storm came from the Portales area in eastern New Mexico and from the southeastern corner of Colorado (see Figure 13). Dust plumes from each area merged over central Texas to create the enormous eastward-heading dust pall.[287]

Both the Portales area and southeastern Colorado are primarily dryland wheat farming areas. Both average 17 inches or less precipitation per year, and both are subject to droughts that strike, as they do throughout the Great Plains, at roughtly 20-year intervals. Both figured prominently in the terrible dust storms of the 1930s.[288]

The team of USGS scientists who studied the February 1977 dust storm followed up their analysis of the satellite pictures with an aerial and ground reconnaissance of the Portales area. They found scenes of desert-like desolation. The wind had scoured plowed fields to depths greater than 3 feet and had smothered others under a blanket of sand.

Figure 13

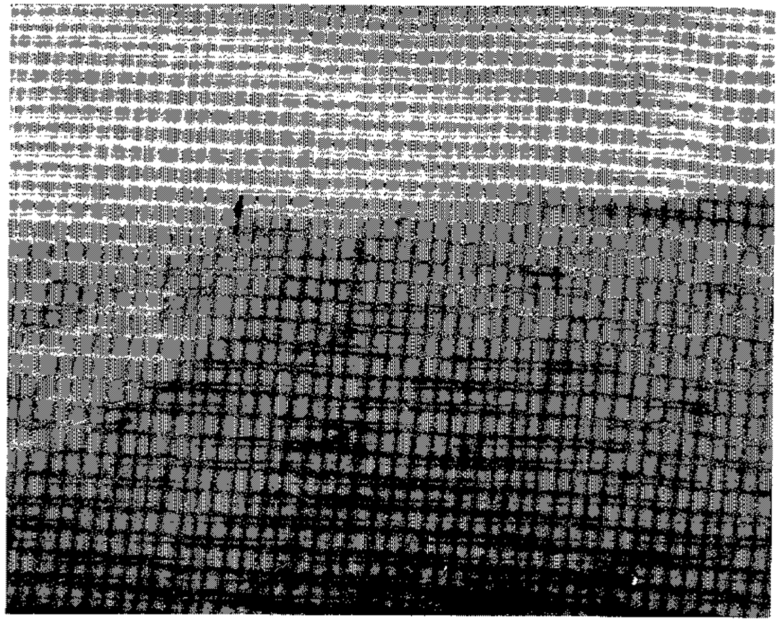
Dust Sources for February 1977 Dust Storm



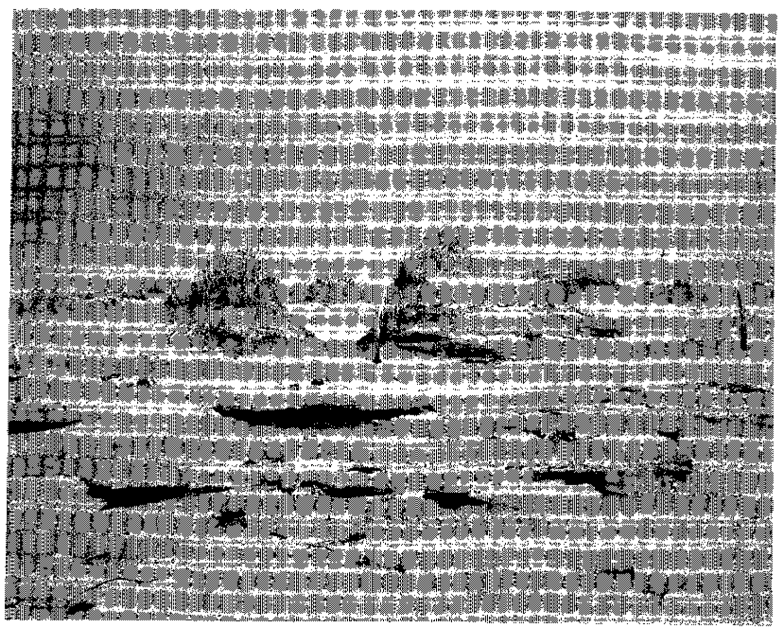
The soils of the area, formed largely of eolian silt and sand, are highly susceptible to wind erosion. Stripped of their native vegetation—grama and buffalo grasses—and desiccated by a prolonged drought, the soils were especially vulnerable in the winter of 1977.[289]

SOIL EROSION IN THE PORTALES AREA

Soil erosion is nothing new to the Portales area. In 1976, a GAO study team visited Roosevelt County, and of the 28 farms sampled, 19 were losing soil at a rate of 12 to 18 *tons* per acre per *year*.[290] Wind erosion of cropland on the Great Plains averages 5.3 tons per acre per year.[291] During the February 23d storm, cropland in the Portales area



Loosely plowed fields in Curry County, New Mexico, in a 35-mile wind (Glenn M. Burrows, Soil Conservation Service).



Severe wind erosion, Roosevelt County, New Mexico, 1953, began on the formerly cultivated field and spread to the rangeland in the background, leaving only clumps of grass (Soil Conservation Service).

(Roosevelt and Curry Counties) probably lost 40 or more tons of soil per acre in less than 24 hours. Soil forms at a rate of about 1.5 tons per acre per year under "favorable agricultural conditions."[292] Such conditions do not exist in the Portales area or, for that matter, in many places on the Great Plains.

The Geological Survey concluded that "a coincidence of economic factors, governmental policies, and land use practices seems clearly to have contributed to the severity of wind erosion that occurred during this particular storm."[293] Specifically, the report notes that increased wheat prices in 1973–74 stemming from the sale of large quantities of wheat to the USSR prompted farmers to plow the Portales area's highly erodible, marginal land. It also cites two federal government policies that encouraged this trend. One was the cutoff of funds for the land retirement plan ("soil bank") of the Agricultural Conservation Program. In 1956, some 241,000 acres of land in this area had been taken out of crop productions for a 10-year period under the soil bank program. In 1966, however, some 63,000 acres were removed from retirement and put back into production when soil bank program funding ended. By 1977, 75 percent of the 241,000 acres had been returned to crop production—primarily wheat, but also grain sorghum. The other federal policy is one that compensates farmers for damage done to crops (wheat, feed, grains, cotton) by wind erosion through the disaster relief programs of the Department of Agriculture, thereby "reducing their incentive to retire marginal land from production."[294]

The USGS report adds that "the soil conservation lessons of the 1930's Dust Bowl have been partly forgotten" and notes: "We observed continuing destruction of windbreaks in Curry and Roosevelt Counties, New Mexico, during our ground investigations a little more than a week after the 1977 windstorm."[295]

Dryland farming in southeastern Colorado illustrates the complex economic calculations, government policies, and forces of nature that are causing day-in and day-out soil losses and land degradation, as well as periodic but violent dust storms.

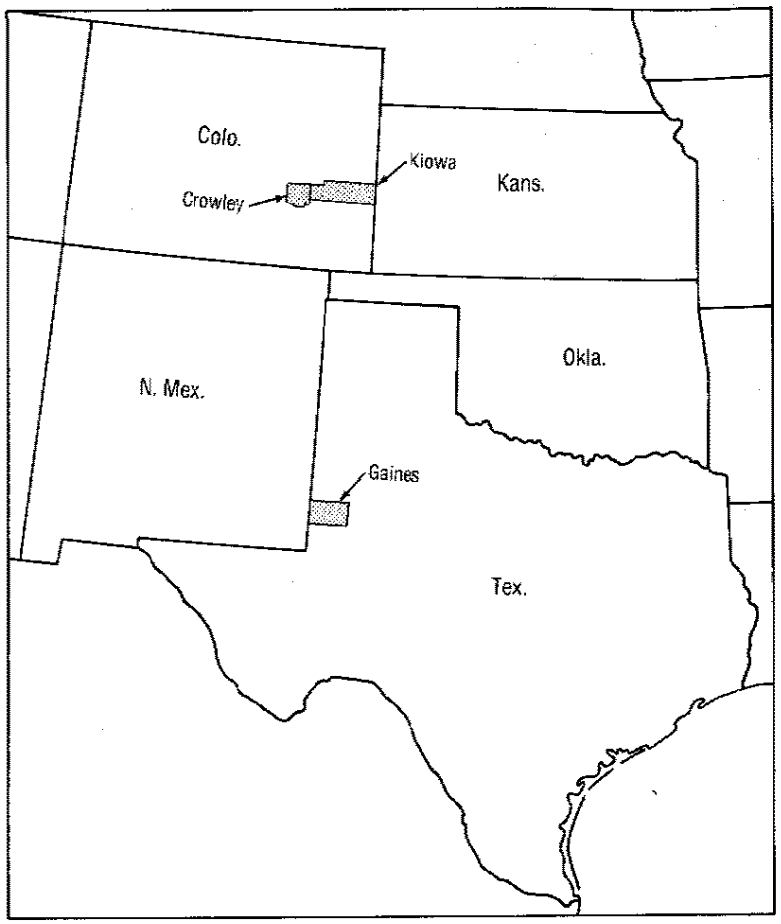
Kiowa and Crowley Counties (see Figure 14), in the southeastern part of Colorado, were also part of the area where the February 1977 dust storm originated. Soil erosion in this area is as serious as in the Portales area. During this major storm, some fields in these counties lost an estimated 150 tons of soil per acre.[296]

KIOWA COUNTY

Conditions are ripe in Kiowa for massive erosion of the soil by the wind. As you move westward from the Kansas state line across Kiowa County, the average annual rainfall drops from about 17 inches to 10–13 inches in western Kiowa and Crowley Counties. Much of the area's native plant cover—again, mainly grama and buffalo grasses—has either been plowed under for dryland farming of crops, especially winter wheat, or overgrazed by cattle. And though windstorms of the intensity of the one in February 1977, with winds gusting up to

Figure 14

Three Counties in the Arid West with Serious Soil Erosion



90 miles per hour, occur only periodically, strong prevailing winds are quite common for this area.[297] Moreover, in western Kiowa County, for example, there are some 150,000 acres of Class VI land under cultivation.* The soil from this land is eroding at a rate of about 20 tons per acre or more per year. SCS are a conservationist Arnold King flatly states: "This area should be grassland." In the moister eastern part of the County, soil erosion is in the 5 to 8 tons per acre range.[299]

Kiowa's long-term soil erosion problem in a function of the arid climate and the cultivation practices of the farmers. About 60 percent of the County is dryland farming of winter wheat, with grazing accounting for roughly 25 percent.

A farmer sows winter wheat in the autumn. Sprouts appear before the first frost. Then the plants ripen in the spring and are harvested in the summer. Hence, from September through March, the field has very little plant cover to protect it from the erosive force of the wind. Then after harvest, the winter wheat field in this area is usually left fallow for a year in order to build up moisture in the soil. During this period, the farmer usually plows the field several times in order to control weeds that consume precious soil moisture. It is during this fallow period that the soil is most vulnerable. The repeated plowings churn up not only the wheat stubble and litter left after the last harvest but also any new plant growth, leaving the soil at the mercy of wind and water.

Most of the time-tested soil conservation practices are little used in Kiowa or Crowley County.

SOIL CONSERVATION PRACTICES

Windbreaks. During the late 1930s and the 1940s, thousands of miles of windbreaks or shelterbreaks were planted across the Great Plains, with federal government assistance, in order to reduce wind erosion of the soil. There is little enthusiasm today for windbreaks, however. Indeed, many of those that were planted have been removed. A good number were cut down during the 1973–74 period when the price of wheat rose to $5 a bushel and farmers eagerly followed the advice of Secretary of Agriculture Earl Butz to plant their fields from fence to fence. The enormous size of today's agricultural equipment also discourages tree or hedge rows. These mechanical leviathans need plenty of room to maneuver and are most efficient when operated over huge open spaces. The SCS, while it still officially favors windbreaks and still helps interested farmers install them, does not in fact emphasize their use as it once did. John Knapp, SCS area agronomist, explains:

*The Soil Conservation Service classifies land thusly:
Class I—Soils have few limitations that restrict their use.
Class II—Soils have moderate limitations that reduce the choice of plants or require moderate conservation practices. (Continued)

(Continued)
Class III—Soils have severe limitations that reduce the choice of plants or require special conservation practices or both.
Class IV—Soils have very severe limitations that reduce the choice of plants or require very careful management or both.
Class V—Soils are not likely to erode, but other limitations, impractical to remove, limit their use largely to pasture, range, woodland, or wildlife habitat.
Class VI—Soils have severe limitations that make them generally unsuited to cultivation and that restrict their use largely to pasture, range, woodland, or wildlife habitat.
Class VII—Soils have very severe limitations that make them unsuited to cultivation and that restrict their use largely to pasture, range, woodland, or wildlife habitat.
Class VIII—Soils and landforms have limitations that preclude their use for commercial plants and restrict their use to recreation, wildlife habitat, water supply, or esthetic purposes.[298]

Windbreaks protect only parts of the field—roughly an area 10 times the height of the trees in the windbreak. They make it difficult to till with big equipment and are not popular with farmers. We are not pushing them. Instead, we are concentrating our efforts on soil conservation practices which are more effective *and* have a better chance of acceptance by the farmers—stubble mulching, reduced tillage, and stripcropping.[300]

The Council for Agricultural Science and Technology* strongly recommends windbreaks:

Properly designed windbreaks in the northern and western Great Plains have proven effective in reducing wind speeds from erosive levels to nonerosive levels. They can be used effectively in conjunction with other agronomic conservation methods such as strip cropping and stubble-mulch tillage. . . .
Windbreaks alter microclimate in the protected zone. They provide more favorable daytime temperature and absolute humidity. Coupled with the decrease in wind speed, this change results in a significant moderation of the evaporative demand and, hence, in the evaporative stress imposed on the crop. Normally, vegetative and reproductive growth of crops benefits from this more moderate microclimate.[301]

Another benefit of windbreaks is that they provide valuable habitat for wildlife in a region where the natural wildlife habitat has been drastically reduced by people over the past 150 years.[302]

Contour plowing is a highly effective way of reducing water erosion of the soil when row crops are planted across rolling terrain. Some grain sorghum, beans, and corn are planted on rolling terrain in Crowley County, but there is little evidence of contour plowing. Rather, up-and-down-hill-plowing seems most prevalent.[303]

Planting row crops in flat, windy areas requires another technique—planting rows perpendicular to the prevailing winds. The study team that examined the Portales Valley found the very worst erosion in fields where row crops had been planted parallel to the westerly-southwesterly winds.[304] In Crowley County, some row crops are planted in this direction.

Stripcropping usually involves planting strips of grass such as annual rye or legumes such as vetch or clover between broad strips of row crops or wheat. The grass or legumes protect the soil from wind and water erosion, especially when fields are fallow, and the legumes provide an added bonus of fixing nitrogen in the soil.[305] Stripcropping in this sense is not practiced in Kiowa or Crowley County because the rye or vetch would consume moisture needed for the cash crop—winter wheat. Instead, the SCS is trying to interest farmers here in leaving strips of wheat stubble between strips where winter wheat is planted. These fallow strips collect moisture for future planting and help protect the land from the wind.[306] In western Kiowa County, however, stubble strips failed to protect the cultivated Class VI land from the ravages of the big windstorm in February 1977.[307]

*CAST is a private body made up of professional organizations such as the American Society of Agricultural Engineers and the Soil Science Society of America.

Elsewhere on the Great Plains, both stripcropping and stubble strips have proven effective in reducing erosion on less erodible land—Class IV or better.[308]

Federal disaster relief programs, administered by the Agricultural Stabilization and Conservation Service of the USDA, specifically discourage stripcropping or stubble strips (as well as discouraging farmers in general from retiring marginal land). The reason: The amount of disaster relief for which a farmer is eligible is based, in part, on the total acreage that he has planted in wheat or some other crop such as grain sorghum. The strips of grass or stubble are not considered a crop in this case, so by planting them, a farmer simply reduced his total crop acreage. Such payments, in the case of drought or wind erosion damage to wheat or feed grains, are calculated on the basis of the following formula:

established per acre yield × 60% × planted crop acreage

If a farmer produces less than that total figure, and in Crowley County and western Kiowa County he frequently does, then the federal government pays him the difference.

By *rotating crops* from year to year, a farmer improves his soil structure, making it more resistant to erosion. In Kiowa County, where essentially monoculture (winter wheat) prevails, there is virtually no crop rotation. In Crowley County, there is some crop rotation, but on the dryland farms in the County it does not significantly inhibit wind erosion.[309]

Conversion to grass is the ultimate weapon in the war against soil erosion on the Great Plains. For example, after the Dust Bowl, the federal government purchased two giant tracts of wind-eroded wheatland south of Kiowa County and, under the supervision of the SCS, returned the land to its native condition—short-grass prairie. Today, it is the Comanche National Grassland, managed by the Forest Service.

In Kiowa and Crowley Counties today, there are more than 200,000 acres of erosion-prone cropland that should be converted to pasture or range. But the trend is in just the opposite direction. Why? Because when the price of wheat rises above $4 per bushel, as it has recently, and the rains return, a farmer can make more of a profit per acre growing wheat on this marginal, highly erodible land than he can by not plowing up the grass and raising cattle on it.

The short-run economics of converting wheatland back to range are very unfavorable. For the sake of illustration, let us look at a hypothetical farmer in western Kiowa County. He owns 1,000 acres of land, most of which is marginal Class VI land. In a better-than-average rainfall year, this land yields 19 bushels of wheat per acre and loses about 20 tons of soil per acre. With wheat at $4.68 per bushel, the farmer grosses $88,920. Say his expenses total $50,500, so his profit for the year is $38,420. Now let us assume that he decides to convert his 1,000 acres to range. The process would probably take place in three stages. First, he plants some species of fast-growing annual, such as rye, in order to develop a litter cover for the soil and build up its organic content. This stage costs $12 per acre and takes 1 year. Next, using a special drill, the farmer seeds grama grass. This stage costs $15 per acre and takes another year. Finally, if the grass has become established, he begins to graze cattle on a limited basis, reseeding those spots that did not grow. Three years have elapsed. The farmer has spent $27,000 just establishing a grass forage, and his yield so far, from the sale of calves or fattened cattle, has been zero. It will take more than 4 years and much higher beef prices than currently prevail for him to begin to gross the $88.92 per acre that he did growing wheat in 1979.

The promise of federal disaster relief payments is a form of collateral for the Crowley or Kiowa County farmer when he goes to the bank to seek financing for next year's operations. Let us return for a moment to the hypothetical western Kiowa County wheat farmer. Nineteen seventy-six was a miserable year for him. Drought drove down his per-acre yield to seven bushels, and he sold his wheat at $2.90 per bushel. He grossed $20,300. His expenses that year were $31,000. Hence, he ended up $10,700 in the red. The government, however, paid him $6,000 in disaster relief, which enabled him to meet his loan payments to the bank. By dipping into savings accumulated in the good wheat year of 1974 and renegotiating his loan with the bank, that is, increasing his indebtedness, the farmer is able to cultivate his Class VI land for another year. The farmer's banker is willing to lend him more money to do so because the banker knows that (a) it might rain or (b) if it does not rain, the farmer will receive federal disaster relief; in either case, the banker gets his money. It is not at all unusual for farmers on the arid western Great Plains to pass their government checks directly on to their local bank without cashing them. As one farmer reported: "Hell, I never see any of that money. I just sign the back and hand the damn thing over to my banker."[310]

The disaster relief programs encourage cultivation of marginal land in still another way. These payments are calculated on the basis of total acreage planted and established yield per acre. The yield figure is set by the local ASCS committee, and according to both John Knapp and Arnold King of the SCS, these committees often set the figure at an unrealistically high level. Thus, the dryland farmer receives more than he should, even in nondrought years. King thinks that inflated established yield figures are a "major reason why those 150,000 acres of Class VI land in western Kiowa County are still in wheat instead of grass."[311]

Agronomist Knapp adds:

> The worst soil erosion in this whole area is in Crowley County, where beans, millet, and grain sorghum are cultivated on several thousand acres of dry, sandy loam soil. As a result, the soil losses are sometimes as high as 50 tons per acre per year. The farmers plowed up rangeland and harvested drought relief benefits.[312]

The federal program specifically designed to convert erosion-prone cropland into grassland is the Great Plains Conservation Program.[313] Under this Program, administered by the SCS, the government assists farmers, on a cost-share basis, to convert cropland to permanent vegetative cover or to reseed rangeland.

According to the SCS, vegetative cover has been established on some 2.4 million acres of the Great Plains under this Program, and 1.9 million acres of rangeland have been reseeded. The agency estimates that no more than 8.3 million acres will be treated or brought under contract by the end of fiscal year 1981. The goal was 16 million acres. Furthermore, the GAO discovered that the "permanent" vegetative cover of the 2.4 million acres of cropland converted under the Program is not all that permanent. The GAO ascertained that 26 percent of the farmers in the Program had recultivated the newly established grassland after their 3- to 10-year contracts with the government expired and that even more planned to do so in the near future.[314]

The Program's prime shortcoming is that it does not provide farmers with an adequate economic incentive for converting their marginal cropland to grassland or, if they do convert, for keeping it in permanent vegetative cover. The GAO reports that there is little or no interest in the Program among farmers in the severely eroded crop-producing areas of western Kansas, eastern New Mexico, or west Texas.[315]

On the other hand, Knapp reports: "Generally, the acceptance of the Great Plains Conservation program has been outstanding... in the 12 county area of southeastern Colorado. We currently have over 300 active, long-term conservation contracts with farmers.... In fact, presently we have 25 new agreements awaiting monies for funding." He does note, however, that there are not many Great Plains Conservation Program contracts in the "highly erosive" parts of Kiowa or Crowley County, where Class VI land is under cultivation because the farmers are unwilling to convert it to permanent vegetation.[316]

The GAO's analysis shows that only 26 to 32 percent of the funds expended under the Program have actually been spent to establish permanent vegetative cover on highly erodible cropland or for the reseeding of rangeland. In recommending passage of the legislation that created the Great Plains Conservation Program in 1956, the USDA indicated to Congress that 95 percent of the Program's funds would be spent for these purposes. Instead, the majority of funds have been spent on such activities as reorganizing irrigation systems, installing livestock watering facilities, digging wells, laying pipeline, and fencing.[317]

In southeastern Colorado, terracing is a soil conservation measure on which considerable amounts of Great Plains Conservation Program money have been spent. Approximately 750,000 linear feet of earth have been terraced annually on dry cropland.[318]

Under the Great Plains Conservation Program, the federal government pays up to 80 percent of the cost of establishing permanent vegetative cover so long as total costs do not exceed $25,000 per contract.

Farmers today need much greater inducement than that if they are going to use this ultimate weapon in the war against soil erosion.

Minimum tillage is the practice being pushed most vigorously by the SCS in Kiowa County as well as in many other soil erosion problem areas of the Great Plains. Minimum tillage simply means that the farmer disturbs the soil as little as possible during planting and harvesting and especially during the period when the field is left fallow. In other words, the farmer makes as few sweeps across his cropland as possible. The idea is to build up crop litter and stubble on the ground. This practice can be extremely effective in controlling soil erosion. In a Nebraska-based study, for instance, soil erosion averaged only 3.4 tons per acre per year under minimum tillage compared with a soil loss of 10.7 tons per acre per year under a "plow-disk-harrow planting system."[319]

According to agronomist Knapp, farmers in Nebraska and Kansas have adopted the minimum tillage technique more readily than in southeastern Colorado. He estimates that perhaps some 200,000 to 300,000 acres in those states are under minimum tillage.[320]

Farmers have been reluctant to adopt minimum tillage elsewhere because of concern that it would reduce their crop yield per acre. Knapp and other soil conservation experts argue that minimum tillage will not reduce production and might even increase production. Initially, however, two problems must be overcome.

One is weed control. The USDA urges farmers to combine minimum tillage with the application of chemicals to kill weeds. The trick is to kill the weeds while preserving the crops. In 1977 in western Kiowa County, atrazine and some paraquat were applied to some 6,400 minimally tilled fallow fields, with the federal government sharing the costs through the ASCS Agricultural Conservation Program. The results were not encouraging. Wheat planted in the autumn of 1978 germinated and then a kill pattern emerged. Knapp reports: "Many fields are complete losses...just massive [wheat] kill. Some others have shown typical streaking and application inconsistencies."[321] The herbicide atrazine, it turns out, breaks down slowly in soils that are relatively alkaline and low in organic matter, such as the ones tested in western Kiowa County. Hence, the atrazine residue kills wheat seedlings. Knapp suggests that atrazine be tried on those cropped soils in the regions that have higher organic content and lower pH and that the dosage rate be reduced.[322]

In other words, chemical control of weeds on fallow fields is no panacea, and it may not be applicable to many of the highly erodible soils on the western Great Plains. In addition, the minimum till-chemical fallow approach raises some tough questions: What effect will the long-term application of these chemicals have on the microbial life within the soil that is so important for the soil's continuing fertility? What effect would widespread use have on the area's water quality—groundwater as well as streams and reservoirs? What effect would it have on wildlife? Minimally tilled grain fields are favorite foraging spots for Canada and Snow Geese, Mallards, Pintails, and other migratory waterfowl. They also attract the Ring-

necked Pheasant.

A second problem with minimum tillage is that it is extremely difficult to drill through wheat stubble, that is, to implant a seed in the soil. Better machinery for accomplishing the task needs to be developed.[323]

Additionally, even if the weed control and drill problems are solved, minimum tillage will not end soil erosion caused by cultivation of arid land. Although the amount of wheat litter and stubble left behind after harvest is considerable, other arid land crops such as cotton, grain sorghum, and beans produce far less effective soil cover. In the case of soils that are particularly susceptible to wind erosion because of their lack of moisture, organic, matter, and clodding, even wheat litter and stubble will provide only partial protection, especially during a major windstorm.

To summarize, many proven soil conserving practices are not widely employed in Kiowa and Crowley Counties because, for the most part, it is not within the short-term economic interest of the farmers to employ them.* Under current market conditions and government policies, soil conservation costs the farmer more than it benefits him. In the long run, of course, continued soil erosion of the magnitude currently experienced now on the western Great Plains will cause a decline in productivity. Eventually the land will produce less crops or grass per acre than it does today because the loss of topsoil means a loss of the vital plant nutrients—nitrogen, phosphorus, and potassium. In more humid areas, these nutrients can be rapidly replaced by the massive application of chemical fertilizers, so long as the farmer can afford them and the supply of these nonrenewable resources holds out. In the dryland farming of arid areas, however, chemical fertilizer use is much more restricted because the lack of moisture greatly impedes their chemical breakdown in the soil.

SOIL PRODUCTIVITY

Has severe soil erosion already caused this land's productivity to decline? A definitive answer to this question is impossible. For one thing, the principal measure of productivity—yield per acre—fluctuates radically from year to year depending on the rainfall. In the drought year of 1976, for example, Kiowa County farmers planted 287,000 acres of winter wheat and harvested 119,000 acres. Their yield was 12.6 bushels per acre, compared with 31.5 bushels per acre for the nation as a whole. In 1977, they planted 305,000 acres of winter wheat and harvested 242,000 acres. Yield per acre rose to 21.2 bushels because of more rainfall.[324] More important, other factors can, for a time, mask declining soil productivity. These include increased use, albeit still limited, of chemical fertilizers, improved strains of wheat or other crop species, and more efficient planting and

*Minimum tillage may prove to be the outstanding exception. With increasing diesel fuel prices, more and more farmers show an interest in minimum tillage as a means of holding down their energy costs. The fewer sweeps they make over their fields, the less diesel oil they consume.

harvesting technology. These and other factors have been at work in southeastern Colorado as they have throughout the nation's farmland. In 1949, a year similar climatically to 1977 (21.2 bushels per acre), the winter wheat yield in Kiowa County was 16 bushels per acre, compared with 15.8 bushels per acre nationally.[325] So yields have improved here, though not nearly as rapidly as elsewhere. It now appears, however, that the rise in yields (rainfall permitting) that characterized the 25 or so years after World War II has ended.

Has the loss of plant nutrients through soil erosion made a difference? No doubt it has, but this cause cannot be separated from other causes. For example, increased cultivation of marginal land also causes a downward pull on overall yield figures.

ABSENTEE LANDOWNERS

Another factor, aside from direct market and government forces that are contributing to the soil erosion problem in this region, is absentee land ownership. Unfortunately, no systematic analysis exists of the extent of absentee ownership or of the condition of absentee-owned land versus farmer-owned land. So we must rely on the testimony of informed observers such as agronomist John Knapp:

> There have been instances where a firm took over farmer-owned land and improved it. It has been my experience in this region, however, when it comes to the ownership of farmland, that the bigger and more absentee the owner, the less likely sound soil management practices will be followed.[326]

Increased grain prices in the 1973–74 period lured outside investors to areas such as southeastern Colorado. In many instances, these individuals made purely speculative investments. They bought rangeland cheap, had it plowed and planted in wheat, reaped a year or two of quick profits, and then sold out when grain prices slumped, thereby achieving a considerable capital gains because it was now cropland and could be resold at a higher price than they had paid for it.[327] The new purchasers were often investors looking for tax shelters. In neither case was soil conservation a management priority. Additionally, throughout the decade, corporations have continued to consolidate their land holdings in the area by purchasing farmer-owned land when the farmer went bankrupt or retired. The managers of these operations are often local institutions such as banks and real estate firms which must answer to investors in Denver or elsewhere. Sometimes such investors have been more interested in maximizing short-term profits rather than conserving the soil.[328]

Almost all the soil conservationists in the arid West interviewed for this report expressed concern over increased absentee ownership of agricultural land. Their concern is grounded on the assumption that a farmer who owns the land that he tills and who lives on the land that he tills is more likely to use sound soil conservation practices, if he can afford them, than a farmer who tills the land owned by someone else—someone who sees dividend checks—not land.

Although this issue lacks supportive data, it is not newly raised. In 1945, Aldo Leopold saw two choices for the American farm. It could

become simply "a food-factory," with "saleable products" the sole "criterion of its success," or it could be "*a place to live*" (emphasis added) whose "criterion of success is a harmonious balance between plants, animals and people."[329]

CROWLEY COUNTY

Crowley County also has most of the major problems besetting arid lands today. It is not hard to find an arid area with one or two serious problems, but it is unusual to find an area, especially one as small as this, that possesses a gamut of arid land ills.

As we have already seen, dry cropland in Crowley County suffers tremendous soil erosion. Moreover, the County's rangeland shows signs of severe overgrazing. Invading species of weeds such as Russian thistle and cacti appear prevalent. A few pastures are almost completely devoid of grass, and many others have extremely sparse grass cover. Fences are half-buried under drifts of soil, and very active gullying appears underway on steeper slopes. In flatter areas, blowouts are readily apparent—these are spots stripped of all vegetation and winnowed by the wind into a shallow sand pit.[330]

The majority of cropland in Crowley County is irrigated, and the major crop is alfalfa. Most of the irrigation water is diverted from the Arkansas River rather than pumped from underground, eliminating overdraft of groundwater as a major problem. Salinization might be a serious problem, however. Salt crusts are visible on a number of irrigated fields. Whether this buildup of salt is caused entirely by the naturally high salinity of the Arkansas River water or to a combination of already saline water and poor drainage is unclear.[331]

An even more ominous problem is the increased urban demand for water. The fast-growing Pueblo and Colorado Springs areas to the west are reaching out to meet their growing water needs. The two cities have bought the water rights of several farmers along the Arkansas River. This development, in turn, has led to abandonment of about 50,000 acres of previously irrigated cropland. Knapp observes: "All these acres are producing today are weeds and dust."[332] Further purchase of agricultural water rights in the Arkansas River Basin by urban users is expected. Dryland farming is not practical, and converting it to perennial grassland takes time and money; therefore, the abandonment of more irrigated cropland is expected. In Colorado, municipalities can condemn irrigated cropland, if need be, in order to obtain the water. This threat makes farmers more receptive to selling their water rights than they are in most other states of the arid West.

The signs of agricultural hard times are apparent everywhere in Crowley County. Aside from the bare, untended fields, numerous deserted farm buildings meet the eye; indeed, about one out of every three farm buildings is deserted. The small towns are full of empty storefronts, and dust and tumbleweed blow down the main streets. One can only wonder whether Crowley County is a preview of what is in store for much of the rural arid West in the future. Is it a preview of what will happen when the water starts running out—either

Soil erosion with winds of 50–60 miles per hour at noon in Dawson County, adjacent to Gaines County, Texas, February 1971 (Bob Kral, Soil Conservation Service).

because of the ravenous appetites of growing urban areas or because of the astronomical cost of pumping the water still left in the ground?

GAINES COUNTY, TEXAS

What are the wisest users of land? First, profitable cattle raising. Second, moderately profitable cattle raising. Third, unprofitable cattle raising. Fourth, to plow the land.

—Cato the Elder
De Agri Cultura

On a spring morning, as you drive east of Hobbs, New Mexico, out across the southern High Plains, with the wind at your back, you can see a brownish haze hugging the land ahead. Soon it envelops you. The sky is cloudless, but you cannot see the sun. Visibility is diminished to about a quarter of a mile. You have entered Gaines County, Texas (see Figure 14), and the substance you see in the air is topsoil—Brownfield fine sand, most likely—blown off fields that are bare and dry because they have been plowed in preparation for planting cotton.[333]

Forty years ago, this was grassland where ranchers grazed cattle. Today it is the ninth most productive county in terms of cash crop output in Texas—a state whose crop output ranks third in the nation.[334] In 1977, a drought year here, Gaines County farmers produced $73 million worth of crops, mostly cotton. In 1976, a wetter year, they produced $76.2 million.[335] The land has paid dearly for this production, however.

SOIL EROSION

Like Crowley and Kiowa Counties, Gaines has a soil erosion problem, but in Gaines the problem is, year-in and year-out, more severe. In Gaines the dominant crop is cotton, not wheat, and unlike Kiowa and Crowley, Gaines also has a serious groundwater depletion problem.

The previously mentioned GAO study team evaluated 39 farms in Gaines County and found that 31 of them were suffering an annual soil loss of 40 tons or *more* per acre. Of the 10 counties (283 farms) across the country that the GAO studied, Gaines County has the worst soil erosion. Table 3 cites the study's findings for the six counties in the arid West that GAO analyzed.

Table 3

Soil Erosion in Six Counties in the Arid West

County	Farms in sample	Estimated annual soil loss (tons per acre)				
		0¢5	5.1¢10	10.1¢20	20.1¢40	Over 40
Gaines, Tex.	39	1	0	2	5	31
Roosevelt, N.Mex.	28	2	7	9	10	0
Finney, Kans.	35	1	23	2	9	0
Benton, Wash.	20	0	11	8	0	0
Whitman, Wash.	30	5	14	11	0	0
Burleigh, N.Dak.	11	7	4	0	0	0

Source: U.S. General Accounting Office, *To Protect Tomorrow's Food Supply, Soil Conservation Needs Priority Attention* (Washington, D.C.: U.S. Government Printing Office, 1977), p. 5.

In the spring of 1979, indications were that the soil erosion in Gaines County was every bit as bad as it was at the time of the study. Soil could be seen blowing along the ground and over roads even during moderate wind conditions—5 to 10 miles per hour. Soil drifts all but covered 4-foot high fences and strips of unharvested wheat and alfalfa. Blowout areas in fields were a common sight, and piles of dirt leaned against telephone poles and walls. In all, Gaines County looked an excellent location for the refilming of John Steinbeck's *Grapes of Wrath.**

There are approximately 750,000 acres of cropland in Gaines County—of which 400,000 is dry land farmed and 350,000 is irrigated with groundwater. Cotton is grown on about 90 percent of this cropland, and wheat and alfalfa account for much of the remainder. There are about 150,000 to 175,000 acres of natural grassland left, but it is being plowed up at the rate of about 10,000 to 15,000 acres per year in order to plant more cotton.[336] About 25 percent of this rangeland appears overgrazed. Particularly noticeable are the relative paucity of blue grama, sand bluestem, and little bluestem—native grasses—and the abundance of mesquite and sand shinnery. One SCS official estimates that most of the County's grassland produces

*The original film version of *Grapes of Wrath*, directed by John Ford, featuring Henry Fonda, Jane Darwell, and John Carradine, and released in 1940, was filmed in Oklahoma and in a Hollywood movie studio.

approximately one-third to one-fourth as much grass as it did in its native state—short-grass, mid-grass prairie.[337]

Gaines County's average annual rainfall is about 16 inches, but from year to year it varies erratically. Since 1923, annual rainfall has ranged from a low of 6.6 inches in 1956 to 37.6 inches in 1941.[338]

The land here is relatively flat—this is high plains.* Prevailing winds are strong and southwesterly from November through April, the period when so much of the ground is bare of vegetation. The sand soils that predominate are fine grained and do not hold moisture well. Hence, they are highly erodible.[339]

According to the SCS and ASCS experts familiar with Gaines County, ignorance is not the problem. District conservationist Walter Bertsch reports:

> The great majority of farmers know what has to be done to stop the soil from blowing, but they can't afford to do it. In the short run, they've got a bank loan to meet.[340]

SOIL CONSERVATION PRACTICES

What *is* being done to control soil erosion in Gaines County? In the main, the time-tested conservation practices are little used.

Crop rotation. As the Gaines County Soil and Water Conservation District's *Program and Plan of Work* states, "Crop rotations of milo, wheat, or other crops high in organic matter are needed to maintain the fertility of the soil and help protect it from erosion."[341] Nonetheless, most farmers here plant cotton year-in and year-out. Prices on the commodity market are such that a farmer can earn more per acre planting cotton here than wheat, alfalfa, milo (sorghum), or any other crop. In addition, cotton requires less water per acre to grow in this climate. Last and by no means least, current USDA policies encourage cotton over wheat or feed grains in arid areas such as Gaines.

The ASCS' formula for computing disaster benefits favors cotton:

established crop yield per acre × 75% × planted crop acreage

If the farmer produces less than this, the federal government makes up the difference. But, as already noted, the formula for computing wheat or feed grain disaster benefits is:

established crop yield per acre × 60% × planted crop acreage

Moreover, to be eligible for disaster payments or federal cost-share programs such as the ASCS Agricultural Conservation Program, a farmer who plants wheat or feed grains must set aside 10 percent of his normal crop acreage in that crop. For example, let us look at a Gaines County farmer who did practice crop rotation in 1977 on his

*Gaines belongs to the physiographic region known as the *Llano Estacado* or Staked Plains.

640 acres of land, with 320 acres in grain sorghum and 320 in cotton. In 1979, he can harvest only 288 acres of grain sorghum, setting aside 10 percent, or 32 acres. For cotton, however, there is *no* set-aside requirement. He can plant all 640 acres of his land in cotton. Obviously, it pays to do so in the short term and that is exactly what most Gaines County farmers do.

In the long term, one-cropping this land year after year in cotton will eventually lead to reduced soil fertility just as it did in the southeastern United States. According to Jim McGehee, the ASCS executive director in Gaines County, "A Gaines County farmer really has no choice under current market conditions and government policies; he has to plant cotton if he is going to have any chance at all of making ends meet."[342]

Stripcropping is not widely practiced here. Those farmers who have tried it usually plant strips of wheat between cotton rows or along the roadsides of cotton fields. Wind erosion is so bad, however, that blown soil collects on these strips, and they end up looking like sand dunes.

Again, market forces and government policies discourage stripcropping. If the strips of wheat or alfalfa survive, they fetch less per acre than cotton. And if they are blasted by blowing soil, the farmer probably cannot collect disaster payments on them because under current ASCS regulations the strips must be of a prescribed width and must total a certain number of acres to qualify as a crop. James Abbott, SCS assistant state conservationist in Texas, tells of Charles Smith, a farmer in Lynn County, just to the northeast of Gaines. Smith was working with the SCS to reduce the erosion of his Brownfield sandy loam and Amarillo sandy loam soils that were eroding at an estimated annual rate of 36.49 tons per acre—4.12 tons from water erosion and 29.26 tons from wind erosion. At SCS urging, Smith planted strips of wheat amidst his cotton—on terrace ridges, turn rows, and field borders. The ASCS, however, ruled that strips were not eligible for disaster payments. Abbott states:

> Now Charles Smith will have to plow up his wheat strips because of what is essentially a bookkeeping decision despite a critical soil erosion problem. He can't afford to keep them under these terms. To those of us in the soil conservation business, it's damn frustrating and disheartening. It should be to a man's advantage to conserve the land. Instead, we kick 'em in the ass.[343]

In addition, of course, any land taken out of cotton cultivation by stripcropping will reduce by that much the amount of cotton disaster payments for which the farmer is eligible.

Windbreaks are virtually nonexistent in Gaines County. Among SCS experts, there appears to be a difference of opinion as to their usefulness as a soil erosion deterrent.[344]

Minimum tillage. The Conservation District's *Program and Plan of Work* reports: "Reducing the required number of trips across the field while producing a crop is the heart of minimum tillage. This process saves time, fuel and labor costs."[345] Farmers here are increasingly adopting minimum tillage because it holds down costs.[346] Unfortunately, the crop residue from cotton is low, and the amount of organic matter that it provides the soil is minimal. The protection that cotton residue affords the soil from the ravages of the wind is minimal too. To be an effective soil conservation practice here, minimum tillage must be combined with crop rotation.

Conversion to grass. The trend in Gaines County is in the opposite direction, even though a good share of the land that is being plowed up is Class VI land. What about the federal government's Great Plains Conservation Program? It was specifically designed to treat the kind of land found in Gaines County, that is, high-erosion cropland that needs permanent vegetative cover. The ASCS' McGehee reports:

> The Great Plains Conservation Program has been a big bust here. It simply is not economically feasible for a farmer to convert his cropland to range under this program. The average farm size here is about 525 acres. You cannot support yourself and your family today raising cattle on that amount of land in this arid area.[347]

The SCS' Abbott vigorously disagrees that the Great Plains Conservation Program has been a bust. In such west Texas counties as Lynn, it has been successful, he reports, encouraging the revegetation of overgrazed rangeland and the development of range management plans that lead to grazing of the land within its carrying capacity. "It would have been more successful at converting high erosion cropland from cotton monoculture to permanent vegetation or to a crop system that provides better cover and residues if the government's commodity adjustment programs and disaster relief had not made this abuse of the land financially advantageous."[348]

Much of the federal soil conservation money spent in Gaines County through such programs as the ASCS Agricultural Conservation Program has, in fact, gone for the installation of irrigation systems or for deep plowing.[349] The Great Plains Conservation Program has spent 37.5 percent of its cost-share funds on grass plantings, 53 percent on irrigation practices, and 9.5 percent on livestock watering facilities and fencing.[350]

A moist soil is less likely to blow than a dry one; hence, irrigation does qualify as a soil-conserving practice even though its primary purpose is to increase production. However, even the huge, quarter-mile-long central pilot irrigation systems used in Gaines County cannot cover all of the land all of the time, and the soils here dry quickly. Therefore the unwatered soil on irrigated land blows. Indeed, during the windswept winter and spring months, the irrigated cropland is virtually indistinguishable from the unirrigated cropland. Furthermore, irrigation has become increasingly expensive.

In deep plowing, the farmer brings to the surface soil from 2 to 3 feet below. In this area, the deeper soil is somewhat heavier because of its relatively higher clay content; thus, it is less susceptible to wind erosion. The Great Plains Conservation Program does not provide cost-share assistance for deep plowing because it is a temporary soil conservation practice. The Agricultural Conservation Program, how-

ever, does provide cost-share assistance. Gaines County is allotted $48,000 per year in the Agricultural Conservation Program. These funds, channeled through the ASCS, go primarily for deep plowing. Because of the limited funding and because of the $3,500-per-farmer limit, the ASCS must turn down 9 out of every 10 requests for Agricultural Conservation Program cost-share assistance. And deep plowing is expensive—costing from $25 to $45 per acre to perform. In 1976, Gaines County farmers were provided with $600,000 in emergency federal funds for deep plowing.[351] Soil conservationists look upon deep plowing, however, as a stop-gap measure at best. Its soil-holding effect is relatively short lived, and it reduces the amount of organic material on the surface of the land—one of the benefits of minimum tillage.[352] No mention of deep plowing is made in the Conservation District's *Program and Plan of Work.*

In the previously mentioned GAO study, 10 of the 39 farms sampled here were participating in some federal cost-share soil conservation program. The annual average soil erosion from these farms was 40 tons per acre, compared with 50 tons per acre from those farms not participating in the federal programs. So the federal effort is having some effect, especially when it comes to minimum tillage, but it falls far short of solving the County's terrible soil erosion problem.[353]

FEDERAL DISASTER RELIEF EFFORTS

In recent years, the federal government has spent several times more money on disaster relief in Gaines County than on soil conservation. In 1977, for example, federal government payments to farmers in Gaines County totaled $3.2 million and broke down thusly:[354]

Disaster provision payments		
Feed grain	$ 164,402	
Wheat	80,031	
Cotton	2,053,298	
Total		$2,297,731
Drought and Flood Conservation Program		400,848
Great Plains Conservation Program		$ 5,581
Agricultural Conservation Program emergency conservation measures		515,603

In 1978, the gap between federal disaster relief payments and federal soil conservation expenditures widened even more. Federal disaster relief payments to Gaines County farmers soared to $10 million, or about $13.33 per acre of cropland, while emergency conservation funds dropped somewhat. Although $10 million is a substantial sum, it is hardly unique in arid land agriculture on the High Plains of west Texas. For example, Dawson County, immediately to the east of Gaines, received $11 million in federal crop disaster payments in 1978, though it has less cropland but more dryland farming than Gaines.[355]

There are 39 counties on the High Plains of west Texas. In 1977, they produced $1.4 billion worth of crops, and the farmers in them received $31.9 million in crop disaster relief—feed grains, wheat, and cotton—from the federal government.[356]

Crop disaster payments from the federal government are an integral part of the agricultural economy of the west Texas High Plains. In Gaines County, for instance, it is not at all unusual for a farmer to take out a $75,000 to $100,000 loan to cover his operating expenses for the coming year.[357] And in a dry year like 1978, that farmer might not break even. For example, a farmer harvests 500 acres of cotton, but because of lack of moisture in the soil and the destructive effects of wind erosion, his yield is only 295 pounds per acre. Assuming that he sold his cotton for about 53 cents a pound, his balance sheet might look something like this:

Costs per acre	$221.50*
Output per acre	156.35
Net per acre	−$ 65.15

In other words, he incurred an operating loss of $32,575 for the year. Under such circumstances, how is he going to repay his $100,000 loan with the bank? His crop disaster payment from the federal government—about $15,000—will cover the $10,000 interest on the loan and leave $5,000 for beginning to repay the principal. In this situation, he will probably then renegotiate the loan, that is, go deeper into debt, and pray for rain. If it comes, he could earn $118.50 per acre or $59.25 at current cotton prices (68 cents per pound) and begin to reduce his total indebtedness. If not, the farmer may seek additional low-cost financing from federal institutions such as the Farmers Home Administration (FmHA) or the Small Business Administration (SBA). Both the FmHA and SBA are currently lending money to Gaines County farmers at a reportedly brisk pace.[358]

The main point is that the erratic climate and fine sand soils of arid Gaines County make the planting of any crop, even cotton, a high-risk endeavor. There are few if any private lending institutions that would consistently bet on the farmer in this farmer-versus-the-elements contest, and without their ante, there would not be 750,000 acres of cropland in Gaines County. The private lending institutions are willing, however, to bet on the farmer plus federal disaster relief versus the elements. In other words, federal disaster payments should be viewed, therefore, as subsidized insurance for bankers *and* arid land farmers. The west Texas bankers profit and the farmers stay in business, for the most part. What is *not* at all clear is whether the general public gains or loses from this arrangement. Are the benefits—presumably lower cotton prices as a result of the increase in supply, greater than the costs—the taxpayer-supported crop disaster payments?

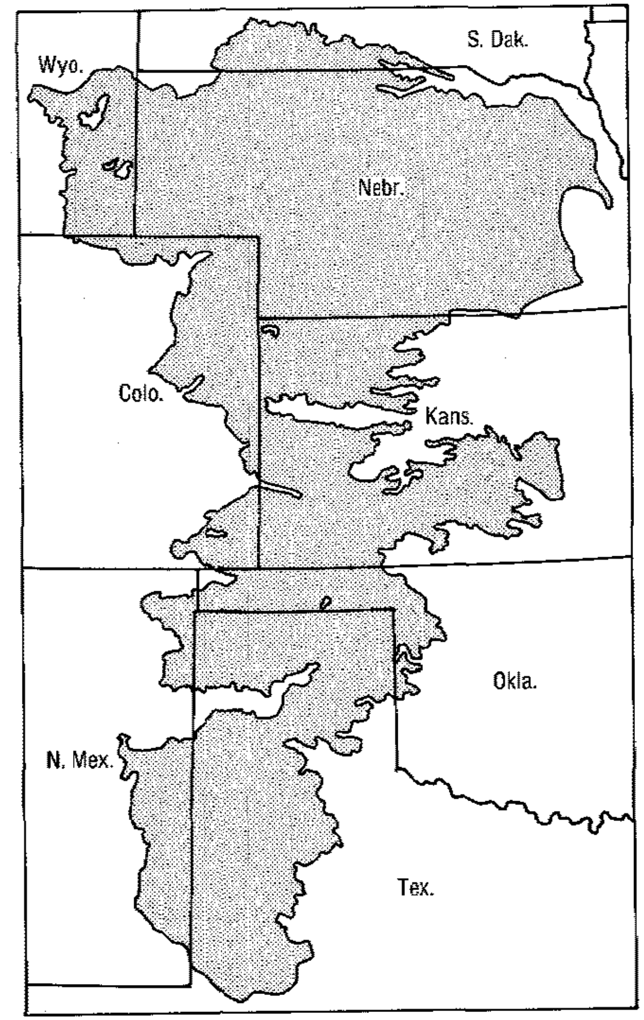
DEPLETION OF GROUNDWATER: THE OGALLALA AQUIFER

James Abbott of the SCS warns that at the current rate of soil erosion in Gaines and adjoining counties, "we are creating a new Great

*The cost for an irrigated acre is about $293; for dry land, about $150 per acre (a half-irrigated, half-dryland farm is assumed).

Figure 15

The Ogallala Aquifer



Source: Edwin D. Gutentag and John B. Weeks, "Water Table in the High Plains Aquifer in 1978 in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming," Hydrologic Investigations Atlas HA-642 (Reston, Va.: U.S. Geological Survey, 1980).

American Desert out there, and eventually the basic resource, soil, will be exhausted."[359] Gaines County farmers, however, may run out of water first.* They are using up their only water source—the

*It is understood here that Gaines County will not literally "run out" of groundwater, but rather that this resource will become too expensive to exploit because of its relative scarcity in the ground.

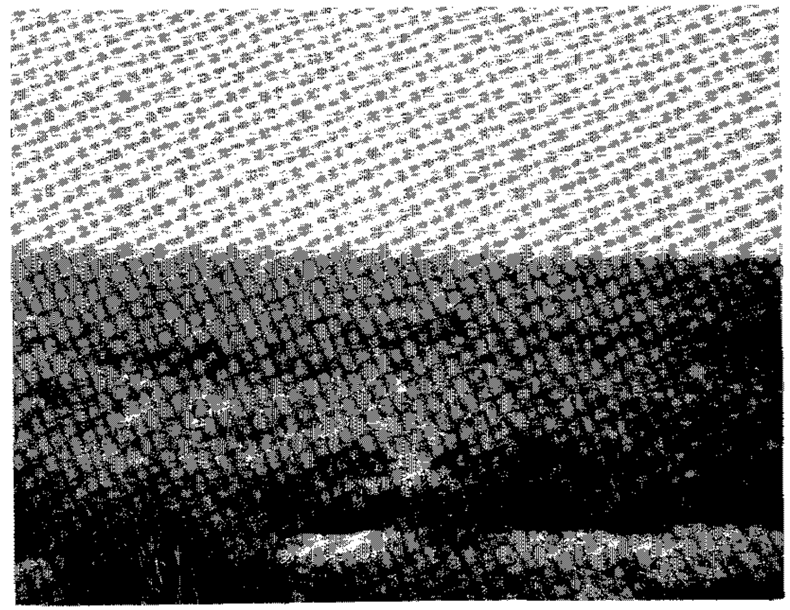
groundwater—at more than twice the rate of natural recharge, that is, they are mining groundwater.[360]

Gaines County sits on the southern end of an underground reservoir known as the Ogallala Aquifer that stretches all the way to Nebraska (see Figure 15). Vast quantities of water are stored in this layer of sand and gravel laid down during the late Miocene and Pliocene eras. Beneath Gaines County alone, there are 9.2 million acre-feet of water.[361] The entire billion-dollar-plus agricultural economy of the Texas High Plains is built upon the overdraft of water from the Ogallala.[362]

How long the water will last is a tantalizing and difficult question. Its answer depends, in large part, on energy prices because it takes energy to pump that water out of the ground, and the more you pump, the more energy it takes. Ten years ago, this underground water cost Gaines County farmers about $1.50 per acre-foot to pump. Today it costs about $60 per acre-foot.[363] The increase is caused by the increased price of natural gas, diesel fuel, or electricity used to power the pumps and to the fact that during this time the water level in Gaines County wells dropped an average 12.8 feet.[364]

The Texas Department of Water Resources reports that the overdraft of the Ogallala Aquifer in Gaines County is "expected to continue, ultimately resulting in reduced well yields, reduced acreage irrigated and reduced agricultural production."[365] The Department projects that the amount of water stored in the aquifer beneath Gaines County will decline to 7.9 million acre-feet by 1990 and 5.6 million acre-feet by 2020. The water level in wells is projected to drop at an average rate of 1.26 feet per year in the 1980s. These projections are, if anything, too conservative. They do not take into account the recovery of oil from inactive oil fields in Gaines County. The process currently being used involves pumping large quantities of water out of the Ogallala and injecting it into the inactive oil wells. As the price of oil continues to climb, recovery of this sort looks increasingly lucrative. To date, oil recovery has accounted for the consumption of several hundred acre-feet of groundwater in Gaines County, where total groundwater pumpage is about 241,000 acre-feet per year.[366] It is feared, however, that oil recovery will soon become a significant factor in the depletion of the area's groundwater supply.[367]

Soil conservationists are concerned that rising energy costs and lowering water levels in wells will lead to the abandonment of once-irrigated cropland that will then become a prime source of duststorms and weeds. They point southward to the Pecos River Basin as a potential harbinger of what may be in store for Gaines County. Higher natural gas prices on the intrastate market made the pumping of groundwater uneconomic there, where large quantities of water are needed not only to irrigate the crops (primarily cotton) but also to leach salts from the soil. As a consequence, some 190,000 acres of cultivated land have gone out of production. "The land is just laying there. It needs to be irrigated or put back into rangeland, but who will pay?" asks D.B. Polk of the SCS.[368]



Abandoned irrigated cropland in the Pecos River Basin in Reeves County, Texas (James D. Abbott, Soil Conservation Service).

The overdraft of groundwater resources, therefore, has a profound, long-lasting implication for Gaines County and the 38 other counties that comprise the arid High Plains of Texas. Several other counties are undergoing even more rapid rates of depletion than Gaines.[369] Charles Bowden predicts:

> By the 1980s water declines should make serious inroads in irrigated agriculture; thirty or forty years hence this commerce of pumped water should be over. The humans of the High Plains will be staring down tens of thousands of dry holes.[370]

Though somewhat less apocalyptic, the Texas Department of Water Resources also sounds a note of warning:

> If this overdraft continues, the aquifer ultimately will be depleted to the point that it may not be economically feasible to produce water for irrigation.... The actions of the water users will determine whether the projections of this study come to pass....[371]

Given such concerns, Texas' continued nonregulation of groundwater is difficult to fathom. The only method used to regulate the amount of groundwater pumped on the Texas High Plains is well spacing.[372] John Graves observes:

> Texas law continues to regard most groundwater as a mysterious blessing... legitimately subject to capture and use in unlimited quantities by any property owner who digs or drives a well.[373]

As a consequence, there exists what economists call a "negative incentive" to conserve the resource. A recent report noted:

If one farmer does not practice water conservation while those around him do, the one who is profligate will benefit from the water belonging to those who are conservative.[374]

It is, in fact, the "tragedy of the commons" all over again.[375] Only this time the commonly held resource is groundwater rather than pasture. Those who take more from the commons prosper more than their neighbors, gaining a clear advantage over those who exercise restraint. Noting the prosperity of the resource depletors, the others increase their use of the common resource too. The long-term consequence for the resource is, of course, ruinous.

Finally, it should be recalled that the federal government has subsidized the rapid depletion of the Ogallala Aquifer—first by price supports for commodities such as cotton, then by crop disaster payments, the various cost-share "soil conservation" programs, as well as by the low-interest loans of the SBA and the FmHA. In addition, federal tax policy encourages the depletion of this resource. High Plains farmers are granted a *depletion allowance* on pumped groundwater, thereby enjoying a tax break similar to that which the oil industry enjoyed for many years and which the mineral extraction industry currently enjoys. The more water they consume, the less tax they pay.

The cost of all these various subsidies has never been tallied, but they might seem insignificant compared to what it will cost to rescue the agricultural economy of the Texas High Plains when the groundwater becomes too expensive to pump. In our society, billion-dollar-plus private economic interests do not lose their investments meekly. They seek aid from the federal government, that is, the general public. When the Ogallala Aquifer water runs out, the farmers, bankers, irrigation system manufacturers, fertilizer producers, and others who have built their livelihoods on the overdraft of this resource will form a powerful lobby. One exceptionally expensive scheme has already been proposed for bringing Mississippi River water to the High Plains of Texas.

NEW STRESSES

At times like these the bravest knight
May find his armour much too tight.

—A.A Milne
Now We Are Six[376]

All signs point toward government and market forces putting even greater stress on the already overburdened water, soil, and vegetational resources of the arid West. Energy-related developments loom particularly large.

COAL

Between 1970 and 1980 the price of crude oil on the world market increased about 2,000 percent. This price increase was the central

economic event of the decade—the one around which so many other economic considerations orbit. And with the price of crude oil still rising, it promises to be the central economic event of the coming decade. For the arid West, the escalating price of crude has resulted in a coal boom, with some promise for the synfuel industry as well.

The arid West contains just over half the nation's recoverable coal reserves—147.2 billion tons.[377] In 1974, the region produced 83.2 million tons of coal.[378] By 1977, it was producing 154 million, an increase of 86 percent. By 1985, the arid West is projected to be producing 460 to 510 million tons of coal, up 200 to 230 percent over 1977. By the year 2000, its coal production is projected to be 780 to 1,115 million tons, up 20 to 120 percent over 1985.[379]

Most of the arid West's coal is found in either the upper Colorado River Basin or the Missouri River Basin. In addition, all the nation's recoverable oil shale reserves are located in the upper Colorado Basin. The question is: *What effect will the development of these energy resources have on the scarce water resources of these Basins?* This question is difficult to answer because of the technical and economic uncertainties that still surround the production of synfuels from coal and oil shale.[380] Moreover, it is not at all clear at this time where the Basins' booming coal production will end up being used. How much will go to electric-generating and synfuel plants *within* the Basins, and how much will be transported by rail or slurry pipeline to facilities outside the Basins? Where the coal is used makes an enormous difference. Simply mining the coal and transporting it out of the Basins takes far less water than does converting the coal within the Basins to some more useful form of energy such as electricity or synfuel. If it were only a matter of the Basins' increasing their energy production to meet their own energy demands, water would not be a serious problem. But in the 1970s, the Missouri and upper Colorado Basins became major energy *export* areas. Today electricity generated in New Mexico or Utah runs air-conditioners in Los Angeles. Coal mined in Wyoming and Montana fuels boilers in Chicago. There is no question that these exports will increase in the future; the difficulty arises in trying to determine the form that they will take.

In an analysis done for the National Academy of Sciences, John Harte and Mohamed El-Gasseir examined coal-related water consumption under a whole range of differing assumptions relating to coal consumption and transport, synfuel production, and electricity production. Their results were startling. Under each of their 12 scenarios, the future additional coal-related water consumption, when combined with the total water consumption for the Missouri and upper Colorado Basins in 1975, exceeded the Basins' water flow rates during low periods* by anywhere from 196 to 267 percent. Harte and El-Gasseir note that because present day water consumption is already a large fraction of what would be available in the

*They based their calculations on the lowest flow rate for a 7-day period which could be expected, on the average, every 10 years.

Missouri and upper Colorado Basins during a drought, "the additional water consumption for scenarios with intensive coal use would greatly exacerbate the existing problem of competition for water." They add: "It is possible that water for future coal-related activities in the West will be diverted from present consumers of freshwater, in particular from crop and livestock growers."[381] This point will be discussed further in the next section.

It is in the upper Colorado Basin that the future water supply appears to be especially tight.[382] A National Research Council report describes the upper Colorado Basin's water supply as a "limited resource stressed by a myriad of demands and with limited if any sources for augmentation and relief."[383]

In 1974, the Department of the Interior projected that the water needs of "pending" energy developments in the upper Colorado Basin would total 873,650 acre-feet by the year 2000.[384] This projection appears too high. A more realistic projection would be 570,000 acre-feet and is based on the following assumptions:

- Coal production of 385 million tons, with the mine operation and population involved in the production consuming about 310 acre-feet per year, but little water consumed in strip mine reclamation;
- Coal-fired electric generating capacity increased by 29,000 megawatts between 1980 and the year 2000 (Interior projected 34,120 megawatts); 9.7 acre-feet consumed per megawatt, with all but 5 percent of the new capacity using wet cooling systems; and
- Synfuel production, stimulated by the $20 billion in government loans and price guarantees provided by the new Energy Security Act of 1980, will come close to reaching the goal of 2 million barrels per day but not by the target date of 1992; synfuel production in the upper Colorado Basin by the year 2000 will include 500,000 barrels per day of oil shale, 200,000 barrels per day of liquified coal, and the thermal equivalent of 300,000 barrels per day of coal gas;* 15,050 acre-feet of water will be consumed per 100,000 barrels of oil shale, 17,850 acre-feet per 100,000 barrels equivalent of coal gas, and 19,300 acre-feet per 100,000 barrels of liquified coal.[385]

Considering that the upper Colorado Basin's allotted share of the River's water comes to 5.8 million acre-feet per year and its present depletions total about 4.04 million acre-feet per year,[386] the consumption of an additional 570,000 acre-feet does not seem all that significant. When viewed, however, in the context of increased water demands for other purposes (industrial, municipal, and irrigation, for example), the situation then looks more serious. Major new water demands in the upper Colorado Basin by the year 2000—including an additional 150,000 acre-feet per year for Denver, an additional 165,000 acre-feet for the Navajo Irrigation Project, and 360,000 acre-feet for Bureau of Reclamation storage projects in western Colorado

*To put these synfuel figures in perspective—during 1979-80, U.S. oil imports ran between 6.5 and 8.5 million barrels per day.

(mostly for land reclamation and supplemental irrigation)—total approximately 1.1 million acre-feet. This projection raises new water demands to 1.7 million acre-feet and total water demand in the upper Colorado Basin to 5.7 million acre-feet, uncomfortably close to the Basin's yearly allotment of 5.8 million acre-feet. The situation becomes still more critical if the upper Colorado Basin suffers a 10-year drought comparable to the one that occurred between 1584 and 1593. Then the average annual amount of water available to the upper Colorado Basin would be 4.6 million acre-feet.[387] The above-mentioned National Research Council report advises:

> The energy demand for water is not seasonal, as irrigation and municipal water supply, but remains a relatively constant year-round supply. Since those energy projects are such capital-intensive developments, *it seems foolhardy to continue with these projects without a guaranteed annual water supply in the face of a severe drought.*[388] (Emphasis added.)

OIL SHALE

Oil shale development threatens the water supply of the upper Colorado Basin in another way as well. Harte and El-Gasseir explain:

> The significant shale deposits of the Piceance Basin in Colorado are in themselves an integral part of the mechanism by which groundwater quality and flow are naturally maintained. A disruption in the system could affect the flow and quality of the White River and ultimately the Green and Colorado Rivers by causing the release of artesian, saline groundwater into fresh water.[389]

For this reason, *in situ* production of oil shale is particularly worrisome. It is the *in situ* process, however, that avoids the problem of disposing of a huge volume of shale after it has been heated (causing it to expand) and its oil extracted. The prospect of waste shale filling tens of thousands of acres of canyons in western Colorado, eastern Utah, and southwest Wyoming is a grim one.

SURFACE MINING

A word about surface mining in the arid West. It remains highly uncertain at this time whether or not a stable, long-lasting (more than 20 years) vegetational cover can be grown on arid land that has been surface mined.[390] A National Academy of Sciences report describes the probability of re-establishing stable vegetation, using the best available technology, on desert land and sagebrush foothills as "low" and on mixed grass plains as "moderate."[391] Coal reserves underlie 128 million acres of land in the arid West.[392] Approximately 38 percent of the strippable coal in this region is found beneath desert and sagebrush and 41 percent beneath mixed grass plains.[393] So surface coal mining certainly has the potential to become a major desertification force. It will not happen overnight, however. Surface coal mining in the West disturbs less land per ton of coal extracted than in the East or Midwest because the western coal seams are generally much thicker; indeed, many are over 50 feet thick. Thus, even during the current coal boom, it is unlikely that surface mining will disturb more than 100,000 acres over the next 30 years.[394]

BIOMASS PRODUCTION

Energy production from biomass—crops, grass, or trees—represents another energy-related stress on the soils and water resources of the arid West. Propelled by market forces—that is, runaway oil prices, strong public support, and increasing government subsidies—energy from biomass is now traveling a very fast track.[395] In a relatively short while it could become a genuine threat to arid land resources in the United States.

A recent SRI study cited more than 1,000 "promising" fuel cycles in biomass energy.[396] Both synthetic liquid and gaseous fuels can be made from biomass. The only fuel alcohol being produced today is ethanol from grain (especially corn) and from some processing wastes. When blended with gasoline, one part ethyl alcohol to nine parts gasoline, it becomes gasohol. About 150–200 million gallons of gasohol per year are now sold in over 800 service stations in at least 28 states. Currently, gasohol sells competitively at about the price of unleaded premium gasoline.[397]

Extensive government subsidies exist for ethanol production. These include $18 to $25 million for research and development of improved production processes, $40 million in loan guarantees, and an investment tax credit of 20 percent for alcohol fuel facilities. Most importantly, the federal government has exempted gasohol from the federal excise tax of 4 cents a gallon. Since ethanol comprises 10 percent of gasohol, this waiver amounts to a subsidy of 40 cents a gallon for ethanol or $16.80 a barrel. In addition, some states also exempt gasohol from state taxes of up to 6.5 cents per gallon. Together, these federal and state subsidies add up to $1.05 per gallon of ethanol or $44.10 per barrel.[398]

A recent Office of Technology Assessment (OTA) study of energy biomass warns that ethanol production from grain or sugar crops beyond 1 to 2 billion gallons per year, or 1 to 2 percent of the nation's current gasoline usage, would inflate commodity prices.[399] This price rise could set in motion forces extremely harmful to arid land resources. The higher prices could, for example, induce arid land farmers to accelerate their depletion of groundwater sources in order to increase production of ethanol feedstock crops such as corn, sugar beets, or sweet sorghum. They might induce some farmers to plow up previously uncultivated Class VI arid land in order to grow ethanol feedstock crops. An even more likely prospect is that the inflated prices will encourage midwestern farmers in particular to increase their corn acreage and decrease their wheat and soybean acreage and for southern farmers to do likewise—increasing their corn, sugar beet, or sweet sorghum at the expense of soybeans and cotton. This trend, in turn, would push up wheat prices, cotton prices, and livestock feed prices, providing arid land farmers in such places as the Portales area of New Mexico with an added incentive to plow up more land in order to plant wheat or, in the case of Gaines County, cotton. The higher feed prices would cause beef prices to rise as well, and together they would give arid land ranchers incentives to

graze their own rangelands more intensively. The costs in terms of soil erosion, denuded range forage, and depleted aquifers have not been calculated. Nonetheless, the OTA was sufficiently concerned about these impacts on marginal lands (arid and non-arid) to recommend that the federal government phase out its subsidies to ethanol when ethanol production from grain and sugar crops tops the relatively modest level of 2 billion gallons per year.[400]

Rocketing heating oil, natural gas, and electricity prices have already stimulated demand for a traditional biomass energy source—wood. Wood stove sales are booming in the arid West. New England is not the only part of the country where an increasing number of people are turning to wood as a supplemental or primary heat source. Wood prices in the arid West reflect this trend. Fuel wood now sells for about $120 to $140 a cord in El Paso, Lubbock, Tucson, and Albuquerque. In San Diego, the price has reportedly reached $200 a cord.[401]

WOOD GATHERING

Reports from National Forests in the arid Southwest indicate rapid increases in fuel wood cutting. For example, on the Cibola National Forest in western New Mexico during the 1978–79 fiscal year ending October 1, some 52,000 cords of fuel wood, primarily pinyon and juniper, were cut—an increase of 30 percent over the previous year.[402] On the Coronado National Forest in southern Arizona, some 14,000 cords of fuel wood were cut in fiscal year 1978–79, an increase of about 55 percent over the previous year.[403]

Wood gathering is a major cause of desertification in other parts of the world such as the Sahel. It could become one in the United States as well. Forests account for 30 percent of the total land area of Utah, 25 percent of Arizona, 23 percent of New Mexico, and 11 percent of Nevada. By contrast, 90 percent of Maine is forested, 87 percent of New Hampshire, 76 percent of Vermont, and 62 percent of Pennsylvania.[404]

The Forest Service allows the free cutting of fuel wood in prescribed areas of the National Forests and the collection of dead wood. In addition, in certain areas, it sells wood through competitive bidding.

In years past, the management of fuel wood resources has been a minor problem for the Forest Service. Now, however, with increased demand, the Forest Service in the arid West is having to inventory its fuel wood resources, especially pinyon and juniper trees, and to develop sustained yield plans for their management. As Keith Pfefferle, supervisor of the Cibola National Forest, reports: "This thing has mushroomed on us. In order to determine whether or not the pinyon and juniper are being overcut, we are inventorying the resource."[405]

A growing problem on some National Forests in the arid West is the illegal cutting of trees for fire wood. Often the trees are cut on a remote portion of a forest, loaded into pickup or flatbed trucks, hauled to a metropolitan area, and sold to a commercial wood dealer. For example, during the winter of 1979, some 4,000 cords of wood were cut illegally from an isolated section of the Lincoln National Forest in southern New Mexico.[406]

EXOTIC PLANTS

More exotic sources of biomass for energy and other products are the subject of growing research and development efforts. Arid land plants have attracted particular interest because of their ability to produce useful substances such as oil or latex and because they are native to the only region in the United States possessing both vast areas of uncultivated land and high solar radiation, that is, the Southwest. For example, such species as *Euphorbia lathyris* (gopher plant) and *Cucurbita foetidissima* (buffalo gourd) are being studied.[407] Scientist Melvin Calvin thinks that *Euphorbia lathyris* might some day produce 10 to 20 barrels of oil per acre. Maximum yields from such plants currently range from 2.5 to 5 barrels per acre.[408]

Two other desert plants—jojoba *(Simmondsia chinensis)* and guayule *(Parthenium argentatum)*—are also the subject of intensive scientific inquiry. Jojoba produces seeds that contain a high-grade lubricating oil that can be substituted for whale oil.[409] Guayule produces a latex whose principal component is identical to that obtained from rubber trees.[410]

The interest in cultivating guayule is sparked by the fact that natural rubber is superior to synthetic rubber for some uses, for example, radial tires. Synthetic rubber is obtained from petroleum, but its supply to the United States is "precarious."[411]

During World War II, under the Emergency Rubber Project, the federal government financed the cultivation of guayule and the harvesting of wild guayule plants. Rubber milled during the life of the project amounted to approximately 3 million pounds, including 900,000 pounds from guayule plantations (32,000 acres) in California and 500,000 pounds from native shrub harvests in west Texas.[412] After the war, the guayule plantations were liquidated. The final report of the project stated:

> The enormous stresses caused by war have diverse effects; they pile up appalling wreckage in some quarters and make scintillating gains in others. The same forces which left billions of dollars worth of useless munitions factories and cantonments in their wake also gave birth to advances in medicine, manufacture and science which might have required a generation.
>
> Occasionally, some luckless program found itself both the beneficiary of the progressive forces and the victim of those of destruction. Such a one was guayule. With 85 percent of its crop destroyed, unharvested, it was a 37 million dollar casualty of the war. At the same time, however, cultural and processing development made greater strides during the brief life of the Project than in the shrub's entire previous history. It is said that a greater weight of scientific investigation was brought to bear on guayule than was ever before devoted to any plant in an equal length of time.[413]

Will guayule or *Euphorbia* plantations spring up across the

American desert? This question is not as farfetched as it might seem. In 1900, it would have seemed highly improbable that the arid areas of California, Arizona, Texas, and New Mexico would someday produce 64 percent of the nation's cotton.[414] The development of guayule or *Euphorbia* plantations hinges, at this time, on the degree to which the government subsidizes the commercialization of these crops (it already is subsidizing the research) and the availability of water. These plants will grow without irrigation, but to achieve economic yields from arid land, irrigation will be necessary in most available areas. And so, once again, the question arises: *Where will the water come from in this water-scarce region?* An important benefit of an arid land crop such as guayule, however, is that it might someday be economical to grow on abandoned acreage in areas such as the Pecos because it requires less irrigation than crops such as barley, cotton, or sorghum.[415]

In addition, jojoba plantations already exist in the arid West, with approximately 3,700 acres in California, 990 acres in Arizona, and lesser amounts in New Mexico and Texas. "Without doubt," states a recent report, "jojoba will eventually become an important agricultural product of arid lands." Jojoba also has potential uses as fuel, chemical feedstock, and a replacement for vegetable oil.[416]

THE MX MISSILE SYSTEM

The construction of the $33 billion MX missile system on some 8,000 square miles of Nevada and Utah will strain the water resources of the Colorado River Basin.[417] During the project's 7-year construction period, its annual consumption of water may total 18,500 acre-feet.[418] Will this water be taken from the already overbooked Colorado River? Will it require aquifer overdraft, and, if so, how will this affect the Colorado River's water supply and its salinity? These and other questions will presumably be addressed in the Department of Defense's environmental impact statement on the MX missile system, currently in progress.

SOLUTIONS

> The Central Valley Project is in many ways the vestigial expression of what might be called the last great age of American engineering. . . .
>
> —T.H. Watkins
> "The New Romans"[419]

Arid land scientist Uwe George observes that, in their struggle for survival against aridity, certain plants and animals have evolved "fantastic—sometimes unbelievable—adaptations." Humans, on the other hand, have evolved no significant physiological adaptations, such as water-storing organs.[420]

STRUCTURAL: HIGH TECHNOLOGY

Our species' adaptations to arid conditions have taken another, although no less impressive, form—technological rather than biological. The Romans, for example, built a network of aqueducts in Spain and southern France that were so splendidly engineered that some are still in use today. Although these aqueducts do not move water as far as many modern day ones, they were built entirely of stone, no cement or mortar was used, and they are entirely gravity powered, thereby expending no energy resources.

An example in our time of human struggle against aridity is the Central Valley Project in California. Authorized by Congress in 1933, the Central Valley Project today is a "complicated concrete jigsaw," supplying central California with about 5 million acre-feet of water per year.[421] Financed by federal money—$3.5 billion to date, built by federal engineers, and controlled by the Bureau of Reclamation, the Central Valley Project, just like a medieval cathedral, will probably never be completed because new elements are constantly added to it. Too numerous to list here in their entirety, Central Valley Project facilities include the big Shasta and Trinity Dams in northern California, a giant pumping station on the southwest corner of the Delta, and the San Luis Reservoir in the San Joaquin Valley as well as hundreds of miles of canal. One of the most recent additions to the project is the 700-foot-high Auburn Dam, under construction on the North Fork of the American River, east of Sacramento. Water from the Central Valley Project serves the municipal and industrial water needs of some half a million people and irrigates crops that had a gross value of $13 billion in 1976.[422]

Is the Central Valley Project, in fact, the "vestigial expression of... the last great age of American engineering"? This question is crucial because schemes far more grandiose than the Central Valley Project have been tabled to meet the arid West's ever-growing need for water. Indeed, the problem of meeting the increasing water demands of arid regions seems to inspire grandiosity among planners and engineers. At the recently held First Global Conference on the Future, for example, engineer Thomas Kierans unveiled a scheme, modeled on the Central Valley Project, which would dam the lower portion of the Hudson Bay in order to turn it into a huge freshwater lake and ultimately deliver about 10 million acre-feet of its water to the Colorado River annually.[423]

In the mid-1960s, a U.S. engineering firm achieved notoriety with a plan to divert giant quantities of water (130 cubic kilometers annually) from Alaska and northwestern Canada to the arid United States and Mexico by means of a network of canals and reservoirs that included a 497-mile trench reservoir in the Rocky Mountains. Of this plan, political scientist Thane Gustafson recently wrote:

> Now, after 15 years of environmental legislation and litigation, such a project could sooner be built on the moon than in the United States or Canada.[424]

Perhaps, but it is also quite possible that grand schemes such as this one or the Texas Water Plan are, as one author suggests, merely undergoing a period of molt, and will revive in the not-too-distant future, especially as the demand for the arid West's agricultural and energy exports mounts.[425]

The Texas Water Plan, for example is one of the most ambitious interbasin transfer plans ever proposed. It was first unveiled by the state in 1966. The major elements of the plan include:

- A system of reservoirs and interbasin conveyance facilities in the eastern and central parts of the state;
- A coastal aqueduct ("Burleigh's Ditch") running over 400 miles from the Sabine to the lower Rio Grande Valley; and
- A trans-Texas canal dug mainly uphill from northeast Texas to the High Plains, with one spur carried on to New Mexico and another south to the trans-Pecos area.[426]

The water that would course through these facilities—ultimately some 17.3 million acre-feet—would come partly from the instate reservoirs but mainly from the Mississippi River. Some 12 to 13 million acre-feet per year would be extracted from the Mississippi and transported across Louisiana by one route or another for delivery at the state line into the Texas water system. The energy requirements for getting the water from northeast Texas to the High Plains would be stiff because of the uphill climb—about 40 percent of the state's total electric generating capacity as of 1970.[427]

How much would the Texas Water Plan cost to build? Ten-year-old estimates vary from $10 billion to upward of $14 billion. Who would pay for it? The United States government and the state of Texas would split the bill into yet-to-be-determined shares.[428]

In 1969, however, the voters of Texas dealt the Texas Water Plan a setback. By a vote of 315,139 to 309,409, they rejected a $3.5 billion bond issue for "water development."[429] As one author notes:

> Big dry-country irrigation is the Texas Water Plan's main curse, the albatross dangling rottenly from its neck. It is the thing that drove planners to the Mississippi.[430]

He adds, however, that:

> [T]he Plan is no dead duck.... It waddles on toward its goal; and one of these days will show up in a bright new set of feathers, unless before that time good sense can seize control in the realm of Texas water.[431]

It will be interesting to see whether the various government studies now being devoted to the overdraft of the Ogallala Aquifer end up recommending new interbasin transfer projects. Missouri or Mississippi River water to western Kansas and Nebraska or Mississipi River water to west Texas are structural high-technology solutions to the inevitable problem of sustaining high-yield agriculture in these arid areas as irrigators deplete the Ogallala Aquifer. One difficulty is that structural high-technology solutions such as these are capital intensive and energy intensive in a time when capital and energy are very expensive. The other difficulty is that the people who live in the basins from which the water is to be taken are becoming increasingly reluctant to let it go. For example, the citizens of the lower Mississippi River Valley have shown no enthusiasm for sending several million acre-feet of the River's water every year to the High Plains of west Texas. The idea of sending Columbia River water to the Colorado

River Basin evokes outright hostility among citizens of the Columbia River Basin. The area's political representatives translated these sentiments into a legal prohibition when Congress considered the Colorado Basin Project Act of 1968. This legislation, which authorized the Central Arizona Project, includes a 10-year moratorium on reconnaissance studies of any plan for the importation of water into the Colorado River Basin.[432] The moratorium, which has recently been extended, is intended to protect the Columbia and Snake Rivers for local use. The Bureau of Reclamation had already begun studying the Snake River for possible diversions to the Colorado River Basin and was considering similar studies for the Columbia River. Said one Bureau official: "When the Congress tells you that you can't even study something, then you know there's a real political problem."[433] Still, water resource experts such as the University of Arizona's Sol Resnick see the Columbia River as a potentially important supplementary source of water for the Colorado in the future, reminding us that the Columbia "loses" about 150 million acre-feet of water to the Pacific Ocean every year.

Despite the obstacles, however, interbasin transfer schemes survive. The previously mentioned Central Arizona Project—*the* structural solution to Tucson's and Phoenix's growing water demand and to the area's groundwater overdraft problem—was made possible by the Supreme Court decision in *Arizona* v. *California*. The Court found in Arizona's favor—setting California's allotment of the Colorado River at 4.4 million acre-feet per year and Arizona's at 2.8 million acre-feet. Consequently, southern California, which currently imports about 5 million acre-feet of water per year from the Colorado, will have to reduce its intake in coming years.[434]

This reallocation of Colorado River water is one of the reasons a major expansion of California's State Water Project is now being pushed. Authorized in 1960, the State Water Project is a classic example of a capital-intensive, energy-intensive structural solution. It transfers water from northern California to central California, like the federal government's Central Valley Project, as well as to southern California. To date, about $2.5 billion has been spent on the State Water Project. The chief beneficiaries, according to a recent report, have been agribusiness corporations in the southern San Joaquin Valley. Many are owned by oil companies (Getty, Standard of California, Shell, and Tenneco) which buy the state water "at bargain basement rates" and irrigate "their vast acres of farmland," primarily to grow cotton. The State Water Project is the state's largest single consumer of electricity—using about 4 billion kilowatt hours of electricity per year.[435]

The California legislature is currently considering legislation that would authorize the building of a major new canal, a couple huge new reservoirs, and related canals. The cost of these new facilities, including the new powerplants that they will require, is likely to be about $11 billion. The cost in terms of energy for making water run uphill will be the annual consumption of an additional 6 billion

kilowatt hours of electricity by the year 2000.[436]

The centerpiece of the proposed expansion of the State Water Project is something called the "Peripheral Canal." This 43-mile-long, 400-foot-wide canal would divert 70 percent of the flow of the Sacramento River upstream of the Delta, return portions of the River's water to the Delta at "critical points," and carry the major share around the Delta to the California Aqueduct for delivery farther south. In this way, water that flows in the north fork of the Feather River in the Sierra Nevadas could end up flooding a cotton field in the southern San Joaquin (Kern County), some 350 miles away, or coming out of a faucet in Los Angeles, some 490 miles away. George L. Baker and Tom DeVries, in their analysis of the proposed addition to the State Water Project, report:

> Standing near the town of Tracy at the southwest corner of the great Delta are two giant pumping plants, one belonging to the federal government and one to the state of California, two huge straws in the same glass. The institutions that draw on the straws are hearing the nasty noises of a nearly empty portion, and they glare at each other and quarrel as they suck. . . .
>
> The Peripheral Canal is to be the solution to the problem: a separate, man-made river big enough to float an oil tanker and isolated from the Delta itself. The solution was simple enough; its execution, however, is a political, financial and engineering nightmare.[437]

The big environmental risk is that if the Project does not return adequate quantities of freshwater to the Delta at "critical points," that is, when river flow into the Delta is low, particularly during high tides when Pacific Ocean water intrudes from the west, the largest inland estuary in the United States will die. And more is at stake than the birds, fishes,* and other creatures that inhabit the Sacramento-San Joaquin Delta. Millions of dollars worth of farmland and recreational businesses in the Delta will perish as well, and the water supply of numerous municipalities and industries will be threatened.[438]

If the proposed expansion of the State Water Project is enacted, Californians will in one century have eclipsed what the Romans accomplished in 4 to 5 centuries of aqueduct system building. It will also give the water basin transfer option (structural high technology) an added boost in the United States at a time when the future of the option is very much in doubt.

Interestingly, American engineers and planners are not the only ones inspired to grandiose water transfer schemes. Soviet engineers and planners are currently considering plans to reverse the flow of several entire rivers in Siberia, rerouting them to Central Asia so that this region's expanding population, industry, and irrigated agriculture (primarily in cotton) will have enough water in the years ahead. In other words, the Soviet Union's booming arid sun belt also needs more water. The Central Asian Diversion Project, which would require constructing a 932-mile-long canal, is, according to one in-

*The Delta and uprivers are important spawning areas for striped bass, shad, and king salmon, among others.

formed observer, "moving rapidly toward advanced engineering and economic studies," and "construction could conceivably begin within the next 5 years."[439]

NONSTRUCTURAL: HIGH TECHNOLOGY

Not all solutions to the water scarcity problems of arid regions are structural high-technology solutions. The Rand Corporation, for example, has suggested a basically *non*structural high-technology solution to southern California's and the lower Colorado Basin's water problems—Antarctic icebergs.[440]

In a National Science Foundation-sponsored study, Rand found that Antarctic icebergs might be both an economic and technically feasible source of freshwater for southern California and the lower Colorado Basin. In its report, Rand outlined an ingenious scheme in which iceberg blocks are collected or "harvested" in Antarctica's Ross Sea, cabled together into iceberg trains, and covered with huge sheets of plastic to inhibit evaporation. The trains would then be pushed by nuclear-powered tugs into prevailing ocean currents and guided northward more than 6,000 miles and parked off Los Angeles. There, waste heat from electric-generating plants and heat exchanged from ambient seawater would melt the ice. The iceberg water, which is, incidentally, far less salty than the water taken from the Colorado River, would then be piped landward for use in southern California. This arrangement would reduce the water intake from the Colorado River by about 1 million acre-feet per year. The Metropolitan Water District of Southern California currently draws 1.2 million acre-feet per year from the Colorado River Aqueduct, which is the longest and most expensive westward diversion of the Colorado River. Rand suggests that some day this area could become a water supplier, with the Colorado River Aqueduct reversed to carry iceberg water to the lower Colorado Basin.[441]

Rand is quite optimistic about the iceberg solution:

> The energy costs are a significant portion of the total costs involved in any acquisition of good quality water. Energy consumption should be less per unit of water supplied from Antarctic icebergs than from interbasin transfers or desalting operations. Thus the use of iceberg water may permit important savings in energy consumption. Furthermore, there are attractive opportunities and advantages for using atomic energy rather than fossil fuels in the importation of Antarctic icebergs. Also, advanced technology plus large investments are advantageous for exploiting the enormous fallow Antarctic iceberg resources. This should be an attractive opportunity for the United States to employ its skill and technology in harvesting and delivering Antarctic ice for the benefit of its foreign exchange.[442]

Rand puts "the total costs of Antarctic iceberg transport, conversion to water, and delivery to wholesale distribution terminals in coastal areas" at about $30 per acre-foot. "Fresh water from icebergs should therefore become an attractive alternative for areas close to deep seawater access routes."[443]

Rand does concede, however, that "the complete efficient harvesting and full exploitation of the Antarctic iceberg resources should not be expected for many years."[444] For one thing, these estimates will have to be recalculated in terms of increased energy costs that have occurred since Rand completed the study in 1973. In addition, the environmental implications of hauling icebergs to Los Angeles will have to be studied.

Most federal research and development money spent on arid land problems over the past 30 years has gone into two high-technology solutions: desalinization, which is structural, and weather modification, which is nonstructural. Improvements in desalinization technology have slashed its cost, but it is still expensive—about $300 per acre-foot. Desalinated water is certainly still too costly for irrigated agriculture.

Weather modification, a government euphemism for rainmaking or snowmaking, has received the greatest share of the Bureau of Reclamation's research and development budget. In fact, the Bureau began rainmaking experiments, at Congress' behest, in 1961. Previously, a small group of scientists in the Southwest in the 1940s and early 1950s had experimented with dumping silver iodide (AgI) from airplanes into convective (cumulus) clouds in order to induce rain. Their results were not conclusive. The theory is that AgI converts supercooled drops in the cumulus cloud to ice crystals, and rain begins when the large ice crystals fall and melt. The early experiments confirmed that cloud seeding did indeed make cumulus clouds bigger, but it did not necessarily cause rain.[445]

The Bureau's research effort took up where these earlier experiments left off. More AgI was dumped into more cumulus clouds. In addition, however, the Bureau began experimenting with the seeding of orographic clouds, that is, clouds that form when moist air is lifted over mountains. These efforts have apparently proven more successful. Silver iodide is released on the upwind side of a mountain range, and these particles transform many supercooled cloud droplets into ice crystals. The ice crystals attract moisture from surrounding droplets and grow large enough to fall to the ground as snow. Although the physics of orographic storms is still not well understood, the Bureau of Reclamation concludes from its experiments in California's Sierra Nevada Mountains, and the mountains of the Colorado River Basin that "the characteristics of treatable storms have been more clearly identified" and that seeding can increase the seasonal snowpack by "about 10 percent."[446] Whether the seeding of cumulus clouds can increase summer rain is a hypothesis still being tested in the Bureau's High Plains Cooperative Program.[447]

A Bureau study now estimates that full-fledged seeding of orographic clouds could increase the average annual water supply in these arid river basins by the following amounts:

- Upper Colorado River Basin—903,000 to 1.3 million acre-feet (Colorado River flow into Lake Powell);
- Gila River Basin—154,000 to 239,000 acre-feet; and
- San Joaquin Basin—1.2 to 1.5 million acre-feet.[448]

Nonetheless, the Bureau remains very cautious about its weather modification program—Project Skywater. The Bureau emphasizes that this is still an "experimental program" seeking to "establish the scientific validity of weather management." A Bureau spokesman explains: "We are moving very slowly because of the serious potential political and legal ramifications."[449]

Will snowmaking in Colorado mean less rain or snow in Nebraska or Kansas? Will the seeding of summer convective storms cause torrential downpours and flooding? These are the kinds of questions that apparently stand in the way of wide-scale application of weather modification by the federal government. According to the Bureau, current scientific thinking indicates that the answer to both these questions is "no." But it would be difficult to prove that cloud seeding did not cause a flood or a decline in precipitation in downwind areas.[450] In addition, the long-term effects of large doses of AgI on the environment, especially on plants, animals, and water, have yet to be determined, although they are currently under study by the Bureau.[451]

Although the Bureau of Reclamation is cautious about the wide-scale application of weather modification technology, the National Research Council is, if anything, downright skeptical:

> A prerequisite for any management program designed to modify a geophysical process, be it snow augmentation, earthquake attenuation, or the subsidence of Venice, is accurate forecasts of the relevant phenomena and all major side effects, based on three-dimensional, time-varying, physics-based, computer models. The snow augmentation movement is not supported in this manner, and scientific credibility for a management program is lost.
>
> . . . [S]tatistical justification for snow augmentation management programs is weak because the statistically randomized portions of snow augmentation experiments have not shown consistent results (positive, negative and inconclusive results abound). Claims of success have been based on *post hoc* analyses in which certain storms and measurement stations have been removed from the analyses—a procedure that is perfectly honest and permissible providing the objective is increased understanding of the phenomena being studied, better simulation models, or more carefully designed future experiments. *Post hoc* statistical analysis does not, however, amount to controlled unbiased tests of the phenomena being studied and are not a justification for management programs, only for further research.[452]

To justify future water-consuming projects on the grounds that current weather modification technology will produce the water needed is "unreasonable," the National Research Council concluded.[453]

A recent report to the Congressionally mandated Weather Modification Advisory Board from its Statistical Task Force concludes that researchers must exercise greater caution in designing and evaluating weather modification experiments if the results are to be convincing. The limited ability of experimenters to predict how a cloud would have behaved if it had not been seeded continues to plague weather modification research.[454]

NONSTRUCTURAL: SOFT TECHNOLOGY

It is puzzling why the Bureau of Reclamation and the USDA have not devoted more of their research and development money to water conservation, that is, soft technologies, for irrigated agriculture. The Bureau of Reclamation itself concedes that "relatively poor farm irrigation efficiency" results primarily from not shutting the water off when the root zone is filled.[455] There are various devices now available that can be used to determine whether a farmer is over irrigating or wasting water. One is the neutron probe, which measures the hydrogen ions in the soil and was developed by the Bureau of Reclamation. This ion count is directly related to the quantity of water in the soil, and water applications can be adjusted accordingly.[456] The most efficient irrigation system would be one in which sensors constantly monitored the crops' moisture needs and automatically activated or shut off the water to the plants. Such a system does not exist, but if ever developed, it could save millions of acre-feet of water per year in irrigated agriculture in the arid West.

Another promising avenue of research for arid land agriculture is genetic improvement of crop species. The USDA has supported such research for years. It usually consists of selecting from a total crop those plants that have the most favorable characteristics; for example, in the case of wheat, high grain yield, or in the case of cotton, resistance to pests. These plants are then bred with plants that have the same or other favorable characteristics such as drought resistance. The process is continued through each succeeding generation until a hybrid, or particularly favorable strain, is isolated.*

In recent years, increased scientific efforts have gone into trying to breed salt tolerance into such crop species as barley. There is no fundamental biological incompatibility between plant life and highly saline conditions. Many wild plants, the so-called halophytes, grow in saline environments. Indeed, wild plant species may be the key to developing salt-tolerant crops. Plant geneticists hope to crossbreed crop species with their wild cousins to transfer salt resistance, which has evolved over the millennia. It is for this reason that plant geneticists view with such alarm the continued destruction of wild plant species and subspecies in such areas as the Mojave and Sonoran Deserts by overgrazing and off-road vehicle use. They see the wild plants that have survived the harsh conditions of the desert—including high salinity—as irreplaceable storehouses of genetic information.

A University of California at Davis scientist, Emanuel Epstein, reports enthusiastically about the prospects of a genetic solution to the problem of salinity:

*This approach is based on the plant genetics of Gregor Mendel. Another approach, molecular genetics, involves a more fundamental effort to engineer plant characteristics that would not have occurred naturally. At present, however, knowledge of the basic biochemistry and physiology of plants is too limited to produce predictable results.

[I]f adequate support is provided, a large measure of success can be predicted with an unusual degree of confidence. If selections of barley can be grown from seed to seed under a regime as extremely saline as seawater irrigation; if in but a few years tomatoes can be generated that produce fruit when irrigated with 70 percent seawater, then even the most sober and judicial appraisal must lead to the conviction that irrigation with brackish and saline waters, both inland and along the coast, using lines of crops specifically created for these conditions, is a feasible option. We ought to pursue it with all the ingenuity, energy and enthusiasm that are so characteristic of American scientific research and its application to problem solving.[457]

The question is: Will salt-tolerant crop species be developed in time to maintain the productivity of such increasingly saline arid areas as the San Joaquin and Imperial Valleys? A recent report on the subject observes:

[T]here is still a great deal to be learned about how plants adapt to salinity and other stresses. Nevertheless, investigators think they now have some promising leads that may ultimately allow expansion of the world's stock of arable land.[458]

Another nonstructural solution that the federal government in particular has pursued is vegetation modification in arid areas. The most common vegetation modification practice has been to destroy juniper and pinyon, chaparral,* or sagebrush and introduce grasses and forbs in their place. The objectives are to increase the forage available for livestock grazing and to increase the water runoff from the land so that a watershed's water supply is enhanced.

In addition, the federal land management agencies have sought to destroy phreatophytes along floodplains because these plants consume water. The word phreatophyte comes from the Greek and means "well plant." Phreatophytes include such species as salt cedar (*Tamarix chinensis*), cottonwood, and mesquite. Estimates of the amounts of water that these plants actually consume vary. Dense stands are said to consume anywhere from about 1.8 acre-feet of water per acre to about 6 acre-feet annually. Few hard data exist, however, on the water savings achieved by clearing phreatophytes.

The practice of destroying phreatophytes has waned in recent years. A 1974 Forest Service report observed:

For many years, flood-plain management consisted of attempts to control or completely eliminate undesirable phreatophytes for water salvage .... More recently interest has increased in preservation or development of the wildlife, recreation, and esthetic values of these areas. It therefore becomes increasingly important to determine the effects of phreatophyte clearing upon the other resources involved. We can no longer justify rather casually the clearing and destruction of phreatophyte vegetation to save water.[459]

Moreover, as the Bureau of Reclamation points out:

Methods used for controlling phreatophytes have included expensive mechanical and chemical eradication measures. Permanent eradication is seldom

*The chaparral community consists of a relatively large number of species. Among them are shrub live oak (*Quercus turbinella*), manzanita (*Arctostaphylos pungens*), and true mountain mahogany (*Cercocarpus montanus*).

achieved and the side effects of such techniques can result in ecological imbalances.[460]

Instead, the Bureau of Reclamation is supporting the development of chemicals, the so-called "antitranspirants," which, when sprayed on phreatophytes, form a kind of waxy film on their leaves and retard their natural transpiration. Experiments with different chemicals have been conducted, but much more needs to be learned about antitranspirants, especially their environmental effects, before they can be widely used.[461]

The destruction of other kinds of vegetation continues to create more water runoff and forage, however. The methods of destruction used by agencies such as the BLM and Forest Service vary—fire, herbicides (e.g., 2,4,D) and machines (rootplows, bulldozers, brushcrushers, and cutters). One common method is to attach a heavy anchor chain between two crawler tractors and drag it across the land undergoing vegetation modification. "Chaining," as it is called, is frequently used in destroying stands of pinyon and juniper trees.[462]

A considerable body of scientific information about vegetation modification has accumulated in recent years.[463] Some important lessons have been learned:

- One should *not* attempt vegetation modification on excessively steep slopes or on particularly unstable soils (those subject to mass slippage when wet); and
- One should *not* try to convert *large* areas of shrubs or trees to grass because it will significantly diminish wildlife populations; instead, small, irregular plots should be treated.

How closely the land management agencies actually adhere to these lessons is not clear from the scientific literature.

The land management agencies have also learned that none of the methods of destruction permanently eradicates certain species of brush such as big sagebrush (*Artemisia tridentata*).* And the more intensive the grazing after grass seeding, the more swiftly the brush will return.[464]

It is not clear from the scientific literature on vegetation modification how many total acres of land in the arid West have actually undergone systematic vegetation destruction by burning, chemicals, or machine and have been seeded for grasses and forbs. Nor is the staying power of the newly planted grasses and forbs clear. Does the new vegetation provide a stable soil cover over the long term—20 or more years? Some ecologists such as Bill Mollison question the whole concept of "managing" wild vegetation, especially species such as mesquite and Russian thistle, whose spread is the result of human abuse of the land. They suggest that the invading species serve the purpose of stabilizing the land and should be left alone so a more

*Big sagebrush is a species with enormous genetic plasticity. Three subspecies are recognized: *A. tridentata tridentata* (found in basins), *A.t. wyomingensis* (Wyoming), and *A.t. vaseyana* (found on mountains).

complex plant community can, over time, evolve naturally. They also question whether eradication efforts provide anything but short-term surcease from the mesquite and Russian thistle.[465]

Until scientific data are available to answer such questions, it will not be possible to answer the much larger question of whether vegetation modification, as practiced by the land management agencies, especially the BLM and Forest Service, causes or impedes desertification.

One thing is certain, however. Water and livestock interests in the arid West continue to support vegetation modification on the public land. The primary opposition to vegetation modification comes from people opposed to the use of herbicides.

In the late 1960s, for example, the Forest Service sprayed extensive chapparal areas on the Tonto National Forest in order to increase runoff into the Salt River Basin, that is, to increase the water supply of the growing Phoenix metropolitan area. This action aroused limited but vocal local opposition in the Globe, Arizona, area; further, when several people claimed that the spraying had made them sick and caused miscarriages among their livestock, the controversy attracted the attention of the national news media for a short while. The controversy soon faded because there was no scientific evidence available at the time to corroborate these charges. Since then, however, such evidence has emerged. On March 1, 1979, the EPA announced a ban on all uses of 2,4,5-T on forestlands, pastures, and utility and railroad rights-of-way. The ban was imposed because of evidence from a recent epidemiological study in the Alsea Basin in Oregon that reported that eight women living near a forest sprayed with 2,4,5-T miscarried soon after the spraying. In addition, a growing number of Vietnam veterans exposed to the notorious Agent Orange used by the United States in Vietnam as a defoliant complain of long-term ill effects to their health. Agent Orange is an equal mixture of 2,4,5-T and 2,4,D.[466]

What effect will the government's continued use of herbicides such as 2,4,D have on the long-term health of humans living near or vacationing in the sprayed areas? Although far less research has been done on 2,4,D than on 2,4,5-T, disturbing questions have been raised for years by scientists concerning its fetotoxic, mutagenic, and teratogenic potential.[467]

NONTECHNICAL, NONSTRUCTURAL RESPONSES

The *nontechnical, nonstructural* solutions to the arid West's resource problems such as groundwater overdraft or excessive soil erosion have attracted relatively little attention. This reaction is not too surprising. Technical and structural solutions very often involve what political scientists call "distributional policies" in which the general public pays for something that benefits specific interests—economic and regional, for example. In distributional policies there are specific

winners—hence a strong lobby, and no specific losers—hence the opposition to any specific distributional project, say, a water project, is often weak, at least until recently.

If, on the other hand, a nontechnical and nonstructural solution becomes a matter of public policy, it may involve regulatory or redistributive measures. Here there are clear losers—therefore an organized opposition—and no specific winners. For this reason, nontechnical and nonstructural solutions encounter rough sledding in our political process, especially when they affect the allocation of scarce resources.

A good example is the problem of the Colorado River's increasing salinity. A desalinization plant at Yuma has been authorized, that is, a technical and structural solution. This is a classic case of distributive politics at work. Specific interests benefit—the farmers of the Wellton-Mohawk; the business interests who will build, equip, and service the plant; and the state of Arizona, which is credited with the desalinized water that is returned to the River. In addition, other specific interests in the Colorado River Basin which do not benefit directly from the desalinization plant support the project so that their own distributive projects will be supported in return. Distributive policies encourage coalition building. In legislative politics, this is known as logrolling. The general public pays. Good relations with Mexico are the chief benefit to the general public. This benefit could be achieved through a whole range of regulatory or redistributive policies aimed at irrigated agriculture along the River, but opposition would be intense.

Grazing on the public land is another good example. In years past, a BLM manager who sought to reduce the grazing allotments on the public rangeland in his district (a redistributive policy) found himself the center of a small political storm stirred by the affected livestock interests. His superiors at the agency received inquiries and complaints from Members of Congress from the area. Concerned about next year's budget before the Congress, they often intervened—ordering the manager to retract his decision or risk being transferred to another district. Today BLM often sweetens its grazing plans that reduce grazing allotments with "range improvements" (distributive policies) such as construction of additional range watering facilities and vegetation modification.

In the case of Tucson and its dwindling groundwater supply, limiting water consumption (a regulatory policy) would seem to an outsider to be a logical solution, but it apparently has not been politically feasible. Many of the people who have moved to this desert oasis have come from parts of the country with much wetter climates and have brought with them water-consuming habits such as lawn watering that are ill suited to the desert. More important, to limit water use is to limit economic growth, and many vested interests in the area—developers, construction companies, financial institutions—have a big stake in continued economic growth. So, instead of conserving water or doing without more water, cities such as Tucson look to the federal government to provide inexpensive water.* It will be particularly interesting, therefore, to see how the regulatory policies in Arizona's new water law affect water consumption in Tucson. Will Tucson actually have to practice thrift in its use of water, or will it be able to continue its relative profligacy by continuing to buy out agricultural water rights?

One of the major efforts to examine nontechnical, nonstructural solutions to water supply problems was made by economists Maurice M. Kelso, William E. Martin, and Lawrence E. Mack.[468] They tracked the past and present changes in the Arizona economy and projected those changes into the future to identify their effect on water demand. They concluded:

> By creating a water market or establishing an allocative agency charged with facilitating water transfers from uses of lower value productivity to uses of high value productivity, the Arizona economy can continue to grow without restraint stemming from "water shortage."[469]

By "uses of lower value productivity" Kelso, Martin, and Mack mean agriculture. By "uses of high value productivity," they mean industry, that is, the production of non-agricultural goods and services. Kelso, Martin, and Mack envision less water being consumed by farmers but more by industry. Exactly how this transaction is to be accomplished, however, is not made clear. Their term "facilitating water transfers" is not concrete enough. What if the owner of water rights in a particular place does not want to be facilitated? Is "facilitating water transfers" really a euphemism for the unpleasant business of condemning a person's property right—in this case, his water right, establishing a "fair" compensation and seizing it for other "higher" uses? Is it a euphemism for the often expensive business of buying out someone who is not eager to sell?

Such questions have implications beyond Arizona. Ninety percent of the water consumed in the Colorado River Basin today is consumed by agriculture. So when planners discuss non-agricultural developments that have hefty water requirements, such as large-scale synfuel production, they often speak of the need to "facilitate" the transfer of water from agriculture to these new uses. Ranchers and farmers, however, can be very stubborn, as coal strip mining companies on the northern Great Plains have discovered. They do not necessarily see their use of either the land or the water as a "lower value" use. Their commitment to their land and to their way of life is often strong. They resist being "facilitated."

Kelso, Martin, and Mack are confident that if "water-related institutions" evolve that can "facilitate change in water development and use so that each unit used will make its maximum (or at least a greater) contribution to economic well-being, Arizona can continue its *rapid rate* of population, output, and income growth over the next 50-year period, through 2020, *without* obtaining additional raw water supplies." (Emphasis added.) As they see it, the water problem is one of "man-made rather than of nature-made restraints."[470]

Their work was published in 1973. There is some indication that water-related institutions to "facilitate" water transfers that they envisioned may, in fact, be emerging in the arid West. In Arizona, there is the new Department of Water Resources as well as a tough new law. In Colorado, municipalities are now empowered to condemn the water rights of irrigators if necessary—a powerful incentive for agriculture to sell out. In Utah, electric utility companies have found irrigators willing to sell their water rights. For example, the Utah Power and Light Company has purchased the rights to 18,000 acre-feet of water per year from two separate irrigation companies and a water conservation district in order to supply its Huntington and Emery generating plants in Emery County. The Nevada Power Company is currently negotiating with the Washington County Conservancy District for 10,000 acre-feet of water to supply its St. George, Utah, generating plant.[471]

One analyst, David Abbey, cites these water transfers as one of "several reasons to be optimistic about reallocation as a solution to the water supply problem," a view which has been echoed by other analysts. The other reasons to be optimistic, according to Abbey, include "the belief that, as it becomes more expensive to increase supply, the laws will be modified to improve the functioning of the private market rights" and the nature of the water organizations themselves:

> Two types of organizations, the mutual incorporated ditch company and the water conservancy district, account for about two-thirds of the total water use in the 11 western states. In the case of ditch companies, for example, the water rights are owned by the company. Water is distributed to stockholders on the basis of shareholdings. Shares are exchanged relatively freely within the area served by the company. . . .[472]

Nonetheless, there is, as Abbey cautions, "no last word on the reallocation issue." He adds: "There is a market for water in all states, but the transaction costs of exchange and the availability of undeveloped surface water are much greater in some places than others."[473] The ultimate success or failure of the reallocation solution for the water problems of the Colorado Basin or other basins within the region will really boil down to the willingness of the ranchers and farmers to sell out and the ability of the water buyers—energy companies and municipalities—to pay what will certainly be the rising price for water rights.

The initial success of the reallocation solution in Colorado, Utah, and Arizona has *not* eliminated the "necessity" for federally subsidized structural solutions. In Arizona, non-Indian water interests (agricultural, industrial, and urban) still press for the Central Arizona Project; in Utah, it is the Central Utah Project; and in Colo-

*The water is inexpensive because the users are not paying the full cost of the project. In calculating the capital cost for such a project, the federal government does *not* use the going market rate. It assumes an interest rate (6-5/8 percent) which presumably reflects what it has cost the federal government, on the average, to borrow money over the past several years. In our inflationary age, such a figure is always below the prevailing interest rate, that is, the one that Arizona would have to pay if it were to build the project.

rado, it is the Fryingpan-Arkansas Project—designed to divert 69,200 acre-feet of water per year from the western slope of the Rockies to the water-hungry eastern slope and plains.

The water supply picture of the arid West is further muddled by the continuing uncertainty over Indian water rights. In this region, most water rights are governed by the appropriation doctrine. As this doctrine evolved in the West, it meant that title to specific amounts of water goes to the user who first put the water to beneficial use. Hence, it is known as the "first-in-time is first-in-right" or "use it or lose it" doctrine. An appropriate water right is transferable just like a title to land, and it is subject to forfeiture or loss through non-use.

The Supreme Court ruled in 1908 in *Winters* v. *United States* that when public lands are withdrawn or reserved from the public domain, the then-unappropriated water necessary to fulfill the purposes for which the land was withdrawn is also reserved and exempted from appropriation under state laws. Consequently, an Indian reservation acquires reserved water rights that vest on the date the reservation was created and are superior to later appropriations under state law.[474]

The problem is that the amounts of water to which the Indians have a right, under the Winters or reservation doctrine, have never been quantified and non-Indian interests have appropriated water that almost certainly belongs rightfully to the Indians. The GAO warns:

> These reservation-related water resources are often the main source of water supply for irrigation, communities and industries and other uses off the reservations. Assertion of the reserved rights could pose a threat to investments and economics which are dependent on the water resources in which the Federal Government and Indians have undetermined but potentially extensive rights....
>
> The lack of certainty concerning Federal and Indian reserved rights makes it virtually impossible for new appropriators and state administrators to determine what, if any, reservation-related water is available for appropriation and what water uses created under State law may be superseded by reserved rights.[475]

And the GAO adds:

> [M]any Indian reservations are expected to require significant water quantities to satisfy reservation purposes. Major capital investments in the same water supply may have already been made by non-Indians.[476]

This uncertainty could well become a source of increasing water rights conflict in the arid West. The National Congress of American Indians indicates that each tribe will, in its own time, determine the quantity of water that it thinks it has a right to under the reservation doctrine and will seek to secure these rights through negotiation or litigation.[477]

The federal government has played a contradictory role in this matter. On the one hand, the federal government has defended Indian water rights in cases such as *Winters* v. *United States*; *United States* v. *Rio Grande Dam & Irrigation Company*; *United States* v. *City of Tucson, Farmers Investment Company*; and *United States and Pyramid Lake Paiute Tribe* v. *Truckee-Carson Irrigation Project*. Indeed, it is the duty of the federal government to defend Indian water rights under its fiduciary responsibilities as a trustee. On the other hand, as the National Congress of American Indians has pointed out, the federal government has encouraged and subsidized non-Indian water use "to the detriment of Indian interests."[478]

The National Congress of American Indians, in fact, proposes that the federal government should immediately terminate federal subsidies to all non-Indian water development in the West and argues:

> It is inconsistent with the federal government's responsibility as trustee to continue to stimulate growth in the West through subsidized water development, and it is irrational in view of the fact that the limited water supply in the arid West cannot support a population greatly expanded over its present size. Any new water projects undertaken should be entirely locally funded. This will eliminate the egregious conflicts of interest to which the Federal government is now subject partly as a result of its construction and funding of water projects in conflict with Indian water rights.[479]

The adjudication of Indian water rights could play havoc with existing water use in areas such as the Truckee and Carson River Basins in Nevada, the Santa Cruz Basin in Arizona, and the Colorado River Basin. In other words, *Winters* v. *United States* poses a serious "redistributive threat" to the water status quo in the arid West.[480] How it will affect the region's future desertification is impossible to say at this time. However, under the status quo, Indian lands are undergoing some of the most severe desertification in the arid West.

CONCLUSIONS

Desertification in the arid United States is flagrant. Groundwater supplies beneath vast stretches of land are dropping precipitously. Whole river systems have dried up; others are choked with sediment washed from denuded land. Hundreds of thousands of acres of previously irrigated cropland have been abandoned to wind or weeds. Salts are building up steadily in some of the nation's most productive irrigated soils. Several million acres of natural grassland are, as a result of cultivation or overgrazing, eroding at unnaturally high rates. Soils from the Great Plains are ending up in the Atlantic Ocean.

All total, about 225 million acres of land in the United States are undergoing severe desertification—an area roughly the size of the 13 original states.

The federal government subsidizes both the exploitation and conservation of arid land resources. But the subsidies for conservation are meager compared with those for exploitation. The net effect of federal subsidies is to encourage production, not conservation. Low interest government loans for the installation of irrigation systems encourage farmers to mine groundwater. The prospect of federally financed water delivery systems encourages arid land municipalities and industries to mine groundwater as well. Federal disaster relief and commodity programs encourage arid land farmers to plow up natural grassland to plant crops such as wheat and, especially, cotton. Federal grazing fees that are well below the free market price encourage overgrazing of the commons.

Federal subsidies are, in other words, a major force behind the desertification of the United States. But they certainly are not the only force. The market provides powerful incentives to exploit arid land resources beyond their carrying capacity, as was evidenced during the 1973–74 hike in wheat prices.

The short-run economics of conserving arid land resources appear to be almost always unfavorable. When commodity prices are high relative to the farmer's or rancher's operating costs, the return on a production-enhancing investment is invariably greater than the return on a conservation investment. And when commodity prices are relatively low, arid land ranchers and farmers often have to use all their available financial resources to stay solvent. Economic survival, not conservation, is their prime concern. For the subsistence rancher or farmer, of course, survival is a permanent preoccupation. Efforts to combat desertification that do not take these economic realities into account will either flounder politically or will cause considerable human hardship.

The incentives to exploit arid land resources beyond their carrying capacity are greater today than ever. The government is now offering huge new subsidies to produce synfuel from coal or oil shale as well as alcohol fuel from crops. Moreover, commodity prices are on the rise; a bushel of wheat at $6 and a pound of cotton at $1 are very real possibilities in the near future, and they will provide farmers and agribusinesses with a powerful incentive to over-exploit arid land resources. The existing federal government cost-share programs designed to help finance the conservation of soil, water, and vegetation pale in significance compared to such incentives.

Thus, in the short run, agricultural output from the arid West will certainly increase—at the expense of the region's soil, water, and vegetational resources. In other words, desertification will continue. Indeed, it will spread.

The long-term prospects for increased production from U.S. arid land agriculture look unpromising, however. The rich San Joaquin Valley is already losing about 14,000 acres of prime farmland per year to urbanization and could eventually lose 2 million acres to salinization. Increased salinity of the Colorado River could limit crop output in such highly productive areas as the Imperial Valley. Economic projections in Arizona indicate a major shrinkage in cropland acreage over the next 30 years. On the High Plains of Texas, crop production is expected to decline between 1985 and 2000 because of the depletion of the Ogallala Aquifer. And, certainly, the end is in sight for irrigation-dependent increased grain yields from western Kansas and Nebraska as their water tables continue to drop. Future production from such federally financed irrigation projects as the Newlands Project in Nevada are clouded by legal disputes over

Indian water rights. Overall, in fact, the water supply outlook for much irrigated cropland in the arid West is clouded by growing urban, energy, and industrial demands for water and the escalating energy costs of pumping water.

In the final analysis, when viewed in the national perspective, the effects on agriculture are the most troublesome aspect of desertification in the United States. For it comes at a time when the the United States is losing over a million acres of rain-watered crop and pasture land per year to "higher uses"—shopping centers, industrial parks, housing developments, and waste dumps—heedless of the economic need of the United States to export agricultural products or of the world's need for U.S. food and fiber.[481] Today the arid West accounts for about 20 percent of the nation's total agricultural output.

If the United States is, as it appears, well on its way toward overdrawing the arid land resources, then the policy choice is simply to pay now for the appropriate remedies or pay far more later, when productive benefits from arid land resources have been both realized and largely terminated.

REFERENCES

1. Fernand Braudel, *The Mediterranean and the Mediterranean World in the Age of Philip II*, Vol. 1 (New York: Harper & Row, Publishers; 1972), p. 243.
2. University of Arizona, Office of Arid Land Studies, *Desertification Bibliography* (Tucson, undated).
3. John A. Mabbutt, "The Impact of Desertification as Revealed by Mapping," *Environmental Conservation* 5(1):45 (1978).
4. United Nations, *United Nations Conference on Desertification: Roundup, Plan of Action and Resolutions* (New York, 1978), pp. 1–2.
5. H. N. LeHouerou, *La Desertification du Sahara Septentrional et des Steppes Limitrophes (Libye, Tunisie, Algerie)*, Programme Biologique International, Section C.T., Colloque Hammamet, Tunisia (Paris: UNESCO, 1968).
6. UN, *supra* note 4.
7. *Id.* p. 5.
8. David F. Costello, *The Desert World* (New York: Thomas Y. Crowell Co., 1972); James Rodney Hastings and Raymond M. Turner, *The Changing Mile* (Tucson: The University of Arizona Press, 1972), pp. 8-10, 15, 21; Charles Bowden, *Killing the Hidden Waters* (Austin: University of Texas Press, 1977), pp. 13-27, 91-95, 117-25.
9. Harold E. Dregne, "Desertification of Arid Lands," *Economic Geography*: 3(4):329 (1977).
10. Harold E. Dregne, Texas Tech University, Lubbock, interview with author, May 7, 1979.
11. Walter Prescott Webb, "The American West: Perpetual Mirage," *Harper's Magazine* 24(1284):26 (1957).
12. John Wesley Powell, *Report on the Lands of the Arid Region of the United States* (Washington, D.C.: U.S. Government Printing Office, 1879).
13. Wallace Stegner, *Beyond the Hundredth Meridian* (Boston: Houghton Mifflin Company, 1954), p. xxii.
14. Henry Nash Smith, *Virgin Land: The American West as a Symbol and Myth* (Cambridge, Mass.: Harvard University Press, 1950), pp. 220–33; Stegner, *supra* note 12, at 230–31; Erik P. Eckholm, *Losing Ground—Environmental Stress and World Food Prospects* (New York: W. W. Norton, 1976), p. 47.
15. Powell, *supra* note 12, at 20.
16. *Id.* p. 6.

17. *Id.* p. 3.
18. *Id.* p. 22.
19. Smith, *supra* note 14, at 200.
20. Stegner, *supra* note 14, at 328–38.
21. *Id.* p. 343.
22. U.S. Department of Agriculture, Economics, Statistics, and Cooperative Service, Washington, D.C., 1979.
23. U.S. General Accounting Office, *Ground Water: An Overview,* CED-77-69 (Washington, D.C., 1977), pp. 1–4.
24. Martin Fogel and Gerald D. Harwood, *Identification and Analysis of Major Water Problems of Arid and Semi-Arid Lands,* prepared for the National Science Foundation (Tucson: University of Arizona, 1978), pp. 8–29.
25. GAO, *supra* note 23, at i, 1–2.
26. *Id.* pp. 5–7.
27. Frank Quinn, "Water Transfers: Must the American West Be Won Again?" *Geographical Review* 58(1):115 (1968).
28. Jack D. Johnson, "Discussion," in Priscilla Reining, comp., *Desertification Papers* (Washington, D.C.: American Association for the Advancement of Science, 1978), p. 139.
29. Costello, *supra* note 8, at 218.
30. George Crossette, ed., *Selected Prose of John Wesley Powell* (Boston: David R. Godine, 1970), p. 63.
31. Bahe Billy, "Navajo Indian Culture and Lands," in Dean F. Peterson and A. Berry Crawford, eds., *Values and Choices in the Development of the Colorado River Basin* (Tucson: The University of Arizona Press, 1978), pp. 269, 243.
32. *Id.* p. 269.
33. *Id.* pp. 244, 246, 269–72.
34. *Id.* p. 274.
35. *Id.* pp. 240, 271–74.
36. *Id.* pp. 240–41.
37. *Id.* pp. 269, 271.
38. Felix Spencer, Navajo Tribe Livestock Office, Windo Rock, Ariz., interview with author, June 4, 1980.
39. Billy, *supra* note 31, at 272–73.
40. U.S. Bureau of Land Management, *Range Condition Report,* prepared for the Senate Committee on Appropriations (Washington, D.C.: U.S. Government Printing Office, 1975), pp. VII-c-48 to VII-c-53.
41. *Id.* pp. II-12 to II-13.
42. *Id.* p. vi.
43. U.S. Bureau of Land Management, "Managing the Public Rangelands" (public review draft, October 1979), p. 26; U.S. General Accounting Office, *Public Rangelands Continue To Deteriorate,* CED-77-88 (Washington, D.C.: U.S. Government Printing Office, 1977), pp. iii–iv.
44. U.S. Bureau of Land Management, *Final Environmental Impact Statement—Proposed Domestic Livestock Program for the Challis Planning Unit BLM* (Boise, Idaho: January 1977), pp. 1–2, 212.
45. James A. Michener, *Centennial* (New York: Random House, 1974), pp. 555–630, 729–830.
46. BLM, *supra* note 44, at 2–43.
47. *Ibid.*
48. Cynthia Irwin-Williams, "Effects of Environmental Stress on Rural Populations," grant application to the Department of Health, Education, and Welfare, Public Health Service (Portales: Eastern New Mexico University, October 6, 1977), pp. 25, 39–40; U.S. Bureau of Land Management, *Final Environmental Impact Statement—The Proposed Rio Puerco Livestock Grazing Management Program* (Washington, D.C.: U.S. Government Printing Office, 1978), p. II-71.
49. Irwin-Williams, *supra* note 48, at 25.
50. Edward J. Dortignac, "Rio Puerco: Abused Basin," in Carle Hodge and Peter Duisberg, eds., *Aridity and Man* (Washington, D.C.: American Association for the Advancement of Science, 1963), pp. 512–14; BLM, *supra* note 48, at 2–97.
51. Dortignac, *supra* note 50, at 507.
52. Glen E. Murray and Gerry R. Lowry, "SCS and Water Quality: An Overview," *Soil Conservation,* November 1976, p. 97.
53. Vorsila Bohrer, "The Prehistoric and Historic Role of the Cool-Season Grasses in the Southwest," *Economic Botany* 29:204 (1975).
54. Dortignac, *supra* note 50, at 514.
55. Irwin-Williams, *supra* note 48, at 25.
56. Vorsila Bohrer, Eastern New Mexico University, Portales, interview with author, October 19, 1979.
57. Hastings and Turner, *supra* note 8, at 30–46.
58. Cynthia Irwin-Williams, Eastern New Mexico University, Portales, interview with author, October 22, 1979.
59. Bohrer, *supra* note 53, at 203, 206.
60. Robert C. Euler et al., "The Colorado Plateaus: Cultural Dynamics and Paleoenvironment," *Science* 205:1089–1101 (1979).
61. Dortignac, *supra* note 50, at 507, 514.
62. Fred Nials, Portales, N.M., interview with author, October 23, 1979.
63. BLM, *supra* note 48, at I-1, II-71, II-86 to II-95.
64. *Id.* p. II-71.
65. *Id.* pp. III-18 to III-19.
66. *Id.* p. II-14.
67. *Id.* p. II-19.
68. *Id.* p. II-14.
69. Letter from Rex Adams, Eastern New Mexico University, Portales, to author, October 23, 1979.
70. BLM, *supra* note 48, at II-9.
71. *Id.* pp. II-6, II-8.
72. *Id.* p. II-20.
73. *Id.* p. III-38.
74. *Id.* pp. III-18 to III-19, III-38.
75. Bohrer, *supra* note 56.
76. BLM, *supra* note 48, at I-1 to I-39.
77. Nials, *supra* note 62.
78. Dregne, *supra* note 10.
79. BLM, *supra* note 43, at iii.
80. 43 U.S.C. §1901 (a)(4).
81. BLM, *supra* note 43, at 4.
82. William Voigt, Jr., *Public Grazing Lands* (New Brunswick, N.J.: Rutgers University Press, 1976), pp. 253–89.
83. Robert Webb, Stanford University, Palo Alto, Calif., interview with author, September 9, 1979.
84. Robert H. Webb and Steven S. Stielstra, "Sheep Grazing Effects on Mojave Desert Vegetation and Soils," *Environmental Management* 2:206–18 (1978).
85. T. J. Lowi, "American Business, Public Policy, Case-Studies, and Political Theory, *World Politics* 16:691–97 (1963); Milton Jamail, John R. McCain, and Scott J. Ullery, *Federal-State Water Relations in the American West: An Evolutionary Guide to Future Equilibrium* (Tucson: University of Arizona, 1978), pp. 6–8.
86. BLM, *supra* note 48, at IX-19 to IX-75.
87. Voigt, *supra* note 82, at 263–77, 309–22.
88. BLM, *supra* note 40.
89. BLM, *supra* note 40, at VII-39 to VII-64.
90. BLM, *supra* note 48, at III-28.
91. *Id.* p. IX-72.
92. Personal observations of author, April–June 1979.
93. George V. Burger, "Agriculture and Wildlife," in Howard P. Brokaw, ed., *Wildlife and America* (Washington, D.C.: U.S. Government Printing Office, 1978), p. 102.
94. A. Berry Crawford and A. Bruce Bishop, "Carrying Capacity and Planning."

in Peterson and Crawford, *supra* note 31, at 292-93.

95. G. F. Cochran and J. W. Fordham, "Water and Related Resource Problems and Research Needs in the Arid Southwest: A Case Study of Reno/Sparks Area, Western Nevada," in National Science Foundation, "Summaries of Reports: Arid and Semiarid Lands" (Washington, D.C., 1979), pp. 34-36; U.S. General Accounting Office, *Reserved Water Rights for Federal and Indian Reservations: A Growing Controversy in Need of Resolution*, CED-78-176 (Washington, D.C., 1978), pp. 35-37.
96. U.S. General Accounting Office, *National Water Quality Goals Cannot Be Attained without More Attention to Pollution from Diffused or "Nonpoint" Sources*, CED-78-6 (Washington, D.C., 1977), p. 31; Murray and Lowry, *supra* note 52, at 94.
97. Personal observations of author, June 1979.
98. Jack Fronsky, U.S. Soil Conservation Service, Buckeye, Ariz., interview with author, May 15, 1979.
99. Richard Bloyd, U.S. Geological Survey, remarks to the California Desert Conservation Area Advisory Committee, Riverside, Calif., December 1, 1978.
100. Howard Wilshire, U.S. Geological Survey, Menlo Park, Calif., interview with author, November 20, 1979.
101. U.S. General Accounting Office, "The Taking of Prime Farmland—What Should Be Done About It?" (draft, April 1979), pp. 19-21.
102. William Tucker, "The Next American Dust Bowl and How To Avert It," *Atlantic Monthly* 244(1):42 (1979).
103. H. E. Thomas, "Water and the Southwest—What Is the Future?" U.S. Geological Circular 469 (1962), p. 14.
104. GAO, *supra* note 102, at 18.
105. Bowden, *supra* note 8, at 120.
106. GAO, *supra* note 101, at 21.
107. Crawford and Bishop, *supra* note 94, at 293-95.
108. *Id.* p. 293.
109. Eckholm, *supra* note 14, at 115.
110. U.S. Department of Agriculture (River Basin Planning Staff, Soil Conservation Service, Forest Service, Economic Research Service), in cooperation with the California Department of Water Resources, *San Joaquin Valley Basin Study* (Washington, D.C., 1977), pp. 37-44.
111. U.S. Bureau of Reclamation, California Department of Water Resources, and California State Water Resources Control Board, *Agricultural Drainage and Salt Management in the San Joaquin Valley* (Fresno, Calif.: San Joaquin Valley Interagency Drainage Program, 1979), pp. 2.1-2.3.
112. *Id.* p. 2.1.
113. U.S. Department of Agriculture, Economics, Statistics, and Cooperative Service, Washington, D.C., 1979.
114. Bureau of Reclamation, *supra* note 111, at 2.3.
115. *Ibid.*
116. For further details on the crop-producing factories in the San Joaquin, see Mark Kramer, *Three Farms* (Boston: Little, Brown and Company, 1980), pp. 197-274.
117. *Id.* pp. 2.4-2.5; Raymond F. Dasmann, *The Destruction of California* (New York: The Macmillan Company, 1978), pp. 68-72.
118. Bureau of Reclamation, *supra* note 111, at 1.2, 6.3.
119. *Id.* pp. 3.5-3.6.
120. *Id.* pp. 11.1-11.11.
121. *Id.* pp. 9.1-9.9.
122. *Id.* pp. 7.4, 9.4, 17.5-17.6.
123. *Id.* p. 8.4.
124. *Id.* p. 17.5.
125. *Id.* pp. 7.3, 9.8, 12.2.
126. Wilson Clark, "Take Sun and Salt, Add Some Water—The Result Is Energy," *Smithsonian*, October 1980, pp. 143-46.
127. U.S. Bureau of Reclamation et al., "Report of California Interagency Irrigation Water Use and Management Committee" (prelim. ed., Sacramento, May 1978), p. 10.

128. *Id.* p. 16; Gylan Dickey, U.S. Soil Conservation Service, Davis, Calif., interview with author, May 8, 1979.
129. Dickey, *supra* note 128.
130. Bureau of Reclamation, *supra* note 127, at 10.
131. Gylan Dickey, U.S. Soil Conservation Service, Davis, Calif., interview with author, April 10, 1979.
132. Gary Weatherford et al., *Erosion and Sediment in California Watersheds: A Study of Institutional Controls* (Napa, Calif.: John Muir Institute, Inc., 1979), p. 99.
133. *Id.* p. 103.
134. Bureau of Reclamation, *supra* note 111, at 13.4.
135. *Id.* pp. 13.2-13.3.
136. Craig Stroh, U.S. Bureau of Reclamation, Fresno, Calif., interview with author, April 11, 1979.
137. *Ibid.*
138. *Ibid.*
139. Louis A. Beck, Director, San Joaquin Valley Interagency Drainage Program, Fresno, Calif., interview with author, April 11, 1979.
140. Bureau of Reclamation, *supra* note 111, at 6.3, 9.3.
141. Francis Lum, State Conservationist, U.S. Soil Conservation Service, memorandum to Paul Howard, Deputy Chief of Technology, U.S. Soil Conservation Service, Washington, D.C., September 15, 1980.
142. USDA, *supra* note 110, at 55.
143. *Ibid.*
144. Webb, *supra* note 83.
145. USDA, *supra* note 110, at 55.
146. James Clawson, quoted in California Department of Conservation, "California Soils: An Assessment" (draft, April 1979), p. IV-38.
147. W. O. Beatty, U.S. Soil Conservation Service, Fresno, Calif., interview with author, April 11, 1979.
148. USDA, *supra* note 110, at 55.
149. *Id.* p. 56.
150. *Ibid.*
151. U.S. Geological Survey, "Field Observations of the December, 1977 Windstorm, San Joaquin Valley, California" (undated), pp. 1, 8, 10, 18-19.
152. Wilshire, *supra* note 100.
153. USGS, *supra* note 151, at 19.
154. *Id.* pp. 11, 19, 38; Wilshire, *supra* note 100.
155. California Department of Conservation, *supra* note 146, at IV-36 to IV-37.
156. Wilshire, *supra* note 100.
157. USDA, *supra* note 110, at 56.
158. USGS, *supra* note 151, at 7.
159. Paul Chaffey, Director, Fresno Zoo, interview with author, June 25, 1980.
160. USGS, *supra* note 151, at 7.
161. *Id.* p. 17.
162. USDA, *supra* note 110, at 55.
163. Morris Martin, U.S. Soil Conservation Service, Fresno, Calif., interview with author, April 11, 1979.
164. *Ibid.*
165. USDA, *supra* note 110, at 107.
166. California Department of Conservation, *supra* note 146, at IV-39 to IV-40.
167. *Id.* pp. IV-41 to IV-42.
168. GAO, *supra* note 101, at 29-32.
169. GAO, *supra* note 23, at 7.
170. *Id.* p. 15.
171. Susan Jo Keith, *The Impact of Groundwater Development in Arid Lands* (Tucson: University of Arizona, 1977), pp. 20-21.
172. GAO, *supra* note 23, at 15.
173. *Id.* p. 16.
174. Beck, *supra* note 139.
175. Dickey, *supra* note 131.

176. Thomas Holzer, U.S. Geological Survey, Menlo Park, Calif., interview with author, October 1, 1980.
177. Herb Guenther, Senior Biologist, U.S. Bureau of Reclamation, Boulder City, Nev., interview with author, April 13, 1979.
178. Crawford and Bishop, *supra* note 94, at 292.
179. Myron B. Holburt, "International Problems," in Peterson and Crawford, *supra* note 31, at 224; William Curry, "The Desert Blooms, but at an Ever Higher Price," *The Washington Post*, June 25, 1979, p. A3.
180. Guenther, *supra* note 177.
181. Wellton-Mohawk Irrigation and Drainage District, *Crop Production Report 1978;* U.S. Bureau of Reclamation, *Crop Production Report 1955.*
182. U.S. Department of Agriculture, Economics, Statistics, and Cooperative Service, Washington, D.C., 1979.
183. *Ibid.*
184. Jim Naquin, Wellton-Mohawk Irrigation and Drainage District, Wellton, Ariz., interview with author, April 14, 1979.
185. *Ibid.*; Guenther, *supra* note 177; Tom Howell, Wellton- Mohawk Irrigation and Drainage District, Wellton, Ariz., interview with author, April 14, 1979; Edward M. Hallenbeck, Project Manager, U.S. Bureau of Reclamation, Yuma, Ariz., interview with author, April 14, 1979.
186. Wellton-Mohawk Irrigation and Drainage District, *supra* note 179; Crop Reporting Board, *Annual Crop Summary* (Washington, D.C.: U.S. Department of Agriculture, 1979), pp. B-22, B-23, B-30.
187. Jamail et al., *supra* note 85, at 13.
188. Holburt, *supra* note 179, at 224; B. Delworth Gardner and Clyde E. Stewart, "Agriculture and Salinity," in Peterson and Crawford, *supra* note 31, at 124.
189. Holburt, *supra* note 179.
190. Gardner and Stewart, *supra* note 188, at 123.
191. Holburt, *supra* note 179, at 225–27.
192. *Id.* pp. 228–30; Jamail et al., *supra* note 85, at 34–36.
193. Letter from Bruce Blanchard, Director, Office of Environmental Project Review, U.S. Department of the Interior, Washington, D.C., to the Council on Environmental Quality, Washington, D.C., August 14, 1980.
194. Holburt, *supra* note 179, at 235–37; Jamail et al., *supra* note 85, at 37–39; Hallenbeck, *supra* note 185.
195. Hallenbeck, *supra* note 185.
196. *The Yuma Daily Sun*, April 12, 1979, p. 1.
197. Blanchard, *supra* note 193.
198. Guenther, *supra* note 177.
199. Quoted in Jamail et al., *supra* note 85, at 38.
200. Naquin, *supra* note 184; Howell, *supra* note 185; Hallenbeck, *supra* note 185; W. K. Sidebottom, U.S. Bureau of Reclamation, Yuma, Ariz., interview with author, April 14, 1979; Clyde Gould, Manager, Wellton-Mohawk Irrigation and Drainage District, Wellton, Ariz., interview with author, May 15, 1979.
201. Naquin, *supra* note 184.
202. Gould, *supra* note 200.
203. Naquin, *supra* note 184.
204. Quoted in Curry, *supra* note 179.
205. Wellton-Mohawk Irrigation and Drainage District, Advisory Committee on Irrigation Efficiency, *Annual Report of Activities for FY 1978* (Washington, D.C.: U.S. Soil Conservation Service, 1978), pp. 7–43.
206. Sol Resnick, Water Resources Center, University of Arizona, Tucson, interview with author, April 17, 1979.
207. W. K. Sidebottom, Chairman, Technical Field Committee on Irrigation Efficiency, Wellton-Mohawk Irrigation and Drainage District, memorandum to the Advisory Committee on Irrigation Efficiency, Wellton-Mohawk Irrigation and Drainage District, May 11, 1979.
208. Harold Pritchett, U.S. Soil Conservation Service, Wellton, Ariz., interview with author, May 15, 1979.
209. Sidebottom, *supra* note 207.

210. *Id.* p. 3.
211. *Ibid.*
212. Gardner and Stewart, *supra* note 188, at 125–26.
213. Hallenbeck, *supra* note 185.
214. Jamail et al., *supra* note 85, at 38.
215. Resnick, *supra* note 206.
216. Hastings and Turner, *supra* note 8, at 3–5, 32–38; Andrew W. Wilson, "Tucson: A Problem in Uses of Water," in Hodge and Duisberg, *supra* note 50, at 4–5.
217. Karen L. Reichhardt et al., *An Inventory of Riparian Habitats along the San Pedro River* (Tucson: University of Arizona, 1978), pp. 7–17.
218. Hastings and Turner, *supra* note 8, at 21, 271.
219. *Id.* p. 4.
220. *Id.* pp. 279–80; National Research Council, *Climate & Food* (Washington, D.C.: National Academy of Sciences, 1976), pp. 16–18.
221. Hastings, *supra* note 8, pp. 40–41.
222. *Id.* p. 289.
223. Quoted *id.* p. 44.
224. U.S. Department of Agriculture, in cooperation with the Arizona Water Commission, *Santa Cruz-San Pedro River Basins Arizona—Main Report* (Portland, Oreg., 1977), p. 4.12.
225. Hastings and Turner, *supra* note 8, at 275.
226. Letter from Harold Dregne, Lubbock, Tex., to the Council on Environmental Quality, Washington, D.C., August 21, 1980.
227. USDA, *supra* note 224, at 7.6.
228. *Id.* pp. 3.37, 4.12.
229. Donald Steila, *Drought in Arizona* (Tucson: University of Arizona, 1972), p. 63.
230. Jack Johnson, Office of Arid Land Studies, University of Arizona, Tucson, interview with author, January 19, 1979.
231. S. Clark Martin and Dwight R. Cable, "Highlights of Research on the Santa Rita Experimental Range," in *Arid Shrublands*, Proceedings of the Third Workshop of the United States/Australia Rangelands Panel, March 26–April 5, 1973 (Tucson, 1975), pp. 51–57; Dwight R. Cable and S. Clark Martin, *Vegetation Responses to Grazing, Rainfall, Site Condition, and Mesquite Control on Semidesert Range*, Forest Service Research Paper RM-149 (Fort Collins, Colo.: U.S. Department of Agriculture, 1975), p. 8.
232. S. Clark Martin, *Stocking Strategies and Net Cattle Sales on Semidesert Range*, Forest Service Research Paper RM-146 (Fort Collins, Colo.: U.S. Department of Agriculture, 1975), p. 7.
233. USDA, *supra* note 224, at 4.15.
234. *Id.* pp. 3.10–3.15.
235. Hastings and Turner, *supra* note 8, at 236–49.
236. Reichhardt et al., *supra* note 217, at 14–17.
237. David Mouat, Applied Remote Sensing Program, Office of Arid Land Studies, University of Arizona, Tucson, interview with author, April 16, 1979.
238. University of Arizona, Water Resources Research Center, "Groundwater Projections for 11 Basins," *Arizona Water Resources News Bulletin* 78(3):2 (1978).
239. Fogel and Harwood, *supra* note 24, at 15.
240. University of Arizona, *supra* note 238, at 3.
241. Fogel, *supra* note 24, at 15.
242. GAO, *supra* note 23, at 7.
243. GAO, *supra* note 95, at 34.
244. GAO, *supra* note 23, at 7.
245. Bowden, *supra* note 8, at 30, 120.
246. Fogel and Harwood, *supra* note 24, at 17.
247. GAO, *supra* note 95, at 33–34; Kennith E. Foster, "Alternatives for Managing a Finite Groundwater Supply in an Arid Region" (University of Arizona, Tucson, undated), p. 19.
248. GAO, *supra* note 95, at 33–34.
249. Foster, *supra* note 247, at 19.

250. Andrew W. Wilson, "Technology, Regional Interdependence and Population Growth: Tucson, Arizona," *Economic Geography* 53(4):389 (1977).
251. Fogel and Harwood, *supra* note 24, at 16–18, 53–54, 57.
252. Resnick, *supra* note 206.
253. GAO, *supra* note 95, at 34–35.
254. Fogel and Harwood, *supra* note 24, at 15.
255. University of Arizona, *supra* note 238, at 3.
256. Foster, *supra* note 247, at 9–10, 12.
257. University of Arizona, *supra* note 238, at 3.
258. Michele Strutin, "Pulling the Plug on Arizona," *Mother Jones*, August 1979, p. 20.
259. U.S. Bureau of Reclamation, "Central Arizona Project," Information Paper No. 3, Phoenix, 1978.
260. Foster, *supra* note 247, at 21.
261. Carey McWilliams, *Southern California: An Island on the Land* (Salt Lake City: Peregrine Smith, Inc., 1973), p. 185.
262. Bowden, *supra* note 8, at 7.
263. USDA, *supra* note 224, at 3.23, 4.11.
264. Reichhardt et al., *supra* note 217, at 6.
265. Letter from William N. Hedeman, Jr., U.S. Environmental Protection Agency, to the Council on Environmental Quality, Washington, D.C., August 13, 1980.
266. University of Arizona, *supra* note 238, at 3.
267. Keith, *supra* note 171, at 29.
268. *Id.* pp. 11–12.
269. Foster, *supra* note 247, at 20.
270. Hedeman, *supra* note 265.
271. Holzer, *supra* note 176.
272. *Ibid.*
273. Keith, *supra* note 171, at 21–22.
274. USDA, *supra* note 224, at 3.26.
275. Keith, *supra* note 171, at 26.
276. *Ibid.*
277. USDA, *supra* note 224, at 3.26.
278. Melvin E. Hecht et al., "Agriculture: Its Historic and Contemporary Roles in Arizona's Economy," *Arizona Review* 27(11):10 (1978).
279. USDA, *supra* note 224, at 3.33.
280. Johnson, *supra* note 230; USDA, *supra* note 224, at 3.36.
281. Maurice M. Kelso et al., *Water Supplies and Economic Growth in an Arid Environment, An Arizona Case Study* (Tucson: The University of Arizona Press, 1973), p. 105.
282. *New York Times*, June 15, 1980, p. 35.
283. *Ibid.*
284. *Ibid.*
285. Eckholm, *supra* note 14, at 53.
286. John F. McCauley et al., "The U.S. Dust Storm of February 1977" (preliminary, U.S. Geological Survey, Flagstaff, Ariz.), pp. 1–4.
287. *Id.* pp. 9–12.
288. *Id.* pp. 15–16.
289. *Id.* pp. 6, 22.
290. U.S. General Accounting Office, *To Protect Tomorrow's Food Supply, Soil Conservation Needs Priority Attention*, CED-77-30 (Washington, D.C., 1977), p. 16.
291. U.S. Soil Conservation Service, RCA Policy Issue Study Group, "Conservation of the Land Resource Base" (draft, January 1979), p. 10.
292. *Id.* p. 21.
293. McCauley et al., *supra* note 286, at 24.
294. *Ibid.*
295. *Id.* pp. 24–25.
296. John Knapp, Agronomist, U.S. Soil Conservation Service, La Junta, Colo., interview with author, April 18, 1979.

297. *Ibid.*
298. U.S. Soil Conservation Service, *Agricultural Handbook* (Washington, D.C.: U.S. Government Printing Office, 1966), p. 21.
299. Arnold King, Area Conservationist, U.S. Soil Conservation Service, La Junta, Colo., interview with author, June 22, 1979.
300. Knapp, *supra* note 296.
301. Council for Agricultural Science and Technology, *Conservation of the Land, and the Use of Waste Materials for Man's Benefits*, prepared for the Committee on Agriculture and Forestry, U.S. Senate (Washington, D.C.: U.S. Government Printing Office, 1975), p. 16.
302. Burger, *supra* note 93, at 95–102.
303. Personal observations of author, Crowley County, Colo., April 17–18, 1979.
304. McCauley et al., *supra* note 286, at 22.
305. David Pimentel et al., "Land Degradation: Effects on Food and Energy Resources," *Science* 194:151–52 (1976).
306. Knapp, *supra* note 296.
307. King, *supra* note 299.
308. Knapp, *supra* note 296.
309. *Ibid.*
310. A farmer in Seminole, Tex., who wishes to remain anonymous, interview with author, April 20, 1979.
311. King, *supra* note 299.
312. Knapp, *supra* note 296.
313. GAO, *supra* note 290, at 47–55.
314. *Id.* p. 53.
315. *Id.* p. 49.
316. Letter from John Knapp, U.S. Soil Conservation Service, La Junta, Colo., to author, August 14, 1980.
317. GAO, *supra* note 290, at 48–49.
318. Knapp, *supra* note 296.
319. Pimentel et al., *supra* note 305, at 151.
320. Knapp, *supra* note 296.
321. John Knapp, "Direction of Chemical Fallow Trial Work Southeastern Colorado" (La Junta, Colo.: U.S. Soil Conservation Service, undated), p. 8.
322. *Id.* pp. 1–3, 8–9.
323. Knapp, *supra* note 296.
324. Colorado Crop and Livestock Reporting Service, *1978 Colorado Agricultural Statistics* (Denver: Colorado Department of Agriculture, 1978), p. 12; Crop Reporting Board, *supra* note 186, at B-23.
325. Colorado Crop and Livestock Reporting Service, *1951 Colorado Agricultural Statistics* (Denver: Colorado Department of Agriculture, 1951), p. 10; Crop Reporting Board, Agricultural Marketing Service, *Field Crops by States, 1949–54*, Stat. Bull. 185 (Washington, D.C.: U.S. Department of Agriculture, 1956), p. 9.
326. Knapp, *supra* note 296.
327. James Risser, "Soil Erosion Creates a Crisis Down on the Farm," *Conservation Foundation Letter*, December 1978, p. 3.
328. Knapp, *supra* note 296.
329. Aldo Leopold, quoted in Burger, *supra* note 93, at 103.
330. Personal observations of author, Crowley County, Colo., April 17–18, 1979.
331. Donald L. Miles, "Salinity in the Arkansas River of Colorado," Cooperative Extension Service, Colorado State University, report to Region VIII of the U.S. Environmental Protection Agency, May 1977.
332. Knapp, *supra* note 296.
333. Personal observations of author, Gaines County, Tex., April 20, 1979.
334. Texas Crop and Livestock Reporting Service, *1977 Texas Agricultural Cash Receipts Statistics* (Austin: Texas Department of Agriculture), p. 10; U.S. Department of Agriculture, Economics, Statistics, and Cooperative Service, Washington, D.C.
335. Texas Crop and Livestock Reporting Service, *supra* note 334, at 11, 26.

336. Walter Bertsch, District Conservationist, U.S. Soil Conservation Service, Seminole, Tex., interview with author, April 19, 1979.
337. D. B. Polk, State Resource Conservationist, U.S. Soil Conservation Service, Temple, Tex., interview with author, April 20, 1979.
338. Gaines County Soil and Water Conservation District, *Program and Plan of Work* (Gaines, Tex., 1979), p. 21.
339. *Id.* pp. 22–24; Bertsch, *supra* note 336.
340. Bertsch, *supra* note 336.
341. Gaines County Soil and Water Conservation District, *supra* note 338, at 9.
342. James McGehee, Gaines County Executive Director, U.S. Agricultural Stabilization and Conservation Service, Seminole, Tex., interview with author, April 20, 1979.
343. James Abbott, Assistant State Conservationist, U.S. Soil Conservation Service, Temple, Tex., interview with author, April 20, 1979.
344. Bertsch, *supra* note 336; Polk, *supra* note 337; Earl Archer, Area Conservationist, U.S. Soil Conservation Service, Big Spring, Texas, interview with author, April 20, 1979.
345. Gaines County Soil and Water Conservation District, *supra* note 338, at 12.
346. Bertsch, *supra* note 334.
347. McGehee, *supra* note 342.
348. James Abbott, U.S. Soil Conservation Service, Temple, Tex., interview with author, August 29, 1980.
349. Bertsch, *supra* note 336; McGehee, *supra* note 342.
350. Abbott, *supra* note 348.
351. McGehee, *supra* note 342.
352. Abbott, *supra* note 343.
353. GAO, *supra* note 290, at 16.
354. Texas Crop and Livestock Reporting Service, *supra* note 334, at 16–17.
355. McGehee, *supra* note 342.
356. Texas Crop and Livestock Reporting Service, *supra* note 334, at 11–23.
357. McGehee, *supra* note 342.
358. *Ibid.*
359. Abbott, *supra* note 343.
360. Anne E. Bell and Shelly Morrison, *Analytical Study of the Ogallala Aquifer in Gaines County, Texas* (Austin: Texas Department of Water Resources, 1979), p. 1.
361. *Id.* p. 7.
362. Bowden, *supra* note 8, at 119–20.
363. Bertsch, *supra* note 336.
364. Bell and Morrison, *supra* note 360, at 6.
365. *Id.* p. 1.
366. *Id.* pp. 6–8; Bertsch, *supra* note 336.
367. Bertsch, *supra* note 336.
368. Polk, *supra* note 337.
369. Fogel and Harwood, *supra* note 24, at 23.
370. Bowden, *supra* note 8, at 102.
371. Bell and Morrison, *supra* note 360, at 1, 9.
372. GAO, *supra* note 95, at 39–41.
373. John Graves, "You Ain't Seen Nothing Yet," *The Water Hustlers* (San Francisco: Sierra Club, 1971), p. 39.
374. Robert M. Sweazy et al., "Groundwater Resources of the High Plains: State-of-the-Art and Future Research Needs," *Summaries of Reports: Arid and Semiarid Lands* (Washington, D.C.: National Science Foundation, 1979), p. 15.
375. Garrett Hardin, "The Tragedy of the Commons," *Science* 162:1243–48 (1968).
376. A. A. Milne, *Now We Are Six* (New York: E. P. Dutton & Co., Inc., 1961).
377. U.S. Congress, Office of Technology Assessment, *The Direct Use of Coal*, OTA-E-86 (Washington, D.C.: U.S. Government Printing Office, 1979), p. 63.
378. U.S. General Accounting Office, *U.S. Coal Development—Promises and Uncertainties*, EMD-77-44 (Washington, D.C., 1977), p. 4.15.
379. U.S. Congress, *supra* note 377, at 5.

380. Nicholas Wade, "Synfuels in Haste, Repent at Leisure," *Science* 205:167–68 (1979); Luther J. Carter, "Synfuels Crash Program Viewed as Risky," *Science* 205:978–79 (1979).
381. John Harte and Mohamed El-Gasseir, "Energy and Water," *Science* 199:631 (1978).
382. U.S. Department of the Interior, *Report on Water for Energy in the Upper Colorado River Basin* (Washington, D.C.: U.S. Government Printing Office, 1974).
383. John A. Dracup, "Impact on the Colorado River Basin and Southwest Water Supply," in National Research Council, *Climate, Climatic Change, and Water Supply* (Washington, D.C.: National Academy of Sciences, 1977), p. 130.
384. U.S. Department of the Interior, *supra* note 382, at 24.
385. U.S. Congress, *supra* note 377, at 237.
386. David Abbey, *Energy Production and Water Resources in the Colorado Basin*, Reprint 170 (Washington, D.C.: Resources for the Future, Inc., 1979), pp. 294–95.
387. Dracup, *supra* note 383, at 131.
388. *Ibid.*
389. Harte and El-Gasseir, *supra* note 381, at 628.
390. Bland Richardson and Ray Brown, U.S. Forest Service, Forestry Sciences Laboratory, Logan, Utah, interview with author, June 12, 1979.
391. National Academy of Sciences, *Rehabilitation Potential of Western Coal Lands*, prepared for the Energy Policy Project of the Ford Foundation (Cambridge, Mass.: Ballinger Publishing Co., 1979), p. 86.
392. GAO, *supra* note 378, p. 6.26.
393. National Academy of Sciences, *supra* note 391.
394. U.S. Congress, *supra* note 377, p. 246.
395. U.S. Congress, Office of Technology Assessment, *Energy from Biological Processes* (Washington, D.C.: U.S. Government Printing Office, 1980), pp. 11–18.
396. *Id.* p. 87.
397. U.S. Congress, Office of Technology Assessment, *Gasohol* (Washington, D.C.: U.S. Government Printing Office, 1979), pp. 3–10.
398. *Id.* pp. 19–33.
399. U.S. Congress, *supra* note 395, pp. 21–25.
400. *Id.* pp. 61–62.
401. Charles Jourdin, U.S. Forest Service, Gila National Forest, N. Mex., interview with author, October 19, 1979; Keith Pfefferle, U.S. Forest Service, Cibola National Forest, N. Mex., interview with author, October 18, 1979; Howard Shoupe, U.S. Forest Service, Coronado National Forest, Ariz., interview with author, October 19, 1979; Donald Rose, U.S. Forest Service, Lincoln National Forest, N. Mex., interview with author, October 18, 1979.
402. Pfefferle, *supra* note 401.
403. Shoupe, *supra* note 401.
404. U.S. Congress, *supra* note 395, at 139.
405. Pfefferle, *supra* note 401.
406. Rose, *supra* note 401.
407. Jack D. Johnson and C. Wiley Hinman, "Oils and Rubber from Arid Land Plants," *Science* 208:460–64 (1980).
408. U.S. Congress, *supra* note 395, at 329.
409. Johnson and Hinman, *supra* note 407, at 461.
410. University of Arizona, Office of Arid Land Studies, and Midwest Research Institute, *A Sociotechnical Survey of Guayule Rubber Commercialization*, prepared for the National Science Foundation (1979), p. 1.
411. *Id.* pp. 1, 112.
412. *Id.* pp. 4–6.
413. *Id.* p. 6, quoting the Emergency Rubber Project Final Report, 1946.
414. Crop Reporting Board, *Crop Production, 1978 Annual Summary* (Washington, D.C.: U.S. Department of Agriculture, 1979), p. B-28.
415. University of Arizona and Midwest Research Institute, *supra* note 410, pp. 132–45.
416. Johnson and Hinman, *supra* note 407, at 461–62.
417. Eliot Marshall, "MX Missile to Roam 200 Racetracks," *Science* 206:198–200

(1979); Eliot Marshall, "Congress Challenges MX Basing Plan," *Science* 208:1007-09 (1980).
418. Jonathan E. Medalia, *Domestic Considerations Affecting Deployment of a Multiple Protective Structure Basing System for the MX Missile* (Washington, D.C.: Congressional Research Service, 1980), p. 203.
419. T. H. Watkins, "The New Romans," in *The Water Hustlers,* supra note 373, at 154.
420. Uwe George, *In the Deserts of This Earth* (New York: Harcourt Brace Jovanovich, Inc., 1979), pp. 116-17.
421. Watkins, *supra* note 419, at 149-55.
422. U.S. Bureau of Reclamation, *1976 Summary Report* (Washington, D.C.: U.S. Government Printing Office, 1978), pp. iv, 4, 14, 23, 31.
423. Harold Gilliam, "A Continental Water Plan," *San Francisco Chronicle,* July 22, 1980, p. 4.
424. Thane Gustafson, "Technology Assessment, Soviet Style," *Science* 208:1343 (1980).
425. Graves, *supra* note 373.
426. *Id.* pp. 42-56.
427. *Id.* pp. 55-56.
428. *Id.* p. 57-58.
429. *Id.* p. 61.
430. *Id.* p. 75.
431. *Id.* p. 125.
432. Ivol V. Goslin, "Colorado River Development," in Peterson and Crawford, *supra* note 31, at 49.
433. Hallenbeck, *supra* note 185.
434. Jamail et al., *supra* note 85, at 27-30.
435. George L. Baker and Tom DeVries, "Water," *New West,* June 16, 1980, pp. 35-37.
436. *Ibid.*
437. *Id.* p. 39.
438. *Id.* p. 40.
439. Gustafson, *supra* note 424, at 1343, 1345-46.
440. J. L. Hult and N. C. Ostrander, *Antarctic Icebergs as a Global Fresh Water Resource,* prepared for the National Science Foundation (Santa Monica, Calif.: Rand Corporation, 1973).
441. *Id.* pp. v-26.
442. *Id.* p. 9.
443. *Id.* p. vii.
444. *Id.* p. 9.
445. Ralph M. McGehee, "Weather: Complex Causes of Aridity," in Hodge and Duisberg, *supra* note 53, at 137-38.
446. U.S. Bureau of Reclamation, *Reclamation Research in the Seventies* (Washington, D.C.: U.S. Government Printing Office, 1977), pp. 1-5.
447. *Id.* pp. 6-8.
448. *Id.* p. 13.
449. L. Jonez, U.S. Bureau of Reclamation, Washington, D.C., interview with author, February 5, 1979.
450. *Ibid.*
451. Bureau of Reclamation, *supra* note 446, at 9-11.
452. National Research Council, *supra* note 383, at 14-15.
453. *Id.* p. 15.
454. Richard A. Kerr, "Weather Modification: A Call for Tougher Tests," *Science* 202:860 (1978).
455. Bureau of Reclamation, *supra* note 446, at 22.
456. Gordon Lloyd, "Irrigation Management Service—A New Water-Management Tool," *California Agriculture* 31(5):18 (1977).
457. Emanuel Epstein et al., "Crop Production in Arid and Semi-Arid Regions Using Saline Water," prepared for the National Science Foundation (University of California, Davis), p. 41.

458. Jean L. Marx, "Plants: Can They Live in Salt Water and Like It?" *Science* 206:1169 (1979).
459. Jerome S. Horton and C. J. Campbell, *Management of Phreatophyte and Riparian Vegetation for Maximum Multiple Use Values,* RM-117 (Washington, D.C.: U.S. Forest Service, 1974), p. 2.
460. Bureau of Reclamation, *supra* note 446, at 21.
461. *Id.* pp. 21-22.
462. Harold A. Paulsen, Jr., *Range Management in the Central and Southern Rocky Mountains,* RM-154 (Washington, D.C.: U.S. Forest Service, 1975), pp. 14-17.
463. Rocky Mountain Forest and Range Experiment Station, *A List of Published Research, April 1, 1972 through March 31, 1976,* RM-31 (Ft. Collins, Colo.: U.S. Forest Service, 1976), pp. 15-25, 33-36; Dwight R. Cable, *Range Management in the Chaparral Type and Its Ecological Basis: The Status of Our Knowledge,* RM-155 (Ft. Collins, Colo.: U.S. Forest Service, 1975); S. Clark Martin, *Ecology and Management of Southwestern Semidesert Grass Shrub Ranges: The Status of Our Knowledge,* RM-156 (Ft. Collins, Colo.: U.S. Forest Service, 1975); H. W. Springfield, *Characteristics and Management of Southwestern Pinyon-Juniper Ranges: The Status of Our Knowledge,* RM-160 (Ft. Collins, Colo.: U.S. Forest Service 1976).
464. David L. Sturgis, *Hydrolic Relations on Undisturbed and Converted Big Sagebrush Lands: The Status of Our Knowledge,* RM-140 (Ft. Collins, Colo.: U.S. Forest Service, 1975), pp. 12-13.
465. Bill Mollison, U.S. Department of the Interior, Washington, D.C., interview with author, July 3, 1980.
466. Jeffrey Smith, "EPA Halts Most Use of Herbicide 2,4,5-T," *Science* 203:1090-91 (1979); Thomas Whiteside, *The New Yorker,* April 10, 1979, pp. 100-101.
467. Whiteside, *supra* note 466.
468. Kelso et al., *supra* note 281.
469. *Id.* p. 234.
470. *Id.* pp. 251-52.
471. Abbey, *supra* note 386, at 303.
472. *Id.* p. 301.
473. *Id.* p. 303.
474. GAO, *supra* note 95, at 3-4.
475. *Id.* pp. 6-7.
476. *Id.* p. 18.
477. *Id.* pp. 99-105.
478. *Id.* p. 101.
479. *Id.* p. 104.
480. Jamail et al., *supra* note 85, at 56.
481. U.S. Department of Agriculture and Council on Environmental Quality, *National Agricultural Lands Study: Final Report* (Washington, D.C., 1981), pp. v-xvi, 13-17.

A BIBLIOGRAPHY ON THE EFFECTS OF LIVESTOCK GRAZING ON SOILS, VEGETATION, AND WILDLIFE*

Prepared by Robert H. Webb for the U.S. Department of the Interior

Alderfer, R.B. and Robinson, R.R. (1947). Runoff from pastures in relation to grazing intensity and soil compaction. *J. Amer. Soc. Agron.* 29:948-958.

Bement, R.E. (1968). Plains pricklypear: relation to grazing intensity and blue grama yield on central Great Plains. *J. Range Manage.* 21:83-86.

Berry, K.H. (1978). Livestock grazing and the desert tortoise. Trans. 43rd N. Amer. Wildl. Natur. Resources Conf., pp. 505-519.

Black, H.L. and Frischknecht, N.C. (1971). Relative abundance of mice on seeded sagebrush-grass range in relation to grazing. USDA Forest Serv. Res. Note INT-147. 8 pp.

Blaisdell, J.P. and Pechanec, J.F. (1949). Effects of herbage removal at various dates on vigor of bluebunch wheatgrass and arrowleaf balsamroot. *Ecology* 30(3):298-305.

Blydenstein, J., Hungerford, C.R., Day, G.I. and Humphrey, R.R. (1957). Effect of domestic livestock exclusion on vegetation in the Sonoran Desert. *Ecology* 38(3):522-526.

Branscomb, B.L. (1958). Shrub invasion of a southern New Mexico desert grassland range. *J. Range Manage.* 11(3):129-132.

Brown, A.L. (1950). Shrub invasion of southern Arizona desert grassland. *J. Range Manage.* 3(3):172-177.

Brown, D.E. (1978). Grazing, grassland cover and gamebirds. Trans. 43rd N. Amer. Wildl. Natur. Resources Conf.: 447-485.

Brown, J.W. and Schuster, J.L. (1969). Effects of grazing on a hardland site in the southern High Plains. *J. Range Manage.* 22(6):418-423.

Bryan, K. (1928). Change in plant associations by change in ground water level. *Ecology* 9(4):474-478.

Buffington, L.C. and Herbel, C.H. (1965). Vegetational changes on a semidesert grassland range from 1858-1963. *Ecol. Monogr.* 35(2):139-164.

Busack, S.D. and Bury, R.B. (1974). Some effects of off-road vehicles and

*In its original form, the bibliography is annotated. Here only the sources are reproduced.

sheep grazing on lizard populations in the Mojave Desert. *Biol. Conserv.* 6(3):79-130.

Charley, J.L. and Cowling, S.W. (1968). Changes in soil nutrient status resulting from overgrazing and their consequences in plant communities of semi-arid areas. *Proc. Ecol. Soc. Austrailia* 3:28-38.

Cook, C.W. and Child, R.D. (1971). Recovery of desert plants in various states of vigor. *J. Range Manage.* 24(5):339-343.

Cook, C.W. and Stoddart, L.A. (1963). The effect of intensity and season of use on the vigor of desert range plants. *J. Range Manage.* 16(6):315-317.

Cook, C.W., Stoddart, L.A. and Kinsinger, F.E. (1958). Responses of crested wheatgrass to various clipping treatments. *Ecol. Monogr.* 28(3):327-272.

Costello, D.F. and Turner, G.T. (1941). Vegetation changes following exclusion of livestock from grazed ranges. *J. Forestry* 39:310-315.

Cottam, W.P. and Evans, R.F. (1965). A comparative study of the vegetation of grazed and ungrazed canyons of the Wasatch Range, Utah. *Ecology* 26(2):171-181.

Cottam, W.P. and Stewart, G. (1940). Plant succession as a result of grazing and meadow desiccation since settlement in 1862. *J. Forestry* 38(8):613-626.

Council for Agricultural Science and Technology. (1974). Livestock grazing on federal lands in the 11 western states. *J. Range Manage.* 27(3):174-181.

Currie, P.O. and Goodwin, D.L. (1966). Consumption of forage by black-tailed jackrabbits on salt-desert ranges of Utah. *J. Range Manage.* 30(2):304-311.

Currie, P.D., Reichert, D.W., Malechek, J.C. and Wallmo, O.C. (1977). Forage selection comparisons for mule deer and cattle under managed ponderosa pine. *J. Range Manage.* 30(5):352-356.

Daubenmire, R.F. (1940). Plant succession due to overgrazing in the *Agropyron* bunchgrass prairie of southeastern Washington. *Ecology* 21(1):55-64.

Daubenmire, R.F. and Colwell, W.E. (1942). Some edaphic changes due to overgrazing in the *Agropyron-Poa* prairie of southeastern Washington. *Ecology* 23(1):32-40.

Dean, R., Ellis, J.E., Rice, R.W. and Bement, R.E. (1975). Nutrient removal by cattle from a shortgrass prairie. *J. Appl. Ecology* 12:25-29.

Donart, G.B. and Cook, C.W. (1970). Carbohydrate reserve content of mountain plants following defoliation and regrowth. *J. Range Manage.* 23:15-19.

Drew, W.B. (1947). Floristic composition of grazed and ungrazed prairie vegetation in north central Missouri. *Ecology* 28:26-41.

Duce, J.T. (1918). The effect of cattle on the erosion of canyon bottoms. *Science* 47:450-452.

Dunford, E.G. (1954). Surface runoff and erosion from pine grasslands of the Colorado Front Range. *J. Forestry* 52:923-927.

Dusek, G.L. (1975). Range relations of mule deer and cattle in prairie habitat. *J. Wildl. Manage.* 39(3):605-616.

Edmond, D.B. (1958a). Some effects of soil physical condition on ryegrass growth. *N.Z. J. Agri. Res.* 1:652–659.

———. (1958b). The influence of treading on pasture: a preliminary study. *N.Z. J. Agri. Res.* 1:319–328.

———. (1962). Effects of treading pasture in summer under different soil moisture levels. *N.Z. J. Agri. Res.* 5:389–395.

———. (1964). Some effects of sheep treading on the growth of 10 pasture species. *N.Z. J. Agri. Res.* 7(1):1–16.

Evans, G.R. and Tisdale, E.W. (1972). Ecological charactristics of *Aristida longiseta* and *Agropyron spicatum* in west-central Idaho. *Ecology* 53(1):137–142.

Flinders, J.T. and Hansen, R.M. (1975). Spring population responses of cottontails and jackrabbits to cattle grazing on shortgrass prairie. *J. Range Manage.* 28(4):290–293.

Frischknecht, N.C. and Baker, M.F. (1972). Voles can improve sagebrush rangelands. *J. Range Manage.* 25(6):466–468.

Gardner, J.L. (1950). Effects of thirty years of protection from grazing in desert grassland. *Ecology* 31(1):44–50.

———. (1951). Vegetation of the creosotebush area of the Rio Grande Valley in New Mexico. *Ecol. Monogr.* 21:379–403.

Gifford, G.L. and Hawkings, R.H. (1978). Hydrologic impact of grazing on infiltration: a critical review. *Water Resources Research* 14(2):305–313.

Gjersing, F.M. (1975). Waterfowl production in relation to rest-rotation grazing. *J. Range Manage.* 28(1):37–42.

Grelen, H.E. and Thomas, G.W. (1957). Livestock and deer activities on the Edwards Plateau of Texas. *J. Range Manage.* 10(1):34–37.

Hansen, R.M. and Gold, I.K. (1977). Blacktail prairie dogs, desert cottontails, and cattle trophic relations on shortgrass range. *J. Range Manage.* 30(3):210–214.

Hanson, W.R. and Stoddart, L.A. (1940). Effects of grazing upon bunch wheat grass. *J. Amer. Soc. Agron.* 32(4):278–289.

Haskell, H.S. (1945). Successional trends on a conservatively grazed desert grassland range. *J. Amer. Soc. Agron.* 37(12):978–990.

Herbel, C.H. (1955). Range conservation and season-long grazing. *J. Range Manage.* 8(5):204–205.

Houston, W.R. (1963). Plains prickly pear, weather, and grazing in the northern Great Plains, *Ecology* 44(3):569–574.

Howard, W.E., Wagnon, K.A. and Bentley, J.R. (1959). Competition between ground squirrels and cattle for range forage. *J. Range Manage.* 12(3):110–115.

Hubbard, R.E. and Hansen, R.M. (1976). Diets of wild horses, cattle, and mule deer in the Piceance Basin, Colorado. *J. Range Manage.* 29(5):389–392.

Humphrey, R.R. (1968). The desert grassland: a history of vegetational change and an analysis of causes. University of Arizona Press, 74 pp.

Humphrey, R.R. and Mehrhoff, L.A. (1958). Vegetation changes on a southern Arizona grassland range. *Ecology* 39(4):720–726.

Johnson, A. (1962). Effects of grazing intensity and cover on the water-intake rate of fescue grassland. *J. Range Manage.* 15:79–82.

Johnson, W.M. (1956). The effect of grazing intensity on plant composition, vigor, and growth of pine-bunchgrass ranges in central Colorado. *Ecology* 37(4):790–798.

Julander, O. (1962). Range Management in relation to mule deer habitat and herd productivity in Utah. *J. Range Manage.* 15(5):278–281.

Julander, O. and Jeffrey, D.W. (1964). Deer, elk, and cattle range relations on summer range in Utah. *Trans. N. Amer. Wildl. Natur. Resour. Conf.* 29:404–414.

Julander, O. and Robinette, W.L. (1950). Deer and cattle range relationships on Oak Creek range in Utah. *J. Forestry* 48:410–415.

Julander, O., Robinette, W.L. and Jones, D.A. (1961). Relation of summer range condition to mule deer herd productivity. *J. Wildl. Manage.* 25(1):54–60.

Kirsch, D.M. (1969). Waterfowl production in relation to grazing. *J. Wildl. Manage.* 33(4):821–828.

Klemnedson, J.D. (1956). Interrelations of vegetation, soils, and range conditions induced by grazing. *J. Range Manage.* 9(3):134–138.

Knipe, O.D. (1971). Watershed cover and forage utilization. In Lusby, G.C., Reid, V.H. and Knipe, D. (eds.). Effects of grazing on the hydrology and biology of the Badger Wash basin in western Colorado, 1953-1966. U.S. Geological Survey Water-Supply Paper 1532-D, pp. D16–D24.

Knoll, G. and Hopkins, H.H. (1959). The effects of grazing and trampling upon certain soil properties. *Trans. Kansas Acad. Sci.* 62(4):221–231.

Krueger, W.C. and Winward, A.H. (1974). Influence of cattle and big game grazing on understory structure of a Douglas fir-ponderosa pine-Kentucky bluegrass community. *J. Range Manage.* 27(6):450–453.

Larson, F. (1940). The role of bison in maintaining the short grass plains. *Ecology* 21(2):113–121.

Larson, F. and Whitman, W. (1942). A comparison of used and unused grassland and mesas in the badlands of South Dakota. *Ecology* 23(4):438–445.

Launchbaugh, J.L. (1955). Vegetational changes in the San Antonio prairie associated with grazing, retirement from grazing and abandonment from grazing and abandonment from cultivation. *Ecol. Monogr.* 25:39–57.

Laycock, W.A. (1967). How heavy grazing and protection affect sagebrush-grass ranges. *J. Range Manage.* 20(4):206–213.

Leopold, A. (1921). A plea for recognition of artificial works in forest erosion control policy. *J. Forestry* 19:267–273.

Longhurst, W.M. (1957). A history of squirrel burrow gully formation in relation to grazing. *J. Range Manage.* 10(4):182–184.

Lowrie, D.C. (1963). Effects of grazing and intensive collecting on a population of the Green Lynx spider. *Ecology* 44(4):77–781.

Lull, H.K. (1959). Soil compaction on forest and range lands. U.S. Forest

Lusby, G.C. (1961). Hydrology of small grazed and ungrazed drainage basins, Badger Wash area, western Colorado. U.S. Geological Survey Research Article 59. pp. B141-B143.

———. (1971). Precipitation, runoff, erosion, and sediment yield. In Lusby, G.C., Reid, V.H. and Knipe, D. (eds.). Effects of grazing on the hydrology and biology of the Badger Wash basin, western Colorado 1953-1966. U.S. Geological Survey Water-Supply Paper 1532-D. pp. D24-D50.

Marquiss, R. and Lang, R. (1959). Vegetational composition and ground cover of two natural relict areas and their associated grazed areas in the Red Desert of Wyoming. *J. Range Manage.* 12(3):104-109.

McCarty, M.K. and Mazurak, A.P. (1976). Soil compaction in eastern Nebraska after 25 years of cattle grazing management and weed control. *J. Range Manage.* 29(5):384-386.

McLean, A. and Tisdale, E.W. (1972). Recovery rate of depleted range sites under protection from grazing. *J. Range Manage.* 25(3):178-184.

Morris, M.G. (1967). Differences between the invertebrate faunas of grazed and ungrazed chalk grassland. I. Responses of some phytophagous insects to cessation of grazing. *J. Appl. Ecology* 4:459-474.

———. (1968). Differences between the invertebrate faunas of grazed and ungrazed chalk grassland. II. The sample turves. *J. Appl. Ecology* 5:601-612.

———. (1969a). Differences between the invertebrate faunas of grazed and ungrazed chalk grassland. III. The Heteropterous fauna. *J. Appl. Ecology* 6:475-487.

———. (1969b.) Populations of invertebrate animals and the management of chalk grassland in Britain. *Biol. Conserv.* 1(3):225-231.

———. (1971). Differences between the invertebrate faunas of grazed and ungrazed chalk grassland. *J. Appl. Ecology* 8:37-52.

———. (1973). The effects of seasonal grazing on the Heteroptera and Auchenorhyncha (Hemiptera) of chalk grassland. *J. Appl. Ecol.* 10:761-780.

Mueggler, W.F. (1950). Effects of spring and fall grazing by sheep on vegetation of the upper Snake River Plains. *J. Range Manage.* 3(4):308-315.

Mundinger, J.G. (1976). Waterfowl response to rest-rotation grazing. *J. Wildl. Manage.* 40(1):60-68.

Norris, J.J. (1950). Effect of rodents, rabbits, and cattle on two vegetation types in semidesert range land. *Ariz. Agri. Expt. Sta. Tech. Bull.* 353. 23 pp.

Norton, B.E. (1975). Effects of grazing on desert vegetation. OS/IBP Desert Biome Res. Memo. 75-50, Utah State Univ., Logan. 6 pp.

Olsen, F.W. and Hansen, F.W. (1977). Food relations of wild free-roaming horses to livestock and big game, Red Desert, Wyoming. *J. Range Manage.* 30(1):17-20.

Orr, H.K. (1975). Recovery from soil compaction on bluegrass range in the Black Hills. *Trans Amer. Soc. Agri. Engr.* 8(6):1076-1081.

Peden, D.G., Van Dyne, G.M., Rice, R.W., and Hansen, R.M. (1974). The trophic ecology of *Bison bison* L. on shortgrass plains. *J. Appl. Ecol.* 11:489-497.

Peek, J.M., Johnson, R.D., and Pence, N.N. (1978). Successional trends in a ponderosa pinebitterbrush community related to grazing by livestock, wildlife, and to fire. *J. Range Manage.* 31(1):49-53.

Phillips, P. (1939). The distribution of rodents in overgrazed and normal grasslands of central Oklahoma. *Ecology* 17(4):673-679.

Pickford, G.D. (1932). The influence of continued heavy grazing and of promiscuous burning on spring-fall ranges in Utah. *Ecology* 13(2):159-171.

Pieper, R.D. (1968). Comparison of vegetation on grazed and ungrazed pinyon-juniper grassland sites in southcentral New Mexico. *J. Range Manage.* 21(1):51-53.

Potter, L.D. and Krenetsky, J.C. (1967). Plant succession with released grazing on New Mexico range land. *J. Range Manage.* 20(3):145-151.

Ratliff, R.D. and Reppert, J.N. (1974). Vigor of Idaho fescue grazed under rest-rotation and continuous grazing. *J. Range Manage.* 27(6):447-449.

Rauzi, F. (1963). Water intake and plant composition as affected by differential grazing on rangeland. *J. Soil Water Conserv.* 18:114-116.

Rauzi, F. and Smith, F.M. (1973). Infiltration rates: three soils with three grazing levels in northeastern Colorado. *J. Range Manage.* 26(2):126-129.

Reid, V.H. (1971). Trends in small-mammal populations. In Lusby, G.C., Reid, V.H. and Knipe, D. (eds.). Effects of grazing on the hydrologyand biology of the Badger Wash Basin in western Colorado, 1953-196. U.S. Geological Survey Water-Supply Paper 1532-D. pp. D50-D65.

Reynolds, H.G. (1958). The ecology of the Merriam Kangaroo rat (*Dipodomys merriami* Mearns) on the grazing lands of southern Arizona. *Ecol. Monogr.* 28(2):111-127.

Rich, L.R. and Reynolds, H.G. (1963). Grazing in relation to runoff and erosion on some chaparral watersheds in central Arizona. *J. Range Manage.* 6:322-326.

Richens, V.B. (1967). Characteristics of mule deer herds and their range in northeastern Utah. *J. Wildl. Manage.* 31(4):651-666.

Robertson, J.H. and Kennedy, P.B. (1954). Half-century changes on northern Nevada ranges. *J. Range Manage.* 7(3):117-121.

Robinson, R.R. and Alderfer, R.B. (1952). Runoff from permanent pastures in Pennsylvania. *Agron. J.* 44(9):459-462.

Rummel, R.S. (1951). Some effects of livestock grazing on ponderosa pine forest and range in central Washington. *Ecology* 32(4):594-607.

Schuster, J.L. (1964). Root development of native plants under three grazing intensities. *Ecology* 45(1):63-70.

Severson, K.E. and May, M. (1967). Food preferences of antelope and domestic sheep in Wyoming's Red Desert. *J. Range Manage.* 20(1):21-25.

Sharp, A.L., Bond, J.J., Neuberger, J.W., Kuhlman, A.R. and Lewis, J.K.

(1964). Runoff as affected by intensity of grazing on rangeland. *J. Soil Water Conserv.* 19:103–106.

Short, H.L. (1977). Food habits of mule deer in a semidesert grass-shrub habitat. *J. Range Manage.* 30(3):206–209.

Shreve, F. and Hinckley, A.L. (1937). Thirty years of change in desert vegetation. *Ecology* 18(4):463–478.

Smith, A.D. (1949). Effects of mule deer and livestock upon a foothill range in northern Utah. *J. Wildl. Manage.* 13(4):421–423.

Smith, D.A. and Schmutz, E.M. (1975). Vegetative changes on protected versus grazed desert grassland ranges in Arizona. *J. Range Manage.* 28(6):453–458.

Smith, J.G. and Julander, O. (1953). Deer and sheep competition in Utah. *J. Wildl. Manage.* 17(2):101–112.

Smoliak, S. (1965). A comparison of ungrazed and lightly grazed *Stipa Bouteloua* prairie in southeastern Alberta. *Can. J. Plant Sci.* 45:270–275.

Tanner, C.B. and Mamaril, C.P. (1959). Pasture soil compaction by animal traffic. *Agron. J.* 51(5):329–331.

Taylor, W.P., Vorhis, C.T. and Lister, P.B. (1935). The relation of jack rabbits to grazing in southern Arizona. *J. Forestry* 33:490–498.

Trumble, H.C. and Woodroffe, K (1954). The influence of climatic factors on the reaction of desert shrubs to grazing by sheep. In Cloudsley-Thompson, J.L. (ed.). The biology of deserts. London, The Institute of Biology. pp. 129–147.

Turner, G.T. (1971). Soil and grazing influences on a salt-desert shrub range in western Colorado. *J. Range Manage.* 24(1):31–37.

Turner, G.T. and Costello, D.F. (1942). Ecological aspects of the prickly pear problem in eastern Colorado and Wyoming. *Ecology* 23(4):419–426.

Van Dyne, G.M. and Vogel, W.G. (1967). Relation of *Selaginella densa* to site, grazing, and climate. *Ecology* 48(3):438–444.

Vogel, W.G. and Van Dyne, G.M. (1965). Vegetation responses to grazing management on a foothill sheep range. *J. Range Manage.* 19:80–85.

Vorhies, C.T. and Taylor, W.P. (1933). The life histories and ecology of jack rabbits, *Lepus Alleni* and *Lepus californicus* ssp. in relation to grazing in Arizona. *Univ. Ariz. Agric. Expt. Sta. Tech. Bull.* 49:471–587.

Weaver, J.E. and Albertson, F.W. (1940). Deterioration of midwestern ranges. *Ecology* 21(2):216–236.

Webb, R.H. and Stielstra, S.S. (1979). Some effects of sheep grazing on Mojave Desert vegetation and soils. *Environ. Manage.* 3:517–529.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1981 334-983/8306