Chapter II

Land productivity Problems

“Shoestring” erosion on very poor condition rangeland

Photo credits: USDA—Soil Conservation Service

Row erosion **in cornfield caused** by **heavy** rains

Contents

List of Tables

List of Figures

Chapter II

Land Productivity Problems

A variety of processes can damage the productivity of the Nation’s croplands and rangelands. The greatest threat to land productivity is erosion, but other influences can also be important. Compaction and inadequate drainage can reduce crop yields. Salinization can force lands out of production. Withdrawing too much water from ground water supplies can limit future agriculture. Land subsidence, whether related to ground water withdrawal or other factors, can harm productivity with no hope for restoration.

SOIL EROSION

Congress first appropriated funds to study soil erosion in 1928. Research stations were established and both the process of erosion and its effects on crop yields were studied extensively. By the early 1950’s, many studies indicated how much yields would be reduced with each inch of topsoil lost. U.S. Department of Agriculture (USDA) officials, judging the data *to* be adequate on that aspect of the problem, closed out most of the research on how erosion affects yields. But because there has since been a revolution in agricultural methods, the old data on yield reductions are inadequate for decisionmaking by Government or individual farmers.

Research on the causes and rates of erosion and on techniques for controlling erosion did continue after the closing of the erosion research stations, as much because of concern about erosion-caused water pollution as because of concern about agricultural productivity, Thus, much is known about methods and direct costs of controlling erosion, but very little about the benefits of such investments or, conversely, about the short- and long-term costs of allowing erosion to continue at its present accelerated rates.

The Mechanics of Soil Erosion

Water and wind cause soil erosion. The force of raindrops striking exposed earth detaches soil particles, which are then carried away if the water runs off the surface rather than soaking into the soil, Even without the force of raindrop splashes, runoff water can detach and carry away soil. Thus, the exposure of bare soil and the rates and volumes of overland waterflow are the critical factors in water-caused erosion.

There are four major categories of water-caused erosion: 1) sheet erosion is the removal of a soil layer of fairly uniform thickness by runoff water; 2) rill erosion occurs as small channels form on the soil surface; 3) gully erosion is an advanced state of rill erosion, where the channels become deeper than 1ft; and 4) streambank erosion is the process of stream widening. Of these types, sheet and rill erosion cause the most damage.

Most serious erosion by water occurs where land has one or more of the following characteristics, and erosion control generally involves modifying these:

- steep slopes or long slopes that allow runoff water to gain momentum;
- Ž exposure of tilled, bare soil without protection by cover crops or organic residue, This often occurs between the harvesting of one crop and the establishment of the next crop’s leaf canopy;
- row crops alined up and down steep or moderate slopes;
- runoff from upslope pastures flowing across cropland;

- poor water absorption and poor drainage that result in less water entering the soil and more water running off;
- poor stands of low-quality vegetation; and
- lack of vegetation along streams.

Wind causes erosion when it blows across poorly protected soil with enough force to lift and move soil particles. Drier and more finely granulated soil is more susceptible to wind erosion. Since soil is driest and vegetation poorest during droughts, which are characteristic of the Great Plains and Western States, this is where the highest wind erosion rates occur. As recently as 1977 several drought-stricken regions experienced severe duststorms. Soil surfaces stripped of vegetation for dryland farming and overgrazed rangeland provided much of the soil for these recent storms (Wilshire, et al., 1980) as they did for the infamous dust bowl storms during the prolonged drought of the 1930's.

Although eroded soil is commonly described as "lost," it does not in fact vanish, Much of the soil moved by water remains in the same field, but farther down the slope. The portion of the soil that is actually lost from cropland or forage-producing land varies from one site to the next, depending on the shape of the slopes and other factors. (On the average, about one-fourth of the cropland soil moved by water erosion each year becomes sediment in streams and about 8 percent reaches the ocean (Miller, 1981). The fate of wind-carried soil is less well-known, but the reported wind erosion rates do not always represent net losses from the affected region.

With both wind and water erosion, the material that is most likely to be lost is the best part of the soil: water soluble plant nutrients, lightweight organic matter, and tiny clay particles, which have the highest ability to store fertilizers and naturally occurring nutrients. These are moved first and farthest by both wind and water erosion.

The soil that moves downslope in the field is less fertile and more subject to drought than it was before it was moved. How croplands and rangelands are generally affected by deposits of such soil is not well understood. Nutrients transported with the eroded soil may benefit the site where the soil is deposited, but, conversely, superior soils may be buried by inferior material. Further, drainage can be impeded by deposited soil and soil particles carried by the wind can severely damage vegetation and cause partial or complete loss of crops.

Erosion is a self-reinforcing process, It lowers the fertility and water-holding capacity of the soil by removing nutrients and organic matter. As a consequence, plant growth is less and the soil is less protected. So the erosion accelerates more and more, unless the cycle is broken by a change in farming practices or a change in land use.

Estimating Soil Erosion Rates

The universal soil loss equation (USLE) relates measurements of five variables to estimate water-caused sheet and rill erosion. The variables are: precipitation; erosion potential of the soil type (which depends on texture, structure, and organic matter content); length and steepness of slope; type of plant cover and management conditions (tillage); and supporting practices for erosion control (e. g., terraces, contour farming, and stripcropping).

Research on USLE began in the 1940's, and by 1965 Soil Conservation Service (SCS) personnel were able to use it to estimate sheet and rill erosion rates accurately on most unirrigated croplands and to predict how erosion would be affected by changes in management or by specific conservation measures. Since 1965, more sophisticated computer models have been developed for more precise estimates, but USLE remains the most important technique because it is based on a pragmatic set of measurements and the calculations can be done on site. USLE has been adapted for erosion estimates on other land uses, but still needs refinement for conditions such as irrigated land and for atypical sites where soils are highly weathered (e.g., the Caribbean islands), poorly drained with long slopes (e. g., the Mississippi Delta), or where precipitation is atypical (as in parts of the Western States where most erosion is caused by snowmelt runoff). Recently, USDA increased the research budget for the soils laboratory at Purdue University to further refine US LE.

A similar equation to estimate wind erosion (WEQ) uses measurements of five variables: soil erodability, soil ridge roughness, climate, width of field, and vegetative cover. Estimates from WEQ are not considered to be as accurate as the USLE estimates and fewer SCS personnel are expert in its use, Consequently, wind erosion data are lacking for much of the United States.

USLE and WEQ have vastly improved the reliability of erosion data for every level of conservation decisionmaking. Conservation plans for specific farms rely heavily on erosion rate predictions to indicate the appropriate level of management conservation structure investment, At the regional and national level, the equations are now used in the National Resource Inventory INRI) conducted periodically by SCS to collect information for Government policymaking.

The accuracy of the NRI data depends not only on the USLE and WEQ equations but also on the design of the sample survey that determines what fields are measured for the inventory. The first year that the equations were providing accurate estimates for the national survey was 1967, but the sampling procedure was flawed and the 1967 data are not considered to be reliable for comparison to more recent data. The 1977 NRI was the first national survey to use a valid sampling procedure and the modern equations. The next NRI is under way in 1982. Until the 1982 data are available, the only reliable set of data on erosion rates at the national scale are from the 1977 NRI.

The 1977 NRI data are considered accurate estimates of sheet and rill erosion on croplands and pasturelands for most States, rough estimates of sheet and rill erosion on rangelands in the Western States, and fair estimates of wind erosion in the 10 Great Plains States. Wind erosion in the other States and gully and streambank erosion in general are not well covered by that NRI. The 1982 NRI will improve on those weaknesses, and the data for sheet and rill erosion are expected to be comparable for the two surveys. Unless otherwise indicated, erosion rates cited in this report refer to the NRI estimated amount of soil eroded (in tons per acre) in 1977.

Magnitude of Soil Erosion

Water-caused erosion on non-Federal land totals about 5 billion tons per year. Of that, 5 percent is from roads and construction sites, 6 percent from gullies, 11 percent from streambanks, 3 percent is sheet and rill from pastureland, 8 percent is sheet and rill erosion from rangelands, 38 percent is sheet and rill erosion from croplands, and the remaining 29 percent is sheet and rill erosion from forests and other land. Thus, the greatest sheet and rill erosion occurs on the 413 million acres of cropland.

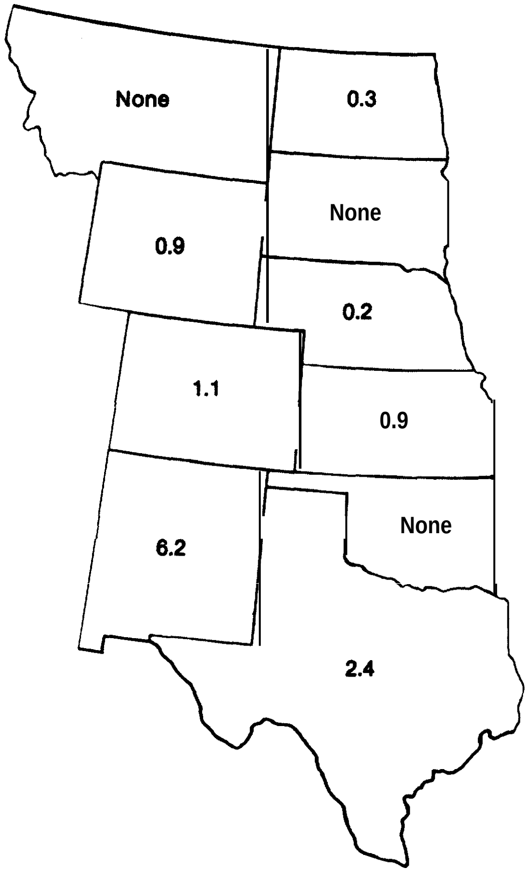
No similar national data exist on wind-caused erosion. For the 10 Great Plains States where the wind erosion is greatest, an estimated 1.5 billion tons of soil are moved by the wind each year (fig, 1). Of that, 45 percent is from the 10 States’ rangelands, and 55 percent is from the croplands (table 1).

Cropland

Erosion occurs on nearly all the Nation’s 413 million acres of cropland, but a high proportion of both water- and wind-caused erosion is concentrated on a relatively small proportion of the land. The national average sheet and rill erosion rate on cropland is 4.7 tons per acre (USDA, NRI, 1980), but much of the land is eroding more slowly than this. Half the cropland has sheet and rill erosion rates of 2 tons per acre or less. At the same time, the most rapidly eroding 2 percent of the land has erosion rates over 30 tons per acre and accounts for 25 percent of all the sheet and rill erosion from cropland (see table 2).

The distribution of wind erosion over the landscape is similarly uneven. In the Great Plains States, wind erosion on croplands averages 5.3 tons per acre, but some 53 percent of

Figure 1.—Average Annual Wind Erosion (tons per acre) on Non-Federal Rangeland in the Great Plains States



NOTE The average is 18 tons per acre

SOURCE: 1977 National Resource Inventories

the erosion occurs on 9 percent of the land. This highly fragile cropland erodes at rates over 14 tons per acre.

Pastureland

pasture is land where planted grasses, legumes, or other herbs are managed to produce forage. It is seldom tilled, so it has a perennial vegetative cover. Because the land must be relatively well watered to repay the investment in management, the vegetative cover is typically abundant enough to protect the land from accelerated erosion. Thus, the national average erosion rate on pastureland is 2.6 tons per acre. Higher rates of pastureland erosion that do occur are concentrated on a relatively small part of the land, where poor management, steep slope, low moisture-holding capacity or drought are typical. Most of the pastureland has sheet and rill erosion rates below 2 tons, while the 11 percent of the land with rates over 5 tons accounts for half of the total sheet and rill erosion on pastureland. Wind erosion on pastureland is generally insignificant, but damage is reported occasionally, especially where overgrazing or drought destroys the plant cover (table 3).

Approximately half the grazing capacity of private lands in the United States is on pasture. Erosion threatens relatively little of this land, but improved management—more fertilizing, liming, reseeding, and better livestock management—could increase forage production by as

Table 1.–Wind Erosion on Cropland and Rangeland[a] in the Great Plains States, 1977

	Cropland				Rangeland[a]				
	Erosion, tons per acre per year				Erosion, tons per acre per year				
State	2	2-4.9	5-14	14	2	2-4.9	5-14	14	Total
			(1,000 acres)						
Colorado	4,849	1,788	2,037	2,419	23,258	55	82	406	34,894
Kansas	19,816	3,946	3,786	1,258	15,765	112	112	287	45,082
Montana	8,177	3,747	2,657	774	38,834	—	—	—	54,189
Nebraska	17,698	1,625	1,016	360	21,626	234	46	95	42,700
New Mexico	720	346	659	557	27,316	4,841	5,282	4,657	44,378
North Dakota	18,719	5,598	2,486	110	10,393	48	58	65	37,477
Oklahoma	8,233	1,379	1,543	628	14,537	15	14	–	26,349
South Dakota	9,873	5,620	2,356	343	22,191	7	—	—	40,354
Texas	12,982	1,962	6,249	9,246	85,749	2,539	2,784	4,329	125,840
Wyoming	2,112	271	527	60	24,947	403	281	538	29,139
Grand total	103,179	26,282	23,316	15,755	284,616	8,254	8,659	10,377	480,402

[a] Non. Federal rangeland Only.

SOURCE: 1977 National Resource Inventories

Table 2.—Annual Sheet and Rill Erosion on Cropland and the Amount of Erosion in Excess of 5 Tons per Acre, by Erosion Interval, 1977

Erosion interval (tons per acre)	Total acres (millions)	Cumulative percentage of acreage	Total sheet and rill erosion (millions of tons)	Cumulative percentage of erosion	Total erosion in excess of 5 tons per acre (millions of tons)	Cumulative percentageof erosion in excess of 5 tons per acre
0-1	131.6	31.8	49.2	2.6	0.0	0.0
1-2	74.6	49.8	110.6	8.3	0.0	0.0
2-3	51.5	62.3	127.5	14.9	0.0	0.0
3-4	35.9	71.0	125.0	21.4	0.0	0.0
4-5	26.0	77.3	116.3	27,4	0.0	0.0
5-6	17.6	81.6	96.2	32.4	8.2	0.9
6-7	12,6	84.6	81.8	36.6	18.6	2.9
7-8	9.3	86.9	69.4	40,2	23.0	5.4
8-9	7,3	88.7	62.0	43.4	25.4	8.1
9-10	5.8	90.1	54.6	46,2	25.8	10.9
10-11	4,8	91.3	50.2	48,8	26.3	13.7
11-12	3.7	92.2	43.1	51.0	24.4	16.3
12-13	3.0	92.9	36.9	52.9	22,1	18.7
13-14	2.8	93.6	37.1	54.8	23.3	21.2
14-15	2.4	94.2	34.6	56.6	22.7	23.6
15-20	7.8	96.1	134.8	63.6	95.8	33.9
20-25	4.4	97.1	98.0	68.7	76.0	42.1
25-30	2.9	97.8	80.6	72.9	65.8	49.2
30-50	5,5	99.1	209.9	83.8	182.4	68.8
50-75	2,3	99.6	133.8	90.7	122.5	82.0
75-100	0.8	99.9	64.4	94.0	60.6	88.5
100+	0.7	100,0	109.8	100.0	106.3	100.0
Total,	413,3		1,925.8		929.2	

SOURCE 1977 National Resource Inventories

much as 50 percent (USDA, 1981) while reducing erosion. Unfortunately, a more likely scenario is that a significant part of the land used for pasture in 1977 will be converted to use for row crops and small grains, and that this shift will cause a significant increase in erosion on that land (Miller, 1981).

Rangeland

Rangeland is land where the natural plant cover of grass, forbs, or shrubs produces forage for livestock and wildlife, but where management is typically limited to manipulations of livestock grazing patterns. Reseeding, fertilization, tillage, and other inputs are uncommon. Erosion is the major force degrading the inherent productivity here, too.

Because rangeland is located in the arid and semiarid Western States and in Alaska, climatic limitations on plant growth make the land highly susceptible to any misuse that leaves the soil exposed to wind, rain, and snowmelt runoff. Overgrazing is the most common misuse of rangelands. It causes partial or complete destruction of the grass cover. The overall condition of U.S. rangeland is discussed in chapter III.

Sheet and rill erosion on the 414 million acres of non-Federal rangeland averages 2.8 tons per acre (see table 4 and fig. 2). As on croplands and pastureland, much of the erosion is concentrated on a relatively small part of the land. The sheet and rill erosion rate is over 5 tons on the most rapidly eroding 12 percent of the land. That 12 percent accounts for 57 percent of total sheet and rill erosion on non-Federal rangelands.

Neither is wind erosion evenly distributed on rangelands. Most non-Federal rangeland has wind erosion rates of less than 2 tons per acre, but the most susceptible 3 percent of the land, eroding at 14 tons and more per year, accounts for 31 percent of the total wind erosion.

Table 3.—Sheet and Rill Erosion on Pastureland, by State (excluding Alaska)

State	USLE, tons per acre per year			
	< 2	2-4.9	5-13.9	14+
	1,000 acres			
Alabama	3,681	321	120	—
Arizona	11	—	—	—
Arkansas	3,765	838	599	426
California	1,028	57	38	4
Colorado	1,317	128	107	46
Connecticut	103	6	3	·
Delaware	21		1	—
Florida	5,399	89	55	—
Georgia	2,960	221	40	13
Hawaii	596	201	113	82
Idaho	1,058	—	6	45
Illinois	2,013	412	350	295
Indiana	1,480	258	239	170
Iowa	3,101	678	573	178
Kansas	2,071	413	144	73
Kentucky	3,624	835	686	590
Louisiana	2,759	107	59	20
Maine	246	—	3	—
Maryland	388	60	25	13
Massachusetts	85	3	3	—
Michigan	1,116	76	24	14
Minnesota	2,752	77	44	16
Mississippi	2,994	589	279	179
Missouri	8,352	1,881	1,747	843
Montana	2,528	80	4	35
Nebraska	2,120	422	227	130
Nevada	260	—	38	·
New Hampshire	95	—	—	—
New Jersey	139	1	—	4
New Mexico	341	1	—	40
New York	2,050	130	75	31
North Carolina	1,607	252	163	8
North Dakota	1,514	30	—	—
Ohio	1,749	377	311	178
Oklahoma	7,064	1,132	440	77
Oregon	1,678	84	5	—
Pennsylvania	1,386	206	118	87
Rhode Island	16	2	—	—
South Carolina	1,185	28	24	5
South Dakota	2,384	21	8	—
Tennessee	3,920	964	405	185
Texas	15,942	1,780	857	189
Utah	580	46	—	—
Vermont	456	34	3	12
Virginia	2,114	475	434	251
Washington	1,215	21	16	—
West Virginia	835	351	486	365
Wisconsin	2,173	313	202	50
Wyoming	701	25	10	—
Total United States	104,972	14,026	9,084	4,654
Caribbean	289	107	173	294
Grand total	105,261	14.133	9.257	4,948

SOURCE 1977 National Resource Inventories.

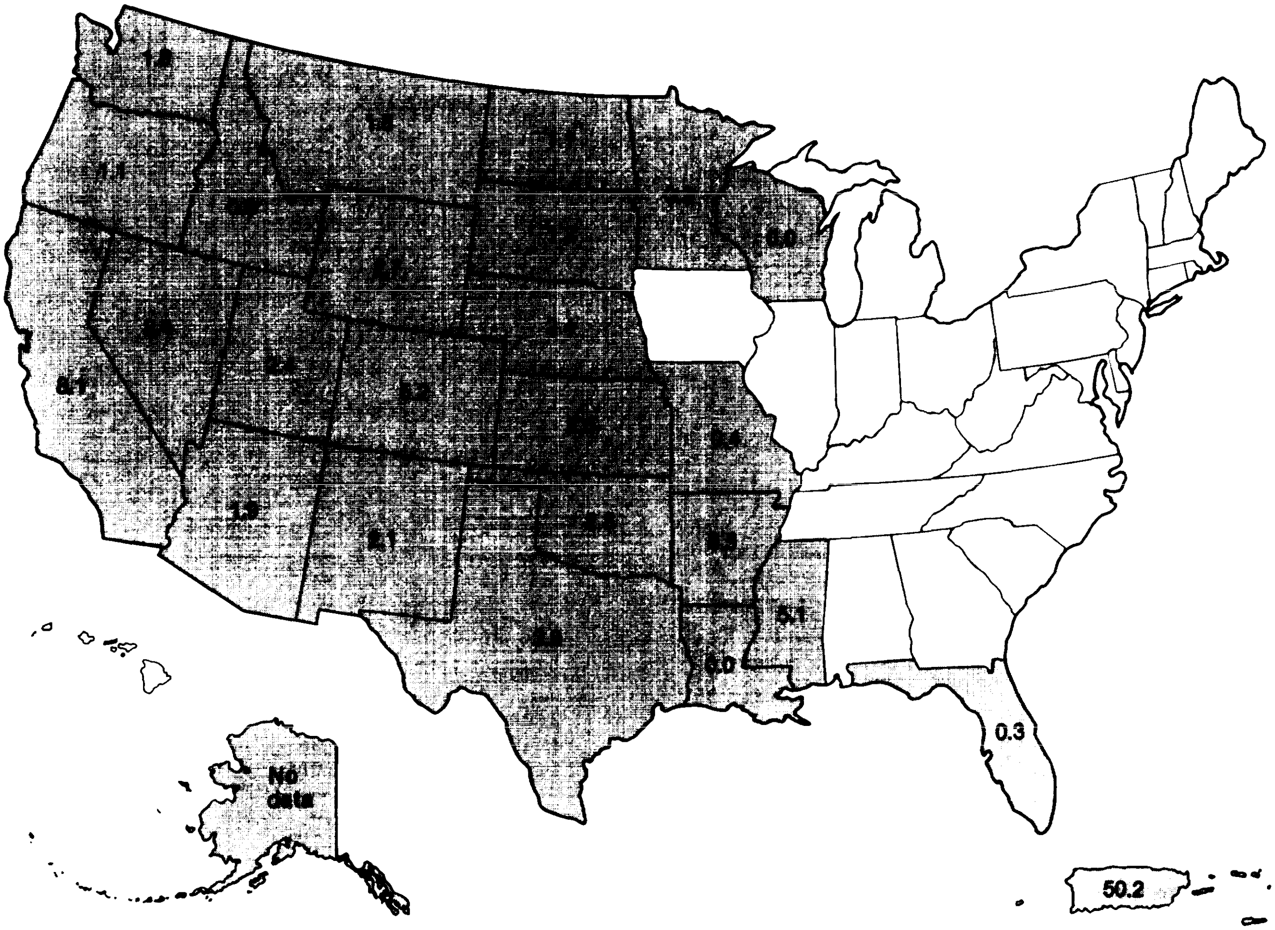
Table 4.—Sheet and Rill Erosion on Rangeland,[a] by State, 1977

State	Hangełanf’			
	Erosion, tons per **acre** per year			
	< 2	2-4.9	5-13.9	14+
	1,000 acres			
Alabama	—	—	—	—
Alaska	—	—	—	—
Arizona	25,544	5,417	3,981	149
Arkansas	90	61	53	44
California	9,607	2,439	3,049	2,459
Colorado	15,659	3,867	2,586	1,689
Connecticut	—	—	—	—
Delaware	—	—	—	—
Florida	3,002	15	—	—
Georgia	—	—	—	—
Hawaii	—	—	—	—
Idaho	6,315	171	89	14
Illinois	—	—	—	—
Indiana	—	—	—	—
Iowa	—	—	—	—
Kansas	11,692	2,470	1,643	471
Kentucky	—	—	—	—
Louisiana	326	—	—	—
Maine	—	—	—	—
Maryland	—	—	—	—
Massachusetts	—	—	—	—
Michigan,	—	—	—	—
Minnesota	110	—		—
Mississippi	15	10	—	5
Missouri	35	—	—	—
Montana	32,088	3,609	2,110	1,027
Nebraska	15,378	4,129	1,953	541
Nevada	4,970	1,1!39	1,074	108
New Hampshire	—	—	—	—
New Jersey	—	—	—	—
New Mexico	33,896	5,190	2,195	815
New York	—		—	—
North Carolina	—		—	—
North Dakota	9,736	394	229	205
Ohio	—	—	—	—
Oklahoma	10,954	2,095	1,095	422
Oregon	8,615	1,195	285	15
Pennsylvania	—	—	—	—
Rhode Island	—		—	—
South Carolina	—		—	—
South Dakota	19,496	1,489	947	266
Tennessee	—		—	—
Texas	74,009	10,427	6,158	4,807
Utah	7,271	1,090	646	378
Vermont	—	—	—	—
Virginia	—	—	—	—
Washington	4,580	926	444	91
West Virginia	—			
Wisconsin	4	—	—	—
Wyoming	19,547	2,670	2,779	1,173
Total United States	312,939	48,863	31,316	14,679
Caribbean	1	11	8	44
Grand total	312,940	48,874	31,324	14,723

[a] Non.Federal rangeland only

SOURCE 1977 National Resource inventories

Figure 2.—Average Annual Sheet and Rill Erosion on Non”Federal Rangeland, by State (tons per acre)



NOTE The national average IS 28 tons per acre

SOURCE 1977 National Resource Inventories

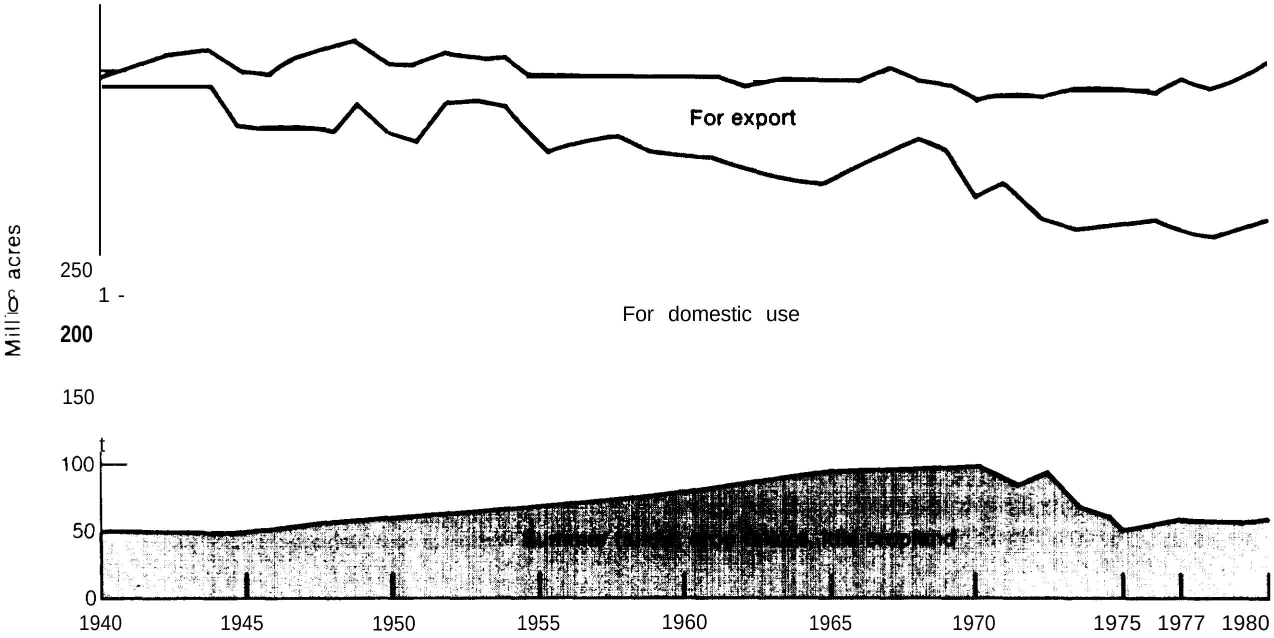
potential Croplands

As export demand for U.S. crops continues to grow, the Nation will see changes in cropping patterns and gradual increases in the acreage farmed (CEQ-NALS, 1981). Between 1969 and 1980, for example, increased demand caused a 22-percent increase in the acreage planted to crops in this country. Land in row crops increased by nearly 50 million acres, while wheat alone increased by 27 million acres. The amount of cropland planted to row crops grew from 40 to 53 percent (fig. 3).

Generally, the best croplands are already in use, so the land available for conversion to cropland is inherently less suitable for farming, Thus, increased erosion can be expected as these more susceptible lands are brought into use. In one study designed to examine this issue, Miller (1981) used the 1977 NRI data to project sheet and rill erosion rates that would occur on potential cropland should these lands be cultivated for row crops and small grain crops.

First, the study looked at the 69 million acres of land classified as cropland that was actually being used for rotation hay, pasture, or other uses. If this land was converted to row crops and small grains and cultivated with conserva-

Figure 3.—Acreage for Domestic Use and Export, 1940-80



SOURCE "Changes in Farm Production and Efficiency" USDA Preliminary '78-80 data —Economics and Statistics Service

tion tillage, it was projected to erode an average of 9.9 tons per acre. This is 83 percent higher erosion than current rates for row crop and small grain cropland.

Next the study examined acreage with high, medium, and low potential for conversion to cropland (table 5). "High potential" land is land with favorable physical characteristics where there is evidence of similar land nearby having been converted to cropland. There were 39 million acres of such land in 1977, most of it in use as pasture. If conservation tillage were used to bring high potential land into row crop and small grain production, the expected average erosion rate would be 6.5 tons per acre, 20 percent above the current average erosion rates for row crop and small grain cropland,

If conservation tillage were used to bring the 87 million acres described as having "medium potential" for conversion to croplands into production, the expected average erosion would be 9.6 tons per acre, 77 percent more than the current average erosion.

The actual amount of land that will be converted to crops in the future depends both on demand and on how successful improved management and technologies are in increasing yields from the cropland already in use. An estimated 36 million to 143 million acres of additional cropland may come into production by 2000(Cook, 1981). Ideally, the first land converted would be that with the lowest erosion potential, But analysis indicates that on the average the lands that are available for conversion are substantially more susceptible to erosion than the lands already in use, so erosion will increase. The newly cropped land will contribute greatly to the Nation's production of wheat, corn, and soybeans, but the cost in

Table 5.—Potential for Cropland use According to the 1977 National Resource Inventories (SCS) (millions of acres)

	High	Medium	Low	Zero
Pastureland. ., ... ,	18	33	47	35
Rangeland	9	30	98	271
Forestland	7	24	109	230
Other.	2	4	15	51
Total	36	91	269	587

SOURCE National Agricultural Land Study (1981) terms of soil losses and water pollution may be substantial.

Areas With High Erosion Rases

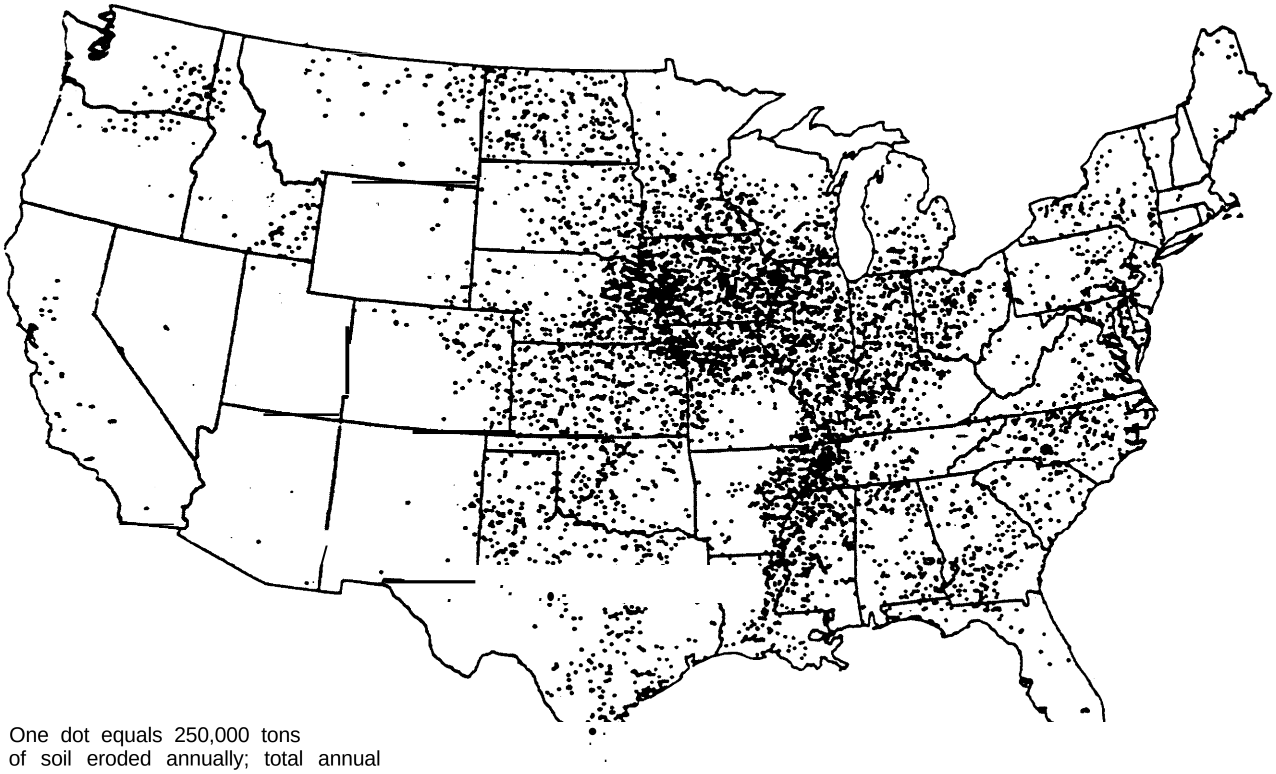
Every year, the Nation's row crop and small grain cropland erodes at an average rate of 5.4 tons per acre. Yet topsoil is thought to form at a rate of only 0.5 ton per acre or less. Thus, even though knowledge of soil formation rates is grossly inadequate, it appears that soil is lost at least 10 times faster than it is formed (Larson, 1981). Agricultural areas experiencing high erosion have been identified in most parts of the United States (fig, 4). Some of the important high erosion areas include:

Hawaii.—After native vegetation has been stripped from semitropical soils for cultivation, the soils are susceptible to sheet and rill erosion under heavy rains, especially on sloping land, In 1977, Hawaii cropland eroded at an average annual rate of 14.2 tons per acre.

Southern High Plains.—Dryland and irrigated cotton farming dominates this region of western Texas and eastern New Mexico. The loamy soils are susceptible to wind erosion, especially during winter and early spring windstorms when the fields are bare, Annual wind erosion here averages 20 to 50 tons per acre.

The *Palouse* Basin.— This region covers parts of eastern Washington and adjacent Idaho along the western border of the Idaho panhandle, and is dryfarmed for wheat, barley, peas, and lentils. Most of the cropland is hilly and possesses erosive loess* soil with slopes

Figure 4.—Cropland Sheet and Rill Erosion, 1977



One dot equals 250,000 tons
of soil eroded annually; total annual
soil loss equals 2 billion tons.
Most serious sheet and rill erosion occurs in the
Corn Belt and Delta States and west Tennessee.

SOURCE: 1977 National Resource Inventories

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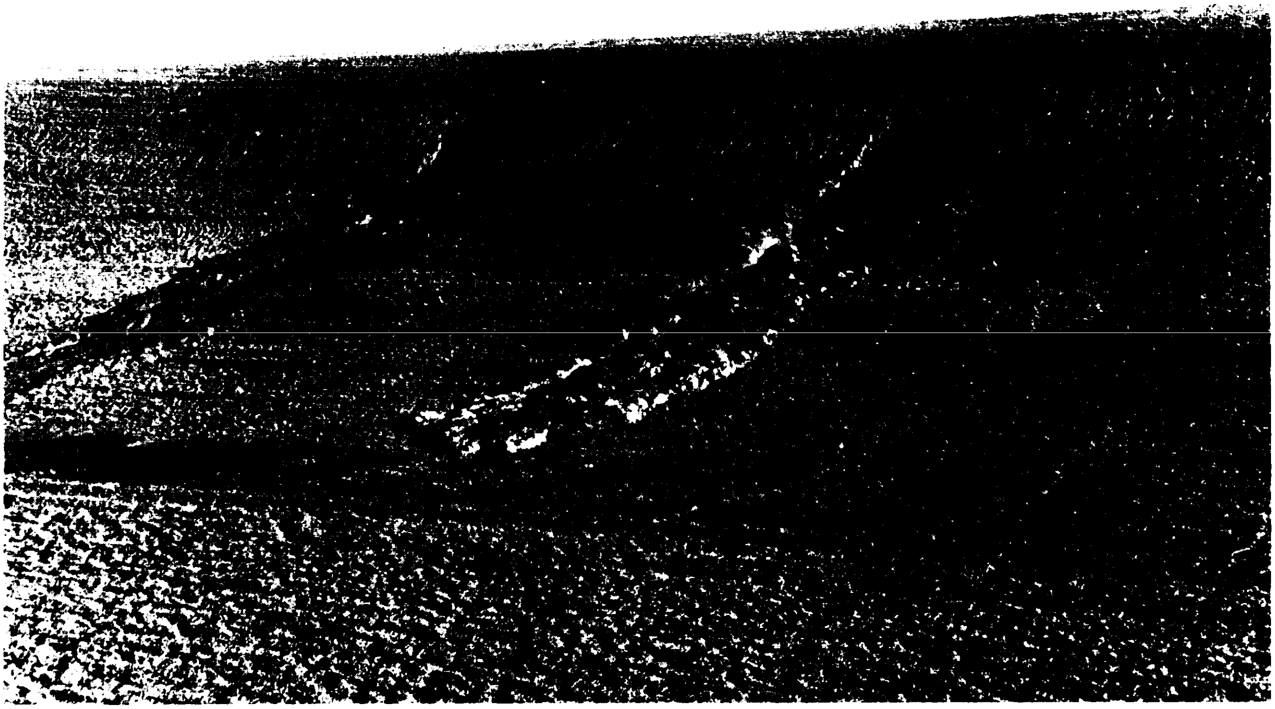
*Loess is a fine-grained, wind-deposited sediment of glacial origin that was formed some 10,000 years ago, whose composition and texture is reasonably homogeneous.



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from 15 to 25 percent. Runoff from melting snow and heavy rains causes erosion of 50 to 100 tons per acre.

Texas Blackland Prairie. —This region comprises an important farming area in east-central Texas. Two-thirds of it is cropped mainly in cotton and grain sorghum. Rainfall averages 30 to 50 inches and the terrain is gently rolling. Many of the region's soils are highly erodible; sheet and rill erosion averages 10 to 20 tons per acre per year.

The Corn Belt States.–Iowa cropland eroded (sheet and rill) at an average rate of 10 tons per acre in 1977, Illinois cropland at 6.8 tons per acre, and Missouri cropland at 12 tons per acre.

Southern Mississippi Valley.—The soils of this area are deep, fertile, and erodible. Much of the cropland is sloping, some steeply, and row crops are grown without adequate conservation practices. In 1977, Tennessee cropland experienced average sheet and rill erosion of 17 tons per acre, and Mississippi cropland 11 tons per acre.

Aroostook County, Maine. -Potatoes are grown here on lands with slopes up to nearly 25 percent. Since cultivation began, the upper 2 ft of soil have been lost to erosion. Some sloping fields are losing as much as an inch of soil per year.

The Caribbean,—Agricultural soils in Puerto Rico and the Virgin Islands are eroding at extremely high rates. The 1977 NRI indicates that cropland here experienced average sheet and rill erosion of 49 tons per acre, and rangelands 50 tons per acre.

Effects of Erosion on Crop Production

Soil erosion reduces inherent land productivity in a variety of ways:

- loss of soil organic matter and of fine clays, and, thus, loss of plant nutrients and nutrient-retention capacity;
- loss of a soil's water retention capacity as organic matter is removed and soil structure deteriorates; and
- loss of rooting depth as soil becomes thin.

In the absence of fertilization (whether by commercial products or by animal or green manure) or the application of other capital inputs, crop production suffers as erosion progresses. Numerous studies have documented this phenomenon, but few of them have been conducted since the 1940's.

As the National Soil Erosion-Soil Productivity Research Planning Committee of USDA has explained (Williams, et al,, 1981), there are two reasons for the lack of research on the effects of erosion on crop production: 1) such experiments are costly and time-consuming and years of data are needed to evaluate the effects of the generally slow process; and) crop production has been adequate in the past, resulting in little incentive for investment in this type of research. A few recent field experiments demonstrate that erosion can drastically reduce crop yields. However, climatic characteristics vary widely throughout the United States and have important effects on both soil erosion and crop production, Therefore, research conducted in one physiographic land area often cannot be generalized.

Some studies have examined the relationship between soil erosion and crop yields. But this is not necessarily the same as the relationship between soil erosion and productivity because technology can mask the impacts of erosion. Excessive erosion may or may not change crop yields but it invariably requires farmers to apply more inputs (including fertilizers, seeds, pesticides, irrigation, etc.). Substituting technology for soil entails a real cost because of the value of the resources, such as energy, used, Such substitutions could become more difficult if escalating energy prices make fertilizer, irrigation, and other inputs even less affordable to farmers. Thus, there are hidden and very poorly quantified costs associated with erosion, and these costs are not reflected by crop yields alone.

The studies that document the relationship between erosion and yields can provide a rough indication of the effect of current farming practices on inherent land productivity. Hagan and Dyke (1980) compared estimated yields on eroded and noneroded sloping soils using data from SCS soil surveys. For the Corn Belt, they estimated that for each inch of "A" horizon (topsoil) lost through erosion, corn yields were reduced by 3 bushels per acre. Other evidence shows that as soil erodes and changes from the slightly eroded to the severely eroded class, yields are reduced 23 bushels per acre for oats, and 1.1 tons per acre for hay (McCormack and Larson, 1980).

In western Tennessee, crop yields from severely eroded Memphis loam formed on thick loess were 14 percent less than yields from the same noneroded soil, Yields from severely eroded Granada soil were 26 percent below those from its noneroded equivalent and the yields from the severely eroded Brandon soils were 50 percent less (table 6), Table 7 shows the direct relationship between topsoil losses and decreased corn yields.

Note, however, that studies conducted in the North-Central United States, in areas where soils are formed in thick loess, show that erosion has little or no effect on productivity. A study of three experimental sites near Council Bluffs, Iowa, indicates that whereas corn yields were lower on the more eroded sites at the beginning of the study, the yield differences largely disappeared after a few years (Spomer, et al., 1973). A similar study, also in western Iowa, showed that even after some 7 ft of loess soil had been removed, crop yields were about the same as on the original soil surface (Moldenhauer and Onstad, 1975). Erosion of thick loess soils does little damage to crop yields in the short term because the underlying material is similar to that which has been eroded. Where

Table 6.—Summary of Buntley-Bell Erosion Study (1976)

Degree of erosion	Crop yields				
	_ Corn bu/acre	Soybeans bu/acre	Wheat bu/acre	Cotton lb/acre	Fescue tons/acre
Memphis silt ***loam:***					
2 **to** 5 ***percent slope***					
Noneroded.	110	40	54	1,060	4.2
Eroded	105	36	52	1,030	4.2
Severely eroded.	95	32	48	940	4.0
Grenada slit loam:					
O to 5 percent slope					
Noneroded	***95***	40	53	940	4.0
Eroded	***85***	30	46	875	3.7
Severely eroded. ., ...	70	24	40	750	3,2
Brandon silt loam:					
2 to 12 percent slope					
Noneroded.	***80***	30	49	815	4.0
Eroded . . ..'. . . .	70	20	47	750	3.3
Severely eroded, ...	45	16	38	535	2.7

SOURCE Buntley and Bell, 1976

Table 7.— Effect of Topsoil Loss on Corn Yield

Original topsoil thickness 10 to 12 inches	Percent decrease in corn yield
2 inches eroded (8 to 10 inches remaining), .'. . . .	7
4 inches eroded (6 to 8 inches remaining).	14
6 inches eroded (4 to 6 inches remaining). ., ... ,	25
8 inches eroded (2 to 4 inches remaining), ...,	37
10 inches eroded (2 inches or less remaining). .. ,	52

SOURCE Pimentel et al 1976

the loess is thin and the underlying material is dissimilar to the eroded loess, crop yields show dramatic decreases (Buntley and Bell, 1976).

Scientists do not fully understand the mechanisms that cause yield reductions from erosion. Certainly a major factor is the reduced water retention capacity of soils from which organic matter has been eroded, In addition, loss of organic matter reduces the capacity of soils to store plant nutrients such as nitrogen, calcium, potassium, and, to a lesser degree, phosphorus.

When reduced productivity results solely from loss of nutrients, it can often be restored by applying fertilizers. Studies have shown, for example, that some eroded Corn Belt soils recover most or all of their lost productivity with adequate application of chemical fertilizers. Soils of the Southeastern United States behave differently, however, because these are deeply weathered and lack the type of soil clay minerals that can hold fertilizer nutrients for plants. These soils rely heavily on organic matter for nutrient storage, so yields on eroded soils are measurably lower, even after nutrients are supplied by fertilizers.

It is not clear whether the continued application of chemical fertilizers to maintain productivity will be economical over the long run as soils erode. Of growing concern are the rising amounts and costs of nitrogen and phosphate fertilizers required to maintain yields as less fertile subsoils are exposed and cultivated, And where the productivity of eroded soil declines for reasons other than nutrient loss (e. g., loss of moisture retention capacity), it is sometimes difficult for farmers to identify the cause of the decline or its remedy.

Overall, adequate knowledge about how' various soil types are affected by long-term erosion is lacking. As long as only sparse data exist, there is the risk that the productive capacity of the land will be impaired permanently.

The recent formation of the National Soil Erosion-Soil Productivity Research Planning Committee within USDA is an encouraging development. The committee was given three objectives:

1. to determine what is known about the problem of the effects of soil erosion on

soil productivity by: a) defining it, b) identifying research accomplishments, and c) identifying current research efforts;

2. to determine what additional knowledge is needed; and
3. to develop a research approach for addressing the problem.

With adequate funding and followup, this effort could be a significant step toward answering the soil erosion/soil productivity question.

Tolerable Level of Soil Loss

"It is not possible to prevent erosion, " notes a recent text on soil conservation, "but it is both possible and necessary to reduce erosion losses to tolerable rates. Tolerable soil loss is the maximum rate of soil erosion that will permit the indefinite maintenance of soil productivity" (Troeh, et al., 1980).

Soil loss tolerances (T-values) are set by SCS and profess to consider the depth of soil, the type of parent material, the relative productivity of topsoil and subsoil, and the amount of previous erosion.

The maximum tolerance loss, 5 tons per acre per year, is for deep, permeable, well-drained, productive soils, The minimum loss rate, 1 ton per acre per year, is for shallow soils having unfavorable subsoils and parent materials that severely restrict raot penetration and development (Troeh, et al., 1980), Soils that have experienced severe erosion receive a lower T-value than comparable noneroded soils,

The USDA Soil Erosion-Soil Productivity Research Planning Committee (Williams, et al., 1981) has noted:

> SCS periodically reviews the soil loss tolerance limits (T-values) for all major soils , , . . *There is essentially no research base to support T-values;* they were established and are revised on the basis of collective judgments by soil scientists (emphasis added).

The most important reason for setting the maximum T-value at 5 tons per acre per year is that this fits the rough estimate of the yearly rate of "A" horizon formation on well-managed, permeable, medium-textured cropland soils. At this rate, an inch of subsoil becomes topsoil every 30 years. However, soil horizon formation rates vary greatly, and are likely to be much slower in soils of finer [i.e., higher clay content) texture.

It has been stated that the "fallacy" of this criterion is that it does not consider that the root zone becomes more shallow as erosion occurs. Thus, the weathering of parent rock or deeper soil horizons is a distinctly different phenomenon from the formation of the "A" horizon, In most soils it proceeds much more slowly. Understanding root zone formation is vital to predicting the long-term effects of erosion, but data on these rates are very scarce. Renewal at 0.5 ton per acre per year is thought to be a useful estimate for most unconsolidated materials. For most consolidated material [rock), rates are much slower (McCormack and Larson, 1980).

In practice, however, it would be extremely difficult—if not impossible—to limit erosion on most cropland to 0.5 ton per acre per year without either major reductions in production or fundamental changes in the methods of agriculture. The T-value that USDA has designated for most soils (almost 60 percent of the soil types] is 5 tons per acre per year. Because of data inadequacies, this value may be too high for some soils and too low for others.

USDA's T-values provide farmers with a realistic target at which to aim as they work to reduce their soil erosion rates, but the values do not provide scientifically grounded criteria for determining whether the long-term productivity of the land is being sustained under today's agricultural practices.

Other Costs Associated With Erosion

Although they are difficult to quantify, there are costs other than decreased crop yields associated with soil erosion. One cost is the fertilizer value of eroded topsoil. If the losses of the major plant nutrients—nitrogen, available phosphorus, and available potassium—in the 2 billion tons of soil removed by sheet and rill erosion each year are calculated at current prices, they would have an annual value of roughly $8 billion (CAST, 1982). Some of these nutrients are deposited on lower slopes; however, as much as half are lost from cropland areas. They contribute to water pollution or are deposited on flood plains not used for cropland.

If 25 percent of eroded soil is lost as sediment (Miller, 1981), a conservative estimate is that the costs associated with the replenishment of fertilizer nutrients lost to erosion range from $1 billion to $4 billion each year. Dredging costs attributable to erosion have been estimated at $60 million (McCormack and Larson, 1980).

Flood plain overwash and sedimentation of reservoirs caused by eroded soil are other results of erosion, but estimates of their costs vary enormously, from $50 million (CAST, 1975] to $1 billion (McCormack and Larson, 1980]. CAST estimated the cost of water treatment necessitated by erosion at $25 million for 1975.

The state of the art for estimating these types of costs is poorly developed. A team of agricultural economists and agronomists recently examinecl the relationship between increased crop acreage and nonpoint source pollution in Georgia. They concluded that the impacts of erosion on sediment, water quality, and the health of humans and wildlife were hard to measure in dollar terms:

> Because of limited resources, the work was based on secondary data. Deficiencies in such data became clear during the research. Data on land use changes, input use. and chemical loadings were unavailable, which forced us to simplify assumptions. While a similar study in the future could collect primary data on these factors, developing nonpoint-source pollution policy from the data currently available could be difficult and/or lead to considerable error.
>
> More research and analytical data are clearly needed in the area of nutrient and pesticide loadings. The state of knowledge in this area was so. deficient that weak assumptions were made to calculate nutrient loadings, and calculation of pesticide loadings proved impossible.
>
> A major commitment to an agricultural in format ion system and more research is unqueationably necessary to support a nonpoint-source pollution policy (White, 1981).

Conclusions

Erosion's effects are not new. At its peak, Mesopotamia supported a population of 25 million; by the 1930's, Iraq, which now makes up a major proportion of the territory controlled by that ancient civilization on, supported only 4 million. Much evidence points to soil erosion as a significant factor in the deterioration of the culture (Troeh, et al., 1980). Elsewhere in the Mediterranean Basin are other examples of lands that were once grain-rich and grass-rich that are now impoverished: North Africa (Tunisia, Algeria, Morocco), the southern Italian peninsula and Sicily, and Asia Minor.

Erosion is a self-reinforcing process. Erosion causes a loss of soil fertility and as a result plant growth diminishes. This in turn results in less plant cover to protect the soil and less plant residue to enrich it. Consequently, more erosion occurs, the land becomes progressively less fertile, and the loop continues. Thus, erosion is an important problem for this Nation to combat.

The fact that most of the country's erosion occurs on a relatively small amount of land has only recently been widely recognized by national policy makers. However, even the relatively lower erosion rates that occur on most cropland may be causing significant degradation of land productivity because these lands account for most of the Nation's agricultural production.

A conservative estimate of total cropland erosion assumes that wind erosion is significant only in the 10 Great Plains States and that gully and streambank erosion do not affect cropland significantly. Thus, cropland erosion is estimated to be the sum of sheet and rill erosion plus Great Plains wind erosion, or 2.8 billion tons a year. This is an average of 7 tons an acre each year for the Nation's total 413 million cropland acres. This soil erosion rate is much greater than the most optimistic estimates of soil formation rates.

Because much of the research on the effects of erosion on yields has been conducted in the thickly Ioess-covered areas of the North-Central United States, it is likely that the magnitude of the adverse effects of erosion on crop yields is underestimated for other important U.S. croplands where the soils are thinner. Increased research is needed to determine the effects of water and wind erosion on crop yields in these other areas.

Information on the rates of soil formation for important agricultural soils under specific climatic and technological conditions also is needed. In addition, existing methods for estimating soil erosion need to be improved. But conservation efforts cannot be deferred until this information becomes available. Research results should be used as they become available to improve existing conservation programs and technologies,

There are indications that some arid and semiarid areas that have been converted to irrigation, especially center-pivot irrigation, may be returned to dryland farming or grazing or may be abandoned because of rising pumping costs and declining ground water levels. If this becomes widespread, significant increases in wind erosion can be expected.

The extent to which cultivated land has been affected adversely by erosion and has consequently reverted to pasture or rangeland, woodland, or brush is not known. The productive capacities of most soils in the United States are reduced to some degree by erosion. An active research program into the damage suffered and the causes of the damage to a wide range of cropland and rangeland soils is needed as a basis for formulating rational conservation programs.

The land that is most likely to be brought into row-crop and small-grain production in the years ahead will erode at higher rates, on the average, than the land now used, even if conservation tillage practices are used. With Federal conservation funds constant, or even lowered as was predicted at the end of *1981,* and with large amounts of land being brought into more erosive agricultural use, the capacity of existing programs to check or reduce soil erosion on U.S. farmlands will be greatly stressed. This will accentuate the need to find more cost-effective means of reducing erosion, and the need to take steps to discourage production of row crops and small grains on land where cost-effective measures will not result in acceptable erosion rates.

DRAINAGE

Farmland drainage has been the primary agricultural water management and farm reclamation activity in this country. There are about **270** million acres of wet soils in the United States, including about 105 million acres of cropland where wetness is the dominant constraint on production (USDA, NRI, *1980).* Wet soils can be extremely fertile and productive because they commonly contain more organic matter than soils that are not as wet. The Southeast has the largest acreage of wet soils, followed closely by the Corn Belt, the Great Lakes, and the Southern Delta States (fig. 5).

Although only certain wet soils are classified as “wetlands,” much of 3,8 million acres of wet soils converted to cropland between *1967* and 1975 were indeed wetlands (USDA-RCA, 1980). Their conversion meant the loss of valuable wildlife habitat, reduced flood prevention, loss of the natural cleansing capacity of watersheds, and other services. On the other hand, drainage of wet cropland enhances crop production significantly.

Drainage provides benefits in six major areas:

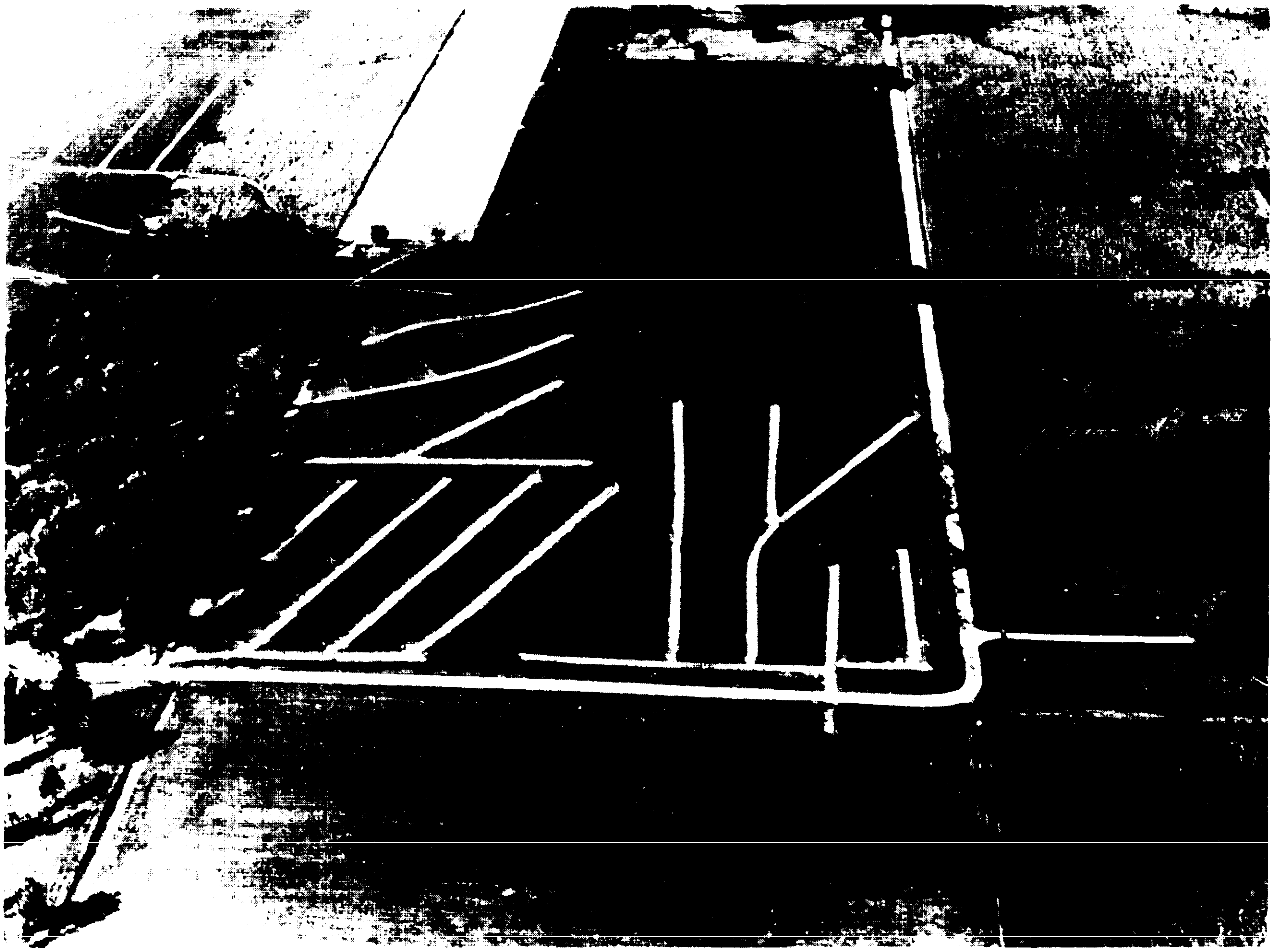

Photo credit USDA-Soil Conservation Service

Till drainage system on Crosby silt loam, O to 3 percent slope, 100 ft spacing

the roots of most cultivated crops will not penetrate saturated soil, poor drainage can also result in a shallower root spread and a commensurate reduction in plant size, stability, and yield. Deeper root growth helps crops withstand drought, and lower water tables provide a greater volume of soil from which plants may obtain nutrients and moisture. Soil structure is damaged when tillage or harvesting operations are done while the soil is too wet. Excess water also increases the likelihood of compaction and obstructs the loosening activities of soil biota.

Drained fields can be planted earlier because of earlier accessibility of machinery to fields and higher soil temperatures. Improved drainage will usually advance the potential planting or seeding date by 1 or 2 weeks (Irwin, 1981). From May 1 to 15, each day of delay reduces corn yields by 1 bushel per acre, and in the latter half of May, each day of delay reduces yields by 2 bushels per acre (USDA-SCS, 1975]. Furthermore, earlier planting broadens the selection of crop varieties available for the farmer to grow, advances the maturity date, and produces higher final yields. Drainage also offsets uneven field ripening of grain crops, allows more flexibility in harvest time, and increases the potential for double cropping.

Water-saturated lands promote surface runoff of rainwater, inducing erosion and increasing the problem of flooding on downslope land. A well-drained *soil* reduces erosion because surface runoff is substantially reduced when more water can infiltrate into the soil. The top layer of soil is richest in organic matter and applied chemicals, so using drainage to reduce runoff can reduce losses of sediment and some nutrients. This also reduces the contamination of runoff waters and enhances the distribution of fertilizer nutrients through the upper soil layers. In areas of high salinity, drainage will promote leaching and removal of salts.

Drainage of waterlogged lands can also help control health hazards to man and livestock, such as mosquito- and fly-borne diseases, certain worms, and liver flukes. Removal of excess water removes the breeding ground or favorite habitat of these carriers and thus reduces their populations.

Good drainage makes the onland disposal of organic waste material, increasingly under consideration as an alternative to ocean disposal, environmentally safer. Adequate aeration and warm soil temperatures are necesary for the efficient decomposition of wastes into usable plant nutrients.

Investment in farmland drainage systems occurred throughout the last century, peaking in the mid-1930's. Research to improve these systems was performed extensively by USDA agricultural research stations and land-grant colleges until the late 1960's. During the 1960's, however, growing concern over the loss or degradation of actual wetlands (v. wet soils) discouraged investment in drainage systems. As a result, drainage has been specifically exempted from USDA cost-sharing programs in most instances, and SCS technical assistance on drainage has been limited by personnel reductions and the pressure of higher priority demands for the expert's time (Ochs, 1981).

Technologies developed in the mid-1960's for more efficient and cost-effective installation of drainage tiles represent the latest advances in the field, Corrugated plastic drainage tubing was developed to replace the heavier and shorter-lived clay tiles, with significant cost savings to farmers. This tubing can be installed more quickly and effectively using laser beam grade control. In addition, trenchless machinery was developed to install tiles faster than earlier deep-trench operations. Two new technologies under study are well-point drainage for vertical, rather than horizontal, movement of excess water, and reversible drainage, which introduces as well as removes water through porous tubes, The latter technique would be especially applicable to the climatically variable Southeastern United States.

The dearth of drainage research during the 1970's has resulted in a lack of data in many important areas. Few analyses are available on design procedures, system maintenance, and integration of drainage with modern cropping systems to maximize production. Such basic information as the lifetime of drainage systems is not available. Furthermore, while information on the costs and benefits of farmland drainage is available, it is frequently site specific and therefore is of little value to individual farmers. Compounding this problem is a lack of synthesis of the research completed in the 1960's and before, and of the data available from other nations.

The need for such information is growing. There are indications that the drainage systems constructed in the early 1900's, particularly in the Midwest, are now out of date and in need of repair. Drainage systems can often repay the farmer's investment within 2 to 4 years (Ochs, 1981), so farmers with adequate information and capital would probably not allow subsurface drainage systems to decay seriously. The outlets, however, are frequently municipal waterways or other such systems demanding collective management. These canals and ditches require occasional clearing of weeds and accumulated sediments, as well as other maintenance. Nondestructive and efficient techniques and machinery recently have been developed in Germany, but costs are high, Such operations must be done locally. Cost-sharing programs with local municipalities, revolving loan funds, and greater development of farmers' cooperatives could aid in rejuvenating the outlet system. Federally guaranteed loans could speed the repair of both the drainage and outlet systems to the benefit of farmers, consumers, and society.

SOIL COMPACTION

Routine operation of farm machinery ("traffic") and trampling by livestock can harm land productivity by compacting the soil. In croplands, compaction can damage the structure of the soil near the surface and can create a "traffic pan, " which is a persistent layer of densely compacted soil just below the depth to which the soil is tilled. On rangelands, which are not normally tilled, compaction compresses surface soil causing an effect called "shingling" where wide areas have a surface so dense that water cannot infiltrate and plants cannot reproduce. Animal traffic and off-road vehicle traffic can form compacted pathways on rangelands where plants cannot grow and gully erosion may begin. The severity of both cropland and rangeland compaction varies with the nature of the site's soil.

Concern over compaction has increased in recent years, partly because the large, heavy machinery characteristic of modern farming is thought to cause more compaction than lighter machines. In general, the role of technology in causing and treating cropland compaction is relatively well known; however, the extent to which compaction is a constraint on U.S. cropland productivity is not so well known. On rangelands, the problem is not well understood and practical technologies to correct it are not well developed.

Process and Effects

Because the potential for compaction varies greatly among different types and conditions of soils, and because compaction affects different plants in different ways, generalizations must be made with caution. The basic physical effect of soil compaction is collapse of the large pores between soil particles. In most agricuhural soils, it is desirable to maintain the larger pores because they allow ready movement of air and water, One of the chief functions of tillage is to increase or restore these large pores in the soil.

Thus, water infiltration and percolation are impeded by surface and subsurface compaction. The consequences include poor drainage or standing water in a field, increased water runoff and soil erosion, and slower rates of crop residue decomposition. A compacted wet soil may remain colder for a longer time during the spring, delaying planting or slowing seed germination. Compaction-caused drainage problems also encourage higher rates of soil nitrogen loss through anaerobic microbial denitrification. The presence of a traffic pan can impede root penetration and the proper development of root crops such as potatoes and sugar beets. Surface compaction reduces the nitrogen-fixing nodule mass on soybean roots (Voorhees, 1977b) and alters the geometry of root growth, keeping roots out of the uppermost part of the soil profile where applied fertilizers are most available (Trouse, 1981). Traffic pans may keep roots from growing below the upper tilled layer and so deny access to moisture during drought or to nutrients available below the tilled layer,

Under certain conditions, a moderate amount of cropland compaction has been shown to be beneficial. Soybean yields on moderately compacted Minnesota soils have been 25 percent greater than on noncompacted soil in dry years. In some soils, the wicking effect of smaller, compacted capillary pores has the advantage of bringing water and dissolved nutrients to germinating seeds, and it may also explain the higher toxicity of herbicides on compacted soils. Compacted soils, if dry, can warm more rapidly in the spring, and the presence of a subsurface pan can help to retain water that might otherwise percolate away from roots. Corn grown on compacted soil has been shown to mature earlier and to have a lower ear moisture content. Traction is sometimes better on a compacted soil, but the greater energy required to till such soil probably outweighs the traction benefits (Voorhees, 1977a, 1977 C),

More typically, compaction reduces crop yields. * Yields of corn grown on clay soil are decreased with increased machine contact pressure and number of field passes, sometimes by as much as 50 percent (Raghaven, et al., 1978). Deeper than normal tillage, called subsoiling, is sometimes used to reduce compaction in dry years and can increase corn yields by as much as 100 bushels per acre in the Southeastern Coastal Plain (Cassel, 1979). In one study, yields for corn and cotton in Alabama rose 83 percent with subsoiling under crop rows and controlled traffic (Trouse, 1981). The effects of compaction on overall productivity sometimes may not be evident because they can be masked by use of other inputs such as irrigation and fertilization. In crop rotations that do not foster significant buildup of organic carbon, wheel-traffic-induced soil compaction may increase soil aggregate size and stability slightly, resulting in improved production even though organic matter content is decreasing. Thus, by substituting for the aggregating effects of organic matter, compaction may mask soil deterioration (Voorhees, 1979).

Technological Causes and Remedies

Factors that determine the degree of compaction occurring on a cropland site include: the pressure (pounds per square inch) exerted by machinery tires; the proportion of the field that gets pressed by the tires; the number of times per year the area is pressed; the type and frequency of tillage that loosens the compacted soil; various features of the soil type (including texture and percent organic matter); and especially the moisture content at the time it is pressed by machinery tires. The interaction of these factors is site specific and usually difficult to determine.

Certain soil types are more susceptible to compaction than others. The sandy loam of California, the Mississippi Delta, and the Southeastern Coastal Plain are especially susceptible to formation of traffic pans. Moisture is the most critical variable for any specific site, as compaction effects increase sharply when moisture content is above an optimal level. In certain soils, compaction can also increase because of too little moisture

Average tractor weight has more than doubled in the past three decades as a cause and a consequence of the increasing size and efficiency of U.S. farms. Modern four-wheel-drive tractors now weigh as much as *33,000* lb (Voorhees, *1978).* The pressure exerted by the tires, however, has not doubled because the tires are now wider and better designed. However, the pressure per square inch is generally less important than the proportion of the field that is compacted, The wider tires press more soil on each pass, but make fewer passes to do the same job, and the larger machinery can allow field operations to be timed to drier conditions when compaction potential is relatively low, Yet there is little evidence to indicate whether farmers consider compaction prevention in their use of machinery. More farmers may be using larger equipment—four-wheel-drive, dual-wheel tractors* in particular–to get into fields under wet conditions (Robertson, 1981).

A trend that more surely indicates increased compaction is the increasing proportion of cropland used for row crops that require more tillage than close-grown crops such as hay or oats. Fortunately, the compaction associated

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* During 1981, OTA conducted extensive research on the CAP and Agricola serches of 1980,

*Voores'(1977c)states that dual wheels do not prevent compaction, they just change its distribution. Compaction from duals may not be quite as deep, but it can be more than twice as wide. "

Photo cre~lt' O~A staff

Modern farm equipment has grown larger and heavier, raising concern that compaction may harm productivity on susceptible soils

with this trend may be offset to some extent by increased use of conservation tillage and the no-till method. However, reduced tillage will generally not counteract subsurface compaction that already exists and even no-till does not completely eliminate traffic and consequent compaction effects.

Some compaction is unavoidable in most cropping systems, but farmers can modify their operations to limit compaction. The least costly adjustments include timing operations to drier soil conditions, limiting the number of field trips (the first pass over any spot accounts for 80 percent of total compaction), and confining wheel traffic to the same paths each pass. However, sometimes it is not economically feasible to rotate crops with meadow or to delay planting or harvest until soil moisture is suitable because of the income and yield reductions associated with these practices.

The practice of subsoiling—plowing deeper than the conventional 7 to 8 inches to break up compacted soil layers—is becoming more widespread in the Midwest as it has shown its effectiveness in counteracting compaction in the Coastal Plains States, California, and elsewhere. Subsoiling reduces soil density and hardness and increases the volume of macropores to promote aeration, internal drainage, and more rapid infiltration of water (Cassel, 1979). The practice takes significantly more tractor power, however, so the value of yield gains must be compared to the increased fuel cost. These tradeoffs change as compaction effects accumulate and as relative prices change.

The most radical technological proposal for dealing with cropland compaction is development of "wide span" equipment that would confine wheel traffic to a small part of a field by spanning many rows with an arching, bridge-like tractor. Prototypes of the machine are being developed (Trouse, 1981).

Research Needs

Compaction on Croplands

While considerable research has been conducted in several regions of the United States concerning the causes, effects, and cures of traffic pans (and, to a lesser extent, of the more subtle soil structure changes in the plow layer), no nationwide research effort has been mounted. Compaction is generally seen as a regional problem. Thus, there is no data base to determine the extent to which compaction is limiting U.S. soil productivity, Experts disagree: Voorhees (1979) reports that: "except for root crops, crop yields probably are not being suppressed yet as a result of normal soil compaction in the northern Corn Belt . . . . Regardless, the relatively good soil tilth enjoyed by farmers in the region should not be taken for granted. Once soil is compacted, it maybe more difficult to restore than previously. " In contrast, Trouse (1981) states that: "every acre that is plowed suffers some compaction, " and "we have compaction even in our best fields, and it is hurting us. "

More information is needed before these questions can be answered with any certainty. Data on compaction could be collected by NRI, for example, although each item added to the inventory.

Little is known about how farmers perceive the effects of compaction, In areas where traffic pans are important constraints on crop yields, some information is generally available to help farmers decide whether the yield increases from subsoiling will pay for the extra fuel used. More complex decisions regarding timing of operations, for example, are less well supported by hard data. How well farmers diagnose and monitor cropland compaction problems is another unknown,

Compaction on Rangelands

Even less is known about rangeland compaction. Overgrazing has led to dense soil surfaces over much of the Western rangelands, and this "shingling" is a severe constraint on productivity. It prohibits water infiltration, resulting in more arid conditions for the plants; it accelerates erosion; it severely constrains seed germination and the survival of seedlings when seeds do germinate. Shingling is generally believed to be caused by the trampling of animal (mainly livestock) hooves. Another phenomenon that also contributes to the shingling effect is soil capping. This is a thin crust caused by the force of raindrops striking unprotected (lacking plant cover) soil surfaces, The direct impacts of livestock trampling are most harmful in the spring when soil is moist, after the sporadic heavy rains characteristic of much of the semiarid range, and on the moist soils along streams (Gifford, et al,, 1977; Cope, 1980),

The scientific literature on rangeland soil compaction and capping is scanty. Soil scientists historically have concentrated their attention on croplands where the returns on research investments are more obvious,

The usual way to improve compacted, overgrazed rangeland is to alter grazing pressure to be consistent with carrying capacity and, in cases of severe land deterioration, to reintroduce desirable plants through reseeding. One method to deal with capping or compacted crusts is to concentrate a herd of cattle on the affected area for a very short time (2 to 3 days) to churn up the soil surface. Another method is to roll a "soil imprinter, " a heavy, usually water-filled drum with a textured surface, over the ground to break up the shingled surface (Dixon, 1977). However, fuel costs may make this impractical. Where compaction is deep, there may be no technological solutions except tillage, which is likely to be expensive, and excluding livestock.

Conclusions

Cropland compaction is probably a constraint on productivity in many regions, but technologies to deal with it do exist. No major

Federal policy decision to increase the effort to educate farmers about compaction, or to support their use of practices that would prevent or cure the problem, is likely as long as little is known about its significance in relation to other problems.

On rangelands, the compaction and capping of soils is a constraint on productivity. Generally, overgrazed rangeland has good regenerative capacity once proper grazing management is instituted. In some instances, however, particularly in the arid Southwest, reseeding of desirable species must precede improved grazing management in range rehabilitation. The problem of shingling and the processes of compaction and capping have not been high-priority research topics for range science. The consequences of compaction are well understood, but too little is know about its causes, prevention, or economic reparation.

SALINIZATBON

Salinization is primarily a drainage problem aggravated by the misapplication of irrigation water. Where water is applied to fields, the Sun and crops extract almost pure water, leaving salts behind, If that salt is not flushed deeper into the ground by rainfall or additional irrigation, it can gradually concentrate in and on the surface soil, first damaging and ultimately destroying the land's productivity.

But flushing salt into the ground does not necessarily solve salinization problems. If subsurface conditions are relatively porous, the saltwater may contaminate the ground water supply from which the irrigating water is drawn. If subsurface conditions are relatively impermeable, the salty water may drain into nearby rivers, Irrigators downstream will ultimately reuse it, The saltwater may also accumulate beneath the surface so that a salty, "perched" water table builds up. This may eventually rise near enough to the surface to contaminate the root zone.

Most crops cannot survive in saline environments. The effect of salinity is to increase the osmotic pressure in the soil water, which works against the water extraction mechanism of the plant roots.

There are no data on the overall amount of cropland in the United States that has been salinized or is undergoing salinization, An informed guess is that 25 to 35 percent of the irrigated croplands in the West have salinity constraints on productivity (van Schilifgaarde, 1981],

Some data are available on specific areas where salinization is a recognized problem. At present, it is severe on the western side of the San Joaquin Valley of California, one of the country's most fertile regions. Here, excess saline irrigation water accumulating beneath the surface is invading the root zone and is reducing crop yields on some 400,000 acres of land. The cost of the resulting crop loss is estimated at $31.2 million per year (Sheridan, 1981). If the saline subsurface water is not drained from the cropland, it is projected that 700,000 acres will have reduced output by 2000, for an annual loss of $321 million. If unresolved by 2080, an estimated 1 million to 2 million acres of cropland in the San Joaquin Valley will be salinized out of production.

Three alternative sinks for the valley's salt are the Sacramento-San Joaquin Delta, the Pacific Ocean, and local evaporation ponds, A drainage system to carry the irrigation runoff to the Delta, an estuary of the San Francisco Bay, would cost $1,26 billion for the central drains, plus the costs of underground drains to carry the water from the farmers' fields (USDA–RCA, 1980). Further, the saline water could cause serious environmental damage to the estuary itself, which is the largest wetlands area on the west coast. In addition to its importance as a wildlife and fisheries habitat, the estuary is the major source of water for municipalities, industries, and agricultural operations located nearby.

Piping the drainage water to the Pacific could cost even more because of the high energy required to pump the irrigation runoff over the intervening mountains. If farmers were required to pay the entire price of these engineering solutions to the drainage problem, the costs would be on the order of $75 per acre per year (Sheridan, 1981).

The third solution makes use of as much of the drainage water as is possible in irrigation of salt-tolerant crops, The best irrigation water would be used first on salt-sensitive crops, and the increasingly salty runoff would then be used to irrigate more salt-tolerant crops. Finally, the highly saline water would be drained into evaporation ponds, providing some wildlife habitat, or be disposed of in other ways (van Schilifgaarde, 1981). The costs of establishing this integrated irrigation system have not been estimated, but would depend partly on the profitability of farming the salt-tolerant crops (see discussion in ch. IV). This use would reduce the volume of drain water requiring disposal. Although the drainage problem is not eliminated, the reduced volume makes the options for disposal more viable. This scheme would require substantial changes in farming practices, and getting farmers to participate may be as formidable a difficulty as paying the costs of more conventional engineering solutions.

A key issue in these schemes is who pays. Costs of a drainage system would presumably be shared among the Federal Government, the State of California, and the San Joaquin farmers. If the capital cannot be raised, there is another solution to the drainage problem—to continue the present system until the soil becomes too salty, then to switch to more salt-tolerant crops, and eventually abandon 20 percent or more of this highly productive San Joaquin cropland.

Another type of salinity problem has developed in the Colorado River Basin. Here, too, the water is becoming more saline, and thus less useful for irrigation and other purposes. The source of about two-thirds of the salt in the river is natural drainage of salt-laden geological formations; the remaining third is saline runoff from irrigation (Frederick, 1980). Salt concentration is increasing because most of the water diverted from the river for use is consumed, ultimately evaporating, while that which is returned by irrigation drainage systems is highly saline.

The problem is the disposal of the salt. Potential solutions include expensive engineering approaches and less expensive but more difficult system management changes. Eventually, as Colorado River water use and reuse becomes more expensive, a combination of structural and management approaches will probably be adopted. One possible engineering approach is to build a desalinization plant near Yuma, Ariz., to remove salt from the drainage water. The river management approach, already being implemented by some farmers receiving Federal technical assistance and cost sharing from USDA programs, begins with increasing irrigation efficiency. Crop yields are maintained with less water use by improving on-farm systems with such techniques as land leveling, ditch lining, and alternative irrigation systems. If enough farmers improve irrigation efficiency, a significant improvement could be achieved. However, as nonagricultural use of the Colorado River increases, farmers may still need to shift toward more salt-tolerant crops and to the use of drain sinks other than the river, such as local evaporation ponds.

Saline seeps are a soil-and-water problem occurring in Montana, North and South Dakota, Wyoming, and Canada’s prairie provinces. This problem is the combined result of regional geology and farming practices. Farmers traditionally alternate strips of wheat with strips of fallow to conserve moisture. This summer-fallow system can actually conserve too much water—in some places, the water thus saved has infiltrated through the upper layers of soil, picking up salts, and has formed a perched water table above an impermeable layer of shale. In downslope areas, the salt-laden water seeps out, creating saline seeps—unproductive swampy areas. Some saline seeps are as large as 200 acres. They affect about 400,000 acres in the Northern Plains of the United States; the total including Canada and parts of Texas and Oklahoma may reach 2 million acres.

Saline seeps may be battled by using a creative management technology called "flexible cropping" developed by USDA scientists and cooperating farmers, Under flexible cropping, water conditions are monitored carefully. Alternative crops are planted, including alfalfa, safflower, and sunflower, each of which uses more water and draws it from deeper in the soil. Continuous cropping is practiced whenever possible to avoid water accumulation in the perched water table, but the option to fallow land remains if water is limited. This approach demands more complex management than summer fallow, but participating farmers have demonstrated that it can keep significant areas in production that might otherwise be lost, (This technology is discussed in detail in app. A, "The Innovators.")

Conclusions

The U.S. agricultural sector must continue to develop innovative systems to conserve productivity on land that is threatened by salinization. The proportion of cropland involved is relatively small—30 percent of the irrigated land in the West amounts to only 5 percent of all the Nation's cropland—but the land is disproportionately productive because of long growing seasons and the high economic value of irrigated crops. (An assessment of water-related technologies to maintain agricultural production in the arid and semiarid regions of the United States was begun by OTA in July 1981.)

GROUND WATER DEPLETION

Introduction

The next several decades will bring a marked decrease in the availability and quality of the Nation's ground water, This could significantly reduce the productivity of much irrigated agricultural land, especially in the Southwestern United States. The most severe problems will probably be confined to the West, but some Eastern States will suffer local water shortages and water quality problems that will affect agricultural productivity,

Technologies that alter irrigation and farming systems to conserve water while continuing to produce crops profitably can prolong the productivity of ground water resources, These technologies vary from modest but effective changes in the way water is applied to major changes in farm management such as converting to perennial crops or drip irrigation, Although changing the technologies used may reduce ground water demands in some areas, the actual reduction in ground water withdrawals that will result from new agricultural technologies probably will be modest and will only postpone the exhaustion of some major U.S. ground water reservoirs.

The technological change most likely to occur in Western regions during the coming decades will be the return of some irrigated lands to dryland farming or grazing, This conversion will cause sharp decreases in production. Also, as wind erosion and other problems associated with dryland farming develop, a continuing, gradual decrease in land productivity can occur,

Although some schemes for recharging overdrawn aquifers* have been proposed, the lack of local water to replenish depleted supplies and the high energy costs involved in transporting water from distant sources may preclude such remedies. Schemes for long-distance water transport will have to be compared to the alternatives of farming additional, potentially erosive, croplands in the more water-abundant East or intensifying production on existing agricultural lands (Vanlier, 1980).

The data and information bases relating water and agricultural productivity are obtained largely by Federal and State agencies. At the

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*An aquifer is a water-bearing underground layer of permeable rock, sand, or gravel.

local level, county agencies and quasi-governmental units collect a variety of water data specific to their management needs. The information is dispersed among a number of sources including large Federal water data banks. The data available are adequate for general planning, but considerable effort will be required to aggregate them into a format clearly adapted to policy makers' and planners' broader needs.

The Nation's ground water resources could be affected adversely by a number of changing agricultural technologies and by future land and water use policies as well as by the growing needs of water for energy development. The principal factors that will affect the availability and suitability of ground water for agricultural use are:

- ground water overdraft (mining),
- water-quality degradation,
- reduction in streamflow and discharge of springs, and
- subsidence and collapse of the land surface.

Ground Water Overdraft

Hidden beneath the land surface in almost every part of the United States is water that fills the openings in beds of rock, sand, and gravel —called ground water. Studies of the U.S. Geological Survey (USGS) indicate that more than 97 percent of U.S. freshwater resources are located underground. The Nation's ground water resource supplies about *70* percent of the irrigation water for the 17 Western States (Lehr, 1980).

In many areas, ground water is a readily available source of potable water. Half the population in this country gets its drinking water—either partly or completely—from ground water supplies (Costle, 1979). Because ground water is a high-quality, low-cost water source, its use grows at the rate of several percent each year. Ground water use has grown from 35 billion gallons a day in 1950 (Murray, 1970) to an estimated 82 billion gallons a day in 1975 (CEQ, 1980),

Withdrawing ground water from an aquifer in excess of the long-term rate of recharge is called ground water overdraft, mining, or depletion. Ground water mining is common in arid or semiarid areas of the United States where precipitation is low and recharge rates are slow (fig. 6). Water is available from these aquifers only because it has accumulated in the ground over many thousands of years.

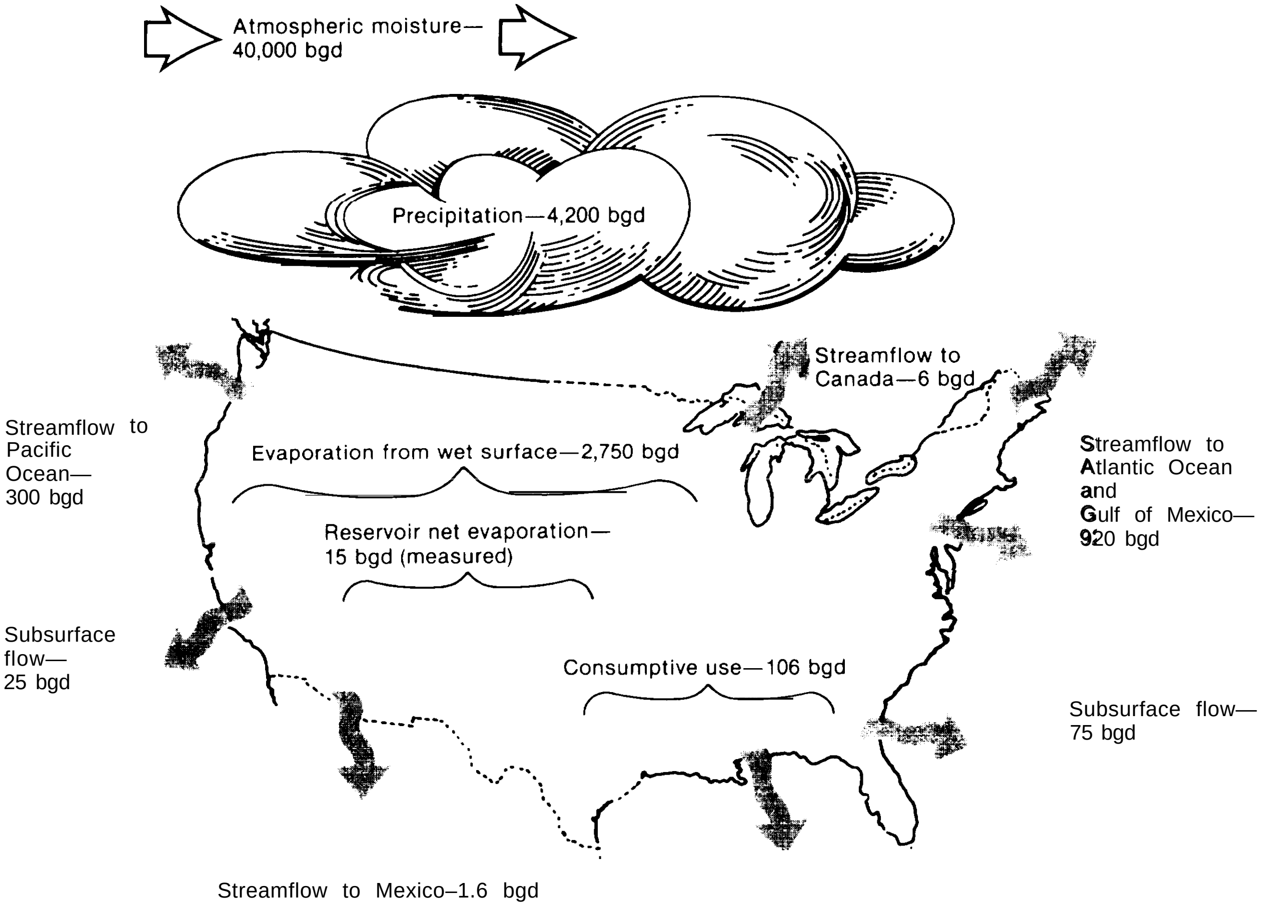
Ground water overdraft lowers ground water levels, subsequently reduces the thickness of water-saturated sediments, and in some places degrades water quality. Declining water levels reduce the total amount of water available. In order to meet demands, pumps must be set deeper and larger motors installed. In some cases, new wells are needed. These investments increase operating costs.

Over the past several decades, ground water overdrafts have reduced agricultural productivity. The greatest reductions, however, are expected to occur in the next three or four decades. Most such losses in agricultural productivity will be permanent because alternative water sources already are fully committed to other uses.

The major areas of ground water overdraft are in Texas, Nebraska, Colorado, Kansas, Oklahoma, New Mexico, Nevada, Arizona, and California. Major ground water overdraft problems also are reported in the lower White River area of Arkansas and the Souris and Red River basins in North Dakota and Minnesota (Vanlier, 1980). Shortages have raised conflicts in other regions as well.

In Iowa, proposals have been considered to prohibit ground water use for irrigation because of acute shortages. In Nebraska, the ground water situation is prompting officials to consider allocating available ground water. In the first court conflict between ground water users, the Nebraska Supreme Court held that an irrigator can be held liable for costs incurred as a result of disturbing a neighboring ground water supply (Lehr, 1980).

Figure 6.—Water Budget for the Conterminous United States



NOTE bgd = billion gallons per day
SOURCE Water Resources Council, 1978

One of the most dramatic instances of ground water depletion occurs in the Ogallala Formation, an aquifer stretching approximately 1,000 miles from Nebraska to Texas. It underlies roughly 150,000 square miles (mi^2) and varies in thickness from 1 to l, zoo ft. USGS, in an ongoing study of the Ogallala and certain associated aquifers, reports that 46 percent of the 177,() 177,000-mi^2 study area now has less than 100 ft of water-saturated sediment. Ground water pumping, which began in Texas in the 1930's, has caused the following declines in the region's watertable:

Percent of 177,000 mi^2	*Watertable drop in feet*
14	10 to 25
5	25 to 50
5	50 to 100
2	100 to 150

(Weeks, USGS, 1981.)

The USGS reports that water levels in the Ogallala Formation consistently have been declining in regions where water is pumped for irrigation (Berman, et al., 1977), Declines of 32 to 40 ft were monitored in Kit Carson County from 1964 to 1972. In other areas influenced by irrigation, declines of as much as

16 ft were noted. The USGS findings confirm an increasingly rapid water-level decline in parts of the Ogallala Formation since 1974. More than 98 percent of the pumping from the Ogallala is for irrigation agriculture,

The Ogallala aquifer is recharged by direct precipitation at a rate of only 50,000 acre-ft per year, while 7 million to 8 million acre-ft a year of ground water are withdrawn. Thus, the 93,000 wells pumping to irrigate as much as 65 percent of Texas croplands could exhaust the aquifer, Some additional recharge is supplied from the eastern slopes of the Rocky Mountains. (Details of the Ogallala water budget will be included in the OTA water assessment.)

In fact, ground water depletion in the High Plains section of west and north Texas has been so extensive and expensive that it has compelled abandonment of some once-productive farmland or the return to dryland farming (Hauschen, 1980).

Similar abandonments are occurring in other areas. In the Roswell Artesian Basin of New Mexico, where ground water withdrawal has exceeded recharge for many years, the Pecos Valley Artesian Conservancy District has been purchasing and retiring irrigated acreage, About 3,000 acres have been retired under this program, In the Estancia Basin of Santa Fe County, an estimated 5,900 acres will go out of production by 2000 (Vardier, 1980),

Nearly all major aquifers experiencing overdraft in the arid or semiarid areas of the country ultimately will be exhausted. This does not mean there will be no more underground water in those places, but that it will be so reduced that it cannot be profitably extracted, Lower agricultural productivity and reduced economic activity can be expected in these areas.

Degradation of Ground Water Quality

In addition to declining ground water availability in many aquifers, degradation of ground water quality from increasing salinity and contamination by pesticides, herbicides, fertilizers, animal wastes, and nonagricultural sources of chemicals is on the rise. Heavy pumping of ground water can result in seawater intrusion into freshwater aquifers, and recycling irrigation water to recharge aquifers may make water substantially less suitable for irrigation or other purposes than the aquifer's original water, Because organic chemicals do not degrade efficiently in the slow-moving waters of underground aquifers, recharge water may disperse agricultural contaminants over broad areas where they may remain indefinitely,

Saltwater Contamination

Many aquifers contain both fresh and mineralized (saline) ground water, The lighter freshwater in such aquifers "floats" on the denser saline water. Saltwater/freshwater aquifer systems are best known in coastal areas where freshwater in the landward part of the aquifer is in contact with saltwater in the seaward part, but some also are present in inland areas. When freshwater is pumped from such aquifers, the saline water migrates toward the wells and eventually replaces part or all of the aquifer's freshwater, This exacerbates problems of soil salinity that plague many irrigation projects.

Saltwater intrusion into freshwater aquifers has occurred in many areas undergoing ground water irrigation. In the Roswell Artesian Basin of New Mexico, the artesian head has been declining for many years and now saline waters are encroaching in the aquifer north and east of Roswell, Extensive ground water declines in the Carrizo aquifer in Dimmit and Zwala Counties, Tex., caused reversals in the aquifer's hydraulic gradient, thus allowing poorer quality water to enter areas that previously had good quality water (U.S. Water Resources Council, 1978).

In some places, aquifers are degraded by water leakage from a saline aquifer into overlying or underlying freshwater aquifers via improperly constructed and maintained wells or abandoned wells that have been improperly plugged and sealed, For example, in Dimmit County and adjacent areas of Texas, saline water from the Bigford Formation is leaking through old well bores into the underlying Carrizo aquifer,

Aquifer water-quality degradation has a negative impact on nonirrigation water uses, too. In the High Plains region, ground water quality is declining as the Ogallala aquifer drops, and in some parts of the region the water has become unsuitable for domestic use. This may have a serious adverse impact on the economy of the area (Vanlier, 1980).

When withdrawals lower aquifer water levels, poor-quality surface waters can infiltrate. The problem of saline recharge to aquifers used for irrigation water is exacerbated locally by degradation of surface water quality, For example, in the Trans-Pecos region of Texas the ground water is becoming saline, in part from recycling irrigation waters. The U.S. Water Resources Council noted that in the San Joaquin Valley in California there is a need for a valley-wide management system that would dispose of or reclaim saline water to help prevent degradation of the San Joaquin River and ground water supplies.

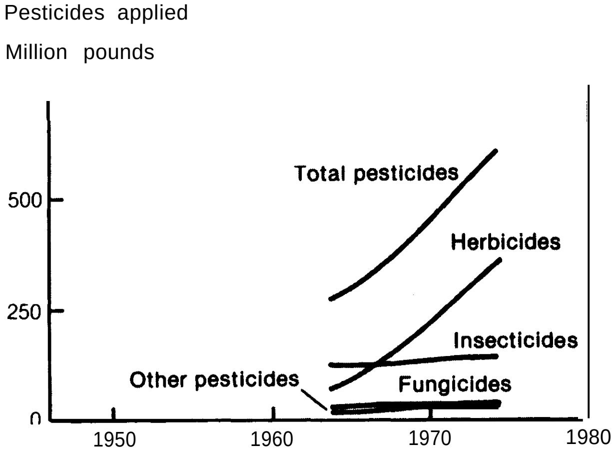
The contamination of freshwater aquifers by infiltration of saline surface waters and agricultural drainage has not received the attention given to other sources of ground water contamination, but it is a factor that must be considered in long-term planning for agricultural productivity.

Pesticide Contamination

USDA reports that more than *1,800* pesticide compounds are marketed and that an estimated *1.25* million tons will be applied on American soils by *1985* (see fig. *7).* Approximately 5 percent of the pesticides will reach the Nation's waters, A *1970* report of the Working Group on Pesticides cautioned that the potential for ground water contamination must be analyzed from the perspective of the properties of the pesticide, hydrological traits of the disposal area, and the volume, state, and persistence of the pesticide. For example, greater hazard occurs when high concentrations of pesticides are deposited near shallow wells or in regions of thin and highly permeable soil.

Residues of DDT; 2,4-D; lindane; and herbicides are the focal point of ground water contamination discussion and research. Arsenate compounds used in insect control in Maine's blueberry fields have been detected in shallow ground water, and chlorinated hydrocarbons used on Massachusetts cranberry bogs were reported in a sand and gravel well, Soil samplings in the Houston black clay of three watersheds in Waco, Tex., demonstrated that DDT had penetrated the soil and percolated down into the ground water (Lehr, *1980).*

Figure 7.— Pesticides Applied



SOURCE Pesticides applied, 1964: *Quantities of Pesticides Used by Fanners in 1964,* USDA Economics, Statistics, and Cooperatives Service (Washington: U.S Government Printing Office, 1968), agr econ. rep. 131, pp. **9, 13, 19, 26. 1966:** *Farmers Use of Pesticides in 1971—Quantities,* USDA Economics, Statistics, and Cooperatives Service (Washington' US. Government Printing Office, 1974), agr. econ. rep. 252, pp. 6, 11, 15, 18, 1971 and 1976: *Farmers' Use of Pesticides* in *1976,* USDA Economics, Statistics, and Cooperatives Service (Washington. U.S Government Printing Office 1978), agr econ. rep 418, pp 6, 9, 15, and 20. Cited in CEO, 1981 Envirorr. *Trends.*

A field study in which toxaphene (an insecticide) and fluometuron (a herbicide) were applied to the topsoil and observed for *1* year showed that both compounds were found in underlying ground water 2 months after application (LaFleur, et al., 1973). Residues persisted throughout the l-year observation period.

Contamination by Organic material and Pathogens

In general, ground water does not have the natural cleansing mechanisms of surface water. Although most removal of readily degradable organic compounds occurs very near the water's point of entrance into the aquifer, some sorption (binding of organics to mineral substrates) and biodegradation do occur within the aquifer. Sorption affects the rate of travel of organic contaminants and allows the accumulation of organic materials in or on subsurface solids. Biodegradation depends on a number of variables including pH, temperature, and having a primary source of organic material on which the bacteria can subsist. Relatively little is known about how organic materials degrade in ground water; possible interactions between primary and secondary substrates and bacteria are not known, nor are the effects of sorption on the rate of transformation, The breadth of organic compounds that maybe reduced by biological activity are unknown and methods for assessing the potential of a specific aquifer for microbial activity are also lacking (McCarty, 1981).

There are conflicting reports on the levels of fertilizer pollution in ground water. According to the General Accounting Office, heavy reliance on fertilizer contributes to an estimated 1 million metric tons of dissolved nitrogen in ground and surface waters, In the Seymour water-bearing formation in Texas, jumps in nitrate levels of from less than 50 to 165 ppm can be traced to fertilizer use (Lehr, 1980). Yet, nitrates from fertilizers and from natural reservoirs of nutrients in fertile soils are indistinguishable, and some experts have claimed that, apart from occasions when a spring application of fertilizer nitrogen may be followed by very heavy rain, the problem of high nitrate levels in drainage water (which can infiltrate aquifers) is not so much one of fertilizers as of soil fertility, especially after ploughing (Armitage, 1974). Because high nitrate levels in ground water used for drinking can present a health hazard for infants up to the age of 3 months, this nutrient contaminant needs careful monitoring.

Nearly half of all documented waterborne disease outbreaks in the United States result from contaminated ground water. Certain viruses, some of which may constitute a health hazard to humans or livestock, may be absorbed onto soil organic matter and clays and move downward slowly in the ground water (Gerba, **1981]**, while others may remain free in infiltrating water and enter the ground water more quickly. Fecal coliform bacteria counts are commonly used to monitor for contamination by animal wastes. As livestock management is intensified, and as onland waste disposal systems develop, consideration must be given to potential infiltration of pathogens into the ground water below.

Reduced Streamflow and Spring Discharge Caused by Ground Water Pumping

Water-well pumping lowers ground water levels in the well vicinity. In part, this may reduce the natural discharge of water from the aquifer, much of which is through springs and seeps along and beneath streams. If ground water levels are lowered below the level of a stream, water can infiltrate from the stream to the aquifer, and areas along streams that under natural conditions received water from the ground now accept water from the stream. The resulting decline in the streamflow reduces the availability of surface water for other uses, including irrigation.

Sometimes the changes in the water regimen that can result from pumping ground water for irrigation can be beneficial in that some of the water tends to accumulate in the ground and can be pumped later during the irrigation season, Ground water irrigation, however, requires energy for pumping, whereas diversion of surface waters generally is accomplished through gravity flow. As energy costs increase in future decades, irrigation systems with lower energy requirements probably will take precedence.

Standardized data on ground water quality is needed for responsive policymaking. The USGS catalog of Information on Water Data might be useful as a prototype (Vanlier, 1980). In it, ground water quality is outlined in terms of four traditional categories: physical, chemical, biological, and sediment related. Identified within each category are a number of factors (e.g., turbidity, pH, coliform bacteria content, sediment particle size) that should be measured at regular intervals. Frequent measurement of these indicators will promote the early detection of a contaminant by a monitoring system, Sufficient leadtime is important for corrective action.

Conclusions

The continuing decline of ground water quality and quantity apparently is not caused by lack of data or knowledge. The probability that agricultural productivity in the High Plains region would decline during the latter part of the 20th century, and that economic problems would consequently emerge, has been clearly recognized locally and nationally for the last several decades (Vanlier, 1980). Rather, the decline is caused by a lack of a coherent, national resource-use philosophy and water management policy. This has led to a separation of policies toward surface and ground water.

The separation of ground and surface water issues results in administrative mismanagement of both resources, These two elements are mistakenly not seen as part of the same hydrologic cycle. This insular treatment extends in many cases to the laws pertaining to their use, to the Federal agencies and institutions that regulate and control them, and to the research and development that guides their future uses.

To ignore a substantial hydrologic imbalance costs money—money in production costs, farm income, crop prices, food prices, etc. For cropland affected by ground water depletion, salinity, and subsidence problems, a total calculation of ground water-related damage has not been compiled.

Directly entwined with ground water economic impacts is the ripple effect felt by society. As ground water problems increase in severity, interactions between producers directly affected and those not affected can be expected to change land values. For example, agricultural producers' net income along the Colorado River would drop because of crop yield reductions and increased production costs as salinity increases. On the other hand, the lands of a producer of the same crop in an area without salinity problems would increase in relative agricultural value.

Eventually, this imbalance will spur production relocation and passing of increased costs on to consumers. The rural business community of banks and agricultural suppliers, too, is ultimately influenced through changes in service demands and the tax base, And if the irrigated dry Western States are compelled to revert to dryland farming, the ultimate effects on food prices and the entire economy would be substantial.

The national agricultural policies that have the greatest effect on ground water resources are economic. For example, the quantity of water used to irrigate rice in Arkansas doubled between 1970 and 1975 as a result of relaxation of acreage controls (Halberg, 1977). It is not known if Government acreage controls and crop price-support programs increase ground water pumping for irrigation where otherwise it would be unprofitable,

Most individual farmers understand the costs and risks of their decisions to continue to pump water from aquifers that are experiencing overdraft or declining water quality. The individual farmer, however, is left with little choice except to use the water under his own land to maximize his profits. If he does not pump the water, his neighbors will. Farmers cannot unite to save water for some future date when each has made substantial individual investments in land and equipment. The specter of low agricultural prices and high production costs in areas of major ground water overdraft undoubtedly inhibits the individual farmer's decision to invest in expensive technologies to save water.

SUBSIDENCE

Land subsidence could become more common in the United States as the use of ground water and subsurface mineral resources intensifies, Subsidence can occur in various circumstances: when cities, industries, and irrigation agriculture withdraw large amounts of ground water; when coal and other mineral resources are mined; when there is solution mining of subsurface mineral deposits, such as salt; or when large amounts of petroleum have been extracted. All of these activities can result in the slow subsidence or the unexpected collapse of the land surface. If agriculture overlies these areas, it can suffer slow or immediate consequences.

Land subsidence is often the result of the combined influence of human activities and the land's natural proclivity to such disturbances. Certain soils and terrains are much more likely to suffer subsidence than others. Clays, for example, generally compact and subside more than coarser sediments such as silts and sands. Thus, it is often difficult to isolate the specific cause or causes of land subsidence.

But how does ground water withdrawal, irrigation, or perhaps the draining and farming of organic-rich soils cause subsidence? Because water commonly fills the spaces between the rocks and particles that make up underground sediments or sedimentary rock, it contributes to the volume of land. When wells are drilled and ground water is removed faster than it is replaced naturally, the ground water level drops, The loss of the water's buoyant support of the rock and mineral grains leads to increased grain-to-grain stress in the aquifer below. If the stress is great enough to cause the individual grains to shift and move close together, land subsidence results. Subsidence can take place in small increments over decades and, therefore, may go unrecognized in its early stages,

The effects of subsidence on agriculture have been most extensive in areas where ground water withdrawal for irrigation is common. For example, water withdrawal has greatly affected agriculture in the San Joaquin Valley of California. During 40 years of irrigation pumping, some 2,500 mi^2 in three main areas have suffered subsidence, Some areas sank as much as 20 ft; in 1967, some land was sinking at rates up to 1ft a year (Marsden and Davis, 1967). The gradual lowering of the land surface damaged expensive water-well casings, irrigation systems, buildings, drainage and flood-control structures, and other manmade structures. As the land subsided, flow directions were reversed in irrigation canals that normally had slopes of 0.3 ft per mile and major structural changes were required to maintain irrigated crop production. Such changes included raising or rebuilding bridges, pipelines, and other associated structures. Costs are high for repairing such damage. In California's Santa Clara Valley, subsidence costs are estimated at $15 million to $20 million (Lehr, 1980).

Similarly, in California's San Jacinta Valley approximately 5,400 miz of cropland have subsided at the rate of 1.2 ft a year since measurements began in 1935. Subsidence has reached nearly 28 ft in areas where irrigation wells pump as much as 1,500 acre-ft of water per year (Lehr, 1980).

Withdrawal of large amounts of ground water from the gulf coast aquifer underlying the Houston-Galveston, Tex,, area parallels the California experience. In this case, most ground water withdrawals have been for industrial and urban uses. Nevertheless, agricultural lands are affected adversely. Land subsidence there began as a result of ground water withdrawal starting as early as 1906. During a 26-year period, 1943-69, in the Houston area, a region some 15 miles in diameter suffered 2 ft of subsidence. An area with a diameter of about 60 miles, much of it rural land, suffered at least 6 inches of subsidence during the same period, These depressed land surfaces act as catchments during heavy hurricane-associated rainfall and, thus, periodically limit the land's usefulness for crop production (Flawn, 1970).

Land subsidence can be halted, but not easily, Water can be pumped back into the aquifers to end subsidence, and a slight rebound of the land surface may occur. But in areas where water is scarce, what would be the recharge water source? Subsidence can be slowed by reducing ground water withdrawals or by pumping only from widely dispersed wells. These approaches have promise only where alternative sources of freshwater are available for irrigation agriculture. Finding alternative water sources is becoming increasingly difficult.

Introducing irrigation water into very dry areas that are covered by alluvial or mud-flow sediments with large pore spaces can cause reorientation of the sediment particles and thus cause subsidence. A 27-month irrigation test on such sediments along the western side of the San Joaquin Valley in central California caused a 10.5-ft drop in the land surface, resulting in damage to roads, pipelines, and transmission lines (Flawn, 1970).

When drained, peat and other organic-rich soils are subject to oxidation and decomposition of the exposed organic matter, thereby causing shrinkage and subsidence. Drained organic soils in the Sacramento-San Joaquin delta area of northern California subsided 12 to 14 ft between 1850 and 1950 (Flawn, 1970). A similar situation exists in the Belle Glade area of Florida where half of a lo-ft peat deposit has disappeared from agricultural fields through oxidation over a 50-year period, Under original conditions, the peat accumulated at about 1ft per 400 years (Shrader, 1980), Subsidence on organic soils in Florida's Everglades agricultural area varies from 1.5 to 3.1 cm/year depending on the land use (Lehr, 1980),

Conclusions

Land subsidence can affect agriculture adversely. These changes are typically permanent, and subsided land cannot be restored to its original state. In most areas of land subsidence, relevant data are collected largely by State and local agencies. In California, for example, USGS, in cooperation with the State, maintains a network of land subsidence stations and wells. The data on subsidence seem to be sufficiently accurate and adequate for most agricultural planning purposes.

Agriculture's investments in irrigation systems are expensive and normally are designed for a long useful life. But where ground water withdrawals for irrigation cause subsidence, sustainability of the agriculture system is jeopardized. Subsidence related to changes in organic soils affects land productivity, as well, because continual changes in the topography of the land may interfere with irrigation systems and other infrastructure,

UTILITIES OTHER THAN CROPS AND FORAGE

Agricultural lands are managed to produce crops and forage, but other, less quantifiable services from the land are also vitally important to the Nation's well-being. These benefits are often taken for granted or assumed to come solely from nonagricultural land, The quality of air, water, ground water, fish and wildlife habitats, and esthetic and recreational areas are all directly related to croplands, pasturelands, and rangelands.

An agroecosystem does not end at the edge of a field or pasture, but includes the boundaries—fences, hedgerows, windbreaks, nearby fallow fields, riparian habitats, and adjacent undeveloped areas. As the quality and quanti-

Photo credit: USDA—Soil Conservation Service

A cool, clear unpolluted stream in the Monongahela National Forest

ty of these areas is changed by agricultural activities, the utilities obtained from the land also change.

Effects on Air Quality

Vegetation and soil are major factors in the balance of gas cycles. Plants, through photosynthesis, remove carbon dioxide and are the primary source of atmospheric oxygen. Soil plays a less well-known role in the nitrogen cycle. Nitrogen oxides are an important factor in the destruction of stratospheric ozone, and agricultural activities affecting nitrous oxide (N_2O) are coming under increasing scrutiny. Soil can act both as a source and as a sink for atmospheric N2O during periods of moderate soil-water content.

N2O is produced during denitrification in soils when the soil nitrate content is high, the temperature is conducive to high respiratory oxygen demand by soil biota, and the water content causes restricted soil aeration. Any agricultural activities affecting nitrate content, water content, or soil temperature will affect the yearly flux of nitrogen oxides. For example, converting grassland to annual crops is likely to release N2O to the atmosphere.

Soil micro-organisms can eliminate air pollutants, such as carbon monoxide and various gaseous hydrocarbons, in the lower portion of the atmosphere that comes into contact with the ground (Alexander, 1980). In addition, plants are effective in removing pollutants such as sulfur dioxides (SO_2), from air and converting them to less toxic or harmless substances. Plants absorb SO_2, which then reacts with water to form phytotoxic sulfite. This is slowly oxidized within the plant cells to relatively harmless sulfates. If too much gas is absorbed too rapidly, however, the plant suffers the consequences of retaining a dangerous level of the toxic sulfite within its cells (Dairies, et al., 1966). It is difficult to measure the amount of pollution with which an ecosystem comes into contact, and more difficult still to measure how much of the pollution is removed.

Another way in which soil and vegetation help maintain air quality is by controlling wind erosion. Wind erosion introduces 30 million tons of particulate to the U.S. atmosphere each year. Soil organic matter and vegetation anchor the soil and keep it in place. Conventional tillage removes plant cover and pulverizes soil, thus impairing its binding functions. Crop residue management, stubble mulching, no-till farming technologies, irrigation, and appropriate grazing management—technologies discussed later in this report—can decrease wind erosion.

Forests, woodlands, shrubs, and the taller farm crops also filter the suspended particulate matter from moving air masses and return it to the soil, improving the layers of air immediately above the ground. When vegetation is removed, as it was for the expansion of agriculture in the 1930's, the effect on quality of air and life is dramatic:

> More than 6 million acres were put out of production by dust storms; farmsteads were partially buried and damaged or totally destroyed and abandoned; the health of people and livestock suffered; many animals died of dust suffocation; machinery was damaged or destroyed; ditches and waterways were filled; valuable topsoil was lost; and soil fertility was seriously impaired for years to come (Walker, 1967),

Effects on Water Quality

When properly managed, land acts as an efficient "living filter" in the water cycle. Plant roots absorb nutrients, microbes degrade complex organic molecules, and the soil's organic and inorganic colloids have tremendous adsorptive capacity. Any agricultural activity that reduces any of these three mechanisms reduces the land's ability to provide clean water. Some of the major forms of water pollution associated with agriculture are silt from soil erosion, nutrient runoff from large feedlots, and concentration of chemicals (including those from pesticides and fertilizers) in return flows from irrigation systems.

Increased sedimentation of streams and other bodies of water, primarily a result of erosion, has many adverse effects. Fish feeding and breeding areas may be destroyed by silt. Streams may become broader and shallower so that water temperatures rise, affecting the composition of species the stream will support. Riparian wildlife habitats change, generally reducing species diversity.

Pollutants and nutrients associated with eroded sediments can have adverse impacts on aquatic environments. Concentrations of toxic substances may kill aquatic life, while nutrients in the runoff can accelerate growth of aquatic flora. This can aggravate the sedimentation problem and lead to accelerated eutrophication of the water bodies. Eutrophication is a process that usually begins with the increased production of plants. As they die and settle to the bottom, the micro-organisms that degrade them use up the dissolved oxygen. Sedimentation also contributes to exhausting the oxygen supply, especially in streams and rivers, by reducing water turbulence. Thus, the aquatic ecosystem changes dramatically.

Phosphorus and nitrogen are the major nutrients that regulate plant growth, Soil nitrogen is commonly found in water supplies. Phosphorus, on the other hand, is "fixed" in the soil, so runoff typically contains relatively small amounts, Under normal conditions, phosphorus is more likely to be the limiting factor in aquatic plant growth. Since phosphorus (along with potassium, calcium, magnesium, sulfur, and the trace elements) is held by colloid material, it is abundant in waters receiving large amounts of eroded soil.

Natural eutrophication is generally a slow process, but "cultural" (man-caused) eutrophication can be extremely rapid and can produce nuisance blooms of algae, kill aquatic life by depleting dissolved oxygen, and render water unfit for recreation. Replenishing the oxygen supply is a costly remedy because of the energy required to mix and dissolve such a sparingly soluble gas into aqueous solutions.

The nutrients reaching water supplies from natural sources, however, vary widely depending on the land and soil type, Water from highly fertile, unfertilized agricultural lands can have a higher content of plant nutrients than water from heavily fertilized, well-managed cropland low in natural fertility, Nutrient losses from properly fertilized soils, in fact, can be less than from soils to which no amendments are added, since a vigorously growing crop will use the available nutrients (Smith, 1967).

Another aspect of water pollution from agricultural sources is the danger to human and animal health by runoff from livestock feedlots. Coliform and enterococcus bacteria living in the fecal waste of the animals can reach water supplies if the runoff from these feedlots is improperly managed. If allowed to percolate slowly through the soil, however, the coliform and enterococcus bacteria are adsorbed on colloidal material and die. This natural filtering mechanism is very efficient—more than 98 percent is removed in the first 14 inches of soil.

Effects on Ground Water Resources

Another essential service provided by a properly managed environment is that it provides clean recharge water for ground water aquifers. Most of the removal of readily degradable pollutants occurs near the water's point of entrance into ground water reservoirs, provided the environment is conducive to microbial action. Precipitation filters through the ground and recharges ground water at a rate of approximately 300 trillion gallons per year (CEQ, 1980).

Reducing the percolation and filtration capabilities of soils, contaminating surface waters, and lowering water tables all hinder aquifer recharge. Improved grazing management, technologies to reduce erosion and runoff into surface water, controlled ground water withdrawal, and artificial recharge with fresh or purified water are technologies that enhance the land's ground water recharge function.

Effects on Fish and Wildlife

Wildlife are broadly affected by agricultural activities. The most widespread problems are a result of expanding cropping and grazing into wildlife habitats, overgrazing of riparian areas, and agricultural activities that contaminate aquatic habitats.

As American settlers cleared forests and plowed prairie land for cultivation, many wildlife species vanished, Some species that were adapted to open areas continued to prosper, The cottontail, bobwhite, crow, robin, red fox, skunk, and meadow mouse benefited as forests were opened to fields. Forest edge-loving species, such as the white-tailed deer, increased as more of their favored environment was available, but later declined as forest clearing increased. Other species could not adapt to the changed environments, however.

In the West, wilderness prairie animals—bison, pronghorn antelope, mule deer, and grey wolf—began to decline almost immediately as their habitat disappeared, Large species and predators were especially affected, By the turn of the 20th century, wilderness animals had virtually vanished from the East, from much of the prairie further west, and from the more fertile valleys of the Far West.

The abandonment of farms, particularly upland farms with sloping fields, sometimes improves habitat for wildlife, though the diversity of species is still greatly reduced from the original flora and fauna. Some conversion of farmland to protected forestlands and vacationlands also occurs.

As crop yields on sloping uplands decline with erosion and fertility loss, farmers sometimes convert upland fields to pasture and drain lowlands for crops. Wetlands drainage removes habitats for migrating and resident waterfowl, and can remove the last remaining winter cover for some species of wildlife such as pheasants. The removal of fence rows and shelter belts also reduces wildlife habitat.

Irrigation of drylands, though, actually provides new habitat into which pheasants and other wildlife can expand, Habitat also is enhanced by the more than 2 million acres of farm ponds, dugouts, and stock tanks that have been created, Especially where protected from livestock, these waters and their shoreline vegetation provide habitat diversity and niches for birds, amphibians, reptiles, fish, and other wildlife (Burger, 1978).

Mechanization also has had a dramatic impact on wildlife. For example, mechanical cornpickers leave more waste grain after corn harvests than handpicking. Canadian geese, mallard ducks, and other field-feeding waterfowl have benefited substantially from this new food source. As a consequence of this drainage of wetlands, irrigation of drylands, and creation of waterfowl refuges, the migratory paths of many wildfowl have changed.

Land-forming, chemical treatments, and other agricultural technologies often affect wildlife adversely, The replacement of contour plowing and stripcropping by leveling and filling surface irregularities in fields removes wildlife habitat on farmlands. Various agricultural chemicals have deleterious effects on wildlife. For example, bioaccumulated chlorinated insecticides produce eggshell thinning in several predacious birds. Other insecticides that have found their way into streams can significantly reduce invertebrate populations on which many fish depend (NAS, 1974).

Adverse effects from chemical applications are not new. In Colorado, the pesticide Paris Green, used by farmers to counter a grasshopper invasion in 1931, nearly eliminated the newly introduced ring-necked pheasant. Pesticide pollution is also responsible for the emergence of pesticide-resistant populations of agricultural pests. A shortage of data exists, however, on the adaptations of these pests on a biochemical or genetic level. Thus, the long-term effects of pesticides on pest populations are unknown (Winteringham, 1979).

Cattle and sheep grazing and man's control of fires in the Western States have been responsible for changing large areas of grassland into shrubland, thereby reducing the productivity of those lands for wildlife and water resources (Littlefield, 1980). Competition between some wildlife—e, g., bighorn sheep and American elk —and livestock also can occur.

Overgrazing reduces the perennial native grasses on which cattle thrive and allows sagebrush, a less nutritious forage, to increase. Seedings of introduced grasses (e.g., crested wheatgrass) can provide good replacement forage for livestock, but wildlife generally does not prosper in such monoculture.

Overgrazing of riparian habitats is particularly detrimental, both to the wildlife that depend on streamside vegetation and to the aquatic life in streams and lakes. Riparian habitats are generally more productive of plants and animals and are more diverse than the surrounding range, Abuse or misuse of these more fragile waterside habitats thus can be especially damaging.

Generally, sheep do little damage to riparian habitats because they prefer open vegetation areas. Cattle, however, are particularly damaging to riparian habitats because they prefer the succulent growth and because they congregate in large numbers over long periods, especially during the often critical periods of spring and summer. Deer and elk rarely congregate enough to do damage (Cope, 1980)

Riparian soils generally have high infiltration capacities and release captured water slowly to streams. Cattle grazing in these areas, however, reduces riparian vegetation, compacts soils, and destroys overhanging streambanks, all of which promote erosion and increase the sediment load of the stream.

Stable streambanks hold sediment, control water velocities, give cover to aquatic life, and supply terrestrial foods to the ecosystem. When streambanks are broken down, sediments from the debilitated streambank and from runoff on nearby lands pollute the stream. Thus, eutrophication may begin along with all of the concomitant changes in the riparian and aquatic ecosystems. Fish production is suppressed by elevated water temperatures, fish foods and spawning beds are buried by sediments, and aeration is reduced. Game fish, such as trout, are reduced or eliminated, and replaced by hardy but less desirable species (e.g., chubs) that can survive in shallower streams with lower oxygen content.

Grazing also can intensify bacterial and pesticide pollution. Flushing of animal feces into aquatic systems may cause algal blooms that reduce photosynthesis by aquatic plants, make less oxygen available to aquatic life, and release toxic wastes under anaerobic conditions.

Conclusions

The food and fiber products supplied by the Nation's agricultural lands represent only a part of their value. Agroecosystems play an essential role in maintaining air and water quality, in recharging underground aquifers, and in providing fish and wildlife habitat. Although these benefits are often difficult to measure, they are an important dimension that should not be underrated by agricultural policymakers.

CHAPTER II REFERENCES

Alexander, M., "How Agriculture Technologies Affect Productivity of Croplands and Rangelands by Affecting Microbial Activity in Soil, " OTA background paper, 1980.

Armitage, E. R., "The Run-Off of Fertilizers From Agricultural Land and Their Effects on the Natural Environment, " *Pollution and the Use of Chemicals in Agriculture* (Ann Arbor Mich.: Ann Arbor Science Publishers, Inc., 1974), pp. 43-60.

Borman, R. G., et al., "Water Level Changes in the Northern High Plains of Colorado, 1956 to 1976, " U.S. Geological Survey, Lakewood, Colo., Water Resources Division, 1977.

Buntley, G. T., and Bell, Frank F., *Yield Estimates for the Major Crops Grown on Soils of West Tennessee,* Agr. Expt. Sta. Bulletin 561, 1976.

Burger, George, "Agriculture and Wildlife, " *Wildlife and America* (Washington, D, C.: Council on Environmental Quality, 1978), pp. 89-107.

Cassel, D. K., "Subsoiling," *Crops and Soils Magazine,* October 1979, pp. 7-10.

Cook, Kenneth A., "The National Agricultural Lands Study Goes Out With a Bang, " in *Journal of Soil and Water Conservation,* vol. 36, No. z, March-April 1981, pp. 91-93.

Cope, O. B., "Impacts of Rangeland Technologies and of Grazing on Productivity of Riparian Environments in the United States Rangelands, " OTA background paper, 1980.

Costle, Douglas, "Statement of Douglas Costle, Administrator, Environmental Protection Agency, before the Subcommittee on Oversight and Review, Committee on Public Works and Transportation, " U.S. House of Representatives, implementation of the Federal Water Pollution Control Act, hearing July 18, 1979.

Council for Agricultural Science and Technology, "Soil Erosion: Its Agricultural, Environmental, and Socio-economic Implications, " report No. 92, January 1982.

———, "Land Resource Use and Protection, " report No. 38, January 1975.

Council on Environmental Quality, "Environmental Quality: The Eleventh Annual Report of the Council on Environmental Quality, " Washington, D. C., 1980.

——— "National Agricultural Lands Study, " Washington, D. C., 1981.

Dairies, R. H., Leone, Ida H., and Brennan, Eileen, "Air Pollution and Plant Reponses in the Northeastern U.S., " *Agriculture and the Qual-*

ity of Our Environment (Washington, D. C.: American Association for the Advancement of Science, 1966), pp. 11-32.

Dixon, R. M., "New Soil Implement Makes a Good Impression, " *Crops and Soils Magazine,* June-July 1977, pp. 14-16

Flawn, Peter T., *Environmental Geology: Conservation, Land Use Planning, and Resource Management. (New* York: Harper & Row, 1970.)

Frederick, Kenneth D., "Irrigation and the Future of American Agriculture, " *The Future of American Agriculture as a Strategic Resource* (Washington, D. C.: The Conservation Foundation, 1980).

Gerba, C. P., et al., "Quantitative Assessment of the Adsorptive Behavior of Viruses to Soils, " *Environmental Science and Technology,* vol. 15, 1981, pp. 940-944,

Gifford, G. F., Faust, R. H., and Coltharp, G. B., "Measuring Soil Compaction on Rangeland, " *Journal of Range Management,* 30:457-460, *1977.*

Hagen, L. L., and Dyke, P. T., "Yield-Soil Loss Relationship, " Proceedings of Workshop on Influence of Soil Erosion on Soil Productivity, USDA-SEA-AR, Washington, D. C., 1980.

Halberg, H. A., "Use of Water in Arkansas, 1975, Water Resources Summary 9, Arkansas Geological Commission, State of Arkansas, " prepared by the U.S. Geological Survey in cooperation with the Arkansas Geological Commission, 1977,

Hauschen, Larry D., "Increasing Water Scarcity: Some Problems and Solutions, " *Cross Section,* 1980.

Irwin, R. W., "On-Farm Drainage Benefit," University of Guelph, Ontario, 1981, p. 14,

LaFleur, K. S., "Movement of Toxaphene and Fluromethoron Through Soils to Underlying Ground Water, " *Journal of Environmental Quality,* 2(4):515-518, *1973.*

Larson, W. E., "Protecting the Soil Resource Base, " in *Journal of Soil and Water Conservation,* vol. **36, No. 1, January-February 1981,** pp. 13-16,

Lehr, J. H., "Database on Ground Water Quality and Availability, " OTA background paper, 1980.

Littlefield, Carroll D., Ferguson, D., and Holte, K, E., "The Impacts of Grazing and Rangeland Management Technology Upon Wildlife, " OTA background paper, 1980.

Marsden, Jr., S. S., and Davis, S, N., "Geological Subsidence, " *Scientific American,* vol. **216, 1967, pp. 93-100,**

McCarty, P. L., Rittman, B. E., and Reinhard, R., "Trace Organics in Ground Water," *Environmental Science and Technology,* 15(1):40-51, January 1981,

McCormack, D. E., and Larson, W. E., "A Values Dilemma—Standards for Soil Quality Tomorrow, " presented at Soil Conservation Society of America, annual meeting, Dearborn, Mich., August 1980.

Miller, Arnold, *Expanding Crop Production and Soil Erosion: Land Resources, Conservation Practices and Policy Changes,* unpublished manuscript, June 15, 1981.

Moldenhauer, W. C., and Onstad, C, A., "Achieving Specified Soil Loss Levels, " *Journal of Soil and Water Conservation,* vol. 30, 1975, pp. 166-167.

Murray, C. Richard, "Estimated Use of Water in the United States in 1970, " U.S. Geological Survey Circular 676, 1970, pp. 20-21,

National Academy of Sciences, *Productive Agriculture and Quality Environment,* Washington, D. C., 1974.

Ochs, Malter, U.S. Department of Agriculture, Soil Conservation Service, personal communications, July 1981.

Pimentel, David, et al., "Land Degradation: Effects on Food and Energy Resources, " *Science, vol. 194,* pp. *117-128, 1976,*

Raghaven, G, S. V., et al., "Effects of Soil Compaction on Development and Yield of Corn (Maize)," *Can. J. Plant Sci.* 58:435-443, *1978.*

Robertson, L. S., Department of Crop and Soil Sciences, Michigan State University, personal communication, 1981.

Schwab, G. O., Fausey, N. R., and Weaver, C. R., "Tile and Surface Drainage of Clay Soils, " Ohio Agricultural Research and Development Center Research Bulletin #1081, 1975.

Sheridan, David, *Desertification of the United States,* Council on Environmental Quality, 1981,

Shrader, W. D., "Effect of Erosion and Other Physical Processes on Productivity of U.S. Croplands and Rangelands, " OTA background paper, 1980,

Smith, G. E., "Fertilizer Nutrients as Contaminants in Water Supplies, " *Agriculture and the Quality of Our Environment* (Washington, D. C.: American Association for the Advancement of Science, 1967), pp. 173-186.

Spomer, R. G., Shrader, W. D., Rosenberry, P. E., and Miller, E. L., "Level Terraces With Stabilized Backslopes on Loessial Cropland in the Missouri Valley: A Cost-Effectiveness Study, " *Journal of Soil and Water Conservation,* vol. 28, No. 3, 1973, pp. 127-131.

Troeh, F. R., Hobbs, J. A., and Donahue, R. L., *Soil and Water Conservation for Productivity and Environmental Protection* (Englewood Cliffs, N. J.: Prentice-Hall, 1980).

Trouse, A., Research Soil Scientist, U.S. Department of Agriculture, SEA-AR, personal communication, 1981.

U.S. Department of Agriculture, Soil Conservation Service, "An Assessment of the Energy Saving Potential of Soil and Water Conservation, " April 1975.

U.S. Department of Agriculture—Resources Conservation Act, *The Soil and Water Resources Conservation Act: 1980 Appraisal* (review draft pt. 1), 1980.

——, "Basic Statistics: 1977 National Resources Inventory (NRI), revised February 1980.

U.S. Water Resources Council, *The Nation Water Resources, 1975-2000,* vol. *4,* Texas Gulf Regional (12], Washington, D. C., 1978.

Vanlier, K. E., "Groundwater and Agricultural Productivity: The Information and Data Base, " OTA background paper, 1980.

van Schilifgaarde, Director, U.S. Salinity Laboratory, Riverside, Calif., personal communication, 1981.

Voorhees, W. B., "Soil Compaction, Our Newest Natural Resource, " *Crops and Soils Magazine 29(5],* 1977a.

——, "Soil Compaction, How It Influences Moisture, Temperature, Yield, Root Growth, " *Crops and Soils Magazine 29(6),* 1977b.

—— "Soil Compaction, Good and Bad Effects on' Energy Needs, " *Crops and Soils Magazine 29(5),* 1977c.

——, "Soil Tilth Deterioration Under Row Cropping in the Northern Corn Belt: Influence of Tillage and Wheel Traffic," *Journal of Soil and Water Conservation,* July-August 1979, pp. 184-186,

Voorhees, W. B., Senst, C. G., and Nelson, W. W., "Compaction and Soil Structure Modification by Wheel Traffic in the Northern Corn Belt," *Soil Science Society of America Journal* 2:344-349, *1978.*

Walker, Kenneth C., "Agricultural Practices Influencing Air Quality, " *Agriculture and the Quality of Our Environment* (Washington, D. C.: American Association for the Advancement of Science, 1967), pp. 105-112.

Weeks, J. B., personal communication, 1980; and Weeks, J. B., and Gutentag, E. D., "Bedrock Geology, Altitude of Base, and 1980 Saturated Thickness of the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, " USGS Hydrologic Investigations Atlas 648, 1981.

White, Fred C., "Relationship Between Increased Crop Acreage and Non-Point Source Pollution: A Georgia Case Study, " *Journal of Soil and Water Conservation,* vol. **36, No. 3, 1981,** pp. 172-176.

Williams, J. R., et al., "Soil Erosion Effects on Soil Productivity: A Research Perspective, " *Journal of Soil and Water Conservation,* 36:2, *1981,* pp. 82-90.

Wilshire, Howard, USGS, personal communication in *Desertification in the U. S.,* David Sheridan, CEQ 1981.

Winteringham, F. P. W., "Agroecosystem—Chemical Interactions and Trends, " *Ecotoxicology and Environmental Safety 3:219-235,* 1979.