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A TECHNOLOGY ASSESSMENT OF COMMERCIAL CORN

PRODUCTION IN THE UNITED STATES

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PREFACE

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Introduction

Corn (maize, <u>Zea mays</u>) has for many years been number one in terms of economic importance among U.S. field crops. A record crop of about 8 billion bushels is expected in 1981. If realized, this would surpass the previous production record, set in 1979, of 7.94 billion bushels harvested from 72.4 million acres. The market value of the 1979 crop was almost $20 billion. In recent years about 70 percent of the corn grain harvested has been utilized domestically. In 1977-79, U.S. production accounted for 47 percent of total world output, so U.S. corn is highly significant, in economic terms, both nationally and internationally.

The U.S. agricultural research and development system is being asked to achieve not only higher production goals but other important goals as well. These goals include conservation of natural resources (particularly land, water and fossil source energy), improved human nutrition, maintenance of a competitive cost structure, preservation of a healthy environment and still others. Thus, the goals of the agricultural research and development sector (including that for corn) are multi-faceted. The technology used in agricultural production bears importantly on all of these goals.

Several reasons exist for performing an assessment of corn production technology at the present time. These include: (i) the ever increasing world demand for food, and the associated increases in food prices; (ii) the physical limitations of key resources used in corn production and their associated price increases; (iii) concern that a plateau has been reached in U.S. agricultural productivity; and (iv) concern over the alleged wide-spread occurrence of adverse environmental consequences (particularly chemical pollution and soil erosion). In addition, new commercial uses are being found for corn and this may further increase demand. With these key concerns, and others, to guide our analysis, we have undertaken to make a broad-based assessment of corn production technology. Because of the breadth of the topic under investigation, our

description and analysis of individual technologies is necessarily brief. It is not a substitute for comprehensive technical and economic assessments of individual technologies and/or components of technologies.

Study Objective

The objective of this study is to provide a technology assessment of U.S. commercial corn production. The focus is on production of corn for grain,1/ and only those technologies which are relevant to the point of the "farm gate" stage of production are explicitly assessed. However, where there are key linkages between off-farm technologies and corn production technologies, consideration is given to these other technologies as well (e.g., emerging biotechnologies).

In the case of corn production, a number of individual technologies are combined and interrelated. It is not always possible to isolate the independent effect of each technology. In fact, some technologies have only been applied in corn production in conjunction with other technologies with which they interrelate. Some technologies which are important in corn production are also important in the production of other crops, such as soybeans. As a consequence, the process of corn technology assessment must be a pragmatic combination of "partial" analyses with subsequent integrations, aggregations and inferences.

To provide insight into the physical, technical and economic environment in which corn is produced, we have undertaken, in Chapter II, a brief depiction of changes which have occurred in corn production and utilization over recent decades. This period, generally since about 1930, is when increased corn production in the U.S. ceased to be mainly a process of expansion to new agricultural land and became one of adopting new technology and new management practices on existing crop land.

In the final section of this report (Chapter XIII) we have drawn on the findings of our

technology assessment to identify high priority areas of future research and development (R&D) related to corn production. We have also drawn on analyses of other past research to indicate the probable payoff for an effective future program of research and development.

Technology Assessment Defined

Numerous definitions exist for technology assessment and each has its own individual merits and problems. Our preference is to use a broad, inclusive definition and then to collapse those components which are either: (i) not applicable to the assessment of a particular technology; or (ii) beyond our capability to analyze effectively. A USDA Workshop on Technology Assessment (U.S. Dept. of Agriculture, 1977) provided the following definition which we find useful:

"Technology assessment is the formal, systematic, interdisciplinary examination of an existing, newly emerging or prospective technology with the objective of identifying and estimating first and second order costs and consequences, over time, in terms of the economic, social, demographic, environmental, legal, political, institutional and other possible impacts of the technology, including those consequences which may not have been anticipated, intended or desired by the inventors, and of specifying the full range of alternative courses of action for managing, modifying, or monitoring the effects of the technology." (p. 152)

The features of a technology assessment which distinguish it from other forms of evaluation are: (i) the multiplicity of assessment criteria; (ii) the identification of uncertainties and externalities associated with technology; and (iii) the specification of alternative technology options for achieving objectives. The latter feature points up the necessity of evaluating the "opportunity costs" associated with a technology or a group of technologies.

Framework for Assessment of Technologies

In general terms, the assessment framework is given by the definition of technology assessment listed above. However, we have translated this definition into the following specific steps for individual corn production technologies:

(1) provide a definition and description of the technology;
(2) specify the direction and magnitude of the technology;
(3) assess the direct effect of the technology on:

a. per acre yields, costs, profitability, and aggregate production capacity;
b. productivity, as measured by the total output/input ratio and/or by partial productivity or intensity of factor use measures for specific inputs including land, energy and labor;
c. input demand;
d. a broad range of economic, environmental, legal, social, institutional, demographic, political, and safety considerations;
(4) assess other (indirect) effects of the technology in order to help:
a. identify gainers/losers from the technology;
b. identify long-term effects of the technology;
c. identify risks and uncertainties associated with the technology (including vulnerability to shocks from natural forces such as weather, pests, diseases, etc., and from economic forces such as major changes in supply, demand, and prices);
(5) assess feasibility of the technology in terms of criteria listed above; also, are the required inputs available for adoption of the technology on a broad basis?
(6) specify alternative technology options for achieving objectives (this involves mainly an examination of the opportunity costs of the technology under consideration but may also involve identifying non-economic advantages/disadvantages of alternative technologies); and
(7) assess management strategies for the technology - specify (and evaluate) the alternative courses of action for promoting, demoting, managing, modifying, or monitoring the effects of this technology.

The above assessment framework will be applied to individual technologies in the chapters which follow. It will also be applied, in Chapter XII, to corn production technology in the aggregate. Our emphasis was to: (i) examine the existing corn production system and determine likely adjustments to prevailing conditions; (ii) estimate the potential corn production capacity up to the year 2000; and (iii) identify areas requiring further R&D investment.

Footnotes

1/Much of the technology applied to corn produced for grain is also applied to corn produced for silage. There are, however, important differences in the two products. Silage is a high bulk product used exclusively for livestock feed. It must be produced near the point of its utilization in close coordination with the livestock which will consume it. The entire process of production, harvest and storage is based on its utilization as a forage, not a grain, crop. Once, a large acreage of corn was utilized as silage or fodder only if it did not warrant harvesting for grain. Now, however, almost all corn is produced

specifically for either grain or silage and the two, though using much common technology, are very different crops.

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In this chapter a broad picture of U.S. corn production and utilization is presented. The focus is on the period since World War II, although some data go back to 1930. Subsequent chapters of this report will help explain some of the changes that have occurred over the period.

Acreage, Yields and Production, 1930-80

The U.S. acreage of corn harvested for grain, average yield per acre and total production are shown in Table II-1 for 1930-80. The peak acreage of corn harvested for grain, 97.2 million acres, occurred early in this period (1932), whereas the peak in average per acre yield, 109.7 bushels, and in total production, 7.9 billion bushels, occurred only very recently (1979). The first 4 billion bushel corn crop did not come until 1963, but the 1979 crop, only 16 years later, was almost double that size. Thus, it is clear from these rapid yield changes that in the last five decades the technology of corn production has changed dramatically. Important changes continue to occur.

1. Corn Acreage, 1930-80

Acreage harvested for corn grain varied greatly from 1930-50 (Figure II-1), ranging from a high of 97.2 million acres in 1932 to a low of 61.2 in the extreme drought year of 1934. The overall trend was strongly downward during the 1930s and 1940s, leveling off at slightly over 70 million acres in the early 1950s. A further dramatic drop in acreage in the early 1960s was largely in response to the Feed Grain Program of 1961 which was initiated because of chronic low prices and production surpluses for corn and other feed grains. In response to that program, acreage fell from 71.4 million acres harvested in 1960 to 57.6 million acres in 1961 and remained at about that level during the 1960s. Expanded domestic cattle feeding and poultry sectors and a strong demand in world grain markets then combined to push corn grain acreage back over the 70 million mark by the mid-1970s where it remained through 1980. Currently, acreage of corn

harvested for grain makes up about 22 percent of the acreage of principal crops (USDA, 1981). This percentage has declined slightly since the early 1950s due, in part, to a huge increase in soybean acreage.

2. Trend in Corn Yields, 1930-80

During the period 1930-80, U.S. corn yield (Figure II-2) increased by an annual average of 1.7 bu/ac; the average increase from 1945-80 was 2.1 bu/ac. While a straight line trend provides a reasonably good explanation of the 1930-80 yield data, good statistical fits can also be obtained from: (i) an S-shaped curve, showing yields increasing at a decreasing rate (leveling off) in recent years (Menz, 1981); and (ii) a quadratic curve showing yields increasing at an

Figure II-1. U.S. Corn Acreage Harvested for Grain, 1930-80.
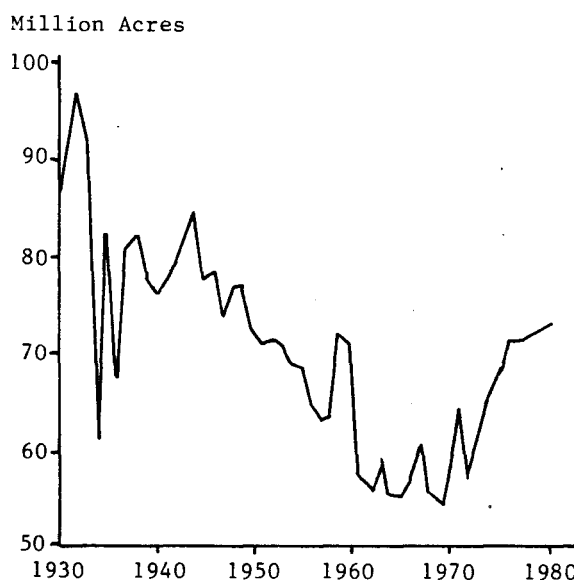
Million Acres

Source: USDA, Agricultural Statistics, 1930-79; Field Crops: Estimates by States 1974-78; and Crop Production, Annual Summary, 1980.

Table II-1. U.S. Corn Acreage, Yield and Total Production, 1930-80

Year	Acreage Planted All Corn (million ac)	Acreage Harvested for Grain (million ac)	Yield per Harvested Acre (bu)	Total Production Harvested for Grain (billion bu)
1930	103.9	85.5	20.5	1.76
1931	109.4	91.1	24.5	2.23
1932	113.0	97.2	26.5	2.58
1933	109.8	92.1	22.8	2.10
1934	100.6	61.2	18.7	1.15
1935	100.0	82.6	24.2	2.00
1936	102.0	67.8	18.6	1.26
1937	97.2	81.2	28.9	2.35
1938	94.5	82.8	27.8	2.30
1939	91.6	78.3	29.9	2.34
1940	88.7	76.4	28.9	2.21
1941	86.8	77.4	31.2	2.41
1942	88.8	79.2	35.4	2.80
1943	94.3	81.9	32.6	2.67
1944	95.5	85.0	33.0	2.80
1945	89.3	77.9	33.1	2.58
1946	88.9	78.4	37.2	2.92
1947	85.0	73.8	28.6	1.11
1948	85.5	76.8	43.0	3.31
1949	86.7	77.1	38.2	2.95
1950	82.8	72.4	38.2	2.76
1951	83.3	71.2	36.9	2.63
1952	82.2	71.4	41.8	2.98
1953	81.6	70.7	40.7	2.88
1954	82.2	68.7	39.4	2.71
1955	80.9	68.5	42.0	2.87
1956	77.2	64.9	47.4	3.08
1957	73.2	63.1	48.3	3.05
1958	73.4	63.5	52.8	3.36
1959	82.7	72.1	53.1	3.82
1960	81.4	71.4	54.7	3.91
1961	65.9	57.6	62.4	3.60
1962	65.0	55.7	64.7	3.61
1963	68.8	59.2	67.9	4.02
1964	65.8	55.4	62.9	3.48
1965	65.2	55.4	74.1	4.10
1966	66.3	57.0	73.1	4.18
1967	71.2	60.7	80.1	4.86
1968	65.1	56.0	79.5	4.50
1969	64.3	54.6	85.9	4.69
1970	66.9	57.4	72.4	4.15
1971	74.2	64.1	88.1	5.65
1972	67.1	57.5	97.0	5.58
1973	72.3	62.1	91.3	5.67
1974	77.9	65.4	71.9	4.70
1975	78.7	67.6	86.4	5.84
1976	84.6	71.5	88.0	6.29
1977	84.3	71.6	90.8	6.51
1978	81.7	71.9	101.0	7.27
1979	81.4	72.4	109.7	7.94
1980	84.1	73.1	91.0	6.65

Source: USDA: Agricultural Statistics, 1930-79; Field Crops: Estimates by States 1974-78; and Crop Production: Annual Summary 1980.

Figure II-2. U.S. Corn Yields, 1930-80.

Bu/Ac

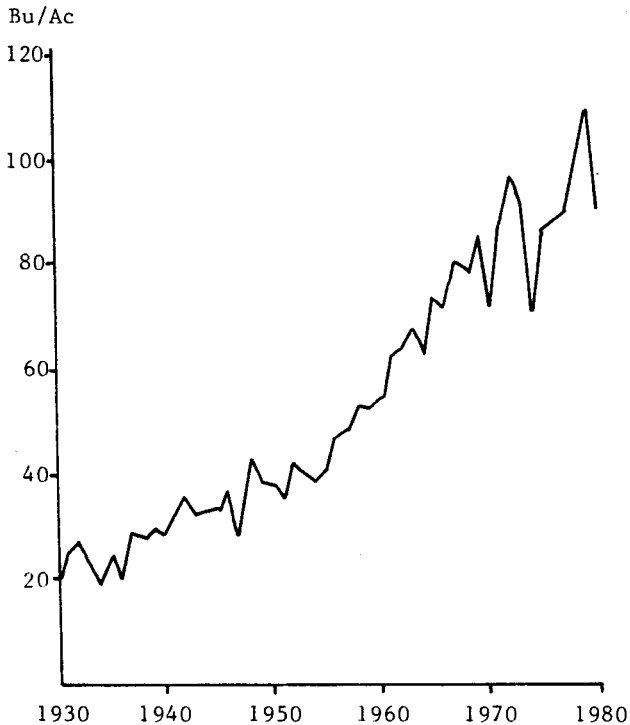Source: USDA, Agricultural Statistics, 1930-
79; Field Crops: Estimates by States
1974-78; and Crop Production, Annual
Summary, 1980.

increasing rate over time (Duvick, 1980). The
implications for the current (1981) underlying
yield trend are quite different in each case,
ranging from 0.5 bu/ac per year (S-shaped) to 1.7
(straight line) to over 2 (quadratic). However,
we see no logical or empirical evidence for de-
picting yields via a quadratic curve which shows
them increasing at an increasing rate. The ques-
tion of whether there has been a secular decline
in corn yield increases since about 1970 is
addressed in Chapter III.

Since the end of World War II, there has been
a dramatic rise in the amount of nitrogen ferti-
lizer applied per acre of corn grown, and there
has been a strong relationship between the amount
of nitrogen applied and corn yield over that per-
iod. Undoubtedly nitrogen has been an important
factor in the yield increases. This relationship
is addressed in detail in Chapter IV.

Some people have argued that the historical
rise in corn yields since 1945 has been associ-
ated with a generally more favorable climate.
However, our own analysis did not corroborate
this. First, nitrogen alone was able to account
for a large proportion of total yield variability

over the period. Second, when a weather variable
was added to the nitrogen variable in a yield
response equation, the co-efficient of the nitro-
gen variable changed only slightly. The weather
variable (W) which we included in the analysis
was July rainfall weighted by the acreage of corn
grown in the U.S. (Butell and Naive, 1978).1/ A
recent study using Illinois data (Swanson and
Nyankori, 1979) also found no systematic effect
by climate on corn yield increases over time
(1950-76). They used detailed measurements of
weather as explanatory variables in regression
equations with yield as the dependent variable.

In summary, corn yields have risen at an
average rate of 2.1 bu/ac since 1945, and are
apparently continuing to rise. Technological
factors, rather than weather, have been largely
responsible. However, there has been an apparent
slowdown in yield increases over the last decade
(see Chapter III).

3. Location of Corn Grain Production

A broad picture of the post-World War II
(1949-74) shift in location of U.S. corn grain
acreage can be obtained from Figures II-3 and
II-4 (U.S. Bureau of Census, 1950, 1978). These
show clearly that there has been a shift away
from a wide distribution of corn acreage, which
included the Southern and Eastern U.S., to a
denser concentration of acreage on the Corn Belt
type soils of the North Central Region. Since
1974, however, there has been some expansion of
corn production into several newly-irrigated
areas and into shorter maturity growing areas.
The latter are principally in the Lake States and
Northern Plains.

In recent years, more than 90 percent of total
production has come from only 15 states. These
states, ranked in order of 1979-80 production,
are shown in Table II-2. Iowa and Illinois rank
as the two top states in production followed by
Nebraska, Indiana, Minnesota and Ohio.

In order to pursue the location of production
topic more effectively, a breakout of 6 U.S.
farming regions and 11 subregions is presented
in Figure II-5 (from Coffman, 1980). Corn pro-
duction for each region for selected years since
1930 is shown in Table II-3. Table II-4 presents
the percentage of total U.S. corn grain production
from each production region over the same period.

The North Central (NC) Farming Region (encom-
passing the Corn Belt and the Lake States subre-
gions) is by far the dominant corn production
region in the U.S. In 1978-80 it produced 71
percent of total production, up from 66 percent
in 1945-47. Eight of the top 15 ranked corn
production states are located in the NC region.

Figure II-3. Corn Acreage Harvested for Grain, 1949.
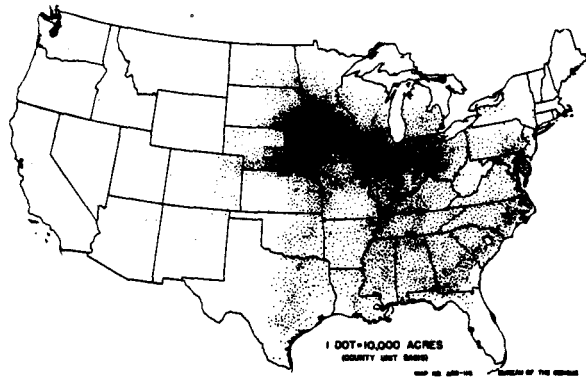
Figure II-4. Corn Acreage Harvested for Grain, 1974.
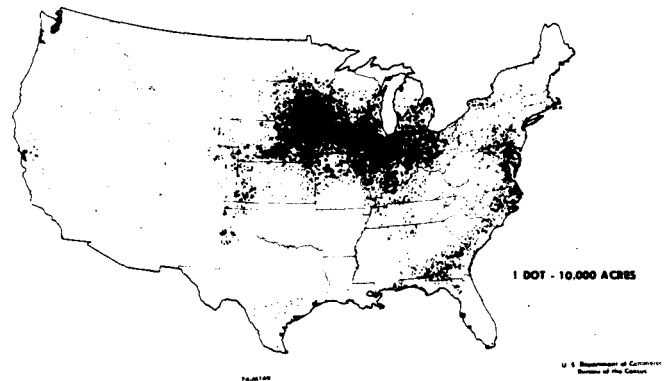
Table II-2. Top 15 States in Production of Corn for Grain

State[a]	Production (million bu)		Acreage Harvested (million ac)		Harvested Yield (bu/ac)	
	1979	1980	1979	1980	1979	1980
Iowa	1,664	1,463	13.1	13.3	127	110
Illinois	1,414	1,066	11.1	11.5	111	128
Nebraska	822	604	7.2	7.1	115	85
Indiana	675	603	6.0	6.3	112	96
Minnesota	606	610	6.1	6.3	100	97
Ohio	417	441	3.6	3.9	115	113
Wisconsin	317	348	3.1	3.4	103	104
Michigan	237	247	2.5	2.6	81	95
South Dakota	211	122	2.9	2.3	74	53
Kansas	172	116	1.5	1.2	117	94
Texas	132	117	1.3	1.3	105	90
Missouri	140	110	2.3	2.1	103	53
Kentucky	133	104	1.3	1.5	102	70
North Carolina	128	104	1.7	1.7	76	60
Pennsylvania	122	96	1.3	1.3	95	75
U.S.	7,939	6,647	72.4	73.1	110	91
Top 15 states as percent of total U.S.	91.8%	92.5%	89.5%	89.9%		

[a] Ranked in order of 1979-80 production - these same states constituted the top 15 in production for 1978, 1979, and 1980.

Source: USDA. Crop Production: 1980 Annual Summary. January, 1981.

Figure II-5. Farming Regions.
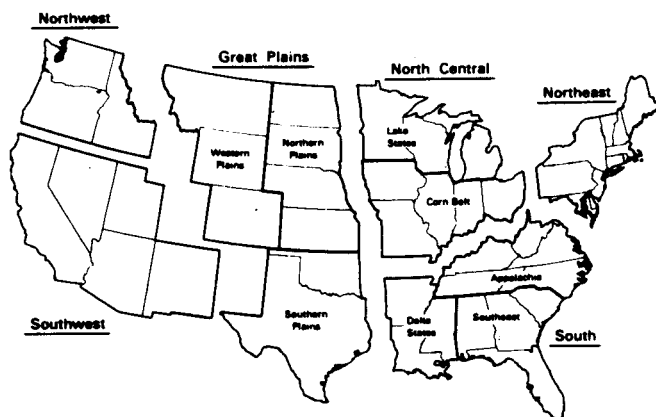
The five-state Corn Belt[2]/ subregion has consistently produced about 55 percent of the corn for grain over the past three decades while the Lake States have raised their share of total production from 10 percent in 1945-47 to 16 percent in 1978-80. Over the same period, harvested acreage of corn for grain increased about 5 million acres in the Lake States and 7 million acres in the Corn Belt for a NC Region acreage total of about 48 million in 1978-80. But the percentage rate of yield increase between 1945-47 and 1978-80 was much lower for the NC Region (148%) than for the U.S. (206%), due mainly to two phenomena: the very low yield levels in some non-NC Region states in 1945-47, and significant increases in irrigation in some areas outside of the NC region in the post 1945-47 period.

The South is the one farming region which has realized a major decline in its share of U.S. corn production since World War II. In 1945-47

Table II-3. Corn for Grain: Production (in million bu) by Region and U.S., Selected Years 1930-80 and 1978-80 Average

| Year | Northeast | NORTH CENTRAL | | | SOUTH | | | | PLAINS | | | | Southwest | Northwest | U.S. Total |
		Lake States	Corn Belt	Total	Appalachian	Delta States	Southeast	Total	Northern	Southern	Western	Total			
1930	37	137	794	930	119	43	91	253	350	105	35	490	5	2	1,717
1935	83	193	1,008	1,202	210	89	123	422	172	119	11	302	5	2	2,015
1940	71	223	1,141	1,364	220	112	118	450	182	127	9	318	4	3	2,210
1945	78	281	1,297	1,578	225	96	123	444	403	74	13	490	3	1	2,594
1950	89	263	1,402	1,665	264	98	130	491	424	81	9	514	3	2	2,764
1955	86	415	1,627	2,042	234	81	146	461	204	53	8	266	14	4	2,873
1960	117	514	2,242	2,756	246	47	133	425	541	34	14	589	11	8	3,907
1965	123	474	2,622	3,096	245	29	145	420	411	21	15	447	14	4	4,103
1970	170	652	2,390	3,042	178	13	83	274	556	39	41	636	22	8	4,152
1975	207	773	3,404	4,177	287	10	191	487	735	126	54	914	37	7	5,829
1976	231	635	3,674	4,310	399	15	260	674	735	196	67	998	45	9	6,266
1977	218	1,088	3,471	4,559	303	11	70	385	954	170	84	1,207	45	11	6,426
1978	249	1,132	3,966	5,099	344	12	151	507	1,084	148	84	1,316	50	14	7,268
1979	265	1,161	4,411	5,572	370	10	190	570	1,229	141	100	1,470	45	18	7,939
1980	218	1,206	3,682	4,888	274	5	109	388	859	122	94	1,075	49	17	6,648
Average 1978-80	244	1,166	4,020	5,186	329	9	150	488	1,057	137	93	1,287	48	16	7,285

Source: Coffman (1980) and Agricultural Statistics, various issues.

the South (encompassing the Delta States, Southeast and Appalachia subregions) produced 19 percent of U.S. corn grain, but this percentage had dropped to 7 percent by 1978-80. This major decline in relative production is mainly the result of a decline in acreage harvested from 20.1 to 7.4 million acres as soybeans have replaced corn. This shift was most dramatic in the Delta States, where in 1945-47 there were 4.6 million acres of harvested corn and 363 thousand acres of harvested soybeans. Comparable acreages for 1978-80 were 184 thousand corn and 11.9 million soybeans. Corn yields have always been, and still are, low in the South (an average of 66 bu/ac in 1978-80).

A farming region of continuing major importance for corn grain production is the Plains (comprising the Northern, Southern and Western subregions). Seventeen percent of U.S. corn grain production came from this region in 1945-47, compared to 17.6 percent in 1978-80. Within the region, the Northern Plains, and the state of Nebraska in particular, dominates in importance. Although the Plains Region harvested 18.8 million acres of corn for grain in 1945-47, this dropped to 13.5 million acres in 1978-80. However, during this same period, average yields increased 310 percent from 23.2 to 95.1 bu/ac. The importance of irrigated corn has increased in the Plains Region in recent years, particularly in Nebraska, Kansas, Texas and Colorado. This explains part of the rapid increase in per acre yields, and the increased importance of the region despite the reduced acreage.

Corn production in the Northeast Farming Region has remained at slightly over 3 percent of total U.S. production for a long time. Although corn production has increased slightly in the Southwest and Northwest Regions, mainly via irrigation, the aggregate production from these two regions totaled less than one percent of U.S. production in 1978-80.

Table II-4. Corn for Grain: Regional Production as a Percentage of the National Production, Selected Years, 1930-80 and Average, 1978-80

Year	NORTH CENTRAL				SOUTH				PLAINS				Southwest	Northwest	U.S. Total
	Northeast	Lake States	Corn Belt	Total	Appalachian	Delta States	Southeast	Total	Northern	Southern	Western	Total			
1930	2.2	5.6	48.6	54.2	6.9	3.5	5.3	15.7	20.4	6.1	2.0	28.5	0.3	0.1	100
1935	4.1	9.6	50.0	59.6	10.4	4.4	6.1	20.9	8.5	5.9	0.5	15.0	0.2	0.1	100
1940	3.2	10.1	51.6	61.8	10.0	5.1	5.3	20.4	8.2	5.7	0.4	14.3	0.2	0.1	100
1945	3.0	10.8	50.0	60.8	8.7	3.7	4.7	17.1	15.5	2.9	0.5	18.9	0.1	0.0	100
1950	3.2	9.5	50.7	60.2	9.6	3.6	4.7	17.8	15.4	2.9	0.3	18.6	0.1	0.1	100
1955	3.0	14.5	56.6	71.1	8.2	2.8	5.1	16.1	7.1	1.9	0.3	9.3	0.5	0.1	100
1960	3.0	13.2	57.4	70.6	6.3	1.2	3.4	10.9	13.9	0.9	0.4	15.1	0.3	0.2	100
1965	3.0	11.6	63.9	75.4	6.0	0.7	3.6	10.2	10.0	0.5	0.4	10.9	0.4	0.1	100
1970	4.1	15.7	57.6	73.3	4.3	0.3	2.0	6.6	13.4	1.0	1.0	15.3	0.5	0.2	100
1975	3.6	13.3	58.4	71.7	4.9	0.2	3.3	8.4	12.6	2.2	0.9	15.7	0.6	0.1	100
1976	3.7	10.1	58.6	68.8	6.4	0.3	4.2	10.8	11.7	3.1	1.1	15.9	0.7	0.1	100
1977	3.4	16.9	54.0	71.0	4.7	0.2	1.1	6.0	14.9	2.6	1.3	18.8	0.7	0.2	100
1978	3.4	15.6	54.6	70.2	4.7	0.2	2.1	7.0	14.9	2.0	1.2	18.1	0.7	0.2	100
1979	3.3	14.6	55.6	70.2	4.7	0.1	2.4	7.2	15.5	1.8	1.3	18.6	0.6	0.2	100
1980	3.3	18.1	55.4	73.5	4.1	0.1	1.6	5.8	12.1	1.8	1.4	16.1	0.7	0.3	100
Average 1978-80	3.3	16.1	55.2	71.3	4.5	0.1	2.0	6.7	14.4	1.9	1.3	17.6	0.7	0.2	100

Source: Coffman (1980) and Agricultural Statistics, various issues.

Additional details on corn acreage and yields by farming regions and subregions are shown in Appendix Tables II-1 and II-2.

Utilization of Corn Grain

The following discussion of corn grain utilization is not intended to be a comprehensive demand-utilization analysis. Rather, it is intended as a depiction of the several components of corn utilization, their general magnitudes and their changes over time.

1. Utilization of Corn 1945-80

In discussing corn technology it is important to identify the end use of the product, as this will influence the type of corn produced, and the technology used to produce it. The major change in the utilization has been where the corn is utilized, rather than how. In 1945, 78 percent of the corn produced was utilized on the farm where it was produced, compared to only 37 percent in 1979. Although the quantity of corn utilized on-farm has not changed significantly, the quantity of corn sold off-the-farm has increased dramatically, both in absolute terms and as a percentage of the total, as is illustrated in Table II-5.

Table II-5. Utilization of Corn on Farm Where Produced and Off-Farm Sales, 1945-80

Pro- duction Year	Utilized on Farm Where Grown	Sold Off-Farm	On-Farm Utilization (% of Total)
	(million bushels)		
1945	2,256	606	78.3
1950	2,399	789	71.0
1955	2,085	1,147	64.6
1960	2,583	1,177	54.5
1965	2,089	2,014	50.9
1970	1,888	2,264	45.5
1975	2,117	3,671	36.8
1979[a/]	2,916	4,847	37.6

[a/] Preliminary.

Source: Agricultural Statistics, various years.

The shift away from on-farm utilization of corn has influenced corn production technology. For example, in early years storage was primarily in corn cribs where ear corn was stored and dried prior to utilization in the farm livestock enterprise(s). As a result of the move toward off-farm sales, there was a shift in the technology used

in corn production. In order to facilitate the handling and storage of large volumes of grain, technologies for field shelling and artificial drying were developed and adopted. Further details are presented in Chapter IX.

Corn production increased from 2.5 billion bushels in 1945 to almost 8 billion bushels in 1979. The annual disappearance of corn over the period 1945-80 is illustrated in Figure II-6 (based upon data in Appendix Table II-3). To illustrate the differential growth in usage in various sectors, the total disappearance is divided into three categories: feed, export, and a category including food, seed and industrial uses.

Figure II-6. Corn Disappearance, U.S., 1945-80.
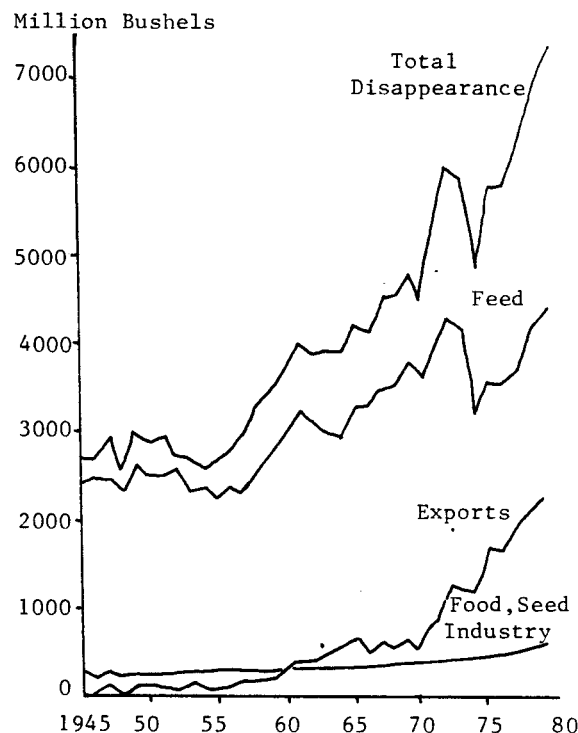
Source: Appendix Table II-3.

1.1 Feed

In 1945, 90 percent of the total utilization of corn was as a domestic feed grain. Although domestic use as a feed grain has grown and continues to be the most important single category, in 1979/80 it accounted for only 60 percent of the total disappearance (the export sector was the dominant growth component over the period 1945-80).

The major feed grains in the U.S. are corn, sorghum, oats and barley. Table II-6 demonstrates the importance of corn in the feed grain market. Over the period 1945-72 corn accounted for between 70-74 percent of the grain fed to livestock. Since 1973, corn has become even more important in the feed grain market, increasing to around 80 percent of that market for the period 1977-80.

Table II-6. Domestic Utilization of Feed Grains

Crop Year	Corn	Total Feed Grains	Corn's Share of the Feed Grain Market
	(million metric tons)		(%)
1945/46	77.3	105.5	73
1950/51	78.1	104.3	74
1955/56	76.2	106.6	71
1960/61	86.6	119.5	72
1965/66	93.6	126.2	74
1970/71	100.3	138.3	72
1971/72	111.4	149.1	74
1972/73	120.5	155.3	77
1973/74	117.1	152.2	76
1974/75	89.3	116.0	77
1975/76	100.5	127.5	78
1976/77	100.4	123.9	81
1977/78	103.8	129.6	80
1978/79	117.5	148.1	79
1979/80	121.8	151.3	80

Source: Corn Annual and Agricultural Statistics, various issues.

1.2 Utilization of Corn by Livestock

The consumption of corn by the various classes of livestock is illustrated in Figure II-7. Hogs have been the major users of corn, followed by fed cattle, dairy, egg production, broilers, other cattle and turkeys. Hogs were the major users of corn in 1960 and they remain so in 1980. The fed beef sector rapidly increased its consumption of corn from 1960 to the early 1970s, reflecting an overall increase in beef production as well as a change in the structure of the industry (with more cattle being finished in commercial feed lots). High corn prices in 1973-74 resulted in an adjustment to a lower level of corn use by that sector. Total utilization of corn by dairy cattle has increased slowly from 1960-80. The reduction in the number of dairy cows has been more than offset by the increase in corn

consumption per cow. Poultry does not consume the quantity of corn that might be expected, given the size of the industry. The reason is that poultry rations are made up of a large proportion of high protein feeds compared with other animal feeds.

1.3 Exports

In 1945 exports accounted for only one-half of one percent of corn disappearance. By 1980 they accounted for 31 percent. Exports are now ranked a strong second behind domestic feed grain as the largest market for U.S.-produced corn. Corn exports from the U.S. accounted for between 70-78 percent of world corn exports between 1976-80.

1.4 Food and Industry

The quantity of corn utilized for food and industry is shown in Table II-7. The major food and industry use is for wet milling (corn sweeteners and starches).

Table II-7. Corn Utilized (in million bu.) in Processed Food and Alcohol

Crop Year	Dry Milled		Wet Milled	
	Breakfast Foods	Corn Meal, Flour and Grits	Sweeteners and Starches	Alcohol and Distilled Spirits
1944/45	12	70	124	37
1949/50	10	68	128	36
1954/55	13	74	139	22
1959/60	16	95	154	31
1964/65	19	110	201	28
1969/70	22	97	216	31
1974/75	24	118	333	16
1979/80	25	142	483	20

Source: USDA, Agricultural Statistics, various years and Feed Situation, various years.

1.5 The Milling Industry

The corn milling industry is made up of two basic types of milling systems: dry milling and wet milling. The wet milling industry's major product is starch and its derivatives, such as

syrups and sweeteners and the by-products are oil and feeds. The dry milling industry's major products are grits, corn meal and flour.

Corn Wet Milling

Corn wet milling is a refining process whereby corn is placed in a water suspension and separated into its components for further processing. Wet milling utilizes the raw product, kernel corn, to produce starch and corn syrups. Oil and meal are valuable by-products.

To provide a rough idea of the proportion of starch and by-products produced in the wet milling of one bushel of corn, Table II-8 (from Carman and Thor, 1979) illustrates a typical mix of products.

Starch has many uses in addition to its being a raw product for sweeteners. The largest user of corn starch is the paper industry which uses starch for a wide variety of purposes, such as increasing the quality and strength of paper,

and as an adhesive (Arthur D. Little, Inc., 1975). The textile industry utilizes starch as a sizing agent and the food industry uses starch as a thickening agent in foods, such as pudding and gravy.

Table II-8. Typical Corn Product Mix Derived from Wet Milling One Bushel of Corn

	Amount (lbs/bu)	% of Total
Starch	33.00	58.9
Gluten feed (21% protein)	15.00	26.8
Gluten meal (60% protein)	2.00	3.6
Crude corn oil	1.75	3.1
Moisture	4.25	7.6
Total	56.00	100.0

Figure II-7. Annual Consumption of Corn by Livestock, U.S., 1960-80.
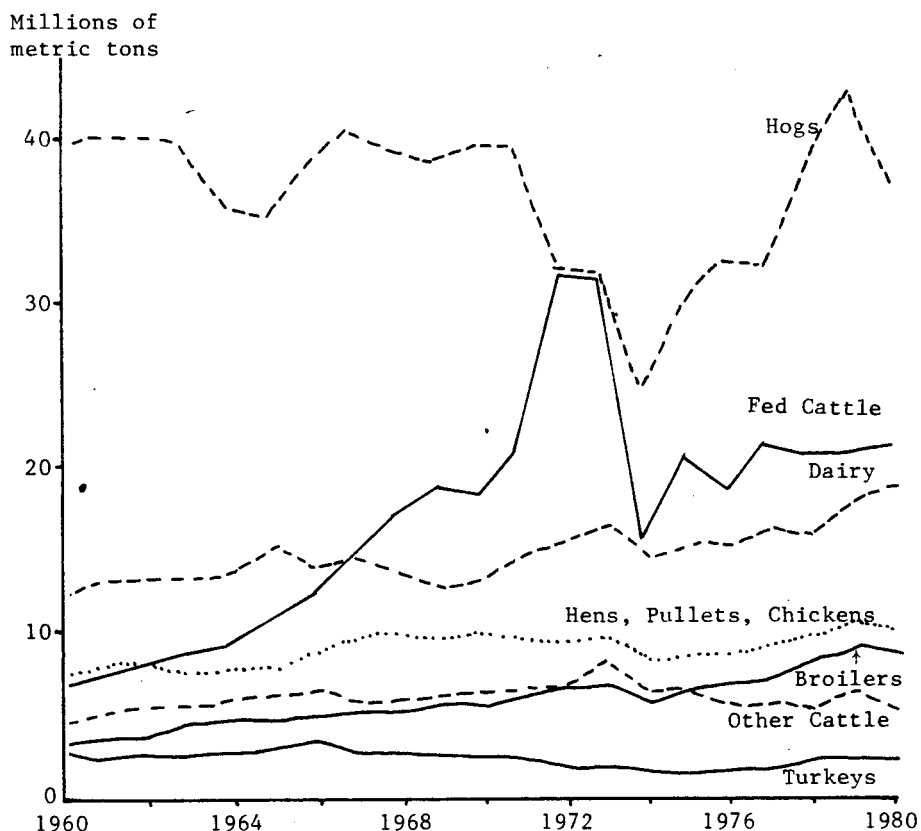
Source: Data for the years 1960-71 was taken from USDA, 1974 and 1975, and from USDA, Feed Situation (various years) for the years 1972-80.

There are three major corn sweeteners made by the wet milling industry: glucose, dextrose, and high fructose corn syrup (HFCS). The relative importance of these sweeteners in the caloric sweetener market is illustrated in Figure II-8, which also reflects the rapid expansion of the HFCS market in recent years. In 1979, HFCS accounted for 11 percent of the total consumption of caloric sweeteners. The expansion of the HFCS market has been at the expense of sucrose and, to a lesser extent, dextrose.

Figure II-8. Annual Per Capita Consumption of Major Caloric Sweeteners in the U.S., 1963-80 (dry basis).

Source: USDA, Sugar and Sweetener Report, ESCS, Dec., 1981.

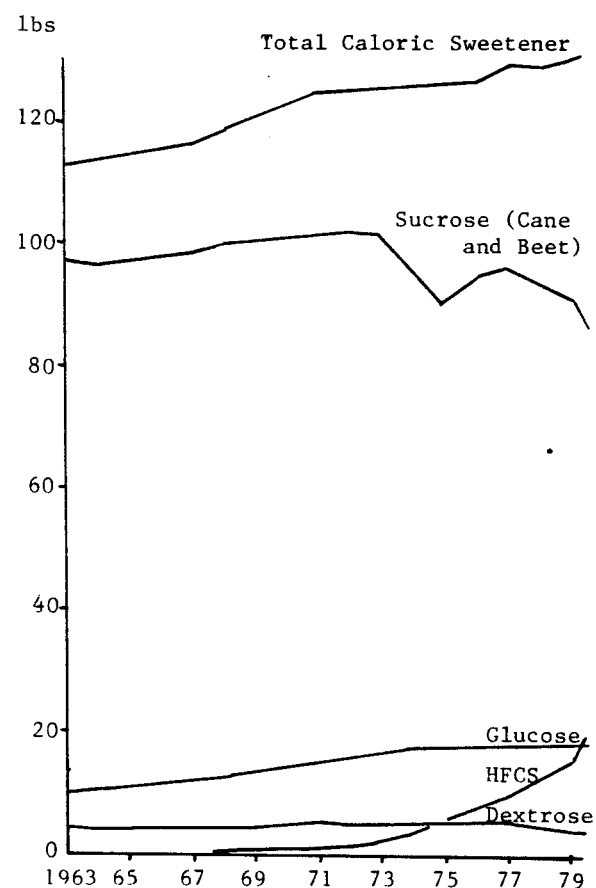HFCS is a potential growth area for corn sweeteners. The current utilization of HFCS is 2.1 million tons (dry basis) a year. There have been a number of projections of future demand for this product. These projections vary. Carman and Thor (1979) estimate that the maximum share of the calorific sweetener market obtainable by HFCS is 20-35 percent.3/ They project demand for HFCS between 2.9 and 3.9 million tons in 1985 and 3.3 to 4.75 million tons in 1990. The corn required to produce these quantities of HFCS is

175 to 241 million bushels (1985 projection) and 200 to 288 million bushels (1990 projection). This compares with the 121 million bushels of corn presently used to produce HFCS.

The by-products of the wet milling process are steep water, corn germ and gluten. Steep water is used in the production of antibiotic drugs. It can also be used in animal feeds. The oil in the germ is removed by heating the germ under pressure. Most of the oil is further refined for human consumption. The remaining portion of the germ is then utilized for feed. The gluten is used to produce high protein animal feed. Most of it is used in corn gluten meal, which is an ingredient of livestock feeds. Some of the gluten is combined with the germ meal and hulls to produce gluten feed. Gluten has other minor uses, such as for paper, plastics and drugs.

Corn oil is a polyunsaturated oil. Its main use in the United States is for cooking oil or as an ingredient of margarine. Corn oil is generally considered to be a high quality edible oil. It has had a small, but growing, share of the total edible oils market, and as is seen in Table II-9, the total production of edible vegetable oils has been steadily increasing. The major edible oil is soybean, which made up 57-67 percent of total fats and oils production in the last 10 years. Corn oil production has steadily increased over this period and its share of the market has increased since 1974.

Table II-9. Fats and Oil Production, 1971-80

	Corn		Soybean		Total
		(million lbs)			
1971	499	(3.6)[b/]	7,892	(57.5)[b/]	13,735
1972	523	(4.0)	7,501	(57.5)	13,051
1973	528	(3.7)	8,995	(63.0)	14,278
1974	465	(3.8)	7,375	(60.0)	12,275
1975	644	(4.5)	9,630	(67.1)	14,360
1976	669	(4.9)	8,578	(63.3)	13,542
1977	738	(4.7)	10,288	(65.3)	15,753
1978	736	(4.4)	11,323	(67.2)	16,854
1979	775	(4.2)	12,114	(66.0)	18,353
1980[a/]	825	(4.7)	11,230	(64.0)	17,560

[a/] Preliminary forecast.

[b/] Numbers in parentheses represent percent of total.

Source: Fats and Oils Situation, various years.

Since corn oil is produced by the corn milling process, any future increase in milling will necessarily result in an increase in oil production. At present, the area of greatest potential growth in the corn milling industry is for the production of high fructose corn syrup. The output of the by-product, oil, is therefore also expected to increase (perhaps by an additional 283.9 million pounds by 1990 - up 34 percent from 1980 - see Appendix II-A for calculations).

Dry Milling

The dry milling industry uses less corn than the wet milling industry. Approximately 120 million bushels of corn are dry milled annually, compared to the 400 million bushels that are wet milled. In dry milling, there are two different processes with different end products. The major portion of the dry milling industry utilizes a de-germing process, which separates the oil-containing germ from the remainder of the kernel. Other mills, known as gristmills, convert the entire kernel into hominy grits and corn meal which have a high fat content.

The mills which use the tempering/de-germing process initially separate the oil containing germ, then use the bulk of the endosperm to produce flaking grits (which are used to produce corn flakes), smaller grits (which are used as brewers grits), meals and flours. The germ cake (germ with oil extracted), bran and high fat portion of the endosperm are utilized to produce hominy feed. Corn oil is obtained by solvent extraction. Table II-10 illustrates the utilization of dry milled corn products.

Table II-10. Utilization of Dry Milled Corn Products

Item	Utilization (% of total weight)
Animal Feeds	34.0
Brewing	23.5
Breakfast Cereals	21.7
Other Food (Snacks, bakery, mixes, etc.)	15.2
Industrial (Non-food)	5.6
Total	100.0

Source: Wells (1979.

1.6 Corn Ethanol Production

A potential growth area in the utilization of corn is its use as a feedstock in the production of ethanol. Ethanol is an alcohol which can be used as a fuel. At present, it is used in the production of gasohol, which is a mixture of 10 percent alcohol and 90 percent gasoline.

Alcohol is made by fermenting and distilling the starch solution. One bushel of corn produces 2.6 gallons of ethanol. In addition, the non-starch portions of the corn kernel are available for oil and feed products (depending on the process used). The outlook for corn as a feedstock for ethanol is very uncertain. There are a number of factors involved, such as the price of corn, the price of competing fuels, the cost of alcohol production, government incentive programs, and the development of alternative liquid fuel sources.

In the context of energy planning, corn ethanol is basically an interim energy product. Two reasons for this are: (i) in the long run, cheaper cellulose feedstocks are likely to replace corn in the production of ethanol; and (ii) alternative sources of energy are expected to be developed by the turn of the century. This investment in corn ethanol plants may only be warranted if substantial subsidies are provided. Nevertheless, it is expected that corn ethanol will be produced by the wet-milling industry to utilize excess milling capacity in the off-season.

The 1980 production of ethanol fuel has been estimated to be in the range of 100-120 million gallons (unofficial governmental estimate). What the real growth will be is, at present, very uncertain. It seems likely, however, that it will be a long time before production reaches the one billion gallon level (which has sometimes been projected and which would utilize about 385 million bushels of corn).

Footnotes

[1]/While July precipitation is only a rough proxy for corn growing weather, it was the most significant climatic variable in Thompson's (1969) analysis. Note that our results are not necessarily in conflict with Thompson's argument that the last 50 years or so of weather have been above the long-run average in terms of their suitability for corn growing.

[2]/The Corn Belt is sometimes defined in terms of a broad soils category including southern portions of Michigan, Minnesota and Wisconsin and eastern portions of Nebraska (see Appendix Figure II-1). In that case the geographical area differs substantially from the 5-state depiction.

[3]/Projections vary as to the share of the total caloric sweetener market obtainable by HFCS. However, even if HFCS captured the total sucrose market, the additional demand for corn would have amounted to only 4.8 percent of the 1979 crop.

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Appendices

Appendix Tables begin on the next page.

Appendix Table II-1. Corn: Acreage Harvested by Farming Region and U.S., Selected Years 1930-80 and Average 1978-80

		NORTH CENTRAL				SOUTH				PLAINS					
Year	Northeast	Lake States	Corn Belt	Total	Appalachian	Delta States	Southeast	Total	Northern	Southern	Western	Total	Southwest	Northwest	U.S. Total
								million acres							
1930	1.7	4.3	29.6	33.9	8.9	4.7	8.2	21.7	17.9	7.4	1.6	26.8	299	56	84.5
1935	2.1	5.5	27.6	33.1	9.8	6.5	10.6	27.0	13.1	6.6	1.1	20.8	250	54	83.3
1940	2.0	5.6	26.6	32.2	9.3	6.7	10.0	26.0	9.2	6.3	0.7	16.3	224	82	76.8
1945	1.9	7.2	28.9	36.0	7.7	4.8	8.0	20.5	14.6	4.5	0.6	19.8	162	34	78.5
1950	1.8	6.4	28.6	35.0	7.4	4.3	6.7	18.4	12.7	3.9	0.4	16.9	124	30	72.4
1955	2.0	8.3	31.3	39.6	6.4	2.7	5.6	14.7	9.4	2.2	0.3	11.8	262	55	68.5
1960	1.8	9.3	34.7	44.0	5.4	1.7	4.6	11.6	12.0	1.5	0.3	13.7	171	106	71.4
1965	1.8	7.4	30.4	37.8	3.7	0.8	3.1	7.6	7.2	0.6	0.2	8.0	182	56	55.4
1970	2.0	7.8	30.8	38.6	3.4	0.4	2.9	6.7	8.7	0.6	0.4	9.7	246	88	57.4
1975	2.4	10.3	35.0	45.2	4.0	0.2	3.5	7.7	9.9	1.2	0.6	11.8	356	72	67.5
1976	2.7	10.1	37.5	47.5	4.6	0.3	4.1	5.0	9.3	1.7	0.7	11.6	429	89	71.3
1977	2.7	11.1	36.3	47.4	4.6	0.3	2.4	7.2	10.6	1.7	0.7	13.1	424	104	70.9
1978	2.7	11.6	36.1	47.7	4.4	0.2	2.9	7.5	11.2	1.5	0.8	13.6	419	136	71.9
1979	2.8	11.5	36.1	47.8	4.3	0.2	2.9	7.4	11.8	1.3	0.8	13.9	395	159	72.4
1980	3.0	12.2	37.0	49.2	4.5	0.2	2.5	7.2	10.9	1.4	0.8	13.1	410	155	73.1
Average 1978-80	2.8	11.8	36.4	48.3	4.4	0.2	2.8	7.4	11.3	1.4	0.8	13.5	0.4	0.2	72.5

Source: Coffman (1980) and Agricultural Statistics, various issues.

Appendix Table II-2. Corn: Yield Per Acre Harvested by Farming Region and U.S., Selected Years 1930-80 and Average 1978-80

Year	NORTH CENTRAL				SOUTH				PLAINS						
	Northeast	Lake States	Corn Belt	Total	Appalachian	Delta States	Southeast	Total	Northern	Southern	Western	Total	Southwest	Northwest	U.S. Total
								bu/ac							
1930	21.7	31.6	26.9	27.4	13.4	9.2	11.2	11.6	19.6	14.2	22.5	18.3	16.7	35.7	20.5
1935	39.8	35.3	36.5	36.3	21.3	13.6	11.6	15.6	13.1	18.0	10.2	14.5	20.0	37.0	24.2
1940	36.4	39.6	42.9	42.3	23.7	16.6	11.6	17.2	19.7	20.0	13.1	19.5	17.9	36.6	28.9
1945	40.7	39.1	45.0	43.8	29.1	20.1	15.4	21.7	27.6	16.3	20.1	24.7	18.5	29.4	33.1
1950	47.5	41.1	49.0	47.6	35.7	22.9	19.2	26.7	33.4	20.9	24.3	30.3	26.5	52.1	38.2
1955	43.1	49.9	51.9	51.5	36.6	29.8	26.3	31.4	21.8	24.0	31.6	22.5	53.5	66.7	42.0
1960	64.3	55.6	64.6	62.7	45.9	27.8	29.0	36.7	45.0	23.6	51.4	42.9	61.8	77.3	54.7
1965	69.6	64.3	86.2	81.9	66.1	37.2	46.9	55.3	57.3	33.1	69.4	55.7	77.9	73.6	74.1
1970	85.7	83.6	77.5	78.8	51.9	33.8	28.9	41.0	64.0	63.6	94.6	65.3	90.2	92.9	72.4
1975	85.2	75.0	97.5	92.4	72.1	44.3	55.0	63.5	73.8	101.3	91.3	77.6	103.6	93.1	86.3
1976	87.1	63.2	98.1	90.7	86.2	53.1	63.3	74.7	79.2	118.4	101.1	86.1	104.9	96.4	87.9
1977	81.4	97.9	95.7	96.2	66.6	42.6	29.7	53.6	89.8	97.1	114.0	92.2	106.3	107.3	90.7
1978	93.3	97.8	109.8	108.2	78.9	56.6	51.4	67.5	96.8	98.3	108.5	97.6	119.3	102.9	101.0
1979	95.4	101.3	122.1	116.6	86.4	53.8	65.5	77.3	104.3	105.6	125.2	105.6	113.9	113.2	109.7
1980	74.4	98.5	99.5	99.24	60.8	32.2	42.8	53.8	78.6	88.7	116.8	82.0	119.5	109.7	91.0
Average 1978-80	87.7	99.2	110.5	108.0	75.4	47.5	53.2	66.2	93.2	97.5	116.8	95.1	117.6	108.6	100.6

Source: Coffman (1980) and Agricultural Statistics, various issues.

Appendix Table II-3. Corn Disappearance, U.S., 1945-80 (millions of bushels)

Year	Total Disappearance	Feed	Exports	Food, Seed, Industry
1945/46	3,010	2,717	17	274
1946/47	3,024	2,761	20	242
1947/48	3,138	2,700	127	309
1948/49	2,545	2,296	7	243
1949/50	2,982	2,617	111	254
1950/51	2,869	2,545	112	259
1951/52	2,883	2,482	117	270
1952/53	2,700	2,555	82	246
1953/54	2,732	2,313	145	242
1954/55	2,594	2,387	104	241
1955/56	2,744	2,242	103	259
1956/57	2,822	2,366	120	268
1957/58	2,997	2,377	184	261
1958/59	3,302	2,535	200	262
1959/60	3,563	2,782	230	290
1960/61	3,679	3,092	292	295
1961/62	3,962	3,212	435	315
1962/63	3,895	3,157	416	322
1963/64	3,848	3,009	500	349
1964/65	3,875	2,956	570	349
1965/66	4,409	3,362	687	360
1966/67	4,185	3,334	487	364
1967/68	4,518	3,523	633	362
1968/69	4,502	3,607	536	359
1969/70	4,801	3,824	612	365
1970/71	4,494	3,592	517	385
1971/72	5,187	4,001	796	390
1972/73	6,000	4,313	1,258	429
1973/74	5,896	4,205	1,243	448
1974/75	4,826	3,226	1,149	451
1975/76	5,793	3,592	1,711	490
1976/77	5,784	3,587	1,684	513
1977/78	6,208	3,709	1,948	551
1978/79	6,906	4,198	2,133	575
1979/80	7,365	4,350	2,400	615

Source: <u>Agricultural Statistics</u>, various years.

Appendix Table II-4. Consumption of Harvested Concentrate Feed by All Livestock, 1960-80 (million metric tons)

Year beginning October 1	Corn[a]	Sorghum grains	Other grains[b]	High protein[c]	Other by-products[d]	Total
			Concentrates			
1960	79.1	10.6	21.3	14.6	11.0	136.5
1961	82.2	10.4	19.2	15.2	11.1	138.2
1962	81.1	9.9	19.3	15.6	11.1	138.2
1963	77.4	12.0	18.7	15.6	11.6	135.1
1964	76.0	10.8	18.5	15.7	11.5	142.5
1965	86.4	14.4	18.5	16.7	11.3	146.4
1966	85.6	15.2	18.9	16.7	11.3	147.7
1967	90.3	13.5	18.5	16.6	11.2	150.5
1968	92.1	15.6	21.3	17.6	11.9	148.8
1969	97.7	16.2	23.0	19.0	12.1	168.0
1970	92.3	17.4	24.1	19.0	11.9	165.1
1971	94.8	17.6	24.8	19.0	11.9	175.8
1972	96.1	17.0	19.8	17.2	18.9	168.3
1973	99.0	17.6	18.7	16.6	18.2	171.0
1974	69.3	10.7	17.2	17.4	18.1	132.7
1975	81.2	13.2	17.2	20.0	19.1	150.7
1976	91.1	11.2	13.8	18.8	18.4	156.6
1977	95.2	26.0		20.5	16.8	158.4
1978	106.7	27.6		21.3	16.6	172.2
1979	112.5	26.8		23.8	17.6	180.7
1980	106.7	23.0		22.8	15.6	168.1

[a] For the years 1960-73, fats fed to livestock were converted to corn equivalents and added to corn.

[b] Other grains includes oats, barley, wheat and rye.

[c] High protein includes oilmeals, animal proteins and grain proteins.

[d] Other by-products includes milling by-products, fats and oils, alfalfa meal, and for the period 1974-80, includes urea, salt, minerals and molasses.

Source: Livestock Relationships for data from 1960-71, Feed Situation for 1972-80.

Appendix II-A. Increase in Corn Utilization and
   Corn Oil Production Resulting from Projected
   HFCS Production

   Estimates of a range of HFCS demand projected
by Carman and Thor are used to calculate the in-
creased demand for corn resulting from the ex-
pected increase in HFCS production (Appendix
Table II-5).

Appendix Table II-5. Projected HFCS Demand and
   Corn Utilization in the Production of HFCS in
   1985 and 1990

	Projected HFCS Demand (1,000 tons)[a]	Projected Utilization of Corn in HFCS Production (1,000 bu)[b]
1985	2,896 - 3,983	175,515 - 241,394
1990	3,303 - 4,753	200,182 - 288,061

[a] Demand projections are from Carman and Thor, the
range of demand occurs because they assume market
ceiling values range from 20-30 percent of the
total sweetener market and sugar prices from
$.20-$.30/lb.

[b] 33 lbs of HFCS are produced from one bushel of
corn.

   The potential increase in corn oil production
due to increases in HFCS production are shown in
Appendix Table II-6. These were calculated on
the basis of estimated quantities of corn required
to produce HFCS (Appendix Table II-5). The range
of projections for each year represent the poten-
tial HFCS demand at various sugar prices and HFCS
market ceilings as estimated by Carman and Thor
(1979). The corn required to produce HFCS in 1980
is subtracted from the estimated future corn re-
quirements to obtain the additional corn required
to produce the new levels of HFCS. This addi-
tional corn utilization is then translated into
corn oil production using the conversion factor
of 1.7 pounds of crude oil per bushel of corn.

Appendix Table II-6. Potential Increase in Corn
   Oil Production Due to Projected Increase in
   HFCS Production

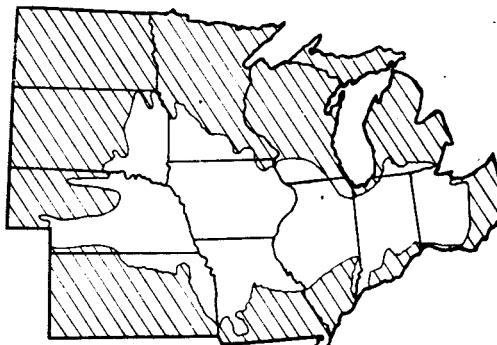|	A	-	B	=	C	D
1985	175		121		54	91.8
	to					
	241		121		120	204.0
1990	200		121		79	134.3
	to					
	288		121		167	283.9

A = Corn Required to Produce HFCS (million bu)
B = Corn Required to Produce HFCS in 1980 (million bu)
C = Additional Corn Utilized for HFCS

D = Additional Crude Oil (million lbs)

Appendix Figure II-1. Location of the
   Corn Belt Soil Area Within the North
   Central Region.

1. Definition and Description

   Conventional plant breeding refers to the use of existing plant breeding techniques applied to the production of corn hybrids. Genetic engineering and related techniques are specifically excluded, being subjects of a separate chapter.

   Desirable characteristics which plant breeders attempt to incorporate into modern hybrids include general yield increases, adaptability to new production techniques (e.g., higher plant populations), climatic adaptability, pest resistance, and grain quality improvements.

2. Direction and Magnitude

   The first lines of hybrid corn became available in the late 1920s. Adoption by farmers was rapid, with the transition from open-pollinated varieties being virtually complete within 10 years, in the major corn producing regions (Sprague, 1980). Early hybrid lines were double crosses. However, subsequent improvements in the per se performance (yield) of inbred parent lines and revision of early pessimism regarding the stability (consistent performance over time) of single crosses, led to a switch to higher yielding single- and three-way cross hybrids. The switch was essentially complete by 1970 (Duvick, 1980a).

   One consequence of improved corn hybrids has been a significant and persistent rise over time in planting rate, a trend which continues (see Chapter IV). New hybrids have been superior in terms of root and stalk strength and ability to withstand stress-induced barrenness (Duvick, 1977). These characteristics have enabled new hybrids to yield well under high population conditions.

   Considerable progress has been made in breeding shorter-season hybrids. The most successful hybrid in recent years, Pioneer 3780, while a good yielder, was most notable for its low moisture content at harvest (an indicator of early maturity). Early maturity has enabled higher

corn yields to be obtained in more northerly latitudes where cold temperatures are a major constraint on yields. Figure III-1 shows the number of "growing degree days" across the U.S. Where the number of degree days is small, short-season hybrids are necessary to achieve good yields. These short-season hybrids have been an important factor in the enhanced competitiveness of the Lakes States Region vis-a-vis other corn growing areas (see Chapter II). In addition to increasing yields in cold environments, short-season hybrids have a role to play in warmer environments, even though their yields are generally less there than long-season hybrids; hybrids of several different maturities may be grown on a farm to spread the work load and reduce grain drying costs (see Chapter IX). Timely harvesting and plowing are facilitated.

   Many diseases have been successfully controlled through the mechanism of host (hybrid) resistance. These include Helminthosporium Leaf Spot and Northern Leaf Blight (for a comprehensive list, see OTA, 1979, p. 16). Insect host resistance has also been identified and incorporated into adapted hybrids for ear worm and the first brood of European corn borer (OTA, 1979, p. 28).
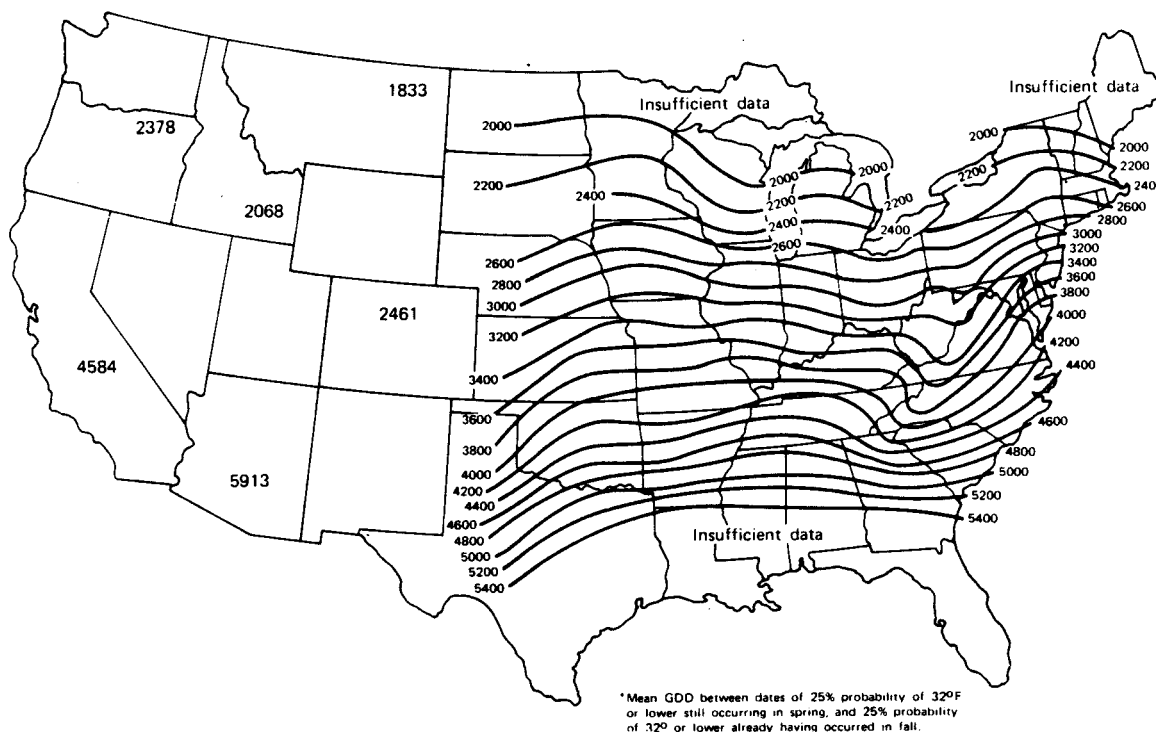
   A major use for U.S. corn is as a feed grain. However corn protein is of low quality because it is deficient in two key amino acids, lysine and tryptophane. High lysine (Opaque-2) hybrids have been developed to overcome that particular deficiency, but at a cost in terms of yield. Waxy corn containing high levels of amylopectin starch, and corn with a high oil content have found a role in meeting a specialized (but relatively small) market demand.

3. Direct Effects of the Technology

3.1 Historical Yield Response

   Yields of corn have grown at a slower rate during the 1970s than in the previous two decades, so that an S-shaped curve provides a statistically better fit to U.S. corn yields since 1930, than

Figure III-1. Mean Growing Degree Days Between 25 Percent Freeze Probability Dates.

*Mean GDD between dates of 25% probability of 32°F or lower still occurring in spring, and 25% probability of 32° or lower already having occurred in fall.

does a linear trend (there are severe serial correlation problems with a linear trend line fit to the data indicating that the residuals around the trend line are bunched, i.e., non-randomly distributed). Since 1970, certain events have caused corn yields to decline below trend - specifically the 1970 corn blight, drought years in 1974 and 1980, and reductions in nitrogen application rates in 1974-75.

Whether the slowing in corn yield increases in recent years is temporary, permanent, or indeed signals a plateauing of U.S. corn yields is not clear. It is the purpose of this section to make some judgment on this issue by examining the recent historical trend in U.S. corn yields in a time series analysis. In order to avoid multicollinearity problems associated with a fine decomposition of "technology" into all of its individual components, we limit ourselves to a distinction between nitrogen and non-nitrogen technologies. The basis for this distinction is found in micro-level agronomic data. In particular, agronomic studies of corn growth have indicated that: (i) at present levels of nitrogen application, the marginal physical product of nitrogen is significantly less than it was during the 1950s

and 1960s (Chapter IV); but (ii) the contribution of plant breeding to corn yields, ceteris paribus, has been constant over time and apparently has been the dominant non-nitrogen technology contributing to increased yield. Consequently, corn yield is taken to be a logarithmic function of a nitrogen variable (N) over the relevant range of N and a linear function of a non-nitrogen technology variable (T). Land, irrigated land, weather and a corn blight dummy variable also entered the regression equation linearly. However, land and irrigated land did not contribute satisfactorily to the explanation of yield variation and were therefore excluded from further consideration.

The base data set (Appendix Table III-1) was obtained from Butell and Naive (1978) through 1977, updated to 1980 from other USDA sources.[1] The period of the analysis was 1954-80. The final equation containing the statistically significant variables is shown below:

(III-1) $Y = -65.9 + 0.95T + 0.09W - 11.5D + 15.9\ln N$
$(-6.3)\quad (2.7)\quad (4.0)\quad (-2.5)\quad (4.0)$

where the variables are defined as:

Y: U.S. corn yield in bu/ac;

N: average nitrogen application rate per acre of corn grown in lbs/ac;

D: dummy variable representing 1970 corn blight; D = 1 in 1970; D = 0 otherwise;

W: a proxy weather variable, viz. acreage weighted July precipitation for 5 major Corn Belt states2/;

T: time trend, or proxy for technology - 1954 = 54; 1955 = 55.....

In a statistical sense, III-1 is a good equation, explaining 95 percent of the total variation in corn yields over the period 1954-80. All of the regression coefficients are highly statistically significant. (Figures in parentheses are t values.) An examination of the residuals from equation III-1 showed no serial correlation, however it did show some underestimation of yield changes in exceptional (good or bad) years. Apparently W is an imperfect proxy for weather, but the precise prediction of individual-year weather effects is not a major concern of this chapter.

Equation III-1 can be used in partitioning corn yield increases due to nitrogen, and non-nitrogen technologies. The contribution of non-nitrogen technologies has been constant over time at approximately one bu/ac/yr (the coefficient of T). On the other hand, the contribution of nitrogen has changed (fallen) over time. The annual contribution of nitrogen to corn yield increases was double the contribution of non-nitrogen, at about 2 bu/ac, during the late 1950s and during the 1960s. However, it has fallen to near zero over the decade of the 1970s. (See Chapter IV for detailed calculations and for comparisons with cross-sectional data on yield response to nitrogen.)

The yield increase attributable to non-nitrogen technologies by the time series analysis (equation III-1) is matched by results from three unique field experiments which also indicated yield increases of around one bu/ac/yr due to non-nitrogen technologies. These experiments (Russell, 1974; Duvick, 1977, 1979) involved the re-creation of corn hybrids which had been prominent at various times from 1930-78. The hybrids' yields were compared under experimental conditions in the 1970s. All experiments were conducted in Iowa under high (but unspecified) fertility conditions. In the first two experiments, average yield gains of approximately 0.8 bu/ac/yr were found, while the latest experiment, performed under above-average environmental conditions, indicated about double that rate of gain (1.6 bu/ac/yr). So the average rate of gain across experiments was just over one bu/ac/yr. In each experiment, the gains, were, in essence, constant over time and there was no evidence of a yield levelling off towards the end of the period. This agreement

in results from diverse sources, engenders considerable confidence in the one bu/ac/yr figure, which Russell and Duvick attributed to genetics, although it was clearly stated by the researchers that modern husbandry techniques (including nitrogen) were necessary for such gains to be realized. It must be noted, however, that although the gain of one bu/ac/yr was obtained without any increase in nitrogen fertilization, the gains were measured at high nitrogen levels and undoubtedly reflected the results of selection by plant breeders for response to nitrogen. The one bu/ac/yr figure is, in some sense, a measure of genetic gain, or perhaps "improvement in genetic potential." It would be an overestimate of the gains from genetics, if it were demonstrated that early hybrids grown under lower fertility and density conditions (representative of the period) had higher yields than under 1970s conditions. No detailed information is available on this point, but preliminary data suggest that no overestimation was involved (Duvick, 1981b).

Based upon equation III-1, the corn yield increase from nitrogen has been 36 bu/ac over the period 1954-80, while the total contribution of non-nitrogen technologies has been 27 bu/ac. These results may be compared with those of Heady and Auer (1966), who found equal contributions to yield from fertilizer and new varieties, for the period 1939-60.

3.2 Future Gains from Conventional Plant Breeding

Experiments have demonstrated clearly that new corn hybrids continue to be superior to their predecessors, given a set of modern production practices, including high fertility. These experiments have shown no slowing in the rate of yield gains, and it is known that a large amount of genetic diversity remains to be exploited (Duvick, 1981a). Gains of around one bu/ac/yr can be expected to continue. However, one bu/ac/yr represents not only the contribution of new hybrids, but also of the other non-nitrogenous technologies which accompanied them (e.g., higher plant populations). The high correlation between these technologies makes determination of their individual effects impossible. However, the major separation which was made between nitrogen and non-nitrogen effects prevents gains to nitrogen from being attributed to plant breeding and vice-versa. This is important since there appears to be little potential yield gain from additional nitrogen in the future (Chapter IV), while there is no evidence to indicate that yield gains from plant breeding and associated agronomic practices will slow. Although the estimate of yield gain from genetics is based upon experimental (vs. farm) yields, the two have risen at the same rate (compare Duvick, 1977, p. 188 with actual Iowa yields from USDA Statistics), lending credibility to the extrapolation of experimental gains to farm gains.

Changes in breeding objectives and/or changes in breeding methods may increase the rate of yield gains in the future. One such potential change in breeding method is towards an increased reliance by plant breeders on recurrent selection methods. A survey by Hallaeur (1979) found that only about 10 percent of practical corn breeding effort in the U.S. is presently devoted to recurrent selection, compared to 90 percent of effort devoted to pedigree and backcross methods. However, in the survey, breeders indicated that proportionately more effort would be put into recurrent selection in the future.3/

Some sources have speculated that there were significant potential yield gains to be made by improving farmers' selection of hybrids from those available. However, an analysis of regional data in Iowa did not support this view (see Appendix III-A). Farmers appear to be doing an adequate job of choosing hybrids suitable for their conditions.

3.3 Costs and profitability

With hybrid seed costs currently at about $15 per acre, it is clear that the gains from hybrids have not all been captured by the seed companies. This is so since, if the gains attributable to new seeds are anything like one bu/ac/yr since 1930, the gains in total revenue by farmers from the new seeds are far in excess of $15. New hybrids have undoubtedly led to some other variable cost increases and total variable costs were $136/ac in 1980 (USDA, 1981). Even if new varieties have been responsible for 50 percent of the total variable production costs, there is still a large net benefit for the farmer from improved seeds. Competition within the seed industry has probably been adequate to ensure high farmer benefits from using improved hybrids.

Given the current U.S. corn yield of 100 bu/ac, an annual yield gain from hybrid production of one bu/ac/yr (at little or no additional cost), results in a current-level one percent/bu/yr reduction in total production costs.

3.4 Resource Use and Productivity

Improved corn hybrids have probably increased output/man-hour in approximately the same proportion as they have increased yields per acre, since labor input per acre would be about the same regardless of yield. Insofar as the productivity of nitrogen has been enhanced by the new hybrids they will have resulted in an increased demand for nitrogen (and consequently, made production of corn more energy-dependent, since nitrogen fertilizer manufacture requires high amounts of energy).

Concurrently with the higher yields due to corn hybrids and increased fertilizer application,

there has been a rise in the application of plant protection chemicals. To what extent this increase in plant protection chemicals has been due to plant breeding is difficult to gauge - certainly the higher potential yield achieved via plant breeding could encourage efforts to protect that potential. On the other hand, insofar as new hybrids achieve resistance to pests, they substitute for the use of chemicals. Overall, there has probably been a major positive effect of improved hybrids on chemical use, but this will not necessarily continue in the future, as a change in emphasis by breeders could result in substitution of new varieties for chemicals.

4. Other Aspects of the Technology

4.1 Institutional Aspects

4.1.1 Consequences of the Technology for Private vs. Public Sector Roles in Hybrid Corn Production

The development of corn hybrids lends itself to privatization, since: (i) individual hybrids are identifiable in terms of both a trade name and agronomic characteristics; (ii) seed cannot be retained by farmers for planting year after year; (iii) the development of hybrid seed is a complex enough procedure to prevent farmers from developing their own hybrids (Regan, 1976). Private companies have been able to capture some economic returns to investment in research via the development and sale of name-brand corn hybrids. Companies such as Pioneer, Funk, and DeKalb began to emerge simultaneously with the release of the early public hybrids (Sprague, 1980). In the mid-1970s, almost all of the corn varieties used in commercial production were private (Hanway, 1977). However many of the parent lines were publicly developed. Although some non-hybrid crops are also in the private domain (e.g., soybeans and cotton), the seed companies have difficulty in capturing the full economic benefits from their seed production investments in these crops (Duvick, 1980b).

In the late 1920s private and public sectors shared the common goal of developing acceptable hybrids. However, by the 1930s, a divergence of responsibilities began and has increased over time. The public sector has moved towards a concentration on graduate training and "basic" research while the seed companies have concentrated on seed production and marketing (Sprague, 1980). The divergence between the two sectors is continuing. The private sector is taking over some of the applied research (e.g., screening for insect resistance) previously done in the public sector. The public sector is taking responsibility in the more "basic" (e.g., risky payoff, long range) research areas, such as determining the physiological basis for variation in yield, and developing new breeding/selection methods. Thirty years ago two public hybrids, U.S. 13 and

and U.S. 505 were prominent. There are today virtually no public hybrids, but publicly developed parent lines are still (surprisingly) important (Zuber, 1975). There is pressure from small seed companies for the public sector to remain active in parent line development. If the public sector does reduce its input into parent line development, it will still have an important role to play in providing genetic material, in the stage prior to its incorporation into inbred parent lines.

This divergence in responsibilities between the private and the public sectors is logical, but it will result in the public sector having a less visible (tangible) research output with possible negative ramifications for public research funding. Indeed, there are indications that universities are again beginning to place some emphasis on'hybrid development in an effort to attract funds from legislators (Duvick, 1981b). At present, the public sector is supplying about one-fifth of the total breeding effort (Duvick, 1981a). A cutback in public sector funding is feared by the seed industry, since most of the important developments in both the theory and practice of plant breeding have come from the public sector (Sprague, 1980).

4.1.2 The Private Seed Companies

The major hybrid corn seed companies in the U.S. are Pioneer and DeKalb. There are also a multitude of medium to small sized companies (see Claffey Prinzinger, 1980). Major changes in the structure of the industry over the past decade have been: (i) the emergence of Pioneer as the market share leader with 31 percent (Pioneer, 1979) at the expense of DeKalb and some smaller companies (Claffey Prinzinger, 1980); and (ii) acquisition of a number of medium-sized companies by large non-seed companies.4/ Of the larger seed companies, only Pioneer and DeKalb remain independent. For most companies, seed corn makes up the major component of total revenue from seed. (Total revenue from corn seed in the U.S. was $1,000 million in 1979.)

Financial press commentary in the 1970s listed the following rationale for the seed company takeovers: (i) excellent potential returns on investment (the seed industry is regarded as having a low capital requirement); (ii) growth prospects; (iii) proprietary nature of the products (given a boost by the 1970 Plant Variety Protection Act); and (iv) potential for large returns to research and development expenditures. Point (ii) refers mainly to non-corn crops, but there has been a modest growth in revenue from seed corn via the increased planting rate per acre, and by real increases in seed prices, as farmers' preference has switched to higher performance single and three-way cross seed. The following figures indicate the rise in seed prices over time for a 50 lb unit of seed (about

three times the usual seeding rate per acre).

	1969	1974	1979
Seed price (50 lbs)	$13.70	$25.00	$45.50

. Seed prices vary between companies and between varieties. Observed prices depend upon cost of production and expected performance. The major companies set the price, but the large number of small independent companies provide competition and their market share would increase if the major companies set prices at too high a level relative to expected performance of the hybrid. The seed industry is generally regarded as being quite competitive, and many farmers plant seeds of several different companies (Newlin, 1974). Even the most outstanding hybrid of recent times (Pioneer 3780) captured only about 5 percent of the total market. This low figure reflects, in part, the need to target varieties to specific locations, which is an important factor fostering competition within the industry. (Pioneer 3780 took up to 30 percent of the market share in some years in some districts in Iowa.) A concentration of the hybrid seed industry which eliminated the small independent companies could slow the pace of technological advance within the industry and would increase the risk of price increases if companies tried to capture a greater share of the revenues from the increased yields due to improved hybrids. Concentration could be hastened as a result of the (anticipated) reduction of public sector input into new parent line development. In the past, the smaller seed companies have depended almost entirely upon university breeders for the development of their inbreds. These companies are now joining forces with the foundation seed companies in forming what can be regarded as a single functioning organization, doing its own breeding and evaluation work. Through this co-operative mechanism, the small companies are expected to maintain their viability in the industry, although there could be some future consolidation of these small companies.

Seed production costs represent about 25 percent of the final delivered price of seed. Other significant components of total costs are (in order of relative size): selling and distribution, transport and handling, and dealer commissions. Overhead is small, at less than 0.5 percent. Pioneer has been spending about 2.25 percent of their total corn sales on hybrid corn research and development. This is considered representative of the industry and based upon this, total industry R&D on corn would have been:

Corn R&D
($m. nominal)

1969....$5	1973.....$9	1977....$21
1970....$6	1974....$11	1978....$22
1971....$8	1975....$16	1979....$23
1972....$8	1976....$18	1980....$26

Using Pioneer Hi-Bred International as a yard-stick, it appears that hybrid corn seed production has been a stable and profitable activity. Total corn earnings and dividends have risen each year. After tax return on equity has ranged between 20-30 percent over recent years. In real dollars, Pioneer's stock price has been steady, with a price/earnings ratio of about 8. It has been possible for seed companies to maintain their profit margins by passing on cost increases to farmers since seed corn represents a relatively small proportion of total corn production costs and the investment by the farmer in seed corn brings relatively large returns.

4.2 Vulnerability of the Technology

The Southern Corn Leaf Blight of 1970 prompted plant breeders to contemplate the problem of the germplasm base in corn. The genetic base of corn in the ground at any given time is undoubtedly narrower than it was 100 years ago, since the very process of genetic improvement implies the selection and growing of only the best material for planting. Based upon data from the American Seed Trade Association Survey of 1975, Zuber (1975) concluded that there had been little change in the genetic base of the growing crop between 1970-75, but Duvick (1981a) did find evidence of some improvement between 1970-80. Furthermore, the genetic material in the ground changes over time. The expected life of a corn hybrid is seven years and it is anticipated that this will shorten in the future (Duvick, 1981a). Genetic diversity in the seed nursery or breeding program is, in some sense, a substitute for diversity in the field (Harlan, 1980), in that it would usually restrict the impact on genetically vulnerable material to only one or two years. While 80-90 percent of commercial corn was in T cytoplasm in 1970, there was a shift to virtually zero T cytoplasm for the 1972 crop year following the 1970 corn blight (Steele, 1978).5/ There are approximately 2800 well-tested acceptable inbred lines of corn on hand in breeding programs today (Duvick, 1981a). Crossing these in all possible combinations would result in some millions of hybrids which would be reasonably acceptable and worth searching for specific required character-istics. There is really more diversity than is apparent from the results of a single-year survey of the planted crop.

Most corn breeders use elite (or adapted) material when searching for pest resistance, in preference to "exotic germplasm" which is not adapted (Duvick, 1981a). The integration of exotic germplasm into adapted lines is a slow process, requiring many generations. Furthermore, all of the exotic genetic material may eventually be used up. Just as the replacement of open-pollinated varieties has eliminated some genetic diversity in the U.S., the success of new corn cultivars on an international scale is

destroying the very genetic variability which made such success possible (Timothy and Goodman, 1979, p. 172).

A detailed account of many germplasm collec-tions, both in the U.S. and worldwide, is avail-able in Timothy and Goodman (1979). They high-light the practical problems associated with the collection and especially with documentation and preservation in developing countries (e.g., break-down of controlled environment equipment, drought or flood while collection is being rejuvenated in the field, poor rejuvenation techniques leading to intercrossing, etc.). Some improvement of preservation technology is possible, perhaps through the application of tissue culture or related techniques.

While corn is the most valuable U.S. crop, the collection maintained by USDA is modest in size, and world collections have been taken very casu-ally (Harlan, 1980). People with an intimate knowledge of the present situation express concern that not enough is being done to correct this situation (Duvick, 1980b; Timothy and Goodman, 1979; Harlan, 1980; USDA, 1979; NAS, 1978). A recent survey of U.S. corn breeders (Duvick, 1981a) found that 50 percent were dissatisfied with U.S. gene bank collections and services. Complaints were in two categories: (i) inadequate size of collection; and (ii) inadequate descrip-tion of agronomically useful traits. A recent GAO (1981) report was also critical of USDA's role in managing plant genetic resources and made a number of recommendations for change.

There has been another, less publicized, con-sequence of the 1970 corn blight. A number of lawsuits were taken out against the seed companies claiming compensation for yield losses. Although none of the lawsuits were successful, the exper-ience has made the companies sensitive about pro-moting innovations which might lead to lawsuits. While a disease or insect attack construed as an "act of nature" is accepted by farmers, if a causal link can be seen between the breeding material and the disease, legal action may follow. This essentially means that the threat of action under the legal system may hinder the seed com-panies from pursuing certain kinds of research. Take a situation where a company develops and advertises a "disease resistant" hybrid. If that hybrid then succumbs to the disease, lawsuits may follow. This potential threat may result in the company's being more cautious in promoting such a characteristic, possibly translating into a slowing of research in certain areas.6,7/ Yet, the social costs of not developing the variety (the annual losses due to the disease) may far outweigh the costs of sporadic breakdown in resistance.

In the previous section, reference was made to the acquisition of seed companies by chemical

companies (see footnote 4 and Claffey Prinzinger, 1980). A continuation of this trend could lead to excessive concentration in the seed industry. Mention was made of potential seed price increases and/or a slowdown in technological progress should this occur. However, if·the seed industry became concentrated in the hands of a few large chemical companies, the most obvious potential danger would be that the whole breeding and selection process could be biased toward varieties which respond well to the application of chemicals. Inadequate attention might be paid to the development of varieties which minimized the use of chemical inputs. Given concerns about environmental pollution by chemicals, it would not seem wise to allow the seed industry to become dominated by large agricultural chemical companies.

5. Alternatives to the Technology

As a production technology, corn breeding has many attributes. It is ecologically positive, requiring relatively small amounts of capital for seed production (by the companies) and for seed purchase (by farmers). While hybrid corn production may have been indirectly responsible for some of the present dependency on chemicals, there is no inherent reason why this should be so. A change in breeding objectives in response to either price changes and/or the regulatory environment can alter this. Plant breeding is an extremely versatile technology, and it has had high economic payoffs. It is difficult to identify any other broadly applicable technology with the same range of attributes, which could effectively substitute for plant breeding. The emerging biotechnologies (see Chapter X) may eventually impact on the genetic material available for corn breeding. Such technologies are, at best, many years away. However, when specific characteristics are desired in a corn hybrid, there may be alternatives available for achieving them which are cheaper than plant breeding. For example, a high lysine corn has been bred and it is a "better" feed for swine than is regular corn. Its economic value is a function of the price of regular corn and the price of soybean meal – an alternative source of lysine (Aldrich et al., 1978). At current (1980) corn and soybean prices, high lysine corn is worth approximately $.18 more than regular corn. Nevertheless, low yields and harvesting problems have prevented its adoption by U.S. corn producers (Creech and Alexander, 1978). In other words, adding protein supplements have proven to be a cheaper source of good quality feed than breeding directly for the higher protein quality in corn. (Progress continues to be made in breeding for high yielding high lysine corn and, in the long run, breeding may turn out to be the cheaper alternative.)

6. Managing the Technology

The following recommendations are made for managing the hybrid corn technology:

(i) Avoid excessive regulation of an industry which has a proven record of success and innovation in catering to farmers' needs.

(ii) Promote competition within the seed industry by facilitating efforts by smaller companies to remain viable and by preventing control of a major component of the seed industry by agricultural chemical companies.

(iii) Encourage the exchange of genetic material between interested parties. If universities withdraw from their role as inbred line producers, they can still be the medium of exchange of genetic material at the base population stage.

(iv) View public research as an input into the seed industry, rather than as a final product. Continue to fund public research even though its output may become less "visible." Encourage the application of more "basic" (non-agricultural) research to applied plant breeding problems in agriculture through research grant incentives (e.g., by demanding that the work be done on agriculturally important crops).

(v) Systematically collect, document and preserve a wide range of corn germplasm.

(vi) Enact legislation which encourages the development of disease and insect resistant hybrids (and hybrids with other desirable varietal characteristics). There is an inherent bias in the existing legal system which could slow such developments.

Footnotes

1/One modification to the Butell and Naive data was to convert their nitrogen variable, "amount of nitrogen applied per acre of corn receiving nitrogen" into "average amount of nitrogen applied per acre of corn grown," by weighting the Butell and Naive variable by the proportion of corn acres receiving nitrogen in each year. This latter measure of nitrogen input seems more appropriate since the dependent variable is average U.S. corn yield. (An attempt to statistically separate out the "rate" and "proportion" effects was not successful – apparently the rate effect has been dominant over the period.) .

2/July precipitation weighted by acreage in 5 major corn producing states (Butell and Naive, 1978). While this is a rough proxy for corn growing weather, July precipitation was the most significant climatic variable in Thompson's (1969) analysis.

3/Pedigree breeding involves the crossing of already improved inbreds, while recurrent selection consists of selfing a base population once or twice, evaluating the selfed lines for the character under consideration, intercrossing the superior lines and repeating the process using the reconstituted population as the source of the new lines (Jenkins, 1978). Recurrent selection theory holds that any improvement effected in a

base population will be reflected in the quality and performance of inbred lines developed from such improved populations and it is anticipated that the frequency of occurrence of favorable gene combinations will be increased by the use of recurrent selection.

4/Company	Purchaser
Northrup King	Sandoz
O'S Gold	Central Soya
Funks	Ciba - Geigy
PAG, ACCO	Cargill

See Claffey Prinzinger (1980) for a more extensive list.

5/Another example of the capacity to multiply new seed was quoted by Pioneer (1979). An initial parent seed stock of 4.5 lbs late one summer was multiplied through two generations in Hawaii into sufficient seed to plant 3500 acres in the following spring.

6/The problem is most likely to arise in relation to pest resistance. One attempt to alleviate this problem was made by the National Council of Commercial Plant Breeders (1976) which suggested that standardized definitions of the terms "immune, resistant, tolerant, susceptible" be adopted to assist in communications between farmers and seed companies. However, the standardized definitions have never been embraced by the industry (Duvick, 1981b).

7/Seed companies may conclude that research funds are more appropriately placed in developing characteristics which are not hindered by such problems of description/promotion. For example, they may concentrate more on higher yields and other "less legally vulnerable" characteristics.

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Appendix

Appendix Table III-1. Data Used in Estimating Equation III-1. (Including Variables Not Ultimately Appearing in Equation III-1.)

Time T	Yield Y(bu/ac)	Nitrogen[a] N(lbs/ac)	Weather W	Acres A(m)	Irrigated/Acres[b] I(m)
54	39.4	16	72	69	1.6
55	42.0	18	101	68	2.0
56	47.4	19	125	65	2.3
57	48.3	21	114	63	2.5
58	52.8	23	231	64	3.1
59	53.1	27	90	72	3.8
60	54.7	30	88	71	3.8
61	62.4	35	153	58	3.4
62	64.7	40	166	56	2.9
63	67.9	44	145	59	3.4
64	62.9	49	106	55	3.3
65	74.1	64	107	55	3.0
66	73.1	76	92	57	3.7
67	80.1	86	96	61	4.5
68	79.5	95	110	56	5.8
69	85.9	100	177	55	4.9
70	72.4	105	102	57	5.4
71	88.1	101	124	64	6.2
72	97.0	110	134	58	6.0
73	91.3	106	145	62	6.0
74	71.9	97	53	65	7.3
75	86.4	98	69	68	7.8
76	88.0	123	95	72	9.3
77	90.8	123	113	72	11.0
78	101.0	120	143	72	11.25
79	109.7	130	156	72	11.5
80	91.0	125	84	73	11.5

[a] See footnote 1/. Early data on the percent of corn acres receiving nitrogen obtained from Mayer and Hargrove (1971, p. 5) - missing years estimated by straight line interpolation.

[b] Calculated from Irrigation Journal Survey since 1972. Prior to 1972 estimated from State of Nebraska Statistics by assuming that Nebraska made up same proportion of total U.S. irrigated corn acreage as in 1972.

Appendix III-A. Farmer Selection of Corn Hybrids: Some Results from the Iowa Corn Yield Test

The large yield differences which frequently occur among corn hybrids grown under comparable conditions raises the question of whether average U.S. corn yields could be increased by improving the hybrid selection procedures of farmers. This appendix attempts to answer that question by analyzing data from the Iowa Corn Yield Test.

The Test presents the yields and other characteristics of approximately 100 corn hybrids which are grown in replicated trials each year in seven districts of Iowa. The hybrids in the Test are regarded as a good representation of the choice available to farmers. (Entry of hybrids in the test is, however, voluntary.) In certain years, surveys are conducted to determine the acreage of Test hybrids actually grown by farmers. It was found that approximately 50 percent of total acreage is represented by hybrids appearing in the Test in the same year as the survey. Survey results (unpublished) were available for the years 1972-74, 1976 and 1978. The Test yields of hybrids which are grown by farmers can be regarded as a proxy for actual farm yields when they are weighted by the acreage of each hybrid grown by farmers. This proxy for farm yields can then be compared with the yields which would have been obtained under alternative selection criteria. (Note that by making comparisons between Test yields, the problem of comparing farm/experimental yields is eliminated.)

While an infinite number of potential selection criteria can be identified, some of the most practical alternatives would seem to be:
   (i) top 5 yielders in previous one year's test;
   (ii) top 10 yielders in previous one year's test;
  (iii) top 5 yielders in previous two year's test; and
   (iv) top 5 yielders in previous three year's tests.

A preliminary scanning of the data indicated that criterion (iv) generally performed unsatisfactorily compared to (iii), so criterion (iv) was eliminated from further consideration. The performance of the remaining selection criteria were then compared with the performance (as exhibited in the Test), of the farmers' selected varieties (Appendix Table III-2).

A hypothetical selection criteria performed better than farmers' selections on average by 2.3, 3.6 and 5.5 bu/ac for criteria (i), (ii), and (iii) respectively. Based upon the published least significant differences of the Tests, these average differences were not statistically significant at the 5 percent level (although some significant differences were observed in individual years).

Large and consistent corn yield increases for farmers from improved hybrid selection do not appear likely, based upon this evidence. Furthermore, there is a bias in the data which supports such a conclusion. In particular, farmers choose hybrids based upon criteria other than yield alone. The top yielding hybrids in the Tests are generally late-maturing and are, therefore, less desirable than is suggested by their yield performance alone.

Some caveats are in order: (i) the Iowa data may not represent the overall U.S. situation; (ii) some yield gains may be possible (if all of the farmers in these 3 districts had grown the popular Pioneer 3780 hybrid, yields would have risen by an average of 4 bu/ac/yr - and this hybrid is relatively early maturing); and (iii) this analysis says nothing about improvements in genetic potential over time, but only about selection from the available genetic resources at a given point in time.

Appendix Table III-2. Yield Advantage for Three Hybrid Selection Criteria Over Farmer-Grown Hybrids

| | Yield Advantage (bu/ac)[a] | | |
Year	Criterion (a)	Criterion (b)	Criterion (c)
1972	1.1	2.7	4.5
1973	9.3	6.6	9.2
1974	-3.9	-1.5	1.1
1976	2.5	2.6	2.7
1978	7.8	7.8	10.1
Average	2.3	3.6	5.5

[a] Average of Test districts nos. 1, 2, 3.

The application of supplementary plant nutrients has made a major contribution to corn yield increases in the U.S. Manufactured fertilizers supply the bulk of nutrients currently applied in U.S. corn production.

Nutrients can be categorized as macro, secondary, and micronutrients, according to the amount of nutrient required. Macronutrients are required in large quantities for plant growth. This category includes nitrogen (N), phosphorus (P) and potassium (K). Figure IV-1 illustrates the total amount of macronutrient fertilizer added to corn since 1947. Secondary nutrients are those required in moderate quantities for normal plant growth. The secondary nutrients include calcium, magnesium, and sulfur. Micronutrients are required in small amounts; these include zinc, iron, copper, manganese, boron, molybdenum and chloride.

The primary applications of fertilizer to corn have been N, P and K. In this chapter these three nutrients are examined in greater depth.

Fertilizer Nitrogen

Nitrogen is an essential mineral required for protein synthesis by crops. Grain formation in crops is dependent upon the attainment of a threshold level of protein. Therefore, N supply is very important in contributing to corn yields. Although large quantities of N are present in the earth's atmosphere, soils, geological formations and oceans, only a small fraction of this total is available to plants. Available forms of N in the soil are the inorganic forms of nitrate, nitrite and ammonium ions. These available forms come about through the process of nitrogen fixation. Nitrogen fixation refers to the conversion of N_2 (atmospheric nitrogen) to a "fixed form" (such as NO_3-, NH_3) in which N is combined with at least one other atom.

Industrial nitrogen fixation (for fertilizer manufacture) and biological nitrogen fixation (e.g., by legumes, nitrogen fixing bacteria) provide the major source of N utilized by crops. Other sources of nitrogen are: (i) mineralization of nitrogen in the soil; (ii) decomposition of organic matter in the soil; and (iii) meteorological phenomena (lightning) that fix atmospheric N, which is then carried to the soil by precipitation.

There are three major reasons why considerable attention should focus on fertilizer N when considering future corn production:
  (i) N has played an important role in past yield increases, and in order to maintain present yields, fertility levels must be maintained (or utilization efficiency improved).
  (ii) N (in its available forms) is not storable in the soil for any length of time. This characteristic sets it apart from phosphorus and potassium. N is subject to denitrification and leaching. If it is not utilized by the current crop, it may not be available to the succeeding one.

Figure IV-1. Fertilizer Applied to Corn in the U.S., 1947-80.
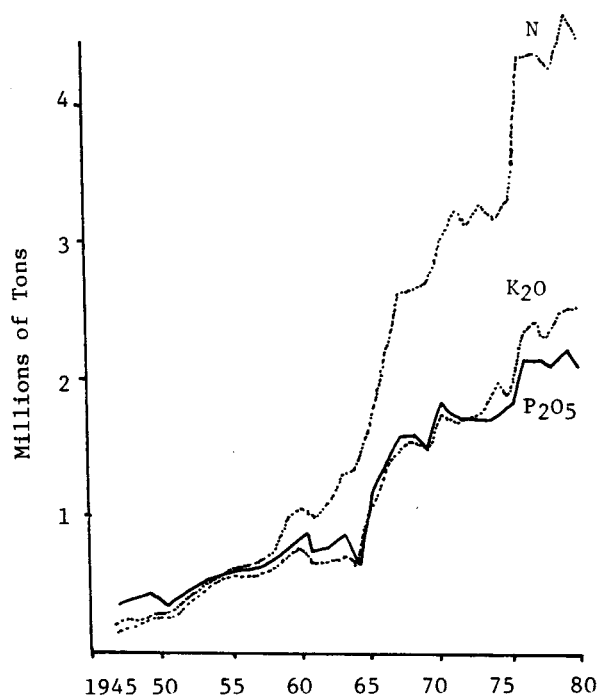
Source: Appendix Table IV-1.

(iii) Fertilizer N production is energy intensive (more so than P and K).1/ With increases of energy prices expected, this input will probably become relatively expensive.

1. Definition and Description of Fertilizer Nitrogen Technology

In this report fertilizer N refers to nitrogen compounds (ammonia and its derivatives) synthesized from atmospheric nitrogen and hydrogen, using the Haber-Bosch or modified Haber-Bosch process.

Fertilizer N is available as a liquified gas, in solution, or in solid form. It is available as a single element fertilizer, or as a mixed fertilizer containing other major and minor nutrients.

Anhydrous ammonia (NH_3) is the basic building block of manufactured nitrogen fertilizers. It is applied directly as a liquified gas and is the most concentrated form of N fertilizer (82% N).

The major sources of N which are applied to corn in the solid (crystalline) state are ammonium nitrate, ammonium sulfate and urea. Ammonium nitrate (NH_4NO_3) is manufactured using ammonia and nitric acid; it is marketed at 34 percent N. Ammonium sulfate, $(NH_4)SO_4$ (21% N), is manufactured from ammonia and sulfuric acid. Urea (NH_2CONH_2) is manufactured from ammonia and carbon dioxide. The clay coated fertilizer grade of urea has a N content of 45 percent.

Nitrogen is also applied in liquid form. Solutions containing N compounds such as ammonia, ammonium nitrate and urea, may be applied directly.

2. Direction and Magnitude of Fertilizer Nitrogen Technology

2.1 Historical Development

The first commercial process fixing atmospheric nitrogen for fertilizer N was the cynamide method developed in 1898. This was followed by the Haber-Bosch method in 1909. Commercial production using the latter method began in 1913 in Germany, and 1921 in the U.S. In modified form, Haber-Bosch continues today as the major method of producing fertilizer N. The process synthesizes anhydrous ammonia (NH_3) from hydrogen and nitrogen under conditions of high temperature and pressure in the presence of catalysts.

In the U.S. the real growth of the fertilizer N industry did not take place until after World War II. Although the war put heavy demands on food production, increased use of fertilizer N during the war did not result because ammonia was required for military purposes. Ammonia

oxidation plants proliferated in an effort to meet military demand. At the war's end, these plants were utilized to produce ammonium nitrate fertilizer and later many were sold to private industry.

In 1980, 40 percent of the 11 million tons of fertilizer N used in the U.S. was applied to corn harvested for grain. The amount of nitrogen added to corn grew rapidly after World War II, from an estimated 83 thousand tons in 1945, to more than 4 million tons in 1980 (Figure IV-1). This increase was due to increases in both the acreage of corn fertilized and the rates of application per acre. In 1947, fertilizer N was applied to 44 percent of the U.S. corn acreage at a rate of 10 lbs/ac. By 1980, 96 percent of corn acreage was receiving fertilizer N at an average rate of 130 lbs/ac (Table IV-1).

Table IV-1. Use of Fertilizer Nitrogen on Corn and Percent of Harvested Acres Fertilized for Selected Years

Year	Average Rate N Per Acre Receiving N (lbs/ac)	Harvested Acres Receiving N (%)
1947	10	44
1950	15	48
1954	27	60
1959	41	61
1965	73	87
1970	112	94
1975	105	94
1980	130	96

Source: USDA, Fertilizer Used on Crops and Pasture in the United States, Stat. Bull. No. 216, 1957; Commercial Fertilizer Used on Crops and Pasture in the United States, Stat. Bull. No. 343, 1964; and Crop Production, ESS, Crop Reporting Board, various years.

2.2 Trend in Form of Nitrogen Application

Since 1945, the form of nitrogen applied to crops has changed. Initially, mixtures (more than one nutrient) predominated. These fertilizers were applied primarily in the pelleted, solid form. By 1949-50, nearly equal quantities of nitrogen were supplied by mixed fertilizers and fertilizers containing only one nutrient (usually referred to in the fertilizer trade as "materials"). After 1950, materials continued

to increase in popularity (by 1960-61, 65% of N was applied as materials).

In addition to the trend towards more materials there has also been a trend towards more concentrated forms (higher analysis) of N and away from solids. Two reasons for this have been: (i) the cost advantage per unit of N; and (ii) improvements in application equipment which facilitated the handling of liquified gas and solutions.

The cost advantages of concentrated forms is due partially to the advantage of using ammonia directly as a fertilizer. Since most other N. fertilizers are made from ammonia, additional processing is required for these. This additional processing increases the cost per unit of nitrogen. The solid forms require drying, pelleting and in some cases, coating, which not only makes them more expensive to produce per unit of N, but also the transport costs (per unit of N) are much higher than with the more concentrated forms. In addition to transportation cost advantages conferred by the reduced weight of the concentrated forms, transportation costs are reduced by using pipelines for the transportation of liquid forms and anhydrous.

Application equipment differs with the type of fertilizer used. The solid powdered and pelleted forms, used earlier, required only slight modifications to previously existing farm machinery. Gaseous forms require pressurized application equipment. The slow acceptance of anhydrous was due, in part, to the difficulty in applying it initially. As anhydrous applicators were refined, anhydrous became a viable option for many more producers.

2.3 Trend in Type of Nitrogen Applied

With the increased availability of fertilizer N following World War II, the solid forms of N were most widely available. Ammonium sulfate was popular at first, then ammonium nitrate became the most widely used form of fertilizer N. During the 1960s, liquid fertilizers began replacing the solid forms of nitrogen, especially in single element (N) fertilizers. By 1968, 62 percent of single element (N) fertilizer was applied as a fluid (Achorn and Cox, 1971). The predominant form of fertilizer N during the 1960s and 1970s has been anhydrous ammonia.

3. Direct Effects of Fertilizer Nitrogen Technology

3.1 Yield Response

Corn yields have increased dramatically since 1945; these increases have been paralleled by increases in the application of nitrogen (Figure IV-2). The corn yield increases cannot all be attributed to N, however. Other factors

have also contributed to increased yields over the period. These are non-nitrogen fertilizers and plant density and genetic potential of the hybrids used.

Although non-nitrogen fertilizer use increased at the same time as nitrogen fertilizers (Figure IV-1), there is a general feeling that nitrogen was primarily responsible for the yield increases, and that P and K were generally adequate to enable increased yields to be achieved by additional nitrogen applications. P and K applications over the period were sufficient to compensate for the amounts of these nutrients removed due to increased yields (Menz and Pardey, 1981). This does not imply that the increases in P and K were unnecessary, but that nitrogen was the major fertilizer limiting yields over the period.

Plant density also increased over the period 1945-80, as hybrids were developed which were not susceptible to lodging, and machinery was developed to adapt corn production to narrow row spacings. Plant population in the Corn Belt in the mid-1940s averaged about 12,000 plants per acre. Earley (1955) found, in an experiment, that moving to densities of 24,000 plants per acre increased yields even at nitrogen application rates as low as 40 lbs/ac. In other words, plant density can limit yields even at low levels of nitrogen.

Figure IV-2. Average Yield and Fertilizer N Application on Corn, 1945 to 1980.

N Application······   ——Corn Yield
(lbs/ac)   (bu/ac)
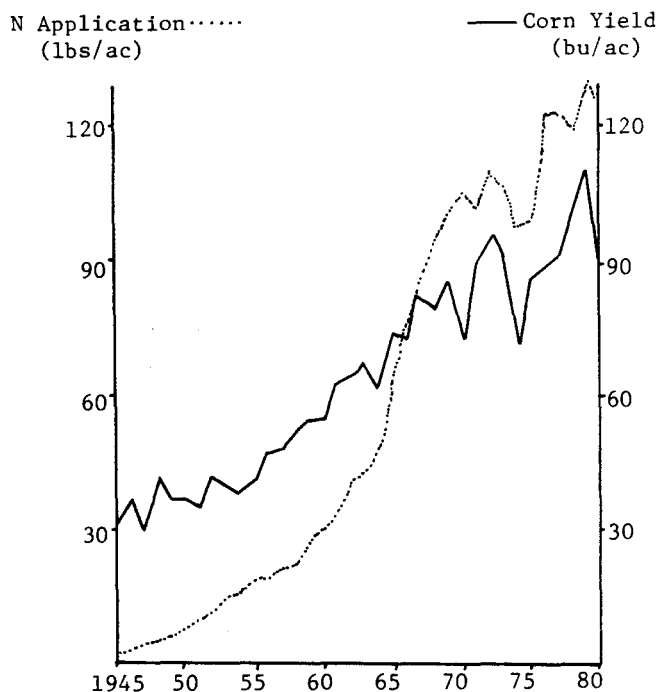
Source: Appendix to Chapter III.

Plant densities did in fact increase over the period 1945-80 (present populations are around 22,000 plants per acre), and it does appear likely that density did limit yields at certain periods. Despite the fact that increases in plant density probably have been responsible for some of the observed increased yields, new hybrids and N levels are thought to be the primary factors responsible.

In Chapter III, the influence of new hybrids and nitrogen on historical corn yield increases was examined. They were found to have contributed approximately equally to corn yield increases since 1954. In this Chapter the contribution of nitrogen is examined in more detail.

Based upon equation III-1 (Chapter III), Menz and Pardey (1981) estimated the contribution of fertilizer N to corn yields for three periods (1954-60, 1961-70, 1971-80). The marginal physical product of nitrogen can be used to examine fertilizer N's past contribution to increases in corn yields. (The marginal physical product of nitrogen (MPP_n) represents the increase in yield due to the addition of one unit of fertilizer nitrogen.) The average annual change in N application was multiplied by the MPP_n (from equation III-1) corresponding to the average level of nitrogen applied in each time period:

	Average Annual Change in N Application Rate (lbs/ac)	Average MPP_n (bu/lb)
1954-60	2.5	.79
1961-70	6.9	.25
1971-80	2.2	.15

Fertilizer N's annual contribution to corn yield is shown in Figure IV-3, where it can be seen to have fallen dramatically over the decade of the 1970s compared with previous decades. Although the contribution was high in both decades prior to 1970, the source of contribution differed. Changes in the contribution are due to changes in the level of N application and/or the magnitude of the MPP_n. During the period 1954-60, the MPP_n was higher (.79 bu/lb) than during the 1960s (.25 bu/lb); however, during the 1960s the lower MPP_n was compensated for by an increase in the average annual rate of application of fertilizer N (from 2.5 lbs/ac to 6.9 lbs/ac). In the decade between 1971 and 1980, both the MPP_n and the annual increase in application rates were lower than for the preceding decade, resulting in a marked decline in the overall contribution of nitrogen to corn yield increases.

3.1.2 Future Yield Increases from Fertilizer N

In considering future potential yield increases from fertilizer N, four factors must be considered which may influence the future contribution from fertilizer N technology:

(i) Yield increases in the past have been influenced both by the proportion of total acres fertilized and the application rate on those acres fertilized. The percentage of total corn acres receiving N increased from 44 percent in 1947 to 91 percent in 1966 (corresponding roughly to the period of the most rapid increase in yields). In 1980, fertilizer N was applied to 96 percent of the total corn acreage. Future yield increases from additional acres fertilized will be be minimal since only 4 percent of the total acreage at present is not receiving nitrogen.

(ii) The increase in yield due to an increase in application rate per fertilized acre is slowing down because of decreased MPP_n at the present high rates of application. The MPP_n is now 0.12 bu/lb, whereas at fertilizer rates of 40 lbs/ac, representative of the late fifties, the MPP_n was 0.4 bu/lb. Given the MPP_n at present levels of fertilization, even if it were possible to profitably increase the nitrogen application rate by 50 lbs/ac, the total farm level corn yield would increase by less than 6 bu/ac (50 lbs/ac x 0.12 bu/ac/lb = 6 bu/ac, at most, since the MPP_n will be less than 0.12 bu/lb over the entire 50 lbs).

(iii) The third factor is the possible escalation in real nitrogen prices. The price of nitrogen is expected to increase more rapidly than most other inputs, due to the importance of the energy input in the form of natural gas. Natural gas is expected to experience rapid price increases in the future. Past trends indicate that fertilizer

Figure IV-3. Fertilizer Nitrogen's Contribution to U.S. Corn Yields During the Periods 1954-60, 1961-70 and 1971-80.
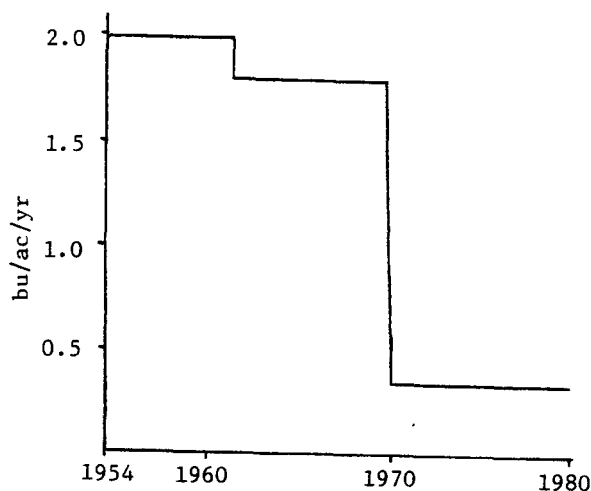
use is sensitive to price changes. The period of nitrogen price reduction in the 1960s and early 1970s coincided with rapid increases in application rates. This was followed by a period of sharp price increases (1974-75) which resulted in a drop in utilization (this reduction in use may have been complicated by the unavailability of fertilizer). As prices dropped again in 1976, fertilization rates increased.

(iv) The fourth factor to consider--increased efficiency of applied nitrogen--may allow a reduction in application rates without decreasing yields. Increased efficiency of utilization means that a higher percentage of the N applied is utilized by the crop, so that present yields could be maintained at lower levels of nitrogen application. The effect of increasing efficiency has essentially the same effects on yield as increasing the rate of N application. Large yield increases are not expected to result since, at present levels of N application, yield increases from additional N are relatively low (.12 bu/ac for an additional lb of N).

The above four factors seem likely to contribute to a levelling off of yields; however new corn hybrids with improved responsiveness to nitrogen may bring about further yield gains (see Chapter III).

3.2 Costs and Profitability of Fertilizer Nitrogen

3.2.1 Historical Trend in Nitrogen Price

Figure IV-4 illustrates the deflated price of fertilizer N (ammonia) from 1953-80. Nitrogen prices declined until the early 1970s. Some factors contributing to this decline were: technological developments in the fertilizer industry (Paul et al., 1977); declining prices of natural gas; and over-capacity in the fertilizer industry during the sixties.

Prices stabilized during the early 1970s as the growth in production capacity slowed. In 1974-75 prices increased sharply in response to higher energy prices and nitrogen shortages (due to a combination of increased demand and slowed growth in capacity). Prices peaked in 1975, then rapidly declined as new capacity (induced by the high prices) increased the supply and high prices resulted in a cutback in use by farmers. The decline in real price continued until 1979, although prices did not decline to the previous (early 1970s) levels. In the future, costs of producing fertilizer N are expected to increase in the long run, due to rising energy prices.

3.2.2 Marginal Analysis of the Profitability of Nitrogen Application

The anticipated increase in the price of fertilizer N has contributed to concern that the use of nitrogen will be curtailed in response to escalating nitrogen prices. One method of examining this issue is to use marginal analysis to compare the present situation with the theoretical economic optimum for fertilizer use. In this case, the use of the input (nitrogen) is expanded up to the level where the marginal factor cost of that input is equal to the value of the marginal product. Thus nitrogen would be added to corn until the value of additional corn produced was just equal to the cost of the additional N applied.

The value of corn produced by an additional pound of nitrogen (value of the marginal product, or VMP_n) was calculated at various levels of nitrogen application using the response curves from the two sets of data presented in Appendix IV-A and using corn price of $2.80 per bushel (Figure IV-5). At the present nitrogen application rate of 130 lbs/ac, using the historical data, the VMP_n was calculated to be $0.34/lb of N per acre. In other words, the value of corn contributed by one additional pound of nitrogen is $0.34. Thus the addition of nitrogen would be profitable up to a price of $0.34/lb. The current cost of applied N is about $0.20/lb. Based on this data, the cost of applied N would have to increase by over 50 percent before eliminating the profit realized from applying an additional unit of N. Similar calculations using the experimental data (Appendix IV-A) showed a VMP_n of $0.78/lb of N. Based on this experimental data, an even sharper increase in N prices would be necessary to eliminate the profit margin.

The question arises as to why corn producers are not currently adding more nitrogen, if it is profitable to do so. There are a number of

Figure IV-4. Deflated Price of Fertilizer Nitrogen (Ammonia)
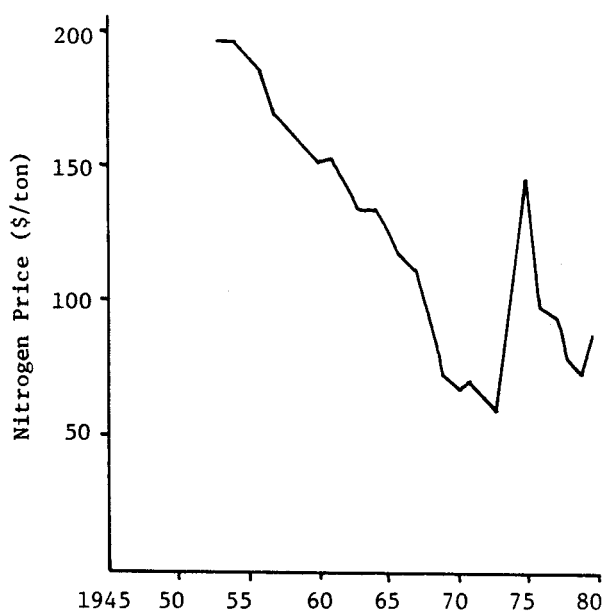
Source: Appendix Table IV-4.

possible explanations. They include the time patterns of adoption of the technology, the possibility of capital rationing, and risk factors.

A classical S-shaped adoption curve was employed to examine the adoption pattern of fertilizer N. Using ceiling values on fertilizer rates derived from the data in Appendix IV-A, it was concluded that the technology of fertilizer N is in the latter stage of adoption. The latter stage of adoption is characterized by: (i) a slowing down in the rate of adoption; and (ii) a decline in productivity growth from additional adoption (Lu and Quance, 1979). The rate of adoption of the technology has slowed during the 1970s (this can be seen in both the rate of application over the period 1945-80 as shown in Figure IV-2 and the proportion of acres fertilized in Table IV-1). The decline in productivity growth (from additional adoption) is supported by both the experimental agronomic data and the historical farm level data. In summary, the time pattern of adoption suggests that the movement toward an economic optimum (i.e., more N applied) probably will continue, but at a slow rate.

The second possible explanation of why producers have not increased nitrogen application rates, to the levels that marginal analysis suggests desirable, is because of capital rationing. When this occurs producers allocate available capital to the inputs giving the highest returns and do not employ the inputs to the point where the VMP is equal to the price paid for the input.

Figure IV-5. Value of the Marginal Product of Fertilizer Nitrogen.
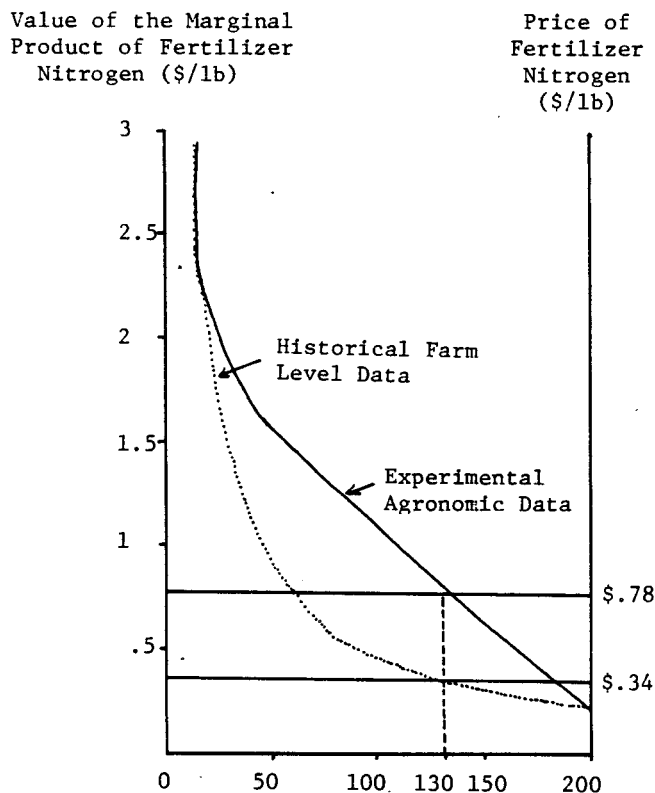
Risk may also play a role in explaining the underutilization of nitrogen in corn production. The two main sources of risk are price (corn price and input prices) and yield variability (due to climatic factors and pests). For example, the yield increasing potential of nitrogen will only be fully realized if there is adequate rainfall. With inadequate rainfall the returns from adding nitrogen will be less than anticipated. (Such was the case in 1980 when drought reduced yields to levels which were achieved at much lower fertilization rates several years earlier.)

3.3 Resource Use and Productivity

Fertilizers are land saving technology; they increase the productivity of land. This use of land saving technology rather than additional land has been influenced by the relative prices of land and fertilizers. Figure IV-6 illustrates that the price of land relative to the three major fertilizers has increased over the period 1945-80 and there has been a corresponding substitution of fertilizer for land. With the expected increase in nitrogen price the future direction of this ratio is uncertain.

4. Other Aspects of Fertilizer Nitrogen Technology

4.1 Environmental Impacts

Nitrogen in the form of nitrate (NO_3-) is a potential environmental contaminant. Nitrates can be a health hazard to humans and livestock at high concentration levels. They also promote the growth of aquatic plants in lakes and ponds. These plants then decompose, reducing the oxygen levels and causing eutrophication of the water body.

Figure IV-6. Price of Farm Real Estate Relative to Fertilizer.
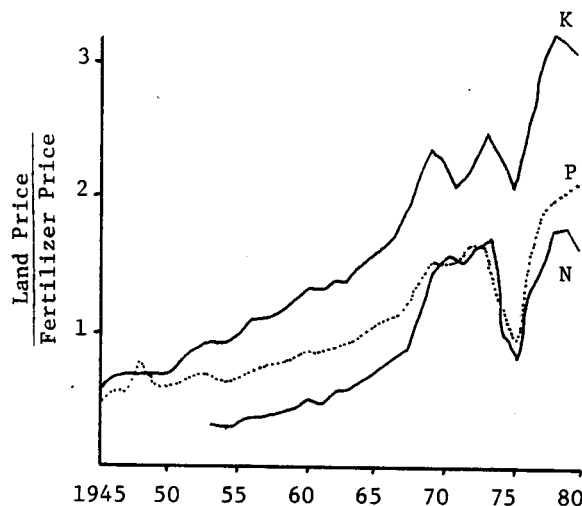
Source: Appendix Table IV-3.

There are two main concerns regarding nitrogen and the environment: (i) nitrates leaching into the ground water resulting in high nitrate concentrations in the aquifer, and (ii) nitrates present in soil drainage systems which end up in surface water.

"Groundwater" is water which has percolated below the root zone and drainage tiles (Aldrich, 1980). At present, not a great deal is known about the fate of nitrates in groundwater. Nitrates flow with water and the rates of flow of groundwater vary, depending upon the type of subsoils and geological characteristics of the area. (In sand, water may move several feet per day, while in dense subsoils it may move only one foot per year.) Nitrates from fertilizer N in groundwater are generally not a problem at present, except in specific situations such as shallow wells or wells where there is seepage into deeper wells (Aldrich, 1980) and also where excess irrigation occurs on sandy soils.

Nitrates in surface water, originating from fertilizers, are primarily from tile drainage systems and from groundwater which drains through the soil into river basins. The increased use of drainage tiles has increased water movement through the soil and thus increased the movement of nitrates. The amount of nitrates from runoff is small because the soil must be reasonably dry to allow fertilizer application equipment to pass over it. This absence of excess moisture promotes absorption of the fertilizer into the soil at the outset of rainfall, thus minimizing runoff. Also, most nitrogen is applied in the ammonium form which encourages attachment to soil particles. Therefore nitrogen is lost only if soil erosion occurs and even then, only if it has not moved downward in the soil before erosion takes place (fertilizer losses through soil erosion are discussed in this chapter in section 4.1 of Phosphorus and Potassium Fertilizer).

A number of studies in Illinois (Aldrich, 1980) examined whether the increased use of fertilizers has increased the levels of nitrates in the rivers in that state. In general, the concentration of nitrates rarely exceeded U.S. health standards of 10 ml/l. However Illinois did experience an increase in the nitrate levels in its rivers prior to the early 1970s. Factors which were identified as contributing to the increase included: (i) the high nitrogen content of the soil, (ii) the increased acreage of row crops which results in a higher release of nitrogen from soil humus than for other crops, (iii) the rapid, increased acreage of tiled systems (which increases drainage of the soil, also increasing nitrate movement in the soil), and (iv) the rapid increase in rates of fertilizer applications. Most of these factors have leveled off and some, such as the amount of nitrogen being released from the soil, are decreasing.

This leveling off is a promising development for Illinois. However, in the remainder of the Corn Belt, these factors which contribute to increased nitrate concentrations may not have reached their peak. There are reasons to be optimistic about nitrate pollution, however. The increased price of fertilizer should result in an increase in efficiency of utilization of applied N. Since an increase in utilization efficiency would remove more of the applied N, less nitrogen from fertilizer would leach into surface and groundwaters. Another reason is that it is unlikely that fertilizer N applicationsrates will continue to increase since at higher application rates there is a leveling off of yield response (see Section 3.) In summary, it appears that the potential nitrate problem from fertilizer N (applied to corn) will become less of a threat because of efforts to increase utilization efficiency and the disincentives (economic and physical) to greatly increase the rates of application.

In some circumstances, such as in irrigation in humid areas, nitrates are more of a problem than in others. Extensive use of irrigation in humid areas increases the movement of nitrates below the root zone, encouraging a build up of nitrates. Humid area irrigation on corn has become more common since 1970 (Chapter V). Another circumstance under which nitrate concentrations tend to be higher is in tile drained areas where heavily fertilized corn has been grown for several successive years (Aldrich, 1980).

4.2 Vulnerability of the Technology

Fertilizer N production is an energy intensive process. Currently, 93 percent of all energy consumed in the manufacturing, transporting, storage, marketing and application of anhydrous ammonia is consumed during the manufacturing process (Achorn et al., 1980).

The manufacture of nitrogen utilizes natural gas both as a fuel and as a feedstock. To produce a ton of ammonia (which is 82% N) about 38 thousand cubic feet of natural gas is required, 58 percent of this is required to provide the hydrogen and the remainder provides the energy used in the production process. Forty to fifty percent of the present cost of manufacturing ammonia is the cost of natural gas. If natural gas prices rise more rapidly than the cost of other inputs, this proportion of the total costs is expected to rise, resulting in a more direct relationship between energy prices and anhydrous ammonia prices (Achorn et al., 1980).[2] Because of its dependence on natural gas, fertilizer N technology is vulnerable to possible escalating energy prices and also to natural gas shortages which could reduce the availability of nitrogen fertilizer.

5. Feasibility of the Fertilizer Nitrogen
   Technology

The present fertilizer N technology is poten-
tially vulnerable because of its dependence on
natural gas and because of potential environmental
problems. The objective in this section is to
examine whether or not fertilizer N will remain
a feasible technology for corn production.

At present, there are some promising indica-
tions that the technology can adapt to the chang-
ing economic conditions and at the same time
lessen adverse environmental consequences. There
are two basic means by which the cost of supply-
ing N to corn could be reduced: reducing the
cost of nitrogen manufacturing and reducing the
losses of nitrogen applied to corn.

Efforts to reduce the cost of manufacturing
nitrogen are currently underway; these include:
finding alternatives to natural gas (such as coal)
and the conservation of heat produced in the man-
ufacturing processes.3/

Loss of applied N is presently in the order
of 50 percent (Hardy et al., 1975). This loss
provides an indication of the scope for improve-
ments in efficiency of fertilizer use. If a re-
duction in the loss of applied N was achieved, a
cutback in the rate of application could take
place without corresponding yield reductions.

A number of management practices can increase
the efficiency of nitrogen use. Standford (1971)
has suggested three areas where improvements
could be realized: (i) more appropriate applica-
tion rates, (ii) timing of application, and
(iii) method of application.

The quantity of nitrogen added to soils very
often exceeds the level which can be utilized by
the crop. Efforts are underway to provide a
method for accurately predicting the amount of
nitrogen supplied by organic matter, thus enabling
the producer to reduce fertilizer application
rates.

The timing of application is important. Corn
requires nitrogen over the entire season. If
nitrogen is added as the crop requires it, the
loss of nitrogen due to leaching and denitrifica-
tion is minimal. A trade-off exists between the
cost (and practical problems) which would result
from continual application and the benefit from
increased utilization of nitrogen. Split appli-
cation, which refers to applying about two-thirds
of the total prior to planting and the remainder
as a side dressing, after the crop is up, provides
the most efficient match of nutrient requirements
and supply at an acceptable cost (labor and appli-
cation cost). Side dressing, however, does in-
volve the risk that wet fields will delay appli-
cation and result in the crop reaching a stage
that will not permit additional application.

If there is to be only one substantial applica-
tion, it is usually in the fall or spring. Fall
application is favorable if fall and winter tem-
peratures are low, so that freezing will prevent
leaching of nitrates (nitrification is slow below
40°F and ceases at 32°F) and soils are not sandy.
In general, in the Central Corn Belt, fall appli-
cation of nitrogen is 75-90 percent as effective
as spring applied nitrogen.

Foliar application of fertilizer is a method
which places the nutrients directly on the plant,
bypassing the soil and associated losses.
Although foliar application is an effective way to
supply nutrients, it is not economically feasible
for the application of macronutrients on corn.
To supply all required nutrients in this manner
would require numerous applications of dilute
solutions to avoid burning the crop.

Efforts to minimize losses in the soil have
been mainly through reducing water solubility or
by maintaining the nitrogen in a soluble, but
protected form. (Chemical compounds can be added---
e.g., oxamides and urea-formaldehydes--or the
nitrogen source can be coated to slow down solu-
bility (e.g., sulfur coated urea). Sulfur coated
urea is, at present, too expensive for application
to commercial corn. Adding nitrogen to the soil
in a water soluble, but protected form, is an
alternative method of conserving nitrogen. Nitri-
fication inhibitors (chemical inhibitors which
slow down the nitrification process), such as
Nitrapyrin, have been shown to slow down nitrifi-
cation. However, it has not yet been demonstrated
conclusively that these result in increased yields
or reduce the amount of nitrates in the drainage
water (Welch, 1979).

6. Alternatives to Fertilizer N Technology

6.1 Biological Nitrogen Fixation by Legumes

At present corn does not fix nitrogen to any
significant degree. Although this route of sup-
plying N to crops may have potential in the
future, at present corn must obtain its nitrogen
from exogenous sources. One source, used prior
to the introduction of commercial fertilizers,
was that of legumes in crop rotations. There are
a number of factors to consider when choosing a
legume to be grown in rotation with corn:
   (i) Legumes differ in their ability to fix
nitrogen. There are also differences within each
type of legume.
   (ii) The profitability of growing legumes
differs; the highest N_2-fixers are not the most
profitable to grow in the Corn Belt. Soybeans
are most profitable, but alfalfa fixes more
nitrogen.
   (iii) The soil nitrogen level is also a factor
to consider. Nitrogen is symbiotically fixed
only if the nitrogen level in the soil is very
low. In an experiment to determine the propor-
tion of nitrogen derived from symbiotic fixation,

the soil, and from fertilizer, Johnson et al. (as reported by Welch, 1979) found that the amount of fertilizer derived from each of these three sources was affected by the rate of N applied. These findings are summarized in Figure IV-7. From these results, it can be seen that if large amounts of nitrogen fertilizer are applied to corn in a corn-soybean rotation, any carryover nitrogen that remains in the root zone will be available for the soybeans, thereby reducing the amount of N_2-fixation taking place.

(iv) Another important consideration is the timing of the release of nitrogen. Slow release of N over the next crop year is the most valuable to the crop following in the rotation.

(v) There are gains from rotations which are not attributable to increased nitrogen, but rather to other factors such as disease and pest reduction and soil conditioning. These are discussed in the section on cropping rotation in Chapter VII.

(vi) Environmental problems (nitrate pollution) may differ with the source of nitrogen since applied N tends to add large quantities of nitrogen in short time periods, whereas legume fixation releases nitrogen slowly, thus the crop may have more opportunity to absorb it.

(vii) Different crops have different labor and machinery requirements. Crop rotations should be tailored to the individual production unit.

Figure IV-7. The Effect of the Rate of Fertilizer Nitrogen on the Percentage of Nitrogen in Soybeans Derived from Symbiotic, Soil and Fertilizer Sources.

Source: Welch (1979).

A number of complex interrelated factors must be taken into account when legumes (in rotation with corn) are used as a nitrogen source. Further research in the area of biological nitrogen fixation should result in more efficient N_2-fixing bacteria and host-bacteria combinations, increasing the attractiveness of the use of legumes as a nitrogen source (or partial nitrogen source).

6.2 Manure

Another alternate source of nutrients is animal wastes. Although the amount of nitrogen present in animal manures in the U.S. in 1979 was nearly 60 percent of that applied as commercial fertilizers (Aldrich, 1980), its potential for nutrient supply is less than this figure suggests. Manure is a highly perishable product and it loses a good deal of its nutrients if not applied to the land in a short period of time. Furthermore, only 39 percent of the manure is produced in confinement and available for spreading on crops. Because of these factors, manure as a source of nutrients offers a realistic alternative only in areas around feed lots.4/ Its potential as an alternative source of nitrogen for commercial corn production is low.

7. Managing the Technology

Fertilizer nitrogen technology has been a valuable contributor to increased yields in U.S. corn production and although it is vulnerable to natural gas prices and shortages, it can remain a feasible technology. However, to ensure this, the cost of fertilizer must be reduced, its efficiency increased, and the potential environmental problems must be avoided.

Research into these areas is required. Another area requiring further research is a method of more accurately determining the requirements of the crop and more accurate methods for testing.

Phosphorus and Potassium Fertilizer

1. Definition and Description of the Phosphorus and Potassium Fertilizer Technology

Phosphorus: For the purpose of this paper, phosphorus fertilizer refers to phosphorus compounds derived from phosphate mineral deposits. There are a number of such compounds, including superphosphate and phosphoric acid. Superphosphates and phosphoric acid are used: directly as fertilizers; to produce other phosphate fertilizers such as concentrated superphosphates; or mixed with nitrogen-containing materials to form ammonium phosphates and nitrophosphates. The most common routes to producing phosphate fertilizers are illustrated in Figure IV-8.
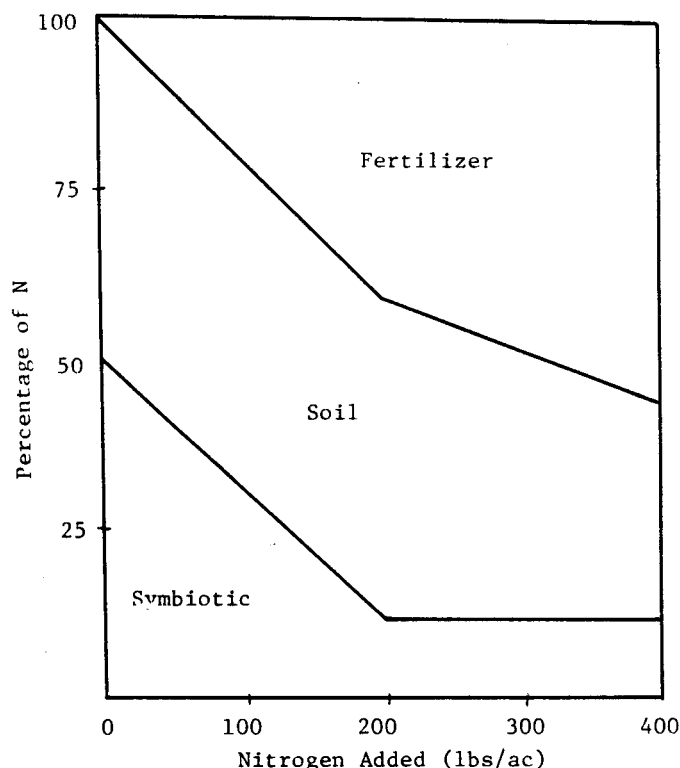
Figure IV-8. Principal Routes of Phosphate
    Processing in the U.S.

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                ┌─────────────┐
                │  PHOSPHATE  │
                │    ROCK     │
                └─────────────┘
                      │
         ┌────────────┼──────────────┐
         │            │              │
         │            │        ┌─────────────┐
         │            │        │ PHOSPHORIC  │
         │            │        │    ACID     │
         │            │        └─────────────┘
         │            │              │
    ┌─────────┐  ┌─────────┐   ┌─────────────┐
    │ORDINARY │  │ TRIPLE  │   │  AMMONIUM   │
    │SUPERPHOS│  │SUPERPHOS│   │ PHOSPHATES  │
    │PHATE    │  │PHATE    │   │             │
    └─────────┘  └─────────┘   └─────────────┘
         │            │              │
         └────────────┼──────────────┘
    ┌──────────────────────────────────────────┐
    │ MIXED FERTILIZERS OR DIRECT APPLICATION   │
    └──────────────────────────────────────────┘
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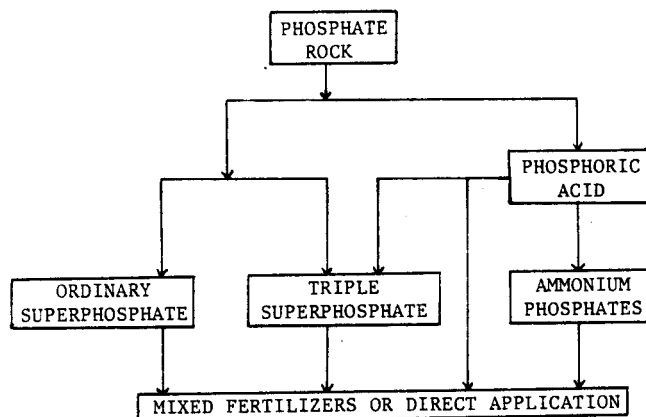
There are two types of phosphoric acid--ordinary phosphoric acid and superphosphoric acid (or polyphosphates). Ordinary phosphoric acid (H_3PO_4) is about 54 percent P_2O_5, or 23 percent P, by weight. It is used in direct application and in the production of concentrated superphosphates, ammonium phosphates, liquid fertilizers and superphosphoric acid. Superphosphoric acid ($H_4P_2O_7$) is a more concentrated form of phosphoric acid, containing between 33 to 37 percent P. It is used primarily in liquid fertilizers, where it makes higher analysis products possible.

Superphosphate (also known as monocalcium phosphate, $Ca(H_2O_4)_2$) is produced by the action of sulfuric phosphoric acid on phosphate rock. Ordinary superphosphates, containing 8.7 percent P, are produced using sulfuric acid and phosphate rock. The more concentrated form of superphosphates (known as triple superphosphates) contain between 19.6 to 20.5 percent P by weight, and are produced using phosphoric acid or sulfuric acid. (If superphosphoric acid is used, higher phosphorus contents can be achieved.) The concentrated forms of superphosphates are used in direct dry applications, mixed fertilizers, bulk blends and slurry fertilizers.

Ammonium phosphates ($NH_4H_2P_2O_4$) are produced by the ammoniation of phosphoric acid. In other words, they are phosphorus materials containing a nitrogen source such as: Ammonium sulfate to produced ammonium phosphate-sulfate (16% N and 8.7% P); anhydrous ammonia to produce ammonium phosphate (11% N and 21% P) or diammonium phosphate (18% N and 20-23% P); ammonia plus superphosphoric acid to produce ammonium poly-phosphates, these are used in liquid fertilizers and contain 10-15 percent N and 15-26.6 percent P.

Nitrophosphates are produced by using nitric acid on phosphate rock. Other forms of phosphorus fertilizers such as calcium metaphosphate ($CA(PO_3)_2$) and potassium methphosphate (KPO_3) have been manufactured but are not generally available.

Potassium (Potash): Potash fertilizer here refers to potash derived from potassium mineral deposits. The major source of potash is from underground potassium salt deposits.

There are a number of potassium fertilizer materials available. The principle source of potassium fertilizer in the U.S. is from potassium chloride (KCl), also known as muriate of potash. Potassium chloride is a water soluble, crystalline product containing between 50 to 52 percent K (60-63% K_2O). It is more concentrated than other forms of potassium fertilizers and its production cost is less. If KCl is used for liquid fertilizer, an 8 percent K solution can be achieved, or a 25 percent K suspension fertilizer can be made.

There are several other potassium fertilizer materials available. Potassium sulfate (K_2SO_4), which contains 42 to 44 percent potassium and 18 percent sulfure, it s preferable source in some crops due to its low level of chloride and the presence of sulfur. However, it is a more expensive source of K than is KCl. It is generally not used on corn unless sulfur is also required. In a similar category is potassium magnesium sulfate ($K_2SO_4 \cdot 2MgSO_4$) which contains 18 percent K, 11 percent magnesium and 22 percent sulfur. It is generally used on soils where magnesium and sulfur are deficient. Potassium nitrate (KNO_3) contains 37 percent K and 13 percent N. This fertilizer is not generally applied to corn, it is used mostly on crops which do not tolerate chloride.

2. Direction and Magnitude of Phosphorus and
   Potassium Fertilizer Technology

2.1 Historical Development

Phosphorus: Phosphate fertilizer derived from phosphate rock became available about 1840. Prior to that time the phosphorus used for fertilizer was from other sources. In Europe, ground bones were used and around 1830 sulfuric acid was used to treat the bone material resulting in a slurry which was applied as a fertilizer.

Phosphate fertilizer which was developed about 1840 was produced by treating phosphate rock with sulfuric acid. This fertilizer was known as superphosphate. The first successful commercial production of superphosphates began in England in 1842.

The development of higher analysis materials is associated with phosphoric acid. Phosphoric acid was first commercially produced in the 1870s in Germany (International Fertilizer Development Center, 1979) from phosphate rock. The phosphoric acid produced was concentrated through evaporation. Phosphoric acid has been used in the fertilizer industry to produce triple superphosphates from the action of phosphoric acid on phosphate rock. These concentrated superphosphates became popular in the 1950s.

Phosphoric acid is also used in the production of mixed fertilizers such as ammonium phosphates. Although ammonium phosphate based fertilizers were produced as early as 1917 in the U.S., it was only during the 1960s that this fertilizer became prominent.

Potassium: Wood ashes, sugar beet wastes and salt peter were the early sources of potassium. Potash (potassium carbonate) was made by leaching wood ashes and concentrating the product; this process was patented in 1790 in the U.S. (Follett et al., 1981). Potassium salt deposits were dis-covered in Germany in 1839. This source supplied the world until the first world war. During the war the U.S. obtained potassium from other sources, including salt lakes. The first large scale muriate of potash mining in the U.S. took place in California in 1916. Other deposits were discovered later in New Mexico.

2.2 Trend in Application

The application of both phosphorus and potas-sium fertilizer to corn has increased in the past forty-five years. This increase is due to both the increased rates of application on those acreages to which fertilizer is applied and the increase in acreage to which fertilizer is applied. Table IV-2 illustrates the growth in phosphorus and potassium fertilizer used on corn. In 1947, 44 percent of the corn acreage was fer-tilized at the rate of 23 pounds per acre of P_2O_5 and 12 pounds of K_2O. By 1980, 87 percent of the corn acreage had P_2O_5 applied at the rate of 66 pounds per acre. Potassium fertilizer was applied to 81 percent of the corn acreage at a rate of 86 pounds per acre.

3. Direct Effects of the Technology

3.1 Yield Response and Aggregate Production Capacity

Phosphorus: Phosphorus is an essential element for the growth of corn, it plays an important role in the transferring of energy within the plant and it is part of the structure of the many or-ganic compounds found in corn. High levels of P in the soil are necessary for high corn yields.[5]

Table IV-2. Estimated Use of Phosphorus and Potassium Fertilizer on Corn and the Percent of Harvested Acres Fertilized for Selected Years, 1947-80

Year	Average Application Rate on Acreage Receiving P_2O_5 (lbs/ac)	K_2O	% of Harvested Acres Receiving Fertilizer P_2O_5 (%)	K_2O
1947	23	12	44	44
1950	23	15	48	48
1954	28	25	60	60
1959	37	37	60	60
1965	50	48	82	77
1970	71	72	90	85
1975	58	67	86	82
1980	66	86	87	81

Source: USDA, Fertilizer Used on Crops and Pasture in the United States, Stat. Bull. No. 216, 1957; Commercial Fertilizer Used on Crops and Pasture in the United States, Stat. Bull. No. 343, 1964; and Crop Pro-duction, ESS, Crop Reporting Board, various years.

In the production of 150 bushels of corn per acre approximately 52 lbs of P are taken up by the crop (Fertilizer Institute, 1976).

Phosphorus behaves very differently from nitro-gen, in that it does not move about in the soil. When phosphorus is applied it becomes "fixed" (undergoes chemical reactions which essentially binds it to the soil particles) and does not leach out of the soil as nitrogen does. In any given year, only 15-20 percent of the P applied as fertilizer is utilized by corn. Most of the applied phosphorus forms a reserve stored in the soil.

Some of the factors influencing the availabil-ity of phosphorus to the crop are: soil temper-ature; the root system of the crop; the nature of the subsoil; the soil organic matter; and the pH of the soil. Soil temperature is important in determining the availability of P to corn since higher temperatures bring about the release of phosphorus from organic matter in the soil. In the spring when soil temperatures are low, there is much less phosphorus available in the soil. Phosphorus deficiencies are most likely to affect corn prior to the plants reaching the height of 2 feet. To avoid deficiencies in the spring, phosphorus can be applied near the corn row. It is usually applied with ammonia (and also with

potassium); the ammonia enhances the plant's ability to take up phosphorus.

The root system of a crop and the nature of the subsoil are important in that the more area from which the roots are absorbing P, the more P will be available to the crop. This is important when considering the manner in which the fertilizer is applied. For example, in the early spring if the soil temperature is low (Northern Corn Belt) the phosphorus should be applied near the seed so that the young corn plant can obtain phosphorus given the seedlings very limited root system.

Potassium: Potassium is an essential nutrient required for the growth and development of corn. It has an important role in the production of corn: in photosynthesis; plant strength and resistance to lodging; the reduction of water loss in transpiration; root and brace root development; and also in the quality of the end product.

Potassium's contribution to increased corn yields has been important. Its role in increasing plant strength, including stalk strength, has made an important contribution to yield by reducing the losses due to stalk rot and lodging. Also it has increased the drought tolerance of crops—an important yield increasing factor. Potassium contributes both to a reduction in water lost through transpiration and to the development of an extensive root system which makes the crop more drought resistant.

The interrelationship between nitrogen and potassium is important when considering nitrogen's contribution to yield. Corn crops with inadequate potassium tend to suffer from lodging. If nitrogen is added to the crop to increase yields, lodging may be severe, unless potassium is also added.

In periods of rapid growth, corn can require up to 3 lbs/ac/day of potassium. Because corn can absorb large quantities of potassium during these periods, the supply of potassium to the roots could become the principle limiting factor during these periods (Follet et al., 1981). Corn requires most of its potassium between its 25th to 50th day after emergence.

To provide adequate potassium, the level of potassium in the soil is built up to a high level. It can be maintained at this level by replacing the amount removed by the crop each year.6/ One bushel of corn grain removes .22 lbs of potassium (Aldrich et al., 1978). Based on this, the average amount of potassium removed from the soil by corn in 1980 was 20 lbs/ac. The amount added as fertilizer that same year averaged 57.8 lbs/ac of corn.7/

3.2 Costs and Profitability

In 1980, the average fertilizer expense for corn production was $47.66/ac, representing 35 percent of the variable costs of corn production (USDA, 1981). Forty-three percent of the fertilizer cost was for nitrogen, 37 percent for phosphorus and 20 percent for potassium. Figure IV-9 illustrates the price of fertilizer relative to other purchased inputs and relative to the price of corn from 1945 to 1980. Although the price of potassium relative to other purchased inputs generally declined over this period, the phosphorus price relative to other purchased inputs showed no clear pattern.

The price ratios of corn to phosphorus and corn to potassium are also illustrated in Figure IV-9. These ratios indicate the number of pounds of fertilizer which can be purchased with one

Figure IV-9. Price of Other Purchased Inputs (OPI) and Corn Relative to the Prices of Phosphorus and Potassium, 1945-80.
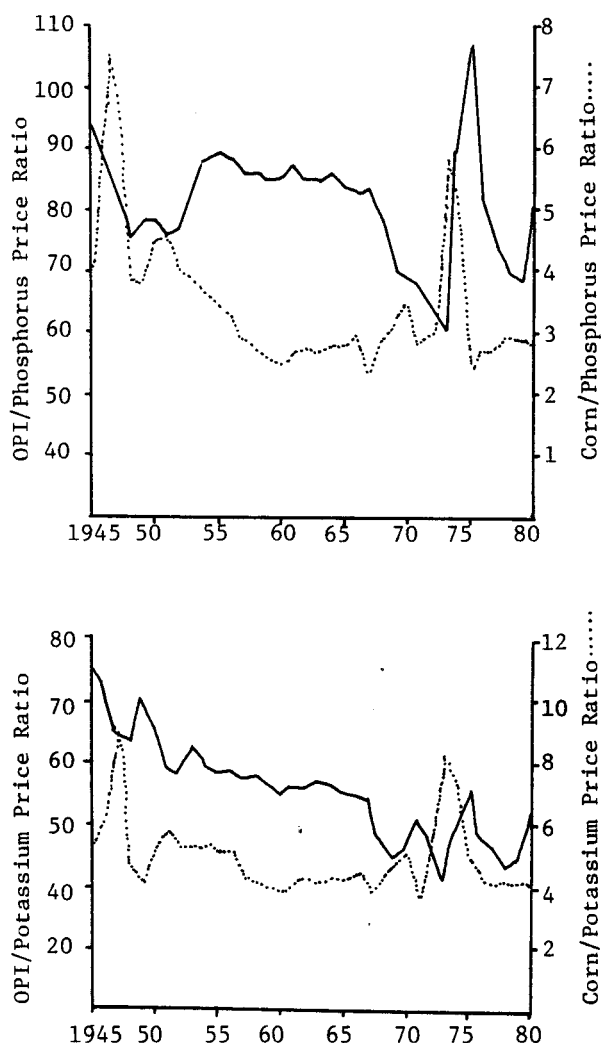
Source: Appendix Tables IV-4 and IV-5.

bushel of corn. A higher ratio is more desirable for producers. For both phosphorus and potassium this ratio has been fairly stable with the exception of two periods when corn prices rose sharply. (Although for phosphorus the general trend from 1945 to 1960 may have been slightly downward.)

The ratios of land price to phosphorus and potassium price are shown in Table IV-3. The price of land has been rising more rapidly than the price of these fertilizers. Since fertilizers are land augmenting technology, this price incentive has been an important factor influencing the rate of fertilizer application.

Table IV-3. Ratio of Land Prices to Phosphorus and Potassium Prices, 1945-80

| | Price Index of Land (1967 = 100) | |
| | Relative to | |
	Price of P_2O_5 [a]	Price of K_2O [b]
1945-49	62.6	69.0
1950-54	66.6	87.6
1955-59	75.8	113.8
1960-64	92.2	140.8
1965-69	125.6	193.6
1970-74	155.6	228.0
1975-78	161.0	268.5

[a] Price of P_2O_5 is the price of 44-46% superphosphate.

[b] Price of K_2O is the price of muriate of potash.

Source: Appendix Table IV-3.

4. Other Aspects of Phosphorus and Potassium Fertilizer Technology

4.1 Environmental Impacts

Like nitrogen, phosphorus is a potential environmental contaminant. Although phosphorus is normally present in lakes and streams from sources such as rainfall and the soil, the quantity is generally limited, thus limiting the growth of algae. The addition of phosphorus to lakes and streams through sources such as fertilizers, feedlots, and urban and industrial wastes, increases the supply of phosphorus, thus encouraging algae growth. It is this additional algae growth which may lead to the eutrophication of the water.

Since phosphorus is relatively immobile in the soil (because it attaches to soil particles), the primary source of phosphorus fertilizer as a contaminant in water is from soil erosion and surface runoff. In soil erosion the phosphorus

attaches to the soil (it also dissolves in the runoff water) and is carried with the soil particles to surface waters. Phosphorus fertilizer lost through soil erosion has been measured up to a level of 60-63 percent of the total amount applied (Holt, 1979). Since most phosphorus originating from fertilizer enters the water systems through surface water drainage and soil erosion, reducing the amount of soil erosion and runoff would also reduce the level of phosphorus in surface and ground water. This can be accomplished, to some extent, through terracing and tillage practices.

To illustrate the effect of various soil management systems on nutrient loss, Holt et al. (1977) estimated the losses of nitrogen and phosphorus on Barnes Loam with 6 percent slopes. The results are shown in Table IV-4. Nutrient losses can be reduced by soil conservation practices which reduce soil erosion.

Table IV-4. Phosphorus and Nitrogen Losses Associated with Various Soil Management Practices

| Conservation Practice | Annual Loss (lbs/ac) | |
	P	N
Conventional Planting	28.5	117.9
Contour Planting	14.2	58.8
Contour Terraces	8.0	33.3
Reduced Tillage (Conventional Planting)		
2500 lbs/ac residue	21.8	90.4
4500 lbs/ac residue	9.6	39.5

By reducing runoff and by forcing the water to percolate through the soil, phosphorus levels in water draining from agricultural land are reduced since, under most conditions, phosphorus forms fairly stable bonds with the soil particles. This would reduce the potential for phosphorus problems, however with a practice such as reduced tillage, fertilizer is not incorporated into the soil. Therefore the runoff water will contain a higher concentration of phosphorus (although the amount of runoff will be less due to the trash covering). Therefore the net effect is not clear. Increased percolation may exacerbate the problem for nitrates since more movement of water through the soil would also increase nitrate movement.

4.2 Vulnerability

In contrast to nitrogen fertilizer, where real prices are expected to increase, phosphorus and potassium fertilizer are not particularly vulnerable technologies. This does not imply that the

prices of these fertilizers will not increase. However, there is no reason to believe that they will increase more rapidly than other inputs.

The potential environmental problems associated with phosphorus fertilizer are likely to become less of a threat due to more efficient utilization by the crop. As the profit margin of corn (both per acre and per bushel) has narrowed, producers have an increased incentive to cut costs. One cost saving technique is for each producer to accurately estimate the required fertilizer and to apply it in a manner which increases the likelihood of its being utilized by the crop. The increased efficiency of phosphorus utilization by the crop reduces the probability of fertilizer phosphorus becoming an environmental problem (and should lessen the problem in areas where it presently is a problem).

Cutbacks in the use of phosphorus and potassium fertilizer due to increasing costs may occur. However, since both of these nutrients have been built up in the soil to a great extent during the past, there is scope for reduction in application rates, by applying only that quantity of fertilizer required for replacing those nutrients removed by the crop.

5. Feasibility of the Phosphorus and Potassium Fertilizer Technology

The phosphorus and potassium technologies should remain feasible. Their real prices are not expected to increase and more efficient utilization of P and K by the corn crop should also keep the costs of these technologies down, as well as reducing environmental problems.

6. Alternatives to Phosphorus and Potassium Fertilizer Technology

An alternative to phosphorus and potassium fertilizer technology is to supply the nutrients from organic wastes such as manure. This alternative is discussed in this Chapter under Section 6 in Nitrogen Fertilizer (also see footnote 4).

7. Managing the Phosphorus and Potassium Fertilizer Technology

Phosphorus and potassium fertilizer technologies are widely adopted, and making major contributions to corn production. Fertilizer technology now requires fine tuning. Part of this fine tuning should be: more accurate testing to indicate required levels of fertilizer application; optimal methods and timing of application; and optimal management practices (e.g., timing of operations, planting dates, water management) which allow the crop to reach its yield potential.

In relation to environmental problems (potential and existing) there are gaps in the

information which require further research (e.g., relating different management practices to levels of phosphorus runoff). Regulation to control phosphorus levels in ground and surface water originating from fertilizers does not appear to be necessary. It appears that, to a large extent, economic forces exist which will encourage the adoption of reduced tillage in many of the areas where soil loss (and phosphorus loss) is a problem. In other areas, where soil erosion is occurring but there is not clear short term economic incentive to adopt conservation practices, added economic incentives and/or regulation may be necessary (see Chapter VII). Also, phosphorus losses to the environment are expected to be reduced as the efficiency of crop utilization is increased and cost-induced conservation becomes more entrenched in management practices.

Footnotes

1/On the average, the BTU requirements for the production of: anhydrous ammonia is 42 million per ton of N; triple superphosphate is 8.15 million per ton of P_2O_5; and potash is 1.9 million per ton of K (Achorn et al., 1980)

2/The rise in real energy prices will increase the proportion of the total cost attributable to the cost of energy. Achorn et al. (1980) have estimated the effect of rising natural gas prices on the proportion of total costs of ammonia production which will be due to natural gas.

Cost of Natural Gas ($/1000 ft^3)	% of Total Cost of Manufacturing NH$_3$, Attributable to Natural Gas
0.30	27.5
0.60	42.3
0.90	53.0
1.80	68.6
2.70	77.2
3.00	79.0

3/An example of this is the pipe cross reactor, which utilizes heat released from the reaction of ammonia and acids (phoric, phosphoric and sulfuric) to replace heat normally supplied by natural gas to concentrate fluids and dry granules.

4/A ton of fresh cattle manure with a moderate amount of bedding will contain 10 lbs of nitrogen, 2.2 lbs of phosphorus, 8.3 lbs of potassium and small amounts of micronutrients (Aldrich, 1978). These nutrients become available over a number of years. One study indicated that a ton of manure could replace 3.6 lbs of fertilizer nitrogen the first year (Aldrich, 1978), and 1.3 lbs of phosphorus and 5.2 lbs of potassium.

5/Although high levels of phosphorus are required, these levels are considerably less than for nitrogen and potassium on a per pound basis.

6/In fact it is only necessary to add slightly less than the amount removed by the crop, since: some potassium will become available from the unavailable forms present in the soil; potassium does not leach (except on sandy soils); most of the potassium added will not become tied up in an unavailable form, and corn removes only that amount of potassium required.

7/In 1980 the amount of potassium removed from the soil by corn grain was 91 bu/ac x .22 lb/bu = 20 lbs/ac. The application rate was 71 lbs of K/ac on 81 percent of the total corn acreage, or 71 x .81 = 57.8 lbs K/ac.

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Appendix

Appendix Table IV-1. Fertilizer Applied to Corn in the U.S., 1945-80

	Nitrogen	Phosphorus (P_2O_5)	Potassium (K_2O)
	(millions of pounds)		
1945	187		
1946	266		
1947	325	746	390
1948	422	812	459
1949	509	833	507
1950	521	799	521
1951	648	871	617
1952	784	962	770
1953	990	1,088	927
1954	1,099	1,154	1,030
1955	1,233	1,233	1,073
1956	1,233	1,246	1,110
1957	1,325	1,287	1,110
1958	1,460	1,372	1,200
1959	1,947	1,601	1,387
1960	2,142	1,736	1,479
1961	2,016	1,505	1,244
1962	2,228	1,582	1,283
1963	2,605	1,752	1,409
1964	2,710	1,168	1,393
1965	3,539	2,267	2,044
1966	4,332	2,794	2,599
1967	5,220	3,168	2,986
1968	5,320	3,190	3,058
1969	5,450	3,034	2,994
1970	6,016	3,661	3,507
1971	6,474	3,497	3,364
1972	6,325	3,415	3,412
1973	6,583	3,418	3,527
1974	6,344	3,528	3,962
1975	6,625	3,372	3,714
1976	8,794	4,311	4,685
1977	8,806	4,284	4,814
1978	8,628	4,254	4,659
1979	9,412	4,446	4,987
1980	9,137	4,197	5,092

Source: Estimated using Average Application Rate from USDA, Fertilizer on Crops and Pasture in the United States, Stat. Bull. No. 216, 1957, Commercial Fertilizer Used on Crops and Pasture in the United States, Stat. Bull. No. 343, 1964; Crop Production, ESS, Crop Reporting Board, various years, and data on Corn Acreage in Table II-1.

Appendix Table IV-2. Price of Nitrogen, Phosphorus and Potassium Fertilizer, U.S., 1945-80 (Nominal Price)

	Price of Fertilizer[a]		
	Nitrogen[b]	Phosphorus	Potassium
	($/ton)		
1945		58	47
1946		58	48
1947		64	51
1948		65	56
1949		65	59
1950		67	57
1951		72	57
1952		74	57
1953	178	76	56
1954	176	78	53
1955	166	78	52
1956	161	77	51
1957	152	77	52
1958	150	79	53
1959	147	79	52
1960	141	79	51
1961	142	81	52
1962	134	80	53
1963	128	81	54
1964	126	81	54
1965	122	81	54
1966	119	83	55
1967	113	84	54
1968	91	78	49
1969	76	74	46
1970	75	75	47
1971	79	77	51
1972	80	78	49
1973	87	88	61
1974	183	150	81
1975	265	214	102
1976	191	158	96
1977	188	148	97
1978	171	153	96
1979	188	172	112
1980	229	203	135

Source: USDA, Agricultural Prices. Statistical Reporting Service, various issues.

[a] Fertilizer prices are: for anhydrous ammonia for nitrogen, 44-46% superphosphate for phosphate, and muriate of potash for potassium.

[b] Anhydrous prices are available only from 1953 to present.

Appendix Table IV-3. Price of Farm Real Estate Values Relative to the Price of Fertilizer.

	Index of Farm Real Estate Values (1967=100)[a]	Farm Real Estate Values Relative to Fertilizer Price		
		Nitrogen[b]	Phosphorus[b]	Potassium[b]
1945	29		.50	.62
1946	33		.57	.69
1947	37		.58	.72
1948	40		.83	.71
1949	42		.65	.71
1950	41		.61	.72
1951	47		.65	.82
1952	53		.72	.93
1953	53	.30	.70	.95
1954	51	.29	.65	.96
1955	53	.32	.68	1.02
1956	56	.35	.73	1.10
1957	59	.39	.77	1.13
1958	62	.41	.78	1.17
1959	66	.45	.83	1.27
1960	69	.50	.87	1.35
1961	70	.49	.86	1.35
1962	74	.55	.92	1.40
1963	77	.60	.95	1.42
1964	82	.65	1.01	1.52
1965	87	.71	1.07	1.61
1966	93	.78	1.12	1.69
1967	100	.88	1.19	1.85
1968	107	1.17	1.37	2.18
1969	113	1.49	1.53	2.35
1970	117	1.56	1.56	2.29
1971	122	1.54	1.58	2.10
1972	132	1.65	1.69	2.24
1973	150	1.72	1.70	2.46
1974	187	1.02	1.25	2.31
1975	213	.80	.99	2.09
1976	242	1.27	1.53	2.52
1977	283	1.50	1.91	2.92
1978	308	1.80	2.01	3.21
1979	351	1.87	2.04	3.13
1980	401	1.53	1.98	2.97

[a] Farm Real Estate Value Index from various issues of Agricultural Statistics.

[b] Farm real estate prices relative to fertilizer prices are calculated by dividing the index in column 2 by the fertilizer prices for anhydrous ammonia, 44-46% superphosphate, and muriate of potash from Appendix Table IV-2.

Appendix Table IV-4. Price of Other Purchased Inputs Relative to the Price of Fertilizer, 1945-80.

	Index of Prices Paid for Purchased Inputs [a] 1967=100	Price of Other Purchased Inputs Relative to Fertilizer		
		Nitrogen	Phosphorus [b]	Potassium [b]
1945	61		95	77
1946	66		88	73
1947	78		82	65
1948	87		75	64
1949	83		78	71
1950	86		78	66
1951	95		76	60
1952	96		77	59
1953	90	198	84	62
1954	89	198	88	60
1955	88	189	89	59
1956	87	185	88	59
1957	90	169	86	58
1958	92	163	86	58
1959	93	158	85	56
1960	93	152	85	55
1961	93	153	87	56
1962	94	142	85	56
1963	95	135	85	57
1964	94	134	86	57
1965	96	127	84	56
1966	100	119	83	55
1967	100	113	84	54
1968	100	91	78	49
1969	104	73	71	46
1970	108	69	69	47
1971	113	70	68	51
1972	121	66	64	49
1973	146	60	60	42
1974	166	110	90	49
1975	182	146	118	56
1976	193	99	82	50
1977	200	94	74	48
1978	217	79	70	44
1979	248	76	69	45
1980	260	88	78	52

[a] USDA, Agricultural Prices. Statistical Reporting Service, various years.

[b] Other purchased inputs relative to fertilizer prices are calculated by dividing column 2 by price per pound of fertilizer from Appendix Table IV-3.

Appendix Table IV-5. Price of Corn Relative to the Price of Fertilizer, 1945-80.

	Corn Price ($/bu)	Corn Price Relative to Fertilizer Price [a]		
		Nitrogen	Phosphorus	Potassium
1945	1.23		42	52
1946	1.53		52	64
1947	2.16		67	85
1948	1.28		39	47
1949	1.24		38	42
1950	1.52		45	53
1951	1.66		46	58
1952	1.52		41	53
1953	1.48	17	39	53
1954	1.43	16	37	54
1955	1.35	16	35	52
1956	1.29	16	33	51
1957	1.11	15	29	43
1958	1.12	15	28	42
1959	1.05	14	26	40
1960	1.00	14	25	39
1961	1.10	15	27	42
1962	1.12	17	28	42
1963	1.11	17	27	41
1964	1.17	19	28	43
1965	1.16	19	28	43
1966	1.24	21	30	45
1967	1.03	18	24	38
1968	1.08	24	28	44
1969	1.16	31	31	48
1970	1.33	35	35	52
1971	1.08	27	28	37
1972	1.57	20	40	53
1973	2.55	29	58	84
1974	3.02	33	40	75
1975	2.54	19	24	50
1976	2.15	22	27	45
1977	2.02	21	27	42
1978	2.25	26	29	47
1979	2.41	26	28	43
1980	2.80	24	27	41

Source: USDA, Agricultural Prices. Statistical Reporting Service, various issues.

[a] Corn prices relative to fertilizer prices are calculated by dividing corn price by price per pound of fertilizer from Appendix Table IV-2.

Appendix IV-A. Marginal Product of Nitrogen

Two sets of data are presented in Appendix
Table IV-6 representing the marginal products of
nitrogen. The data in column 2 represents an
average of a number of agronomic experiments con-
ducted at various locations in the Corn Belt.
The data in column 3 represents the MPP_n derived
from the equation fitted to the historical data
(presented in the appendix to Chapter III). As
expected, marginal products calculated from the
historical (farm level) data are lower than those
from the experimental agronomic data. After
allowing for this difference, there is a reasonable
correspondence between the MPP_n derived from the
alternative sources.

Appendix Table IV-6. Marginal Product of Nitrogen,
    Experimental and Time Series Data

| Nitrogen Level (lbs/ac) | MPP_n (bu/lb) | |
	Experimental Agronomic Data	Historical Farm Data
15	.93	1.05
40	.61	.40
75	.39	.21
100	.39	.16
130	.28	.12
150	.24	.11
200	.07	.08

Source: Historical Farm Data is from the equation
         reported in Chapter III, Experimental
         Agronomic Data is derived from Russell
         and Balko (1980), Illinois Cooperative
         Extension Service (1974), Aldrich (1980),
         Welch (1979), Follet et al. (1981),
         Debertin and Pagoulatos (1980), Fenster
         et al. (1978).

Soil moisture levels are important determinants of corn yields. Together with other climatic factors, soil fertility levels, plant populations, and the genetic traits of corn, rhey set the effective yield limits for this crop. Although soil moisture levels during the June-July flowering period are of key importance in determining corn yields, excessive wetness or dryness of soils at other times can also impact heavily on timeliness of planting and harvesting, on the stand of seedlings and on the quantity and quality of grain harvested.

A number of factors affect soil moisture conditions, including the amount and seasonal distribution of natural moisture (average annual precipitation rates are shown in Figure V-1 for broad geographical areas of the U.S.), evapotranspiration rates, other climatic factors, tillage practices, crop rotations, soil characteristics, and others. The two technologies which impact most on soil moisture are irrigation and drainage. Weather modification is possibly a technology of future relevance, although it has little application potential prior to 2000. We do assess it briefly, however, in order to reach this conclusion.

Figure V-1. Average Annual Precipitation in the United States.

Explanation
inches
0-10
10-20
20-30
30-40
40-60
60-100
Over 100
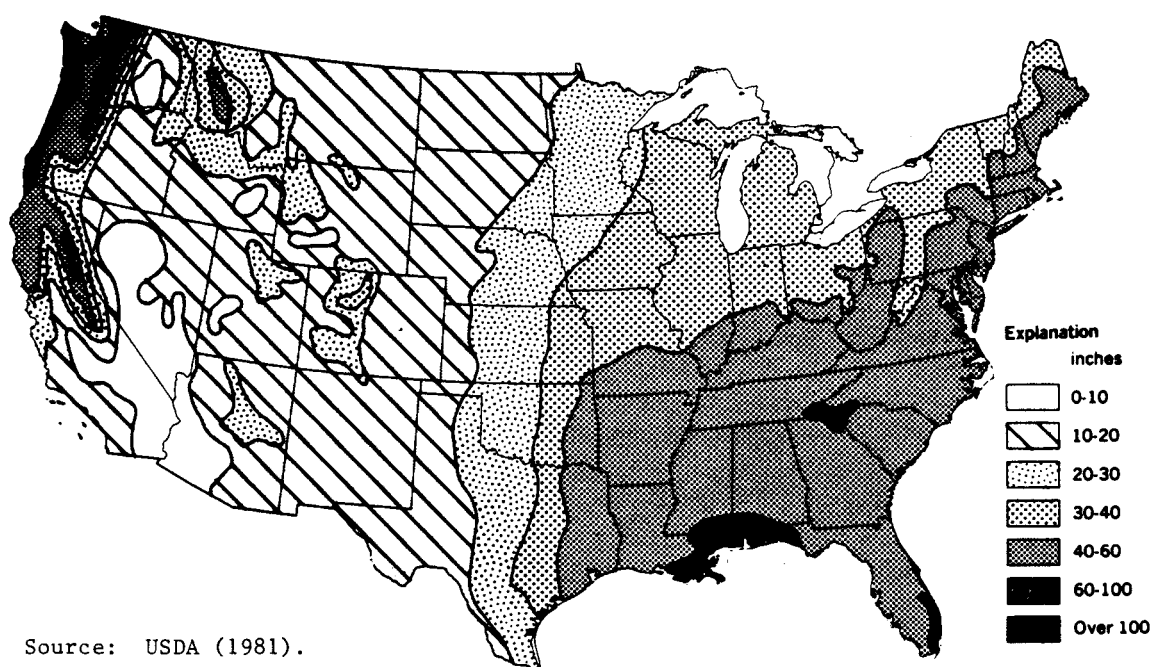
Source: USDA (1981).

Irrigation Technology

1. Definition and Description of the Irrigation Technology

Irrigation is the augmentation of natural water supplies for crop production via the diversion to the soil of additional water from surface or sub-surface sources. "Sprinkler" irrigation refers to any one of several systems by which supplemental water is supplied for crop production via mechanisms other than gravity flow. There are numerous water sources and distribution systems, but all sprinkler systems require some external power source to distribute water under pressure.

Eidman (1978, 1981) lists the following seven sprinkler irrigation distribution systems as those being used significantly for corn irrigation by farmers:
(i) center pivot;
(ii) traveling gun;
(iii) traveling boom;
(iv) boom;
(v) volume gun;
(vi) side-roll tow; and
(vii) hand move.

Primarily because of its low labor requirements (.065 hours per acre per irrigation – one-third or less of any other sprinkler system), the center pivot system is by far the most prevalent. Center pivot systems come in many sizes from "one-tower" to those of one-half mile in length. The most common systems operate by traveling continuously in a circle of one-fourth mile radius, irrigating an area of about 130 acres. Use of the traveling gun or other mobile systems is necessary for irrigating smaller and/or irregular fields. The amount of water applied per irrigation and the number of irrigations per year vary with soil type (primarily soil water-holding capacity), location and season.

"Gravity flow" irrigation systems are also important, particularly in some parts of Nebraska, in the High Plains of Kansas and in the Southern Plains, where level land and fine to medium textured soils permit their use. The "Gated Pipe from Source" is a commonly used gravity distribution system. Another type is the open ditch, siphon tube. With gravity systems both the investment costs and the energy requirements are usually much less than those of the center pivot system, but labor requirements are increased for ditching, moving siphons, etc. On coarser textured soils, the water losses via seepage and percolation can be excessively high for gravity flow irrigation. As a consequence of these labor and seepage considerations, gravity flow technology uses less frequent irrigations with larger water applications per irrigation than for sprinkler irrigation.

2. Direction and Magnitude of the Irrigation Technology

Irrigation of corn in the U.S. has increased dramatically in recent years, reaching an estimated total of 11.5 million acres in 1980.[1] The 13 leading states in terms of irrigated corn production are shown in Table V-1. Nebraska is the leader with almost 5 million acres.

Table V-1. Estimated Acreage of Corn Irrigated in Selected States[a], 1980

State	Irrigated Corn Acreage[b]
	(thousand acres)
California	440
Colorado	1,110
Georgia	390
Idaho	121
Iowa	185
Kansas	1,209
Michigan	156
Minnesota	355
Missouri	148
Nebraska	4,950
South Dakota	215
Texas	984
Washington	155
Total (13 States)	10,418

[a] Includes those states reporting 100,000 acres or more of irrigated corn in 1980.

[b] The 1977 National Resource Inventory conducted by SCS placed the total U.S. irrigated acreage at 58 million acres compared to 61 million acres estimated in the Irrigation Journal Survey for 1980. Thus, the Irrigation Survey data are probably reasonably accurate for the purposes of our use.

Source: Irrigation Journal, 1980 Irrigation Survey.

The development of lightweight aluminum tubing in the 1940s and the subsequent development of the center pivot irrigation technology in the early 1950s were the events which virtually revolutionized sprinkler irrigation. Use of the center pivot system expanded rapidly through the 1960s, and even moreso in the 1970s. Location of irrigated land in the U.S. (1977) is shown in Figure V-2. However, widespread drought in the mid-1970s

(particularly 1974-76) has spurred the rate of corn irrigation expansion substantially even since 1977, particularly in the period 1977-79.

Much of the irrigation of corn in areas adjacent to the 5-state Corn Belt (particularly in Nebraska, Kansas, Southern Minnesota, and Southeastern South Dakota) is now of the center pivot, sprinkler type. Though a high proportion of total irrigated crop acreage in the U.S. (more than two-thirds in 1980) is still irrigated by gravity flow systems, the bulk of the gravity irrigation (particularly that using surface water sources) occurs where corn is not a major crop (e.g., Western states, the Mississippi Delta and in some areas of Texas).

Between 1970-80, total sprinkler irrigated acreage in the U.S. appears to have more than doubled, from 9.8 to 20.0 million acres (Irrigation Journal: 1970 and 1980 Irrigation Surveys). During the period 1974-77 alone, the acreage irrigated from on-farm pumped water increased by 5.2 million acres; 2.4 million acres of this increase came in Nebraska and Kansas, mostly for corn. And, center pivot systems distributed the water on almost half of these added acres (Sloggett, 1979). Thus, the recent push in technology for corn irrigation has mainly used water pumped from underground aquifers and distributed by sprinkler systems. Moreover, it appears likely that a large expansion can be expected over the next two decades in the corn acreage irrigated by central pivot technology in Nebraska and in several other states (see section 3.2.2).

Much of the incentive for irrigation expansion in the 1970s was associated with the profitability of using supplemental irrigation to boost corn yields in Plains States to the west of the Central Corn Belt. Two reasons stand out. First, over much of this region, natural rainfall constrains corn yields both because of its limited total supply and its variability. Second, with modern production technology, corn yields in this area have been highly responsive to added soil moisture.

Figure V-2. Irrigated Acreage in the United States, 1977. One Dot Equals 8,000 Acres Where Irrigation Facilities are in Place.
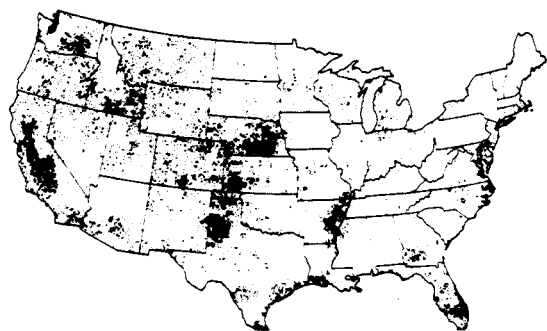
Source: USDA (1981).

Sprinkler systems can be used to irrigate undulating and slightly rolling land without incurring the prohibitively high costs of land leveling. Also, the center pivot technology has supplied labor efficiency by eliminating the high labor requirements involved in moving pipelines. Coupled with free water and low energy and nitrogen prices in the 1960s and 1970s, irrigation became a cost-efficient technology for many corn producers.

A number of conservation and efficiency adjustments can be made to improve the current performance of corn irrigation systems. These will be discussed in section 7. Once these adjustments are made, the future direction and magnitude of sprinkler irrigation technology will depend heavily on six factors: corn yield response to irrigation water, soil water-holding capacity, water availability and the prices of energy, nitrogen and corn.

3. Direct Effects of the Irrigation Technology

No two corn producers encounter identical cost or benefit impacts from acquiring and operating irrigation systems. Yet, most producer decisions are based on a common set of factors which include:
   (i) yield response to irrigation - including impact of irrigation on yield variability;
   (ii) capital investment requirements and operating costs of the irrigation system;
   (iii) availability of reliable water supplies;
   (iv) total benefit-cost relationships for irrigation related expenditures, and
   (v) alternative investment opportunities both in farming and outside.

Currently, because of high interest rates, coupled with high initial investment costs, the benefit-cost evaluations which farmers make for irrigation technology include both (i) the present value of future income streams generated by installation of the technology and (ii) the technology's cash flow performance.

3.1 Yield Response and Production Capacity

3.1.1 Yield Response

Corn yield response to irrigation is highest, ceteris paribus, where natural rainfall is in short supply and the moisture retention capacity of the soil is low. This explains the high incidence of irrigation on coarse textured (mainly glacial outwash) soils in the northern and western fringes of the Corn Belt. On some sandy soils in the central zone of Minnesota, for example, farm-level dryland corn grain yields are estimated at 50 bu/ac, whereas irrigated corn yields, with additional nitrogen fertilizer and with use of chemical pesticides, are estimated at 160 bu/ac (Eidman and Greene, 1978). Irrigated corn yields

on sandy and sandy loam soils in Michigan of
160-170 bu/ac compare with dryland yields of
40-70 bu/ac (Lucas and Vitosh, 1978). Actual farm
level yields for South Central Nebraska are about
55 bu/ac for dryland corn and 120 bu/ac for irri-
gated corn (FEDS, 1980). Similar dryland-irriga-
tion yield differentials also exist in some areas
of the Southeast. Thus, yield responses of 60-120
bu/ac from irrigation are being widely achieved.
This is due in part to the development of improved
hybrid varieties, including short-season varie-
ties, which have produced high yield responses to
irrigation on some soils where dryland corn yields
have, historically, been very low.

Yield response to irrigation has not, however,
been nearly as great on the fine and medium tex-
tured soils of the Corn Belt. This is true partly
because these soils have greater water holding
capacity than do the coarser soils. Also, the
annual average precipitation of 28 inches or more
exceeds that of areas to the west (Figure V-1).
Eidman and Wilson (1981) report corn yield res-
ponses to irrigation in the 40-50 bu/ac range for
finer textured Corn Belt-type soils in South
Central and Southwestern Minnesota.2/ Lucas and
Vitosh (1977) report a 50-60 bu/ac yield response
from irrigation on heavier loam soils in Southern
Michigan. And, although there is a good deal of
inter-year and inter-area variability within the
Corn Belt proper, an average yield response to
irrigation of 30-60 bu/ac appears typical for a
large acreage of fine and medium textured soils.

3.1.2 Increased Production Capacity

Yield data reported from the several major
irrigated production areas were acreage weighted
for both irrigation and dryland corn production.
These data indicate that irrigated yields exceeded
non-irrigated yields by an average of about 65
bu/ac (estimated mainly from FEDS, 1980). Multi-
plying this yield differential by an estimated
11.3 million acres of irrigated corn for grain
(1980 basis) indicates that irrigation technology
has already increased annual U.S. corn production
capacity by an amount of more than 700 million
bushels.

In addition to increasing production capacity,
irrigation technology reduces the year-to-year
variability in corn production. An accurate esti-
mate of reduced production variance due to irri-
gation is not feasible because some irrigated
corn is now grown in areas where dryland corn was
not previously an important crop. In addition,
there have been other important factors affecting
corn yields since the pre-irrigation period.
Nevertheless, it appears that the reduction in
annual production variance from irrigation is in
the range of 300-400 million bushels. This is an
important reduction in production variance both
for individual farmers and for the aggregate corn
production sector.

3.2 Costs and Profitability

3.2.1 Costs

Both the initial investment costs and annual
operating costs of sprinkler systems vary greatly
depending on water sources (well costs are a
particularly important source of cost variance),
type of system, amount of vertical lift required,
and per unit cost of energy used. Eidman (1978)
estimated initial (1977) investment costs to range
from $41,000 to $78,000 for on-farm pump sprinkler
systems, irrigating 130-150 acres. These costs
varied according to well size (600-900 gallons
per minute capacity), lift distance (20, 100, 250
foot lift), energy source (electricity, diesel),
and type of system (center pivot, traveling gun).
Other comparable estimates of around $45,000 have
been made (U.S. Department of Interior, 1979).
Thus, with continuing inflation, current invest-
ment costs for sprinkler irrigation systems cap-
able of irrigating about 130 acres are now in the
$50,000 plus range and climbing. Some of these
investment costs are, however, diminished in real
terms by the ability of investors to claim invest-
ment tax credits and to use rapid depreciation
write-offs of capital costs.

With labor efficient sprinkler systems, energy
costs are the largest single operating expense.
Energy costs, in turn, relate to the two work
functions involved - water pumping and water dis-
tribution. In 1980, natural gas was much the
cheapest (about one-half the cost of electricity,
and one-third the cost of diesel; Frederick, 1980).
Some perspective on current energy costs for irri-
gation can be obtained by considering the cost
of pumping and distributing one acre foot of
water.3/ With electricity as the energy source,
pumping water from a depth of 200 feet and using
a center pivot system for distribution, energy
costs were estimated to be about $15 each for
pumping and for distribution (Frederick, 1980).
Other cost estimates for center pivot systems
indicate variable costs of $18-$30 per acre foot
of water supplied (U.S. Dept. of Interior, 1979).
Thus, all pump-type sprinkler irrigation is energy
intensive, particularly that from deep-wells,
since energy requirements for pumping are essen-
tially a linear function of the lift distance.

In summary, irrigation costs vary greatly be-
tween farmers depending on water source, energy
source, type of irrigation system used, the amount
and frequency of water application and the effi-
ciency with which the system is operated. How-
ever, it is clear that both investment and opera-
ting costs for this technology are relatively
high and are dominated by energy costs.

3.2.2 Profitability

Numerous studies have shown irrigation of corn
to be a profitable technology on the more

drought-prone soils in the western and northern fringes of the Corn Belt (Eidman and Greene, 1978; FEDS, 1980; and others). The rapid increase in corn acreage irrigated during the 1970s verifies these findings. Moreover, the attraction to investors of investment tax credits, rapid depreciation of capital and capital gains income (as opposed to regularly taxed income) has spurred the spread of center pivot technology. This is particularly true in Nebraska where several million additional acres of irrigated corn appears likely in the future (Rathjen, 1981). Such irrigation expansion is made possible by the large water supplies (2 billion gallons or more) underlying that state in the Ogallala aquifer.

Despite the above conclusion, most corn is grown on the medium and fine textured soils of the more humid Corn Belt and adjacent areas. This should continue at least for the next two decades. So, the question of the profitability of irrigation on Corn Belt soils is an important one. Burt and Stauber (1971) provide a conceptual and empirical model for firm-level economic decision making for supplemental irrigation in a sub-humid climate using stored water supplies (reservoirs, ponds, etc.). They include the consideration of "reducing variability of returns" as an important decision criterion. Though it is clear that irrigation water requirements in their study were less than those in areas with coarser textured soils and/or lower precipitation, no broad-based generalizations can be made from their study about the profitability of irrigating major Corn Belt soils. Schoney and Massie (1980) used a computer model based on net future values of cash flows to investigate the break-even corn yield increase required for profitable investment in a traveling gun sprinkler system used for supplemental irrigation. They estimated that an increase of more than 70 bu/ac in corn yields would be required to cover the costs of investing in such irrigation technology.4/ Data from Wilson and Eidman (1981) indicate that an increased corn yield of about 60 bu/ac is required to generate a satisfactory internal rate of return to expenditures made for irrigation technology on fine textured soils in South Central Minnesota. Apland, McCarl, and Miller (1980) concluded that the irrigation of corn appears to be a rather marginal proposition for profit maximizers in the Corn Belt and attractive only to risk averters.

In summary, irrigation on prime Corn Belt soils appears to be a marginal investment at the present time (with actual yield responses in the 30-60 bu/ac range) unless reduction in yield variability is a highly valued goal. Yet, supplemental irrigation of corn on some of the drought-prone soils in the Corn Belt is, even now, an economically feasible alternative (Lazarus and Scott, 1981; Wilson and Eidman, 1981; and others). Higher corn prices and/or a modest increase in yield

response could make irrigation a profitable future technology for those Corn Belt farmers who have access to relatively cheap and dependable water supplies. Some 8-12 million acres in the Corn Belt might reasonably be included in land which, given the right economic incentives, could be induced into irrigation.

3.3 Productivity and Resource Use

Irrigation is mainly a land augmenting technology which has reduced the amount of land required to produce a bushel of corn by amounts ranging from about 30 percent to upwards of 200 percent. It is, however, an energy intensive technology which, compared to dryland production, increases energy requirements per bushel of corn by 25 to 250 percent. It is also a capital intensive technology in most applications, requiring investments of $400 to $600 per acre (for on-farm pump, sprinkler systems) with high variable costs both for energy and supporting inputs, particularly nitrogen fertilizer.

With respect to labor efficiency, irrigation of corn provides a range of situations. Compared to dryland production, the labor-efficient center pivot sprinkler systems actually reduces slightly the direct crop season labor requirements per bushel of corn produced. However, over a large area such as Eastern and Central Nebraska, where a variety of irrigation systems are used, per bushel labor requirements are 5-10 percent greater with irrigation than without (estimated mainly from FEDS, 1980).

3.4 Input Demand

Irrigation technology has resulted in major increases in the demand for water, for fossil source energy and for nitrogen fertilizer.

In 1975, 77 percent of the consumption of water withdrawals in the U.S. was for agriculture, with only 23 percent for all other uses. The latter percentage was up from 10 percent in 1955 and 15 percent in 1965 (U.S. Department of Interior, 1979). Non-agricultural water use is probably now in the 26-28 percent of total usage range, and rising. Both a declining water table in underground aquifers and increased demand from non-agricultural water users have made competition for water supplies intense in some areas. In the Southern Plains, for example, non-agricultural water use is projected to increase by 54 percent from 1975 to the year 2000 (U.S. Water Resources Council, 1978).

Accurate determination of the aggregate demand schedule for water to irrigate corn is impossible, since most water used in corn irrigation is free except for the costs of pumping and distribution. No direct market demand schedule for irrigation water is therefore observable. However, aside

from yield response, the two factors which strongly affect demand are the price of corn, and the cost of energy.

Corn irrigation technology has also increased dramatically the farm demand for fossil energy because irrigated corn is much more energy intensive than dryland production. In the High Plains of Texas, for example, over 60 percent of the energy used for producing corn is for pumping water and 85 percent is for irrigation and nitrogen fertilizer. And, total energy requirements per bushel of corn have been estimated to be 250 percent more than in the Corn Belt (Jensen and Kruse, 1980).

In 1977, about 40 percent of all crop acreage irrigated with on-farm, pumped water used electricity, 34 percent used natural gas, 10 percent diesel, 5 percent LP gas and 1 percent gasoline (Sloggett, 1979). But, the proportional use of natural gas is expected to decline in the future as that energy source declines in availability and increases in cost.

4. Other Aspects of the Irrigation Technology

4.1 Environmental, Institutional and Legal Impacts

4.1.1 Environmental Impacts

Several environmental issues relate not only to irrigation technology used for corn but for other crops as well. First, extensive irrigation has contributed to the heavy mining of groundwater

supplies particularly in the Southern and Central Plains (Frederick, 1980; Figure V-3). With little groundwater recharge capability in the Ogalalla aquifer, a non-replaceable natural resource is being depleted. Short-run gainers are: (i) current irrigation water users; (ii) the current suppliers of irrigation related inputs and other agribusinesses; and (iii) domestic and foreign consumers who benefit from increased food supplies and lower prices. Losers are: (i) the future generations (both producers and consumers) whose economic choices are reduced; and (ii) those farmers and agribusinesses whose capital assets undergo depreciation as future income flows decline. Assuming, however, that the market place provides relatively effective price discounting for capital assets, it is mainly the loss to future generations of the non-renewable water resource which constitutes an important continuing cost.[5]

A second environmental impact of irrigation technology pertains to soil erosion. Some erodable, otherwise unproductive land, has been cleared for irrigation and some additional sediment, nutrient and pesticide pollution has resulted (U.S. Department of Interior, 1979). However, corn irrigation to-date has probably contributed only modestly to soil erosion, since most irrigated land is relatively flat. Even so, in some high water use areas, soil compaction is a problem and this condition increases runoff and erosion (Curven and Massie, 1977).

In aggregate, we estimate that no more than one million acres (less than 10 percent of the total

Figure V-3. Areas of Ground Water Mining in the United States.
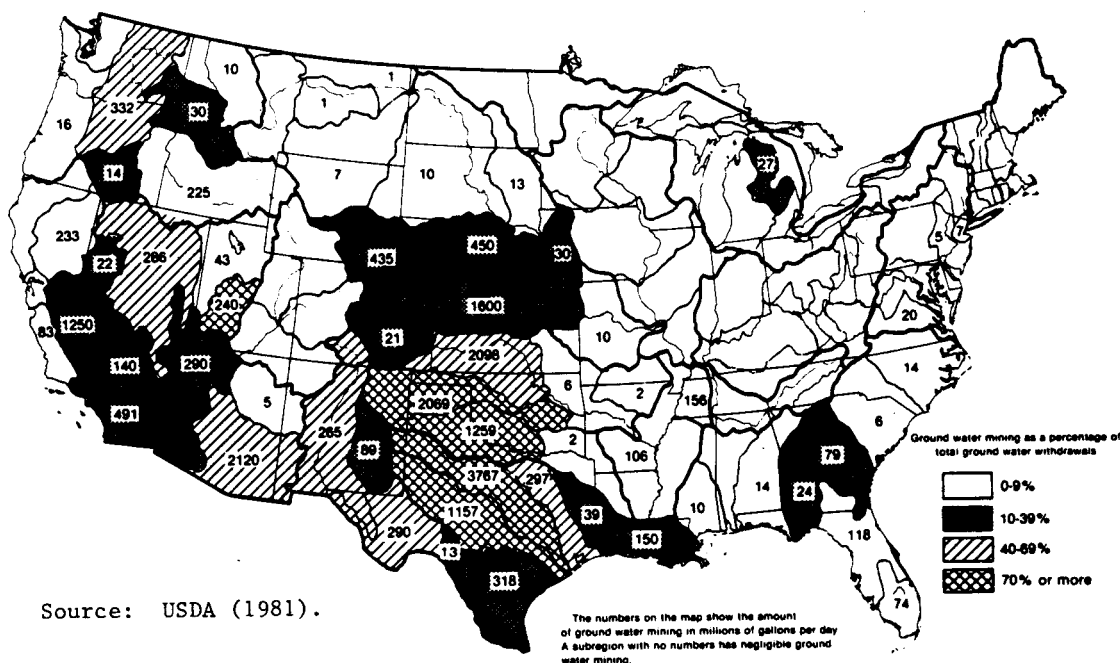
Source: USDA (1981).

irrigated corn acreage) currently suffers from a significant erosion problem due to irrigation. However, a much greater erosion hazard will exist in the future if some irrigated land reverts back to dryland conditions without the protection of the permanent cover which was removed to install irrigation. Rathjen (1981) states that, "substantial numbers of center pivots are being developed on soils that are highly sensitive to wind and water erosion. If the irrigated crop acreage in Nebraska doubles, as some project, to about 12.5 million acres by the year 2000, much of that additional acreage will be more erosion prone than the existing acreage."

A third environmental impact of corn irrigation technology is the nitrate contamination problem which occurs on some sandy soils. It is most pronounced where underground aquifers are located at shallow levels (Griffin and Bromley, 1981) and where heavy nitrogen applications result in the leaching of nitrates through these coarse textured soils into groundwater used for drinking. Such leaching is aggravated by "over-irrigating" which flushes nitrates downward into the underground water supplies.

A final environmental problem, salinity, is associated particularly with irrigation in the arid West. It has not been a problem of substantial consequence on most of the irrigated acreage currently used for corn production. But, much of this acreage has been irrigated for 10 years or less. Thus, salinity problems may yet arise.

4.1.2 Legal - Institutional Issues

From a legal standpoint, the "riparian" (access by land ownership) doctrine applies to surface water use in humid Eastern states and the "prior appropriation" (rights based on prior use) doctrine in the semi-arid and arid Western states (U.S. Department of Interior, 1979). Both doctrines will be put to serious legal tests as water shortages and quality problems become more widespread.

As groundwater aquifers are lowered by high volume irrigating, some existing wells go dry and have to be redrilled at additional cost. In other situations, water supplies for other critical uses are threatened. For these reasons, and because of well interference problems, some states now require prior approval before large-volume wells can be drilled for irrigation purposes. According to Lotterman and Waelti (1981):

> "During the 1970s, well-interference emerged as a highly volatile policy issue in the allocation of groundwater in states bordering the humid East and the arid West.

Well-interference is the lowering of water levels in wells adjacent to, or neighboring a high-capacity well during and shortly after the time the high-capacity well is being pumped. It is generally a temporary hydraulic phenomenon, as distinguished from long-term overall lowering of the water level in an aquifer caused by pumping exceeding recharge.

States such as Minnesota, Iowa, and South Dakota have experienced dramatically increased groundwater irrigation since 1970. Although the actual number of cases of interference in these states is relatively small, significant political impact resulted largely from widespread public unease about the adequacy of water supplied during the drought period of 1974-76.

New irrigation wells interfering with existing domestic wells caused most conflicts. The drought and rapidly increasing groundwater irrigation, caused all three states to review and revise groundwater allocation policies. The revised rules have not received much attention by the public, in practice or court. This kind of attention awaits another drought like that of 1974-76."

As indicated earlier, use of water for non-irrigation purposes has been growing more rapidly than irrigation use and this trend is projected to accelerate in the future (U.S. Water Resources Council, 1978). Thus, one can reasonably expect a much broadened level of competitive interference between corn irrigators and other water use interests in the future.

4.2 Vulnerability of the Technology

In addition to increasing total corn production capacity, irrigation technology reduces the risk (variability) associated with corn production particularly in areas of limited rainfall and/or drought-prone soils. Yet other risks and uncertainties are created: (i) the uncertainty of future water and energy supplies and energy prices; (ii) the increased incidence of insect and disease infestation resulting from increased moisture and land use intensity; and (iii) the nitrate contamination problem.

4.2.1 Water and Energy Supplies and Energy Prices

Water and energy supply-price vulnerability is substantial. In some cases, particularly in the Southern Plains where the rapid mining of

subsurface aquifers is now occurring (Figure V-3), some land currently used for irrigated corn production will, because of water shortages, receive less irrigation water and some will even revert to use for dryland farming.

The decline in irrigation acreage even for the Southern Plains will not become widespread until after the beginning of the next century (U.S. Water Resources Council, 1978). But, signs of adjustment to declining water supplies will be broadly visible in the late 1980s and early 1990s.6/ The early curtailment of water use is already underway in the form of conservation measures which will extend the life of remaining water supplies. With investments for irrigation distribution systems already made, the only economic alternative for most farmers is to extend the life of their irrigation technology by incurring additional pumping costs per unit of water recovered. Also, some farmers will shift to crops requiring less water than corn. Thus, annual rates of water application will be reduced on a rather large acreage, but probably without too much impact on yields. Our assessment suggests that, barring large declines in the current corn/energy price ratio, the reduction in irrigated corn acreage in the Southern Plains will not exceed 15-25 percent by the year 2000. This decline in water use will be abetted by increases in the energy/corn price ratio for some producers as a result of the deregulation of natural gas prices and the expiration of special use privileges for on-farm natural gas supplies.

A high proportion of the acreage of corn now being irrigated (perhaps upwards of 80 percent) appears to have no short-term problem of water availability. Rather, the question facing producers on these acres is whether the future corn/energy price ratio will continue to be high enough to sustain profitable irrigation. Since electricity and natural gas were the energy sources used on about 75 percent of the acreage irrigated with on-farm pumped water in 1977 (Sloggett, 1979), future costs projections for these energy forms should indicate the feasibility of future corn irrigation. Landsberg (1979) projects a general doubling of real energy costs between 1980 and the year 2000. Schurr et al. (1979) project a lower increase of 2 percent per year from 1975 to 2000 with the rate of increase for natural gas outpacing that for electricity. Applying the higher rate of these two energy price projections, (a doubling by the year 2000) to a "currently profitable" center pivot system distributing 18 acre-inches of water lifted 200 feet, results in increases of $25 for natural gas and $48 for electricity over 1980 cost levels. Applying these estimates to the average yield response of 65 bu/ac computed earlier, real increases in corn prices of $.38 and $.74 per bushel, respectively, are required by the year 2000 to offset the higher energy prices. But, the impact of any energy price increases will be moderated by expected

future efficiencies in water use. Since most currently irrigated corn land has a much lower income earning capability for dryland farming, one can probably expect land price reductions, and not abandonment of irrigation, to bear the initial brunt of lowered profitability from irrigation. In the unlikely event that electricity prices were to quadruple by the year 2000, requiring an offsetting increase in real corn proces of about $1.50 per bushel, irrigation technology would probably become unprofitable on as much as 40 percent of the current 11.3 million acres of irrigated corn.

In summary, barring unexpectedly large changes in the real corn/energy price ration, the utilization of irrigation technology will probably decline by the year 2000 only in the Southern Plains, and there by an amount not exceeding 15-25 percent of the 1980 acreage. This acreage decline will be more than offset by a much increased acreage of irrigated corn elsewhere. This conclusion assumes that any future regulation of water for irrigation will be aimed mainly at its use-conservation rather than total prohibition, except possibly on a small acreage where nitrate pollution problems cannot be otherwise controlled.

4.2.2 Changes in Microclimate

Higher plant populations and higher fertilizer applications accompany corn irrigation. The more humid microclimate encourages the spread of disease and insect populations. Increased use of chemical pesticides together with good sanitation practices for handling plant residue materials have adequately handled most pest problems and will probably continue to do so in the future.

4.2.3 Nitrate Contamination

Though currently of a localized nature, the nitrate contamination problem may increase, thus generating regulations on water/nitrogen use in selected areas in order to reduce the health hazards which it presents.

5. Feasibility of Irrigation Technology

Irrigation technology is already in extensive use and its rate of increase (or decrease) will depend mainly on energy and water supplies and energy and corn prices. Trickle irrigation technology is receiving considerable attention for use on tree and vine crops but does not appear to have near-term economic applications for corn production.

6. Alternative Technology Options

An obvious alternative for farmers facing the option of sprinkler irrigation technology is the acquisition and use of additional land for dryland corn production. With rapidly increasing land prices, many individual farmers will probably find

the purchase of irrigation technology to be more profitable than additional land. Moreover, good cropland for use in dryland corn production is in limited supply and can probably be expected to increase in price more rapidly than irrigation equipment. In 1979, the average price of irrigated land in Southwest Nebraska, for example, was in the range of $900 per acre compared to $2,000 to $3,000 in the Corn Belt. Thus, low land prices plus high yield response provide a stronger economic incentive, at this time, for irrigation developments in areas outside the Corn Belt (Sheffield, 1979).

Once land outside the Corn Belt has been developed for irrigation, however, it is not unreasonable to project that future expansion of corn irrigation may be mainly in the more humid areas, east of the Mississippi. This is true because of several factors: (i) the high yield potentials on the better Corn Belt soils; (ii) the relatively rapid recharge capability of both surface and subsurface water reservoirs in humid areas; and (iii) the higher pumping costs, as water tables drop, in the more arid areas of the Southern Plains and the West. As a result, many Corn Belt farmers may choose to incur the $400-$600 per acre cost for irrigation systems in preference to trying to purchase additional cropland, perhaps for $2,500 or more per acre.

7. Managing the Irrigation Technology

Irrigation often gives rise to new or expanded drainage problems, particularly on the finer textured soils. Thus, effective management of irrigation technology may require installation of subsurface drainage systems on some acreage.

With respect to irrigation technology per se, studies have shown that 30-50 percent of total energy expended in pumping water could be saved through better water management and more efficient deep well pumps, irrigation power plants and wells (Jensen and Kruse, 1980). Farmers can improve substantially their scheduling of irrigation to improve yield response and reduce water requirements. Some farmers have, by scientific irrigation scheduling, reduced energy requirements for pumping by 25-30 percent below the average, without reductions in yields.

Also, several types of adjustments are being made in the application of sprinkler irrigation technology. If farmers are already using their least cost energy source, the first adjustment is that of modifying the system to reduce pressure from 70 pounds per square inch down to 30-50 pounds per square inch.

Those farmers using electricity for irrigation can benefit from information on what the non-peak hours are for electrical companies so they can minimize per unit energy costs. Some radio

stations are providing information on evapotranspiration rates, etc., in order to help farmers do a better job of irrigation management. Research is underway to develop moisture sensors in the field and to link them with automatic electronic controls for regulating water applications. Such systems should be available commercially within 5 years.

Finally, attention must be paid to the issues of mining groundwater supplies, to problems of well-interference, pollution and soil erosion. For at least some situations, monetary incentives to reduce these environmental problems could pay high public dividends. For chronic problem areas, legal constraints on water mining and on the incidence of soil erosion and environmental pollution will likely be required to keep these adverse externalities to levels which are socially acceptable.

Land Drainage Technology

1. Definition and Description

Land drainage is defined as the removal and disposal of excess water from agricultural land. The excess water can be surface water or subsurface water. Most natural drainage problems occur in humid or subhumid areas (including the Corn Belt), whereas most man-made drainage problems develop as a consequence of irrigation. With U.S. corn production, most installed drainage is related to excessive soil wetness from natural causes, but most future irrigation on fine and medium textured soils will require installation of effective subsurface drainage systems if such systems are not already in place. Also, since much of the existing irrigated corn acreage is of recent installation, some drainage problems may not yet be evident.

Plant growth and crop yields are constrained in water logged soils because of: (i) poor soil aeration, which results in low oxygen content in the soil and the retention of nitrogen in organic residues rather than in its usable mineralized form; (ii) curtailed nutrient uptake by the plants; (iii) reduced soil bacterial action; (iv) reduced rates of soil "warm up " in spring; (v) inability to perform field operations on a timely basis; (vi) excessive soil compaction; (vii) excessive concentrations of toxic substances, such as sodium and other soluble salts, in some soils; (viii) increased "scalding" of plants; and (ix) other reasons (Luthin, 1966; Schwab et al., 1971). In addition, labor and machine requirements are greater on wet soils.

Drainage is not a new technology. Covered field drains were in use in the Nile Valley as early as 400 B.C. And, land drainage was common in the Corn Belt during the 19th century when

yield increases of 150 percent and returns on drainage investments of 25-50 percent were achieved (Elliott, 1882).

Some agricultural land can be adequately drained by use of surface ditches. Most medium to fine textured "wet soils" used for corn production, however, require subsurface systems. A common goal of subsurface drainage systems is to remove 3/8 to 1/2 inch of water from the soil per 24 hour period, but not all existing systems meet this requirement. Until recently, most of the subsurface drainage of agricultural land in the U.S. utilized clay or concrete pipe, with laterals placed at depths of three feet or more and spaced at 60 to 200 foot intervals. Lateral pipes typically 5 or 6 inches in diameter were used. Trenches were dug, either by the wheel-type excavator or the ladder-type trencher, and pipes were laid in open trenches with or without surrounding envelope material. The entire operation was both costly and labor intensive, but effective. Literally millions of acres of this technology are still in use, and some continues to be installed.

The new technology which has impacted heavily on agricultural drainage of Corn Belt-type soils involved the substitution of small diameter (3, 4 or 5 inch) corrugated plastic tubing for clay and concrete pipes, and the installation of this tubing by trenchless machines. These drain-type plows use laser devices to monitor the placement of the tubing with respect to grade (elevation). The extruded plastic tubing is perforated mechanically in order to permit entry of water into the tube. The entire technology package is technically effective, easy to handle, labor efficient and cheap (compared to the earlier drainage technology).

Development of smooth-walled polyethylene tubing which was largely a British development, first became available for manufacture in the U.S. in 1941 (Schwab, 1955). However, only the smaller (2 inch diameter or less) tubes were economical and these were generally too small for acceptable performance. Meanwhile, corrugated polyvinyl chloride (PVC) tubes were developed and used extensively for drainage in Europe, particularly in Germany and the Netherlands. An estimated 85 percent of all drainage products in Europe are now PVC corrugated tubing (Easton et al., 1977). By 1967, installation of corrugated plastic tubing had begun in the U.S., using conventional trenching machines. Subsequent development of installation equipment proceeded rapidly and the high speed, trenchless, automatic grade control, plow-type drainage equipment was soon available. In contrast to the European situation, where PVC plastics have been used almost exclusively for corrugated tubing, the most common plastics used in the U.S. have been high-density polyethylene (HDPE). The PVC materials are now being manufactured in the U.S. and their use here can be

expected to increase significantly. Laboratory tests indicate that plastic tubing will last 70 years without deterioration (Lidster, 1971).

2. Direction and Magnitude of Drainage Technology

The distribution of "wet soils" in the U.S. is shown in Figure V-4. Nationally, about 105 million acres of these wet soils are classified as cropland, about 25 percent of total cropland (USDA, 1980). Even before the widespread use of plastic tubing, much of the agricultural drainage was in the major corn producing areas. For example, of the total of 59.6 million acres of drained land reported in the 1969 Census of Agriculture, about 65 percent (38.6 million acres) was in the North Central Region.7/ Leading states in total land drained are Illinois, Iowa, Minnesota, Indiana, and Ohio. This distribution of land drainage is the result of these states having a large acreage of flat land with wet soils (Figure V-4), which, when drained, are highly productive.8/

Wherever they will suffice, surface drains are the cheapest form of drainage, but subsurface drainage is required on many wet soils. Prior to the development of plastic tubing, the installation of subsurface drainage of land already under cultivation proceeded slowly. With the advent of the new plastic tubing coupled with rapid increases in land prices and modest increases in corn and soybean prices, installation of subsurface drainage proceeded at an accelerated pace on both new land and previously drained cropland. In recent years, an estimated 3/4 to 1 million acres of land has been tilled annually with this new technology in Southern Minnesota alone (Allred, 1981) and the installation rate has been rapid throughout the Corn Belt, Lake States and in some other areas.9/ It seems likely that most excessively wet, but otherwise highly productive, cropland with "Corn Belt" type soils will be drained using the new plastic tube technology by the mid to late 1980s.10/ Bagley (1977) concludes that, "with today's high level of agricultural enterprise and with investments in fertilizer, herbicides, and hybrid seeds, water control through the installation of subsurface drainage has become almost mandatory." Where physically feasible, the economic incentive will also be great to drain those "wetlands"11/ which have potentially productive soils but which are not currently being farmed. Only regulatory constraints or new incentives for farmers will prevent the rather complete occurrence of such drainage.

3. Direct Effects of the Drainage Technology

3.1 Yield Response and Aggregate Production Capacity

Yield response to drainage depends on the severity of the soil wetness problem which in turn differs greatly by soil type and by

individual fields within the same soil type.
Also, the productive capacity of soils varies.
Anthony (1975) estimated that an "adequate" drain-
age system on land now in production raised corn
yields in South Central Minnesota by 10-40 bu/ac
depending on the degree of the soil wetness prob-
lem. Schwab (1976) recorded an average 50 bushel
increase in corn yields (1962-72) from drainage
of heavy soils in Ohio using "conventional" til-
lage practices while the response from drainage
and "no till" practices was 28 bu/ac. A 12-state
survey in the early 1940s showed that an average
yield increase of 65 percent was associated with
installation of drainage systems (Pierre, Aldrich
and Martin, 1966). When applied to current yields,
this represents an increase of 70-80 bu/ac. Thus,
there have been major corn yield responses from
installation of drainage on land already in pro-
duction, as well as on lands previously too wet
to farm without drainage.

In 1975, it was estimated that installation of
drainage had added more than 30 million acres to
the tillable acreage of the Midwest and increased
production on another 40 million acres (Palmer,
1975). Our estimate is that more than 30 million
acres of corn for grain is now being produced on
land which had been drained and that corn yields
on this land, are, on the average, at least 40
bu/ac higher than they would have been without
drainage. Land drainage technology has probably
contributed 1.2 billion bushels to annual corn
production capacity. This is substantially more
than has been contributed by irrigation.

3.2 Costs and Profitability

Materials and installation costs for 4-5 inch
concrete tile are mostly in the range of $.70 to
$1.10 per lineal foot. With 100 foot spacing
between laterals, a total cost for drainage of
around $500 per acre is common. This per acre
cost is reduced to about $450 per acre with plas-
tic tubing using trench-type installation and to
about $300 with installation by laser controlled,
trenchless plows. Thus, the total per acre cost
range is $300-$500 per acre (Sundquist, 1981).

With projected corn yield increases of 40 bu/ac
or more on land already in production, installa-
tion of drainage is often a highly profitable in-
vestment. Moreover, installation of drainage
technology qualifies investors for investment tax
credits at installation and for capital gain tax
treatment of land value enhancements at time of
sale (U.S. Department of the Treasury, 1981).
Numerous examples exist where recently installed
drainage has generated a net income flow of $100
per acre in the first year following installation.
Thus, for many farmers, installation of drainage
technology pays for itself with increased profits
within 3-5 years. Furthermore, drainage of wet-
lands which are not now cropped, will probably
become financially more attractive as the price of
established cropland increases.

3.3 Resource Use and Productivity

Like irrigation, drainage is mainly a land
augmenting technology. On average, it reduces

Figure V-4. Wet Soils, by State and Crop Production Region (Millions of
Acres).
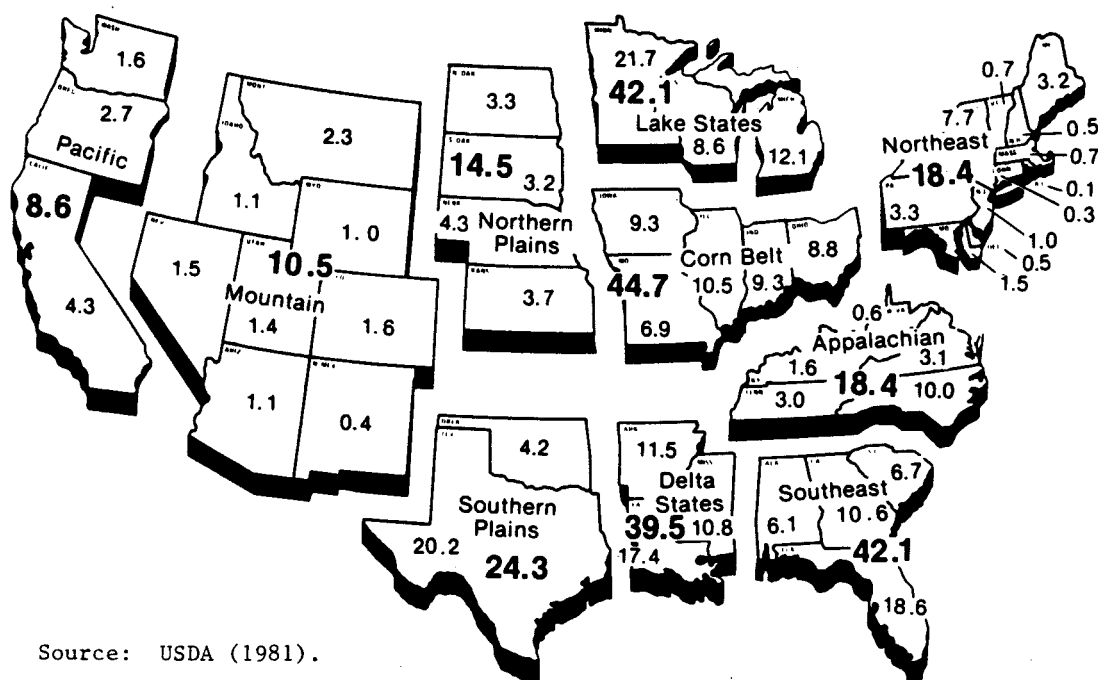
Source: USDA (1981).

the land requirements to produce a bushel of corn by 30 percent or more. Once the initial installation is complete, input costs are minimal. It is estimated that labor and machine productivity for tillage and planting are increased by 10-15 percent with installation of drainage on wet Corn Belt soils. Sitterley and Bere (1960), using long term data for Central Ohio, found that the number of days suitable for tillage field work during the critical April-May period was increased by 50 percent or more, in 80 percent of the years, by implementation of drainage.

In addition to increasing the productivity of machinery and labor which is actually used, drainage technology makes it feasible to produce corn with less investment in reserve machinery and manpower, thereby enhancing overall resource productivity even more. Finally, the drainage of wet soils permits better utilization of plant nutrients, thus enhancing the productivity of fertilizer and related inputs.

3.4 Aggregate Input Demand

Aside from the technical equipment and services required for installation, the only major input involved in drainage is for the material itself. Increasingly, this is plastic tubing. During the world wide shortage of crude oil in 1973-74, a temporary shortage developed for materials from which plastic products are made. Although this shortage is no longer a serious constraint, raw material prices for plastic tubing can be expected to increase along with oil prices.

4. Other Aspects of the Drainage Technology

4.1 Environmental, Institutional and Legal Impacts

There are two major types of environmental pollutants carried via drainage water: (i) toxic pollutants, mainly chemical pesticides; and (ii) nutrients, mainly nitrogen and phosphorus. Nonpoint sources account for more than 50 percent of the pollutants entering the nation's waterways and in the North Central Region, 63 percent of the hydrologic drainage basins are wholly or partially affected by nonpoint source pollution of nutrients and 37 percent by pesticides (USDA, 1980). However, only some of these pollutants come through drainage waters from agricultural lands and only some of them via subsurface drainage.

Most pesticide and phosphorus pollutants enter streams and lakes via overland flow (runoff), rather than via percolation through the soil. For example, phosphorus compounds in the soil are so insoluble that subsurface waters carry away little or no phosphate. This same pattern of movement applies to most other persistent insecticides and herbicides. Thus, installation of subsurface drainage can substantially reduce the overland flow of some toxic pollutants and phosphorus, because it provides additional "in soil" storage capacity for water which would otherwise be diverted to surface runoff. Reducing runoff has the added benefit of reducing soil erosion.

Nitrogen in drainage waters is mainly in the form of nitrates, which do present a pollution problem for well water in some areas. However, those nitrates entering drainage waters (including tile drain systems) are mostly taken up by algae and rooted plants when they enter lakes, streams or reservoirs. When this happens, they are no longer a pollutant, in the nitrate form (Hanson, 1981). Thus, drainage technology is not the origin of the nitrogen pollution problem, and the solution to this problem does not lie with the abolition, or modification, of drainage technology. The pollution problems arising from nutrients and pesticides in corn production are assessed in more detail under the fertilizer and pesticide technology sections of this report.

Drainage technology has had a strong positive impact on corn production from wet soils, and from some wetlands. But it has had an adverse impact on some key competing uses for wetlands which include, among others, recreation and fish and wildlife habitat, the latter including the use of wetlands in the production of migratory waterfowl (Goldstein, 1971). The economic value of wetlands for uses competitive with agriculture is not easily determined because of the "public good" nature of these alternative uses. Goldstein (1971) provides a conceptual model for evaluating waterfowl and wetlands but no reliable estimates of the value of these public goods are available. Thus, an inadequate basis for wetland evaluation is a fundamental problem in assessing the trade-offs between drainage and non-drainage (Reppert, 1980). Nevertheless, drainage technology should probably only be applied to wetlands if the public values the agricultural product gained more than it values the public good displaced. This principle is a difficult one to implement, however, because much of the wetland acreage is privately owned and owners can typically capture the highest economic value from wetlands by draining for crop production. Thus, regulations have now been implemented in some states to constrain the drainage of wetlands for crop production and government subsidies for drainage are no longer available (Leitch, 1981).

5. Feasibility of the Drainage Technology

Drainage technology is already highly feasible and it is becoming more so. Its installation bears a strong complementary relationship with some technologies including mechanization, irrigation and use of chemical fertilizers.

6. Alternatives to the Drainage Technology

Alternatives to land augmenting drainage

technology are mainly those of developing new lands for corn production or using land currently employed in the production of other crops. Both of these alternatives have high costs and have adverse impacts on the environment and/or on the supply of other farm products.

7. Managing the Drainage Technology

Two issues appear to be important in managing drainage technology. First, more effective ways need to be found to evaluate wetlands prior to the decision to drain or not to drain them. But, because of the diversity of social benefits accruing to wetlands, the difficulty of objective measurement, and the variability between wetland areas, the net social benefits can only be determined through systematic, area-specific benefit/cost assessments of wetland drainage projects. The second issue pertains to the disposition of collected drainage waters containing toxic and nutrient pollutants. This topic is discussed elsewhere under fertilizer and pesticide technologies.

Weather Modification

Weather modification is broadly defined as the changing of weather conditions by artificial means. Two types of weather modifications which could have significant impacts on corn production are those of rainfall enhancement and hail suppression. As indicated earlier in this chapter, millions of acres of corn are now irrigated to supplement natural precipitation. But, widespread application of reliable rain enhancing technology would have drastic impacts on corn production on the non-irrigated land. In addition, corn losses from hail are about 10 percent of total crop losses from that source (Changnon et al., 1977) and probably total $100 million or more at current prices. Thus, the overall economic value of effective weather modification for corn production enhancement would be considerable.

The literature on weather modification is voluminous, though most does not relate specifically to corn. The National Academy of Sciences (1973) and Changnon (1975) provide a good overview of the capacity for weather modification and the key problems and issues involved. A rather comprehensive technology assessment of hail suppression was recently completed under the sponsorship of the the National Science Foundation (Changnon et al., 1977).

It is clear that current weather modification technology is such that some increase in rainfall can be induced by cloud seeding, and hail suppression can also be achieved. The results of weather modification attempts are highly variable although there have been some cost-efficient agricultural applications. But, weather modifications deemed desirable by corn producers are certain to be considered undesirable by some others.

A large scale experiment on hail prevention and rainfall stimulation initiated in South Dakota in Spring, 1972 has since been abandoned without definitive conclusions (Donnan et al., 1976). Another experiment (CCOPE) is underway in the Plains States under the auspices of the National Science Foundation, the National Center for Atmospheric Research and the Department of the Interior (Sullivan, 1981). Although research continues in an effort to find reliable technology for weather modification, potential applications are complicated by a variety of technical, legal, sociopolitical and economic impact issues.

In summary, though some weather modification technology is now available, significant applications for corn production enhancement will not likely occur before the year 2000. We thus conclude that this technology will have an inconsequential effect on commercial corn production between now and the end of this century and so we do not proceed with an in-depth assessment.

Footnotes

1/There is some disagreement over the exact amount of U.S. cropland under irrigation. The Census of Agriculture data on irrigation for 1969 and 1974 appear to be low, because of definitional and underreporting problems. Other data, with the exception of national-level inventory surveys conducted by the U.S. Soil Conservation Service (SCS) in 1967 and 1977 and some special area surveys conducted by State Crop and Livestock Reporting Agencies, do not have a statistically reliable sampling base. Moreover, any effort to allocate irrigated acreage to individual crops must utilize a non-statistical basis.

2/These were soils for which the available water capacity (AWC) in the top 60 inches of soil was 9 inches or more. The AWC of a soil is a measure of its capacity to make water available for plant growth. Sand, for example, generally has a comparable AWC of only 3-5 inches.

3/This amount is probably low for coarse textured soils where 12 irrigations per season of about 1.25 to 1.5 inches per irrigation (15-18 inches total) are not uncommon, but high for fine textured Corn Belt soils where 8 inches of supplemental water, or less, per growing season may suffice.

4/They considered irrigation technology having an initial cost of almost $40,000 and which required 75 percent debt financing. They projected a 7.5 percent annual increase in the price of corn and a 12-year planning horizon for investment recapture. As for any "futuristic" analyses, the future corn and energy prices which they assumed are crucial to their results.

5/Some, such as Sanghi and Klepper (1977), conclude that "conservation of groundwatter cannot be left to market forces" and, therefore, institutional (legal) constraints on water use need to be imposed.

6/Our colleague, Philip Raup (1980) provides interesting perspective on the extent to which the major cattle feeding industry now located in the Southern Plains is largely the product of expanded production of irrigated feed crops in that region. Thus, curtailment in irrigation can be expected to impact heavily on cattle feeding as well as on corn production.

7/The 1974 Census of Agriculture reports a much smaller acreage of drained land. It is the general concensus, however, that these 1974 Census numbers are underreported.

8/Wet soils are, in fact, some of the most productive soils in the world because they are more fertile and contain more organic matter than in dryer soils. In addition, the erosion hazard is less, and less energy is needed for crop production (USDA, 1980).

9/Unfortunately there are not statistically reliable estimates of the acreage of land tiled each year. Even if there were, however, it would be difficult to sort out the acreage of newly tiled land from that receiving replacement tiling and/or tiling between the existing laterals on already tiled fields.

10/In fact some regard most cropland as being free of drainage problems (USDA, 1980). In that event, most of the future tiling will be for replacement or for improvement of existing systems.

11/Wetlands and wet soils are not the same. Only a small percentage of wet soils are wet enough to be classified as wetlands.

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1. Definition and Description

This technology assessment deals with past, present and future methods of pest control in corn. "Pests" include weeds, insects and diseases. "Control" can be biological, cultural or chemical.

Concern has grown over environmental contamination from chemical pesticides used in corn production, partly as a result of their increased usage and partly because of the continuing uncertainty over the environmental consequences of their use. The concept of "integrated pest management" has become popular as a potential method for satisfying both crop production and environmental objectives. Integrated pest management is the balanced use of cultural, biological and chemical measures which are most appropriate in light of a careful study of all the factors involved (Way, 1977). Although the potential applicability of integrated pest management techniques is included in part of this assessment, existing methods of control rely mainly on chemicals, and this form of control provides the major focus of the report.

2. Direction and Magnitude

2.1 Herbicide

Weeds are always a problem in corn and must be controlled by some means, usually chemical or cultural. Ninety-eight percent of all corn land received some herbicide treatment in 1980, at an average use rate of 2.9 lbs of active ingredient per treated acre (USDA, 1981).1/ Herbicide use on corn accounts for 53 percent of total herbicide usage in the U.S. (Eichers, 1981).

. Prior to 1976, total herbicide use in corn was increasing rapidly, because of increases in both the proportion of total corn acres treated (Figure VI-1) and in the rates of usage per treated acre. Usage rates per treated acre increased from 1.7 lb/ac to 2.7 lb/ac between 1971 and 1976 (Eichers et al., 1978). However the sharp rise in corn herbicide use appears to have

ceased, since: (i) virtually 100 percent of corn acreage is now receiving treatment; and (ii) the increase in use rate per acre, prior to 1976, was associated with the particular chemical compounds which were being adopted at that time and which required heavy application rates. In contrast, the compounds which have increased in popularity since 1976 have not required increases in application rate (Behrens, 1981). Total herbicide use on corn remained almost constant between 1976-80 at just over 200 million pounds of active ingredient (Table VI-1).

Table VI-1. Herbicide and Insecticide Use on Corn (million lbs of active ingredient)

	1966	1971	1976	1980
Herbicide	46	101	207	209
Insecticide	24	26	32	36

Source: Eichers et al., (1978); Eichers (1981); USDA (1981).

Figure VI-1. Percent of Corn Acres Receiving Herbicides.
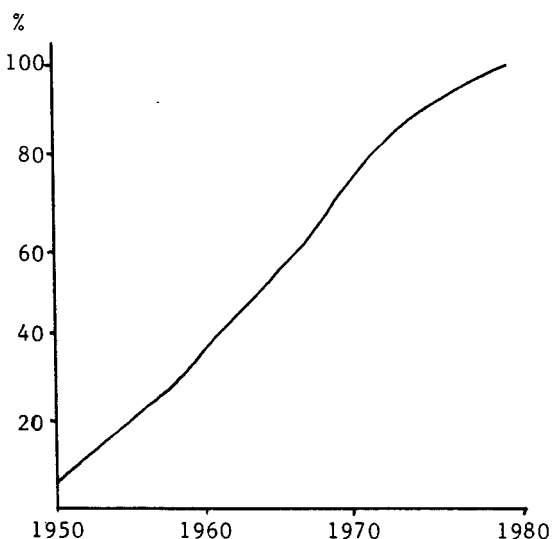
In 1980, the major corn herbicides, and their total usage, were (USDA, 1981):

	million lbs (a.i.)
atrazine	62.5
alachlor	47.4
butylate	45.6
cynazine	19.6
metolachlor	10.4

The two leading herbicides, atrazine and alachlor, are the same compounds which were leading in 1976. However the quantity used of each has sharply decreased over the four year period (cf. Eichers et al., 1978). In contrast, the use of the three next most popular herbicides on the above list increased sharply since 1976. This increase is mainly a reflection of their relative effectiveness.

Foxtails, which are prevalent throughout the Corn Belt, are considered the worst weed group in the area. The tolerance of fall panicum, crabgrass and shattercane to atrazine resulted in the growth of importance of these weeds. However, these weeds have recently become more effectively controlled (with the exception of shattercane) by the widespread application of grass controlling herbicides, such as alachlor. Perennial weeds (e.g., quackgrass) tend to become a problem where reduced tillage is practiced, since herbicides are relatively less effective against them. While many weeds are problems throughout most of the corn growing region, some are limited to subregions. Climbing milkweed is a problem only in the Southern Corn Belt. Quackgrass is a problem only in the Northern Corn Belt. The widespread use of oats and hay in rotation with corn in the latter region make eradication of quackgrass difficult. Atrazine cannot be used in corn in these circumstances because of its persistence. A troublesome new weed in corn is wild proso millet. It was not really evident prior to 1970, but has now spread rapidly in Minnesota, Wisconsin (Harvey, 1979) and more recently to other Corn Belt states. The major weeds in corn, their threat potential and appropriate control measures are discussed in a report by the OTA (1979). They have been included in Appendix Table VI-1.

2.2 Insecticides

The amount of insecticide used on corn is far less than the amount of herbicide, in terms of total quantity, 36 million lbs (Table VI-1), proportion of acres receiving treatment, 52 percent (Pimentel et al., 1979) and percentage of total U.S. usage, 20 percent (Eichers et al., 1978).

The total quantity of insecticide use has been rising steadily, but the rise has been less dramatic than with herbicide (Table VI-1).

The application rate on those acres treated has been constant at about one lb of active ingredient per acre, but the number of acres treated has been rising to its 1979 (52%) level.

Three insects are presently considered to be major problems on corn. These are rootworms, European corn borers and the black cutworm. The corn rootworm complex is the most serious. The northern and western rootworm are distributed throughout the Corn Belt. Prior to 1959, the western rootworm was a minor pest, located primarily in Nebraska and Western Iowa. Its spread was due to the development of resistance to insecticides used at the time. Resistance of the western rootworm to chlorinated hydrocarbons was first noted in Nebraska in 1959. It subsequently spread into most eastern states as the western species invaded territory previously occupied by the northern corn rootworm. While rootworm is the most serious insect pest, an annual rotation out of corn usually obviates the need for chemical control. The second most important soil insect problem is black cutworm. The removal of the insecticide aldrin from the market increased this pest problem for a time, but suitable control chemicals are again available.

The primary aboveground insect pest is the European corn borer, which has been particularly damaging in the Western Corn Belt states since 1978 (Keith et al., 1980). Only a small proportion of corn acreage (5-10%) is chemically treated for aboveground insects (OTA, 1979, p. 38).

The major insecticides used on corn in 1980 were (USDA, 1981):

	million lbs (a.i.)
terbufos	9.3
carbofuran	8.9
fonofos	7.1

This represents a significant change since 1976 (see Eichers et al., 1978). Corn rootworms and other pests have developed resistance to the cyclodiene class of insecticides (OTA, 1979), but the presently-used organophosphates and carbamates are generally effective, although they are considerably more expensive. Rootworm insecticide treatments have more than doubled in price over the last few years.

2.3 Fungicides

The amount of fungicides applied to corn is small and fungicide is applied mainly as a seed treatment. Genetic resistance in corn hybrids has apparently been an effective control measure for many fungal diseases (OTA, 1979, p. 16, 39).

Overall pesticide use in U.S. agriculture has been projected to grow by 0.3 percent per year (Eichers, 1981), which is more or less consistent with trends in corn herbicide use and somewhat below the trend in corn insecticide use occurring since 1976. Future pesticide application rates might even decline as more active compounds become available. However, some growth in total herbicide use in the short-term could come about because of increases in total corn acreage or in the proportion of corn being reduce-tilled.

3. Direct Effects of the Technology

3.1 Yield Response and Aggregate Production Capacity

Losses to specific insects and diseases in corn have been estimated (from NAS 1975a; p. 31, 32) and are reproduced in Appendix Tables VI-2 and VI-3. With present control practices, losses due to disease are perhaps 10-14 percent (NAS, 1975a, p. 33) and 12 percent due to insects (Pimentel et al., 1979). Losses from insects in untreated corn are around 20 percent. Weed losses in the absence of control can range up to 100 percent but some form of weed control is practiced on all corn land.

While there is a large potential gain in yield of up to 26 percent by elimination of all disease and pest problems, it is doubtful whether this potential could ever be achieved. The costs of diagnosis and cure would be expensive. Future changes in pest control technology might make marginal improvements in reducing the total corn yield losses due to pests, but the general consensus is that corn pests are "under control" (OTA, 1979). The main thrust of future technologies (e.g., scouting) will be to reduce the cost and/or negative environmental consequences of maintaining field losses at their present levels, rather than reducing them. (These statements apply to aggregate U.S. yields. On a local or regional level, significant yield losses do occur.)

If there is no significant effect on aggregate U.S. yields from new pest control technologies, then any change in aggregate corn production capacity, resulting from changes in pest control, would have to be the result of bringing more land into corn production. Radical cost reductions in corn pest control would enhance corn competitiveness vis-a-vis other crops, expecially in the Southwest, where pest control costs are high (Eichers, 1981). However, it is doubtful whether changes in chemical pest control technologies would selectively benefit only one crop, such as corn, in a particular region. In general, one might reasonably expect technological innovations in regions where pest control is relatively more expensive, since the profit inducement for such technologies would be highest there. The Corn

Belt is one of the least expensive regions for corn (chemical) pest control (Eichers, 1981). Overall, it is difficult to foresee any large increases in the aggregate production capacity for corn stemming from new pest control techniques.

A number of studies have attempted to show the effects of banning pest control chemicals (including the effects on aggregate production capacity), e.g., Taylor and Frohberg (1977). However, although a total ban on pesticide use would affect aggregate production capacity it does not appear likely that such a radical restriction would be implemented.

3.2 Costs and Profitability

At $15.80 per acre, pesticides accounted for 7.3 percent of total corn production costs in 1980. This represents a fall from 8.8 percent in 1978 (Eichers, 1981). Pesticide prices have risen at only half the rate of "all production items" over the last decade (Eichers, 1981), and this has undoubtedly been partly responsible for some of the increase in pesticide use in corn over the period. The increase has been mainly in the form of herbicides (which have, in fact, become relatively cheaper than insecticide on an active ingredient basis). About two-thirds of the total pesticide costs used on corn are for herbicides, while the other one-third is for insecticides (Lagrone and Krenz, 1980). The one-third proportion of costs attributable to insecticides is higher than the proportional quantities of herbicide and insecticide. This is due to the relatively higher cost of new insecticides (over $10/lb).

Pesticide use has been a profitable pest control strategy, as is reflected by the increased usage (Table VI-1). Headley (1968) estimated that, at 1963 usage levels, an additional one dollar spent on agricultural pesticides would return four dollars to farmers. These figures do not relate specifically to corn, but recent figures indicate that pesticide use on corn is profitable. Miranowski (1980) presents data showing the profitability of corn insecticide treatments while Cashman et al. (1981) found a benefit/cost ratio for corn herbicides of 8/1.

An annual rotation out of corn provides quite effective rootworm control in lieu of chemicals, and it is more profitable than continuous corn (see Chapter VII). Apparently about 21 percent of corn was grown following another corn crop in 1980 (Chapter VII); if all corn was grown in rotation, there would be approximately a 25 percent reduction in insecticide application to corn (calculated from data in Pimentel et al., 1979).

Another insect control technology is to combine chemical application with "scouting" (monitoring changes in the insect or egg population in order

to predict future infestations). While there has been some success with such strategies for corn rootworm (OTA, 1979, p. 88) and the other major corn insects, Pimentel et al. (1979) calculated that a 50 percent reduction in treatment costs would be necessary to pay for the scouting. After surveying experts in this area, Pimentel et al. concluded that such savings would not generally be possible. However, their calculations were based upon a $5/ac cost of insecticide application. At that cost, scouting seemed to be a marginal proposition, but now that rootworm insecticides costs are above $12/ac, scouting will be feasible in many areas. Even if almost all corn moves into a corn-soybean rotation, some application of insecticides for rootworm would continue (25 percent of corn in the corn-soybean rotation was treated in a survey reported by Miranowski, 1980 and Pimentel et al., 1979, found that 29 percent of corn following a non-corn crop was treated with insecticide). Therefore, scouting can be profitable in reducing the number of insecticide treatments, even if crop rotation becomes the primary control treatment (see section 5).

3.3 Resource Use and Productivity

There is presently a strong trend towards less tillage for weed control and seedbed preparation, with a corresponding increased emphasis on chemical control of weeds. This trend is motivated by the prospect of short-term economic gain (see Chapter VII) and it has a major additional long-run benefit of providing good soil erosion contol. Thus, herbicides have both short- and long-term positive implications for labor and land productivity. Although herbicides require fossil fuel inputs in their manufacture their use still represents a net energy saving because of the saving of fuel for tillage (see Chapter VII). The amounts of energy saved are, however, minor relative to the total energy used in corn production (again see Chapter VII).

4. Other Aspects of the Technology

4.1 Environmental, Legal, Institutional

Modern corn herbicides are, in general, strongly adsorbed on soil and they are non-persistent. They are not highly toxic to humans. (The exception is Paraquat, which is used on no-till corn.) While the trend towards reduced tillage may imply an increased level of herbicide use, to counterbalance this there is also a reduction in soil erosion and water run-off (carrying herbicides) so that the net effect of reduced tillage on herbicide pollution may be beneficial (Chapter VII). Herbicides are not generally regarded as being a major environmental problem, especially on Corn Belt soils.

New insecticides for corn are mainly organophosphates and carbamates. They are toxic to

humans and other non-target organisms, but they are less persistent than the formerly-used organochlorines.

The major regulatory weapon for safeguarding the environment against damage from pesticides is the chemical registration process of the EPA. In addition, the RPAR (Rebuttable Presumption Against Registration) system can remove chemicals from the market even after they have been registered. (Some chemicals were on the market prior to the registration regulations becoming effective.)2/

Although there is a need to regulate potentially dangerous chemicals, problems exist with the registration procedures. They are time consuming and expensive for companies to meet (up to $10 million to register a new pesticide, NAS, 1975a, p. 108). Some small companies have not been able to bear these high costs and have left the industry. However, a substantial number of large companies remain. In fact, corn pesticide manufacturer number have remained constant since 1966. Eichers (1980) indicated that there were 26 manufacturers of corn herbicides in 1966 and 21 manufactors of corn insecticides in 1976. But, four firms accounted for 94 percent of the total corn herbicide sales and 81 percent of the total corn insecticides sales (not necessarily the same four firms in each case). Thus there is a certain degree of "market concentration," although compared with 1966, market concentration in 1976 was less for corn insecticides. Overall, there is little evidence that regulatory activities have reduced the number of corn pesticide manufacturers or have increased market concentration in pesticide sales since 1966.

The large investment costs required to register a pesticide automatically biases the research and development system towards broad spectrum herbicides (with larger markets). Ceteris paribus, this is not compatible with the idea of minimizing adverse environmental consequences of pest control. A "minor use" program was instituted to help combat the problem, but with limited success. This program, along with other aspects of the regulatory process has led to the channeling of scarce public-sector, scientific resources away from innovative research into more monitoring/regulatory roles (CAST, 1981).

The 1978 Federal Pesticide Act initiated changes intended to simplify the registration process and to help further in overcoming the "minor use" problem. A "tier" system of registration is being proposed for "biorationals," which could lower the cost of registration to less than $100,000 and could reduce the time taken to meet registration requirements by two and one-half years (Shaffer, 1981). Obviously these changes are strong incentives for promoting biological control which is seen as more environmentally sound and more "target specific" (and therefore

not amenable to development under the present registration system).

Another easing of the regulations has been in terms of allowing the sale of tank-mixed herbicides. (Until recently, only farmers were able to tank-mix herbicides.) Tank mixing of some herbicides is now often the recommended procedure and may provide synergistic effects, or, more simply, broader spectrum control.

5. Feasibility of the Technology

Concern over the environmental aspects of chemical pest control is not likely to have a major impact on corn production. No known environmental hazards have been determined to occur over wide areas (NAS, 1975a).

The application rate of corn insecticides is relatively low. However, presently-used insecticides are not expected to remain effective indefinitely. There is no guarantee that new replacement chemicals will be found, in the light of the obstacles to registration, and the restricted range of chemicals which are effective in rootworm control. However, crop rotation and/or scouting provide effective control measures which could eliminate or drastically reduce insecticide use, thereby slowing the development of insect resistance. A large proportion of corn insecticide usage is prophylactic and 90 percent of corn insecticides are applied at, or prior to, planting (NAS, 1975a, p. 51). However as much as 60 percent were subsequently found in an experiemnt to have been applied unnecessarily (NAS, 1975a, p. 77). The recent rise in insecticide treatment costs have made "scouting" a viable proposition in some areas. Assuming that all corn will be grown in rotation in the near future, 27 million lbs of insecticide would be applied to the U.S. corn crop (assuming 1980 application rates and acreages) - see section 3. If scouting can then eliminate all unnecessary applications, insecticide application would fall from 27 million lbs to 11 million lbs. With the long-run possibility of more insect-resistant corn hybrids, the overall vulnerability of corn insect control seems minimal, although chemical control is in a somewhat vulnerable position.

Corn weed control is a different proposition. On the positive side, weed resistance to herbicide use in corn has not been a major problem (Aldrich et al., 1979), because of the low persistence of most herbicides and the large reservoir of weed seeds in the soil (Gressel, 1978). Furthermore, there are a number of chemical compounds which are able to provide effective weed control in corn. Thus, the removal of a few families of herbicides from the market or the development of some weed resistance would cause little problem (Behrens, 1981), because substitute chemicals are available. On the other hand, the recommended rate of herbicide applications per acre is much

larger than for insecticides (Table VI-1) and the only feasible alternative to herbicides is to increase tillage (with severe soil erosion consequences). While herbicides have low toxicity to mammals, their high application rates and lack of suitable (non-chemical) substitutes suggest that some vulnerability exists (although perhaps more for soil erosion control than for weed control, since the most obvious alternative to herbicides is tillage).

6. Alternatives to the Technology

While the primary reliance on pesticides, especially herbicides, is expected to continue (NAS, 1975a; Carlson, 1979), alternatives do exist. Some of these were discussed in previous sections. New types of weed control (e.g., lasers, radiation) could totally or partially substitute for chemical control. New types of applicators may significantly lower the application rate by wiping herbicides directly onto weeds or by catching and recirculating the herbicide which does not contact the weed (Bode, 1980). Other ways to more efficiently use herbicides would be to use thickeners in the spray to reduce drift; to put a positive electrostatic charge on herbicide droplets (which are then attracted by the negative charge on plants), thus avoiding waste. A potential technology which shows some promise is to attach weed seeds. Seeds could be killed directly by sterilant, or their untimely germination and death could be promoted by chemical treatment. Biological control of weeds in corn is not likely to have a major impact on Corn Belt weeds (OTA, 1979; Behrens, 1981). Most Corn Belt weeds are worldwide problems, suggesting that natural predators do not exist elsewhere.

Another alternative to chemical pest control is insurance. Carlson (1979) discusses possible institutional approaches and problems with pest insurance, which must be regarded as a possibility, although the data base is lacking for the setting of rates, etc. Moreover, it is likely that this would not be a cost effective alternative compared to a well designed and well implemented integrated pest management program.

7. Managing the Technology

Although corn pests presently seem to be "under control," a National Academy of Science report (1975a) recommended that the following contingency action procedures be implemented:
  (i) Make inventories of chemicals other than those in common use, which are effective against specific pests.
  (ii) Adopt legal and administrative procedures in order to move quickly against unforseen pest outbreaks (including region-wide programs).
  (iii) Make inventories of appropriate plant genetic materials.

Non-chemical pest control measures frequently involve the substitution of knowledge (by the farmer or by a scout) for the chemical. The present system, with a heavy dependency on chemicals, is somewhat self-perpetuating in that the chemical companies have a vested interest in providing farmers with information relating to chemical use, but not relating to non-chemical control methods. For example, only 10 percent of insect control information of California cotton growers originates from the agricultural extension service, while 70 percent originates from the chemical companies (Luck et al., 1977). The knowledge base for non-chemical control must come from the public sector (e.g., see Blair et al., undated). A multidisciplinary systems approach is necessary for such research to succeed and ways of funding, organizing and implementing such research have to be found (Huffaker, 1980). It may also be desirable to have increased public involvement in the application of chemicals (training, licensing, etc.) and in the general implementation of community-wide pest control problems (e.g., Menz and Auld, 1977; Auld et al., 1979).

Footnotes

1/"Use rate" is the total amount of herbicide applied to corn divided by the total number of corn acres treated. Since some corn acreage receives multiple applications of herbicide, "average use rate" is not quite the same as "average application rate."

2/An overview of the legal aspects relating to pesticide use in agriculture is given in NAS (1975b), Chapter 8.

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Appendices

Appendix tables begin on the next page.

Appendix Table VI-1. Weed Control Strategies for Corn in the Corn Belt

WEED PEST	Threat Potential Now	Threat Potential 10-15 a/	BIOLOGICAL	Seeding Date	Tillage	Drainage	Crop Sequence	Nutrition	Sanitation	Pre-Emergence	Post-Emergence
ANNUAL BROADLEAF											
Common Cocklebur	1	1	1	2	2	3	1	3	1	2	3	2
Carpet Weed	1	2	1	2	2	3	1	3	1	2	3	2
Common Sunflower	1	2	1	2	2	3	1	3	1	2	3	2
Common Lambsquarter	1	1	1	2	2	3	1	3	1	2	3	2
Pigweed	1	1	1	2	2	3	1	3	1	2	3	2
Velvetleaf (Button Weed)	2	3	1	2	2	3	1	3	1	2	3	2
Smart Weed	1	1	1	2	2	3	3	3	1	2	3	2
Common Ragweed	1	1	1	2	2	3	3	3	1	2	3	2
Giant Ragweed	1	1	1	2	2	3	3	3	1	2	3	2
PERENNIAL BROADLEAF											
Common Milkweed	1	2	1	2	2	2	1	3	1	1	2	2
Honeyvine Milkweed	2	3	1	1	1	1	1	3	1	1	2	2
Hemp Dog Bane	1	1	1	2	2	2	1	3	1	1	2	2
Wild Sweet Potato	2	2	1	1			1	3	1	1	2	2
Field Bind Weed	1	2	1	1			1	3	1	1	2	2
Swamp Smart Weed	1	1	1	2			3	3	1	1		
Morning Glory	1	2	1					3	1			
Witch Weed	0	1-3	1	1	3	3	1	3	?	3		
Wild Cucumber	1	2	1					3	1			
Canada Thistle	1	1	1					3	1			
ANNUAL GRASSES											
Giant Foxtail	2	2	1	2	1	3	1	3	2	2	3	2
Yellow Foxtail	1	1	1	2	1	3	1	3	2	2	3	2
Green Foxtail	1	1	1	2	1	3	1	3	2	2	3	2
Crab Grass	1	1	1	2	1	3	1	3	2	2	3	2
Fall Panicum	2	3	1	2	1	3	1	3	2	2	3	2
Barnyard Grass	2	2	1	2	1	3	1	3	2	2	3	3
Nible Will	1	1	1	2	1	3	1	3	1	2	3	?
Goose Grass	2	2	1	2	1	3	1	3	1	2	3	3
Shatter Cane	2	3	1	2	1	3	1	3	1	2	3	2
PERENNIAL GRASSES											
Quack Grass	1	2	1	2	2	3	1	3	2	1	3	3
Johnsongrass	2	2	1	3	3	2	1	2	1	1	3	3
Bermuda Grass	1	1	1	2	2	3	1	3	2	1	3	3
Yellow Nutsedge	2	2	1	3	3	2	3	3	1	1	3	2

Key:

Threat		Control
1	low	not effective
2	medium	some effect
3	large	moderate to major effect

a/ Threat potential in 10-15 years.

Appendix Table VI-2. An Estimate of the Present and Potential Importance of
    Insect Pests on Corn

Insect	Losses with Present Controls		Losses if Present Controls Not Used	
	Special Local Areas	Cornbelt	Special Local Areas	Cornbelt
European corn borer	M	L	H	M
Western corn rootworm	M	L	VH	M
Northern corn rootworm	M	L	H	M
Southern corn rootworm	VL	VL	L	VL
Black cutworm	M	L	H	L
Wireworm	M	VL	M	L
White grub	L	VL	M	L
Grape colaspis	VL	VL	VL	VL
Seed-corn maggot	L	VL	M	VL
Seed-corn beetle ·	L	VL	M	VL
Armyworm	L	VL	M	VL
Fall armyworm	L	VL	M	VL
Corn leaf aphid	L	L	M	L
Billbug	L	VL	M	VL
Stalk borer	M	VL	M	L
Flea beetle	L	L	M	L
Corn earworm	L	L	L	L
Southwestern corn borer	M	VL	M	VL
Mite	M	VL	H	VL

VL = Very Low (0-1%)

L = Low (2-10%)

M = Moderate (11-35%)

H = High (36-50%)

VH = Very High (over 51%)

Appendix Table VI-3. An Estimate of the Present and Potential Importance of Diseases in Corn

Disease	Losses with Present Controls in Effect		Potential Losses Should Present Controls Fail or Not Be Used	
	Local Areas	In Sector	Local Areas	In Sector
Seed rot	L	L	H	M
Seedling blight	L	L	M	M
Stewarts bacterial wilt and leaf blight	M	L	H	L
Northern leaf blight	H	L	VH	H
Southern leaf blight	M	L	VH	M
Helminthosporium leaf spot	M	VL	M	L
Yellow leaf blight	M	L	H	L
Eyespot	L	VL	L	VL
Crazy top	VL	VL	VL	VL
Sorghum downy mildew	L	VL	H	L
Common corn rust	M	L	M	M
Southern corn rust	VL	VL	VL	VL
Other leaf blights	L	VL	L	VL
Maize dwarf mosaic	M	VL	VH	L
Maize chlorotic dwarf	M	VL	H	L
Bacterial stalk rot	VL	VL	VL	VL
Pythium stalk	VL	VL	VL	VL
Diplodia stalk rot	M	L	M	M
Gibberella stalk rot	M	L	M	M
Fusarium stalk rot	L	VL	L	L
Charcoal rot	L	VL	L	L
Common smut	L	VL	H	M
Nematodes	VL	VL	VL	VL
Storage rot	M	L	VH	M

VL = Very Low (0-1%)

L = Low (2-10%)

M = Medium (11-35%)

H = High (36-50%)

VH = Very High (over 51%)

Tillage practices and crop rotations are both important agronomic technologies. The heavy concentration of corn and soybean row crops in the Corn Belt has had negative consequences for soil erosion control. Crop rotations and reduced tillage are both, in a sense, erosion control techniques. Crop rotations may also have beneficial implications for soil fertility and pest control. Insofar as reduced tillage is expected to increase pest problems in corn, reduced tillage may become especially attractive in conjunction with crop rotations, which can effectively reduce some insect pest problems.

Tillage

1. Definition and Description of Tillage

Tillage refers to the working of the soil. Conventional tillage can be defined as the use of a plow to turn the soil (usually a moldboard plow), or the use of implements such as harrows and disks to condition the seedbed prior to planting and for weed control. Reduced tillage can be regarded as tillage, which: (i) does not involve the use of the moldboard plow (conventional tillage); (ii) uses herbicides as the primary method of weed control; and (iii) attempts to leave enough residue on the soil surface to significantly reduce erosion. Reduced tillage embodies both no-tillage and various forms of conservation tillage. Corn is well-suited to reduced tillage because: it is a vigorous competitor with weeds in the seedling stage; corn is not overly susceptible to herbicide damage; and it is an erosive (row) crop.

The emphasis in this assessment is on reduced tillage, because the predominant trend is away from conventional tillage of corn to reduced tillage. Both types of tillage are discussed, however, since any assessment of reduced tillage must be made relative to conventional tillage. The major characteristics of reduced tillage to be discussed in this report are the short-run economic aspects and the long-run effects on soil erosion.

2. Direction and Magnitude of the Reduced Tillage Technology

The use of 2,4-D to control weeds began in the late 1940s and was a prerequisite to the reduction of tillage. Subsequent developments in the manufacture and application of other herbicides enabled them to be used for weed control in place of tillage. Initially they substituted for post-planting cultivations, but subsequent substitutions were also made for pre-planting cultivations. The development and introduction of the pre-planting herbicide, paraquat, in the 1960s gave reduced tillage a boost (USDA, 1975).

Information on the acreage of corn grown under different tillage treatments is available from surveys carried out under the auspices of No-Till Farmer Magazine (Table VII-1). There has been a consistent increase in reduced tillage for corn, both in absolute terms (column 1) and as a percentage of total corn acreage (column 3). In 1979 and 1980, approximately one-third of the total corn acreage was reduced-tilled (more than any other crop). The survey also estimated that the number of no-till corn acres (included under "reduced tillage" in Table VII-1) has remained at about 4 percent of total corn acreage since 1973. The present trend is away from conventional to reduced tillage, rather than to no-till.

The trend from conventional to reduced tillage is expected to continue. In a recent study, Worsham (1980) surveyed relevant research and extension personnel in the 25 leading corn producing states. He concluded that 48 percent of corn would be under reduced tillage by 1990. This would translate into about 60-70 percent of corn land under reduced tillage by the year 2000. In another recent study, Crosson (1981) estimated that 50-60 percent of U.S. cropland would be reduced tilled by 2010. This estimate is not in conflict with the Worsham estimate if one takes into consideration that the Crosson estimate was not for corn specifically, but rather for all crops and that his estimate was a conservative one. In addition to these two studies, there is

Table VII-1. Acreage of Reduced and Conventional Tillage for Corn, 1972-80

	Reduced Tillage	Conventional Tillage	Reduced Tillage as a Percent of Total
	(million acs)		(%)
1972 -	12.6	58.8	18
1973	16.6	55.6	23
1974	16.7	58.6	22
1975	18.6	56.1	25
1976	19.4	61.9	24
1977	20.9	60.6	26
1978	21.0	58.8	26
1979	26.3	53.7	33
1980	26.6	52.2	34

Source: 1979-80 Tillage Survey, No-Till Farmer, 1980.

an earlier study by USDA (1975) which estimates that 97 percent of all North-Central cropland will be reduced-tilled by the year 2000. Overall, the Worsham estimate appears to be the most reliable one to date for corn.

3. Direct Effects of the Reduced Tillage Technology on Corn Production

3.1 Yield Response and Aggregate Production Capacity

The major effect of reduced tillage on yield is that it can prevent long-term yield losses by controlling soil erosion (this is discussed in section 4). In the short-run, switching to reduced tillage has little effect on yield.

A substantial body of evidence has now been accumulated pointing to the general yield comparability of conventional and reduced tilled corn (for a summary, see McKibben, 1979; Griffith et al., 1977). However, under certain circumstances, yields can vary widely (Unger and McCalla, 1980).

Reduced tillage can increase the aggregate production capacity of U.S. corn production by: (i) bringing land into production which is too steep to farm under conventional tillage without unacceptable levels of soil erosion, and (ii) facilitating multiple cropping by reducing the time between harvesting of the first crop, and planting the second. It is doubtful whether multiple cropping will result in significantly

increased total corn production. Corn is a relatively slow maturing crop and where reduced tillage does make double cropping feasible, corn is not likely to be one of the crops involved. Certainly (i) is valid - additional cropland can be brought into production using reduced tillage (Larson, 1981), however it is difficult to know how much of of this would be used for corn (see Chapter XII). No attempt is made in this report to quantify the amount of land not presently being used for corn, but which could be made suitable for corn production by reduced tillage.

3.2 Costs and Profitability

Cost savings from fuel, labor and machinery purchases are possible with reduced and no-tillage systems. These are summarized in Table VII-2 which shows that savings of $5.50 per acre can be realized by switching from conventional to reduced tillage, and $12.90 per acre by switching from conventional to no-tillage.

These cost savings are partially counteracted by additional herbicide costs (Table VII-3). Purdue University (Richey et al., 1977) herbicide recommendations for corn are 0.65 lbs/ac extra for reduced tillage and 1.4 lbs/ac extra for no-tillage (20 and 44 percent per acre increases over conventional tillage, respectively). Overall, there is a small per acre profit advantage of $3 per acre attributable to reduced tillage (Table VII-3). This is considerably below Crosson's (1981) estimate of $11. The reason for our lower estimate is that we attributed lower machinery and labor cost advantages to reduced tillage. It appears that Crosson's assumption of labor savings (50%) with reduced tillage is too high, as our own estimate (from the literature) of labor savings is about 10 percent of the total labor used in corn production.

In estimating the profit advantage for reduced tillage in Table VII-3 no additional costs have been charged for potential pest (other than weed) problems or for additional fertilizer, although there is some evidence that problems in these areas may be encountered (e.g., Gregory and Musick, 1976; Boosalis and Duopnick, 1976; Thomas et al., 1973; Worsham, 1980; Phillips et al., 1980). However the evidence is conflicting for fertilizer (e.g. Crosson, 1981) and for insect and disease control. Existing practices, perhaps combined with rotations, are expected to satisfactorily cope with any additional problems (Gregory and Musick, 1976). Corn insects and diseases do not usually survive in soybeans, and vice-versa (Richey et al., 1977).

A key factor in the adoption of reduced tillage by farmers is the short-run economic gain to be made. Although there appear to be an even higher profit advantages for no-tillage, this has not

Table VII-2. Cost Savings by Switching from Conventional to
Reduced Tillage and No-Tillage

	Cost Savings ($/ac/yr)		
	Fuel[a/]	Labor[b/]	Machinery[c/]
Reduced Till	$1.50	$1.60	$2.40
No-Till	$4.20	$3.70	$5.00

Source: No-Till Farmer (1980), various issues.

[a/]These figures are in the same order of magnitude as indicated by
USDA (1975, 1980); Wittmus et al. (1975); Richey et al. (1977);
Worsham (1980). Assumes diesel costs of $1/gal.

[b/]Assumes labor costs $5/hr. Labor saved in no-tillage is about 50
percent of total pre-plant and planting labor for conventional til-
lage. The percentage is less for reduced tillage. See Mannering
and Burwell (1968); Derscheid et al. (undated); and Doster and
Phillips (1973) for similar estimates of labor saving.

[c/]Assumes 10 year life of machine, 500 acres of corn/machine. Machine
costs are less with reduced tillage because tractors do not have to be
so powerful. The No-Till Farmer savings figure for no-till ($10.20)
appears to be high when compared with the $5 estimate by Siemans and
Oschwald (1978) and $2 by Doster and Phillips (1973). Consequently
the intermediate figure of $5 has been substituted for the No-Till
Farmer estimate. The minimum tillage savings were more consistent
across sources. The machinery situation is complicated by the fact
that periodic soil renovation may be necessary in some soils
(Parochetti, 1980). However, this will probably be infrequently
enough so that renting the machinery is possible. Planters are now
available which can plant corn both no-till and after tillage, but
these planters may not suffice for other crops in rotation. The
possibility exists that some farmers would have to own both tillage
and no-tillage equipment (Crosson, 1981).

been reflected in the adoption rates (section 2).
Reasons for this could be that: (i) the technol-
ogy is not yet fully developed (especially weed/
pest control aspects); (ii) there is more yield
risk involved with no-tillage (as greater manage-
ment skills are required); and (iii) yields are
slightly lower with no-tillage. (It would take
less than a four bushel decline in corn yields to
eliminate the profit advantage for no-tillage.
Such a decline may exist, although it is not yet
apparent.)

3.3 Resource Use and Productivity

While both labor and energy can be saved by
shifting from conventional to reduced tillage
systems, the savings are small percentages (~10%)
of the total amounts of labor and petroleum-based
energy used per acre of corn. Therefore, the
effect on total energy and total labor use is
correspondingly small. However the savings from
reduced tillage in terms of labor and diesel fuel
used in planting, weed control and seedbed prepa-
ration are nearer to 50 percent. The saving in
diesel fuel is 2-3 gallons per acre. Labor saving
is about 0.3 hours per acre, but the importance of
this saving may be greater than is obvious from
the size of the number taken in isolation. Since
the labor saving occurs around planting time, it
may facilitate timely planting or increase the
acreage planted per person and per machine.

A qualitative comparison between conventional,
reduced and no-tillage systems is made in Table
VII-4.

4. Other Aspects of the Reduced Tillage
Technology

4.1 Environmental Aspects - Soil Erosion

If left unchecked, soil erosion eventually
leads to reductions in crop yields. The maximum
level of soil erosion which can take place without
causing any reduction in crop yields is called
the "soil loss tolerance level" (sometimes abbre-
viated to "T," and usually expressed as a rate of
soil loss per acre per year).

Table VII-3. Profit Advantage for Reduced and
No-Tillage in Corn as Compared With Conven-
tional Tillage

		Extra	Profit
	Savings[a/]	- Costs[b/]	= Advantage/Ac
Reduced Tillage	$5.50	$2.50	$3.00
No-Tillage	$14.90	$5.50	$9.40

[a/]From Table VII-2.

[b/]For Herbicides.

Table VII-4. A Comparison of Characteristics of Several Tillage Systems

Quality	Moldboard Plow (conventional)	Reduced Tillage	No Tillage
Time and labor demand	most	moderate	least
Fuel consumption	greatest	moderate	least
Dependence on herbicides	least	intermediate	greatest
Control erosion	poorest	fair	greatest
Opportunity to double crop	poorest	fair	greatest
Requires learning new system	least	intermediate	greatest
Support machinery when soils are wet	least	good	greatest
Adaptable to poorly drained soils	best	fair	least
Minimize insect and disease problems	best	good	least
Special planter required	no	no	yes
Special problems with soil fertility	no	no	no

Source: Triplett (1976).

In 1977, 33 percent of U.S. corn land was estimated to have annual erosion rates greater than 5 tons per acre (USDA, 1978). This figure of 5 t/ac is slightly above the average rate of loss (4.5 t/ac) thought to be compatible with sustaining crop productivity in the Corn Belt (Lindstrom et al., 1979b). Thus it appears that about 40 percent of corn land exceeds this 4.5 t/ac maximum soil loss tolerance value. In other words, under present soil management practices, about 40 percent of the corn land will experience a permanent reduction in productivity in the future, due to soil losses by erosion.

To illustrate the influence of tillage on soil erosion, the amount of corn land which would exceed the soil loss tolerance level (T) was estimated assuming one type of tillage (based upon the data in Lindstrom et al., 1979a).1/

	Percent of Corn Land Exceeding T Value
Conventional Tillage	69
Reduced Tillage	31
No-Till	24

Clearly, alleviation of soil erosion is a positive environmental consequence of reduced tillage. Furthermore, it appears that reduced tillage has already been successful in shifting significant amounts of corn land from above the soil loss tolerance level to below it. The reasoning behind this statement is as follows:

with no reduced tillage, 69 percent of corn land would exceed the soil loss tolerance level, but it is estimated that presently only 40 percent of corn land is exceeding the tolerance loss level. The difference is in line with the amount of corn presently grown under reduced tillage (34%). It is not realistic to think that every acre of reduced tilled corn has shifted the land from above the tolerance level to below it, and the data are not sufficiently "hard" to suggest such a strong conclusion. However, the evidence does suggest that reduced tillage is being applied with the highest frequency in those areas where soil erosion is a problem.

In an attempt to further support this conclusion, the potential erosion on land used for corn production in each state was compared with the amount of reduced-tilled corn in that state. The potential for corn land soil erosion in each state was taken to be the percentage acres of corn land exceeding the soil loss tolerance level, assuming all corn land is conventionally tilled. The figures are shown in Table VII-5, where it can be seen that a positive relationship does exist between soil erosion potential and implementation of reduced tillage for corn (r = 0.47). Presumably the relationship would be even stronger at an aggregation level less than the entire state (e.g., see Crosson, 1981, p. 21).

The average soil loss weighted by acreage for the Corn Belt is 10 t/ac/yr (Lindstrom et al., (1979b). It has been estimated that on a typical Corn Belt soil, erosion rates of 10 t/ac/yr

Table VII-5. Percent of Corn Land in Conventional Tillage Exceeding
Soil Loss Tolerance Level and Percent of Corn Land Reduced Tilled,
by State, 1980

State	Corn Land Above Tolerance Loss Level (Conventional Till)[a]	Corn Land Under Reduced Tillage[b]
	(% of total)	
Minnesota	32	19
Illinois	76	20
Wisconsin	52	22
Ohio	52	28
South Dakota	49	29
Missouri	98	34
Kansas	80	40
Iowa	72	42
Indiana	69	46
Nebraska	67	50

[a] Calculated from unpublished data of Lindstrom et al. (undated).

[b] From No-Till Farmer Survey, 1980. Missouri and Wisconsin data
from the 1979 Survey (since there was an apparent misprint in 1980
survey figures for those states).

result in a corn yield decline of 3 bu/ac every
15 years (or 0.2 bu/ac/yr, USDA, 1980). On the
assumption that each acre of reduced tillage effec-
tively adds 0.2 bu/ac/yr to corn yield (via a
reduction in soil erosion), almost 5 million
bushels of corn are being added to the harvest
each year (0.2 bu/ac/yr x 0.34 reduced tilled x
73 million acres) with a value of $13.5 million
(at a 1980 corn price of $2.70/bu). In present
value terms, the total future saving from reduced
tillage which has already been implemented, is
$192 million (discounted at 7 percent).

A maximum of 69 percent of corn land can be
brought within soil loss tolerance limits by a
combination of reduced and conventional tillage.
A further 7 percent of corn land can be brought
"under control" by no-tillage. Based upon the
economic incentives calculated in Table VII-3,
free market forces might be expected to bring
about these changes in erosion control. However,
it must be remembered that those figures are only
estimates, and furthermore, they are estimates for
"average" conditions. Some individuals or regions
may not find it profitable to switch to reduced
tillage methods, but even in those cases, reduced
tillage is not likely to be much less profitable
than conventional.

The short term costs of soil erosion to the
farmer often do not provide sufficient economic
incentive for them to control erosion (Waelti,
1981). For example, 3 bu/ac corn yield reduction

every 15 years reduces profits by less than
$1/ac/yr. Furthermore, yield decreases from soil
erosion may not actually be observed because of
their "masking" by other improvements in yield
enhancing technology.

With 76 percent of soil erosion on corn land
controllable by conventional, reduced, and no
tillage, only the remaining 24 percent require
action beyond the implementation of erosion-
controlling tillage techniques. It was determined
(again using Lindstrom et al.'s data) that 96 per-
cent of the excessive soil loss in the Corn Belt,
would be in Iowa, mostly on land sloping at 6-12
percent. For these areas, additional conservation
measures beyond no-tillage will be necessary to
bring erosion within the tolerance limits.
Reduced tillage plus contouring (the latter at a
cost of about $1/ac/yr (EPA, 1978)) would be suf-
ficient to bring erosion within acceptable limits
in most of Iowa. Almost all of the remaining land
could be brought within tolerance limits by
reduced tillage plus contouring at $5/ac/yr (EPA,
1979). One alternative which would reduce erosion
is growing less-erosive crops, however the oppor-
tunity cost of growing these would usually be more
than $5/ac/yr (see section 6). Contouring or
terracing would therefore seem to be the preferred
action, assuming that this would not impose high
"indirect" costs, such as specialized machinery
purchase).

4.2 Environmental Aspects - Chemicals

As discussed earlier, there is a potentially negative environmental aspect to reduced tillage, which is the additional herbicide input required for effective weed control. This, in itself, is not proven to be a problem. The desire to keep chemical use and runoff to a minimum, is based more on the fear of the potential, but unknown, consequences which might result. While herbicide use will increase by about 20 percent with reduced tillage, the concomitant reduction in soil erosion means that herbicide run-off will increase by less than 20 percent, if at all, since herbicides adhere to soil. In an Iowa study (EPA, 1979) pollution from herbicides frequently used on corn was decreased by 25 percent by adopting reduced tillage, implying that the net effect of reduced tillage on herbicide pollution was close to zero (25 percent decrease in pollution by runoff approximately balancing 20 percent increase in application rate). With some herbicides, including paraquat, which is strongly adsorbed on soil and commonly used in reduced tillage, the net effect of reduced tillage on herbicide runoff may be beneficial (Wauchope et al., 1981).

Reduced tillage increases water infiltration and reduces water runoff (with its associated herbicide content). While this increases the amount of herbicides going through the soil, subsurface water contamination by herbicides is rare, because they are not persistent (Wauchope et al., 1981 . Overall, the effect of reduced tillage may well be to reduce environmental damage from herbicides (compared with conventional tillage) despite an increase in herbicide use. This opinion was supported by Hanson (1981).

Reduced tillage may adversely effect nutrient (nitrogen and phosphorus) losses from soils in the following ways (Wauchope et al., 1981): (i) crop residues left on the surface of the soil are a source of nitrogen and phosphorus in runoff; (ii) surface application of fertilizers also increases nitrogen and phosphorus runoff; and (iii) increasing water infiltration into the soil leads to increases in ground water nitrate levels. Overall, reduced tillage probably increases nitrogen problems in runoff and in groundwater; the effect on phosphorus pollution problems is less clear since the increases in surface applied phosphorus in run-off is balanced by the reduction in phosphorus carried in soil (Crosson, 1981).

5. Feasibility of the Reduced Tillage Technology

In general terms, the reduced tillage technology is feasible for corn production, and it can also successfully control soil erosion on most of the nation's corn land, at zero or modest cost. In some areas, however, successful weed control is not presently possible without chemicals.

In all areas, the composition of the weed population will change over time with weeds that are resistant to herbicides (usually perennials) becoming dominant. Indeed, control of perennial weeds was cited as the major problem of reduced tillage in corn in the recent survey conducted by Worsham (1980). Chemical weed control is more difficult under reduced (cf. conventional) tillage conditions, probably because of interception of the chemicals by surface mulch. Yet surface mulch is necessary for the successful control of soil erosion. All of the calculations based upon the Lindstrom et al. (1979a) data assume 3500 lbs/ac corn residue is left on the surface. Removal of surface mulch for other reasons, such as energy production, or to increase herbicide effectiveness, will greatly reduce or decrease the value of reduced tillage in controlling erosion (Lindstrom et al., 1979a). It should, however, be possible to design machinery which temporarily removes the mulch from the ground while the herbicide is applied.

Some research work is presently underway using chemicals, which occur naturally in cover crops or mulches, for weed control (Worsham, 1980). While this is a relatively new area of study, it shows some promise and would greatly facilitate the implementation of reduced and no-tillage. Weed control could be achieved directly by a cover crop of mulch, without resorting to herbicides (Hager, 1980).

The reduced tillage technology for corn is in its infancy and will improve as science, industry and farmers themselves continue to develop and adopt it in the light of their previous experience (e.g., planting on ridges, Behn, 1977). Refinements will have to be made to the machinery and other components of the technology to meet local conditions, and a whole new generation of more flexible machinery may be necessary to allow this to occur.

6. Alternatives to the Reduced Tillage Technology

The major alternatives to reduced tillage methods for achieving soil erosion control are: (i) contouring/terracing; or (ii) switching from corn into less erosive land uses (pasture, small grains). Reduced tillage appears to be more profitable than either of these alternatives. Therefore, they would only have a role to play in areas where reduced tillage, in itself, is not sufficient to control erosion (see section 4). Contouring at $1-2/ac/yr is cheapest, followed by terracing, which at $5/ac/yr is more expensive, but also more effective (EPA, 1978). Introducing small grains, or pasture into the rotation is an expensive form of erosion control (in terms of the foregone returns from corn). USDA (1980b) indicated costs ranging from around $30/ac upwards, depending upon the frequency of these crops in the rotations. Crop budgets for the Corn Belt

region of Southern Minnesota (Benson et al., 1981) show the cost of substituting wheat for corn as being $15/ac. (Substituting alfalfa for corn costs much more.) Where a supplementary erosion control measure is needed, in addition to reduced or no-tillage, earthmoving is the least-cost alternative. Crop rotation does not look economically feasible when viewed strictly from the point of view of erosion control. (The most profitable rotation, corn-soybeans, has no beneficial effect on erosion, as compared to corn following corn.)

7. Managing the Reduced Tillage Technology

Reduced tillage not only can bring short term economic advantages to farmers who adopt it, but can and is, successfully controlling soil erosion on much of the nation's corn land, in the process saving perhaps $14 million annually in corn production which otherwise would be lost. Projections have been made for reduced tillage that it will be implemented on 60-70 percent of corn land by the year 2000. Modest economic subsidies (e.g., on no-tillage equipment) or legislative incentives (e.g., implementation of soil loss tolerance laws) could push the figure higher. Research aimed at enhancing the economic feasibility of reduced tillage (e.g., in areas of weed control, reduced tillage machinery) provide an alternative means of encouraging reduced tillage.

These complementary attributes of reduced tillage - (i) short-run economic advantages for the farmer; and (ii) long-run economic advantages for both the farmer and society - present a unique opportunity for achieving a socially desirable goal (soil erosion control), without any apparent conflict between society and the major affected party (farmers).

A prerequisite to any sensible policy decisions about managing the reduced tillage technology is to arrive at politically and scientifically acceptable soil loss tolerance values. There seems to be a consensus that maintenance of long-term soil productivity is a reasonable objective, but considerable uncertainty exists as to how to translate that objective into practical soil loss tolerance values.

Crop Rotation

1. Definition and Description

Crop rotation refers to a system of growing different kinds of crops in recurrent succession on the same land (Martin and Leonard, 1967). Since corn is a relatively slow maturing (annual) crop, it does not lend itself to double cropping (the growing of two crops per year). Therefore, most of the discussion in this section is in the context of an annual rotation. The within-year (double cropping) rotation will only be discussed as a potential substitute cropping system for corn.

2. Direction and Magnitude of the Crop Rotation Technology

During the 1930s corn was usually grown in rotation with hay and small grains. This was necessary in order to ensure adequate nitrogen for the corn, and because roughage feeds had to be grown for the livestock, which were an integral part of corn-producing farms at the time. Soybeans were not grown extensively in this early period.

Two subsequent developments altered the rotational pattern: (i) the availability of cheap fertilizer nitrogen, which substituted, to some extent, for legume crops; and (ii) widespread adoption of soybean growing in traditional corn-growing areas. (Note that these soybeans did not really "displace" corn, in that corn acreage remained fairly constant.)

The present heavy concentration of row cropping in the Corn Belt (Larson, 1981) and the omission of hay from rotations including corn, has enabled corn farmers to become more specialized producers. They have made large investments in planting/harvesting machinery for corn and in storage/handling/drying facilities for corn. This "structural change" has meant that only a dramatic fall in the relative price of corn would entice corn farmers back to growing small grains or hay. Another reason why corn farmers would not readily return to growing oats and hay is that livestock enterprises, once an integral part of most corn farms, are currently run as independent operations, mostly in regions remote from the main corn growing areas. Thus local (Corn Belt) markets for oats and hay are small. Furthermore, the costs of re-integrating livestock enterprises into present-day corn farms would be large.

At present, the crop most commonly grown in rotation with corn is soybeans. Forty-eight percent of the corn acreage is grown in this rotation. This figure refers to a strict two year rotation and does not include such rotations as soybeans-soybeans-corn. The percentage of "corn following soybeans" would be higher than 48 percent. Twelve percent of corn follows a previous corn crop, but is not "continuous" corn, while another 9 percent of corn is continuous. (These percentages were calculated from data in Lindstrom et al., 1979a, and refer only to the Corn Belt, broadly defined.2/)

Although the proportion of corn in various rotations was not calculated on a regional basis, significant regional variation does exist. An indication of the regional picture can be gauged from the percentage of cropland in different regions of the Corn Belt (Table VII-6). In general, corn is less prominent in rotations in Southern Corn Belt areas, where soybeans are relatively more important. (The exception is the irrigated part of the Southwestern Corn Belt.)

Table VII-6. Percentage of Cropland in Different Regions of the Corn Belt[a/]

		Crop		
Region	Corn	Soybeans	Small Grains	Hay
Central	50	30	10	10
Southern	33	33	11	22
Northwest	50	13	26	13

[a/] Adapted from Lindstrom et al., (1979b).

3. Direct Effects of Crop Rotation Technology

3.1.1 Yield Response

Rotation of corn with other crops has been shown experimentally to increase corn yields. The corn yield response to rotation depends, in part, on the inherent fertility of the soil and to the amount of fertilizer nitrogen added. Soybeans is the most popular crop in rotations with corn. At currently-used fertilizer nitrogen levels (100+ lbs/ac) the EPA (1978) cites a 12 bu/ac corn yield advantage for the corn-soybean rotation over the corn-corn rotation. An extensive six year experiment in southern Minnesota at the University of Minnesota, Waseca (Randall, 1981) resulted in an average corn yield advantage over a range of nitrogen levels for the corn-soybean rotation of 34 bu/ac. Hicks (1981) found a 14 bu/ac yield increase in a two year experiment in the same region. Welch (1977) reported a 23 bu/ac and a 15 bu/ac gain in two separate Illinois experiments. A replicated, multi-year, farm-level experiment in Southern Minnesota showed an average gain of 13 bu/ac (Urevig, 1981). For a summary of other data, see Ewing, 1978; Schrader and Voss, 1980, Welch, 1979. Clearly the corn yield advantage from a corn-soybean rotation is variable, depending upon circumstances, but overall, a 15 percent yield increase, at moderate fertility levels, is not an unreasonable expectation.[3/]

There is evidence that the increase in corn yield following soybeans is not due to nitrogen carryover. First, direct measurement of the nitrogen contribution of soybeans indicates that it is perhaps 30-40 lbs/ac (Schrader and Voss, 1980) with little of this being available early in the corn growing season (Crookston, 1981). Second, a 15 percent increase in corn yield has been found even when very high levels of nitrogen are applied to corn (Welch, 1977; Randall, 1981). Finally, Randall (1981) found that wheat (a non-legume) had approximately the same yield enhancing effect as did soybeans. It is not clear what does cause the yield decrease in continuous corn. (A number of other possibilities for the increases in corn yield when grown in rotation were discussed by Welch (1977), but without any clear conclusion.) There is some evidence that

insects and diseases are more of a problem with continuous corn and it is well established that corn rootworm (the major insect pest of corn) requires corn roots in order to survive. In general, corn insects and diseases do not survive on soybeans, nor do soybean insects and diseases survive on corn (Richey et al., 1977). For example, 87 percent of the corn following corn acreage is treated for rootworm control, compared with 29 percent of other corn acreage (EPA, 1979).

The previous discussion of a 15 percent yield response of corn to rotation was in the context of moderate fertility levels. At low fertility levels, the nitrogen contribution of the legume is more effective at enhancing yield; gains higher than 15 percent could be anticipated (such as after a good alfalfa crop, which can contribute more than 100 lbs/ac of nitrogen - Schrader and Voss, 1980).

3.1.2 Aggregate Production Capacity

As other crops displace corn in a rotation, the aggregate U.S. capacity to produce corn falls (unless soil fertility levels are extremely low). If a corn-corn rotation is changed to corn-soybeans then corn acreage is halved; however there is a compensation of a 15 percent yield increase for the corn which is grown. Overall the production capacity of the corn-corn land therefore, is 50+ (0.15 x 50) = 57.5 percent of its previous level. If the 21 percent of corn which is presently being grown after a previous corn crop was to become a corn-soybean rotation, total U.S. corn production would fall by [21 - (21 x 0.5 + 15%)], or 9 percent, assuming no new corn land came into production.

Under extremely low fertility conditions, the aggregate production capacity of corn could be increased by including alfalfa in the rotation. Yields might increase by more than the 50 percent lost in an annual rotation. However, existing soil fertility levels in U.S. corn land are presently well above such a level. Although sharp rises in energy prices could alter the situation, this is unlikely.

There is some evidence that rotating corn hybrids could have a beneficial impact on corn yields similar to rotating corn with soybeans (Hicks, 1981). While the evidence is only preliminary, and has not been found with all hybrids, if this technolgoy can be understood and developed, there is a potential impact on the aggregate production capacity of corn.

3.1.3 Aggregate Corn Production Capacity and Double Cropping

Double cropping (two crops per year) with corn is not physically feasible in the Northern Corn Belt. In the extreme Southern Corn Belt, and in

the Southeast generally, double cropping with corn is physically feasible but double cropping with crops other than corn is usually more profitable. (Corn is a relatively slow maturing crop and this detracts from its usefulness in double cropping systems.) In the Southeast, winter wheat-soybeans appears to be the most profitable form of double cropping, and monocrop corn is more profitable than wheat-corn (Eddleman, 1981; Lewis and Phillips, 1976). Although it is not clear how widespread double cropping will become, in the Southern U.S. there is a continuing trend out of corn into soybeans. The opportunity for profitable double cropping of wheat/soybeans will probably speed that trend. (Some corn may remain in the system since it is complementary to a double crop of wheat-soybeans in terms of idle labor and machine resources, Eddleman, 1981.)

3.2 Costs and Profitability

The direct cash costs of growing corn fall when other crops are rotated with corn. For example, an acre of corn following alfalfa could be produced at a savings (cf. continuous corn) of $20 for nitrogen (100 lbs x $.20 per lb), $12 for insecticide, plus a 15 percent yield "bonus" (see earlier). Based upon an expected (non-rotational) yield of 100 bu/ac, and variable costs of $136 per acre (USDA, 1981), per bushel variable costs would fall from $1.36 to $.90. While alfalfa is the most useful crop for rotating with corn from the viewpoint of reducing subsequent corn production costs, the direct economic value of alfalfa is not high enough to make it economically viable in rotation with corn (USDA, 1980). This conclusion was confirmed by calculations using data from Benson et al. (1981), which showed an annual net return (loss) of -$82/ac for a corn-alfalfa rotation. This loss is due to the high cost of establishing alfalfa every second year.4/

Soybeans contribute less nitrogen than does alfalfa to the following years' corn crop (40 lbs/ac maximum), although it provides the same 15 percent yield advantage to the corn and in addition, saves $12 in insecticide costs compared to continuous corn. Also the soybeans themselves benefit from the rotation (Abbot, 1979). Data from Hicks (1981) also shows a 4 bu/ac yield advantage for soybeans following corn compared with soybeans following soybeans. A calculation of total benefits to the two year corn-soybean rotation reveals a profit advantage compared with continuous corn or continuous soybeans:5/

additional yield from corn	$40/ac
additional yield from soybeans	$28/ac
savings in insecticide	$12/ac
total profit advantage	$80/ac

This is an extraordinarily high profit advantage over continuously growing one crop on the same land (and no credit was given for the nitrogen contribution from soybeans in these calculations).

4. Environmental Impacts of Rotations

Crop rotations can have positive environmental effects through reducing chemical applications and (potentially) by reducing soil erosion.

Insecticide treatments (mainly for rootworm) are drastically reduced by growing corn in rotation with another crop. However, only 21 percent of corn is presently grown following a previous corn crop. If this percentage is reduced to zero, it is estimated that the amount of insecticide could be reduced by 25 percent (see Chapter VI). Crop rotations are also useful in controlling weeds. The inclusion of alfalfa in a crop rotation can reduce corn nitrogen fertilizer requirements and associated nonpoint pollution (see Chapter IV).

In general, reduced tillage exacerbates pest problems, so that crop rotations become relatively more important in reduced tillage situations. With no-till, crop rotation may be necessary to control perennial weeds.

While the corn-soybean rotation is attractive from the viewpoint of profitability (in the short run), it does not reduce soil erosion compared to continuous corn. In fact, it increases erosion problems (EPA, 1978; Laflen and Modelhauer, 1979). On the other hand inclusion of small grains and/or alfalfa in the rotation reduces soil erosion significantly. For example, the corn-corn-wheat-hay rotation has an erosion rate only 25 percent of the erosion from continuous corn. However, such a rotation cannot compete profitably with continuous corn or corn-soybeans.

5. Feasibility of Crop Rotations

Overall, the corn-soybean rotation looks attractive on paper, and it is, in fact, the most popular rotation involving corn. The corn-soybean rotation reduces pest problems, the soybeans add some nitrogen to the soil, and the rotation has a general yield-enhancing effect. However, there is a problem in that this rotation results in greater soil erosion compared with continuous corn. Some combination of reduced or no-tillage and contouring or terracing would usually be sufficient to bring soil erosion within tolerable limits, if used in conjunction with corn-soybeans. (There would still be large profit advantages for corn-soybeans as compared to continuous corn, even after allowing for contouring or terracing costs.6/). Only in a few extreme cases would it be necessary to incur the cost of moving to corn rotations involving hay and small grains in order to bring erosion under control.

6. Alternatives to Crop Rotations

The alternative to crop rotations is to grow continuous corn. However, this alternative does

not look especially attractive under current and expected price regimes (see earlier sections). The already large proportion of corn grown in rotations is expected to increase, especially in conjunction with reduced tillage. The present, and expected future, popularity of reduced tillage for corn will increase the need for pest control methods to substitute for tillage. Insofar as crop rotations assist in pest control, increases in reduced tillage will decrease the attractiveness of the continuous corn rotation.

7. Managing the Rotation Technology

Estimates of the potential impacts of crop rotations on the aggregate production capacity for corn are a function of the present amount of corn grown after a previous corn crop. Our estimate of 21 percent is somewhat below the common consensus and a more reliable estimate, perhaps via a sample survey, would be valuable.

The reasons for the yield-enhancement effects of rotations remains something of a mystery. Research into understanding this phenomenum could have a large payoff, as it may be possible to promote the yield-enhancing mechanisms through management or other applied research techniques.

Footnotes

1/This manuscript presents the detailed data which was condensed into a series of articles in the March-April issue of the Journal of Soil and Water Conservation. One of these articles is referred to elsewhere in this chapter, viz. Lindstrom et al. (1979b).

2/An independent estimate (EPA, 1979), reported that 40 percent of the U.S. corn crop was "continuous corn." Upon comparison with the Lindstrom et al. (1979a) figures, it appears that the EPA study was really referring to "corn following corn" but even at that, the two estimates vary widely (21 percent versus 40 percent). Since the EPA study used gross estimates made by entomologists, the Lindstrom et al. figures are probably more accurate.

3/It is not clear whether this 15 percent yield reduction observed for corn after corn is maintained over time - it seems that the 15 percent decline may continue for only one or two years (Crookston, 1981).

4/Extending the life of the alfalfa crop to make a corn-alfalfa-alfalfa-alfalfa-alfalfa rotation does not improve the overall profitability of the rotation significantly. While the cost of establishing the alfalfa is spread over 4 years, the costs of foregone revenues from corn is also much larger.

5/Assuming that the net benefits from continuous corn and continuous soybeans are equal.

6/Reduced or no-tillage would not be expected to decrease the profitability of the rotation.

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1. Definition and Description

Mechanization in field crop production can be defined as the use of machinery to perform the necessary tasks involved in the field operations, handling and (on-farm) storage of the product. It can be thought of as the use of implements (such as plows, planters and combines) together with a source of power (usually gasoline or diesel) which increase the productivity of labor.

In corn production, mechanization takes the form of tractors or self-propelled harvesting equipment as a power source, in combination with the mechanical implements used for performing the tasks involved in corn grain production. This chapter examines mechanization in relation to seed-bed preparation, planting, mechanical weed control, and harvesting of the corn crop. The technologies of on-farm drying and storage, irrigation, fertilization and pest control are discussed in other chapters in this report.

2. Direction and Magnitude

The trend towards further mechanization of corn production in the U.S., from 1945 to the present, should be examined within the context of the incentive to mechanize stemming from the desire of individual farmers to produce a larger volume of grain in order to increase income. The volume of grain produced per operating unit is, in turn, determined by the acreage farmed and the yield per acre.

Corn producing farms in the U.S. have typically evolved into 2-person operating units which produce at least one other crop in addition to corn. The acreage farmed per production unit is limited by the amount of land on which available labor can perform timely cropping operations with a full set of modern machinery and equipment. In corn production, each stage of crop development is determined biologically and is influenced by the natural environment. These biological processes determine the time frame within which each farming operation must take place in order that

field losses and/or yield reductions are minimized. Thus, there is an optimal time period within which each task must be performed. The trade-off between increased acreage and decreased per acre yields (caused by untimely operations) is a key factor limiting farm size.

Improved timeliness of cropping operations has been one of the greatest gains from mechanization. However, it is important that this improved timeliness be considered within the context of increasing farm size with a relatively fixed amount of labor. From the producers point of view, the incentive to mechanize has been to facilitate timely operations on ever-increasing acreages of corn within the constraint of the availability of high quality (mainly family) labor. Thus, mechanization has served to relax previous constraints on the acreage of corn which could be produced by one production unit.

An additional incentive to mechanize has been to exploit available per unit (bushel or acre) cost economies.1/ Exploiting these cost economies has involved specialization: the transition from mixed (grain-forage-livestock) farms to highly specialized row-crop (principally corn and soybean) farms. A brief examination of the historical development of mechanization in tillage, planting, mechanical weed control and harvesting of corn is presented in Appendix VIII.

3. Direct Effects of the Technology

3.1 Yield Response and Aggregate Production Capacity

Mechanization is mainly thought of as labor saving (augmenting) rather than yield increasing technology. However, it has also been instrumental in increasing corn yields. Mechanization has facilitated reductions in field losses of corn through harvesting grain at higher moisture content, more timely field operations and earlier planting. All of these have contributed to yield increases.

3.1.1 Harvesting at Higher Moisture Content

The introduction of field shelling, brought
about by technological developments in corn har-
vesting and drying, facilitated the harvest of
corn at higher moisture contents. As is illus-
trated in Figure VIII-1, field losses are related
to the moisture content of the grain. Most ear
corn used to be harvested at 20 percent (or less)
moisture. As field shelling became more popular,
it was recognized that field losses were related
to moisture content and that substantial field
losses occurred if (i) the harvest began when all
the corn had dried to as low as 20 percent, and
(ii) the harvest took place over an extended per-
iod of time. Most corn is now harvested with
kernel moisture content between 25 and 32 percent.
As is illustrated in Figure VIII-1, the optimal
grain moisture level at which harvest should
begin is determined by the number of days required
to complete the harvest. The individual producer
minimizes field losses by choosing to begin har-
vesting at a moisture level which will permit the
completion of the harvest before moisture levels
drop to a level where harvest losses are serious.

3.1.2 Timeliness of Operations

Timeliness of field operations is crucial in
maintaining high yields in corn production.

Figure VIII-1. Effect of Moisture Content at
    Beginning of Harvest and Length of Harvest
   on Field Losses of Corn.
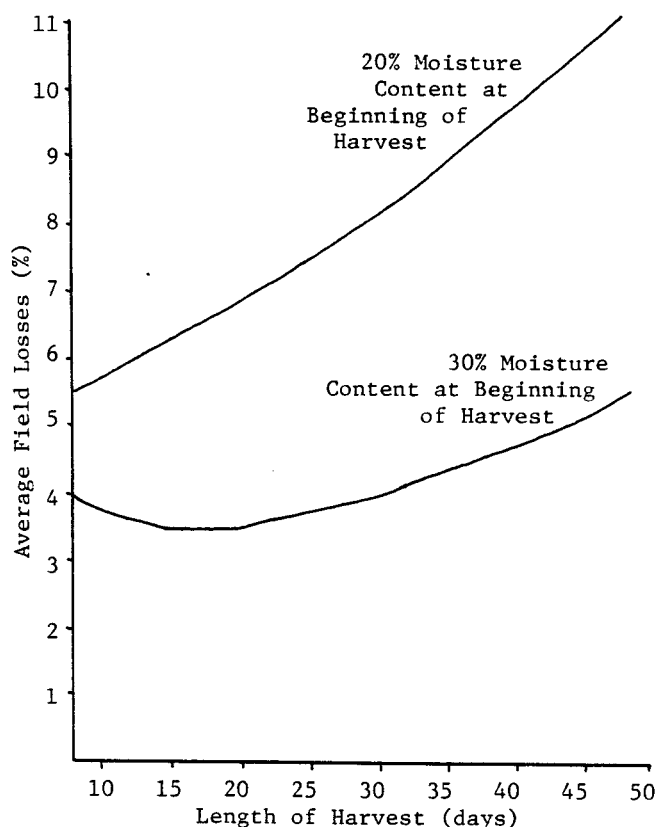
Source: Appendix Table VIII-1.

The timeliness of planting is particularly impor-
tant. The planting operation must be completed
over a short period of time. Corn cannot be
planted until the soil temperature reaches the
desired temperature (60° F ensures prompt germin-
ation); however, it must be planted early enough
so that physiological maturity can be reached
prior to severe frost in the fall. Field opera-
tions can be delayed by poor weather conditions,
therefore the producer must be equipped to com-
plete tasks as quickly as possible. By increasing
machinery size and speed, mechanization technology
has responded to this need on an ever-increasing
acreage per farm.

The concept of calendarization of corn produc-
tion has also been employed by corn producers to
enhance timeliness of operations. Calendarization
is the scheduling of planting dates in accordance
with maturity dates, to spread out the harvesting
season by ensuring that portions of the crop
reach maturity at different dates. This allows
labor, machinery and drying capacities to be
more fully utilized, enabling a one- or two-person
work force to handle a larger acreage.2/ Figure
VIII-2 illustrates the relationship between
planting date and date of maturity for hybrids
of 80-115 day relative maturity.

Figure VIII-2. Effect of date of planting
    and hybrid maturity on date when ear
    moisture content is 30 percent.
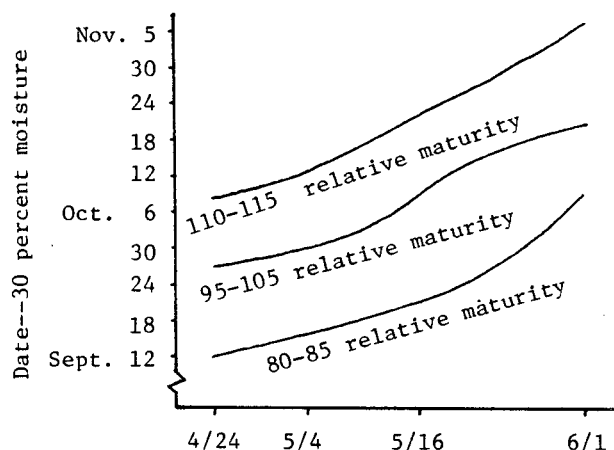
Source: Hicks and Petersen, 1978.

By planting hybrids of differing rates of matur-
ity (late + early maturing), and by staggering
the planting dates, a considerable time spread
can be achieved in the harvesting season.3/
There are trade-offs between earlier maturity
and yields, since early maturing hybrids have
lower potential yields than long season hybrids.
The producer will trade-off increased corn
acreage (made possible by spreading harvest time)
for yield reductions due to these earlier ma-
turing varieties. This trade-off is illustrated
in Figure VIII-3.

Figure VIII-3. Effect of date of planting
   and hybrid maturity on corn yield.
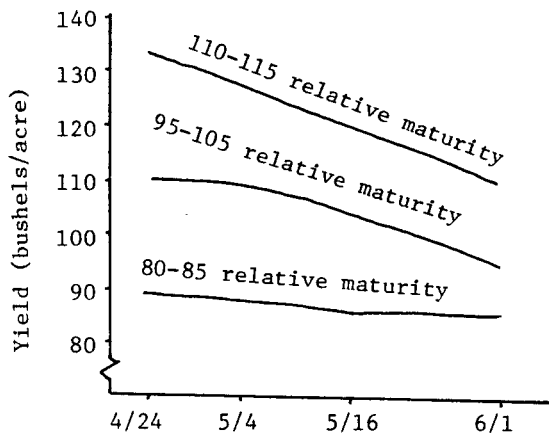
Source: Hicks and Peterson, 1978.

3.1.3 Earlier Planting Dates

   Mechanization has been instrumental in the
move towards earlier planting dates through fall
tillage and more rapid seed bed preparation in
the spring. The move toward earlier planting
dates encouraged the development of longer season
hybrids which have increased yields. The effect
of earlier planting on yield is illustrated in
Figure VIII-3 for hybrids of various relative
maturity requirements. Longer seasoned hybrids
(i.e., 110-115 relative maturity) planted early
in the season result in higher yields (up to 30%
higher) than either these same hybrids, or other
shorter-season hybrids, planted later in the
season.

3.2 Costs and Profitability

   Appendix Table VIII-2 illustrates the
machinery required on a typical 640 acre corn-
soybean farm in the Corn Belt. The current
average investment for a full complement of ma-
chinery on this 640 acre farm is $140,000
($250,000, if the machinery is purchased new).

   Real net returns per acre (returns when both
revenues and costs have been deflated) for corn
production have declined rapidly over the past
40 years, from over $200/ac in 1941-42, to about
$15/ac in 1974-80 (Table VIII-1). To maintain
or increase total net returns in the face of
declining real returns per acre, producers in-
creased their corn acreage. (In 1980, 14 acres
yielded about the same real net returns as one
acre in 1941-42.) This increase was facilitated
by mechanization. Corn acreage per farm is
estimated to have increased by 240 percent
between 1945 and 1978. (The growth in corn
acreage per farm is estimated in Chapter 12 and
illustrated in Figure XII-2.)

Table VIII-1. Real Net Returns in Corn
   Production - Central Illinois

	Net Returns ($/bu)[a]	Yield per acre (bu/ac)	Net Returns per acre ($/bu)
1941-42	3.15	66	207.90
1951-52	2.61	67	174.87
1959-60	.61	95	59.95
1964-73	.61	115	70.15
1974-80	.12	127	15.24

[a] See Table XII-6.

3.3 Resource Use

   Labor: Mechanization of corn production in
the U.S. has facilitated a large increase in
labor productivity. This has been made possible
by the increased land which one producer can farm
as a result of mechanization. Table VIII-2 illus-
trates changes over time in the number of hours
required to produce one acre and one bushel of
corn. As is illustrated, labor requirements since
World War II have decreased dramatically.

Table VIII-2. Estimated Work-Hours Used to
   Produce Corn, U.S. 1900-1979

Year	Work Hours Per Acre			Work Hours Per 100 Bushels
	Total	Prior to Harvest	Harvest	
1900	38.0	22.0	16.0	147
1920-24	32.7	19.2	13.5	122
1940-44	25.5	16.0	9.5	79
1950-54	13.3	8.9	4.4	34
1960-64	7.0	4.3	2.7	20
1970	5.2	2.9	2.3	7
1975-79	3.6	[a]	[a]	4

[a] Not available.

Source: Jones and Allred, 1980 (for years 1900
         to 1970); USDA, Agricultural Statistics,
         1979 (for 1975-79 data).

   Fuel: Using the machinery complement outlined
in Appendix Table VIII-2, the fuel used for field
operations was calculated at 10.03 gallons per
acre. A number of changes have resulted in in-
creased efficiency of fuel use in field operations
for corn production. The replacement of gasoline
tractors by diesel powered tractors reduced the

cost per unit of fuel and increased fuel efficiency. A recent survey of corn production showed that more than 80 percent of the tractors over 50 drawbar horse power (HP) were diesel tractors. The gasoline tractors tended to be smaller (less than 95 HP) and older (Lagrone and Krenz, 1980). Another change in mechanical technology has been the increased width of machinery which resulted in a reduction in fuel consumption per acre. Changes in production practices have also been instrumental in reducing fuel use. Prior to the introduction of herbicides, weed control was accomplished through tillage operations. The use of herbicides for weed control has reduced the number of tillage passes over the field. Reduced tillage reduces fuel consumption by 2 to 3 gallons of diesel fuel per acre (see Chapter VII).

All Resources: Mechanization has facilitated efficiency in the use of all resources. It has been the vehicle through which a number of technological improvements have been implemented, including increased plant density, reduced tillage, efficient placement of fertilizers and herbicides, and field shelling of corn.

4. Other Aspects of the Technology

4.1 Environmental

Early developments in mechanization of corn production may have had some negative impacts on the environment. Examples of this were the deeper and cleaner tillage which tractor power permitted, and an increase in the amount of tillage, which resulted in soil erosion. In recent years, however, the trends in mechanization have had a positive impact on the environment through reduced tillage and more accurate placement of chemicals (less chemicals required).

4.2 Vulnerability of the Technology

The development and refinement of mechanical technology has resulted in a heavy dependence on fossil fuels. The increases in the price of fossil fuels in recent years, and the threat of scarcity, does raise concern since corn production is dependent upon fuel as a source of power. However, energy required in field operations is not the major source of energy consumption in corn production. With dryland corn, both fertilizer and drying use more energy. Energy utilized for field operations in irrigated corn is an even smaller proportion of total energy use. However, even though field operations use less energy than such inputs as fertilizer, field operations may be more vulnerable to supply problems because of the dependence on one type of fuel (predominantly diesel). 4/

There are some promising developments in mechanization technology and in agronomic practices which have served to reduce the fuel requirements, namely reduced tillage and electronic systems on machinery to improve fuel efficiency.

5. Feasibility of the Technology

Mechanization has become an intricate part of corn production in the U.S. In all likelihood the present degree of mechanization will remain feasible in the future. As discussed above, the source of vulnerability in mechanized corn production is the use of fossil fuel as an energy source. As a result of the increased cost of fuel, efforts have successfully concentrated on reducing fuel consumption.

6. Alternatives to the Technology

One alternative to mechanization is to substitute for the power source by using human labor and/or animal power. Neither of these alternatives are particularly attractive since both are relatively more expensive than is gasoline or diesel.

Another alternative would be the use of other methods to accomplish the tasks performed by mechanization. For example, a reduction in tillage used for weed control could come about either by increasing chemical control or through the use of crop rotations. Although chemical applications may require less fuel than tillage, chemicals may represent a costly solution in terms of the environment and the cost of the chemicals themselves (see Chapter VII). As is discussed in Chapter VII, the use of rotations such as corn-soybeans would not totally control weeds. Rotations including small grains would be more successful. The trade off here would be between weed control and financial gains since small grains produce a lower return than soybeans.

Another possible reduction in the use of mechanical technology or fuel power would be partial or total nitrogen self-sufficiency in corn (this alternative is discussed in Chapter X), which would also reduce the number of trips over the field. The development of low priced, slow release fertilizer would also reduce the number of times fertilizer needs to be applied.

7. Managing the Technology

In the absence of any legal or other institutional constraints, and because of reductions in per unit returns, it appears likely that operating units will expand in size in order to exploit the productive capacity and cost economies of available mechanical technology. However, mechanization research directed at further reducing labor requirements in corn production appears of low priority for two reasons. First, there do not appear to be substantial potential

gains from further reductions in labor require-
ments. Second, labor efficient machinery which
is already available is not presently utilized
by many producers. There are, however, potential
gains to be realized from improving the effici-
ency of machinery by improving: (i) fuel effi-
ciency; and (ii) the equipment's ability to per-
form particular tasks.

Footnotes

1/We have not undertaken in this report to
conduct a definitive assessment of cost economies
in corn production. It does appear, however,
that some technical cost economies (per bushel
reductions in production costs) exist for farms
as large as the 640 acre corn-soybean Corn Belt
farm for which machinery costs are computed in
Appendix Table VIII-2 (Miller et al., 1981).
In addition, some market cost economies have been
reported for larger corn farms which purchase
inputs in large volume lots (Krause and Kyle,
1971).

2/Typically both the planting and harvesting
operations involve a two-person work force.
During planting, one person is involved in seed
bed preparation and the other in planting.
During harvest one person is involved in harvest-
ing and the other in grain hauling.

3/Under calendarization the early maturing
hybrids are planted first. These have usually
been developed for northern environs where soil
and growing conditions are not as favorable and
are, therefore, more cold tolerant in the early
part of the season.

4/To provide an idea of the relative magni-
tudes of energy requirements of an acre of corn,
fertilizer (125 lbs/ac) required 21.7 gallons of
diesel fuel equivalents/acre and, using conven-
tional tillage practices, field operations re-
quired 5.2 gallons of diesel/acre. This estimate
uses as equivalent: 0.171 gallons diesel fuel/lb
of nitrogen and 0.015 gallons diesel fuel/lb of
phosphate (Wittmus et al., 1975).

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Appendix VIII

Historical Development of Corn Mechanization

The mechanization of corn production in the U.S. has progressed through three basic stages: the use of hand tools powered by human labor; the development of farm implements and machinery powered by horses; and a third stage, represented by a shift in the power source to mechanical power. The progression through these stages did not occur simultaneously for all tasks involved in corn production (e.g., the move to animal power in tillage occured much earlier than for corn planting and harvesting).

The major trends of mechanization can be examined within the framework of the sources of power used and the three major cropping operations: tillage; planting; and harvesting.

The Power Source

Steam powered tractors were introduced into agricultural production at the turn of the 20th century. These tractors did not in themselves have a significant impact on corn production. However, they were precursors of the gasoline powered tractor, which has facilitated many changes in corn production technology.

Automotive power offered many advantages over human and animal power. For example, the internal combustion tractor could supply more total draft power which could be partitioned easily, supplying small amounts of power to the forward movement of the machine and large amounts to other tasks such as harvesting. Automotive power also offered the advantage that the crop acreage formerly used to produce feed to support draft animals, could now be used to produce crops or to pasture food livestock.

Gasoline powered tractors have undergone radical changes since their introduction. Some of the important improvements in tractors prior to World War II were: the development of the unit or frameless tractor; the row-crop tractor; increased power; reduction in weight, the introduction of pneumatic tires; and the power take-off and hydraulic devices. The power take-off was developed during World War I, and became popular around 1923 (Schlebecker, 1975). It was used to power equipment such as augers and fertilizing machinery. The power lift which raised tillage machinery off the ground to facilitate turning and transporting was widely used after 1928 and was standard equipment by 1945.

The major developments in tractors following World War II have been the shift from gasoline powered tractors to diesel and the increase in drawbar horsepower. A recent survey provides some insight into: (i) the importance and size of tractors on corn farms today; and (ii) the

trend away from gasoline powered tractors (Appendix Table VIII-3). More than 80 percent of the tractors over 50 HP were diesel powered. The gasoline tractors tended to be the smaller, older tractors. One other trend in the mechanical power source has been the trend toward self-propelled harvest equipment. In the Lagrone and Krenz (1980) survey, the amount of corn harvested by self-propelled combines ranged from 77 percent in Iowa to 93 percent in Nebraska and Missouri.

Tillage

Pre-Planting: Tillage prior to planting involves breaking and conditioning the soil. In different forms, the moldboard plow had been the standard soil breaking or plowing tool for corn production in the U.S. Improved design during the 19th century reduced the power required to pull the plow. The moldboard plows of the twentieth century increased in size and the number of bottoms per unit. These larger plows were made possible by the increase in drawbar power to tractors. To illustrate the present capacity of soil preparation equipment, the 5 bottom moldboard plow in Appendix Table VIII-2 will cover 2.9 ac/hr using a 100 horsepower tractor (by comparison, an 8 bottom plow in combination with a 160 horsepower tractor would plow 4.6 ac/hr).

To prepare the seed-bed, further post-plowing soil conditioning is required prior to planting using implements such as harrows. Soil conditioning implements have undergone many improvements in design which improve their performance and ease of handling, such as the degree of automation which has been built into these implements. A predominant trend in soil preparation equipment has been the increase in width and speed of the tillage machinery. Today, harrows and disks are the most popular implements used to condition the soil prior to corn planting.

Post-Emergence Tillage: Post-emergence tillage was the method of weed control prior to the introduction and widespread use of chemical herbicides. At the turn of the 20th century, farmers were using one- and two-row horse drawn implements for weeding. Corn evolved as a row crop in the U.S. to facilitate the use of mechanical weed control. Initially, cultivating equipment was pulled behind the tractor (or horse). Later the implements were mounted on the tractor, this provided for easier handling and permitted one person to operate both the tractor and tillage equipment. Since the maximum number of rows cultivated in one sweep was determined by the size of the planting equipment, as the planting equipment increased in size so did cultivators, reducing the number of hours required for weed control.

The introduction and use of herbicides resulted in a reduction of tillage for weed control. The trend away from tillage as the method of weed control began in the 1950s (2,4-D, the first major herbicide used for weed control in corn, was introduced in the mid-1940s). By the 1970s chemicals had replaced tillage as the predominant form of weed control in corn production (Slife, 1973). Weed control is now accomplished using a combination of herbicides and cultivation. Lagrone and Krenz (1980) report that most farmers in their survey cultivated their fields once for weed control.

Planting

For optimal yield, seed requires accurate placement (spacing and depth) and proper soil covering (so that moist soil comes into contact with the seed). Also the soil covering must be packed so that it retains moisture without soil crusting. An additional requirement is that corn be planted in straight rows. (This facilitates harvesting operations and efficient weed control.)

Modern corn planting technology represents a vast improvement over previous methods. Until the 1850s corn was planted by hand. The horse-drawn planter was introduced in the mid-19th century. Corn at that time was planted in a checkerboard pattern (check - rows) to facilitate cultivation between the rows in both directions (for weed control). The horsedrawn planter had levers which were pulled to release the seed. In the 1870s a check - row device became popular using twine (and subsequently wire) knotted at intervals which tripped the mechanism for release of the seed. The introduction of the planter plate for metering corn occurred about 80 years ago. These planter plate metering devices (and a belt type metering system) were standard equipment until 1970. This type of metering system required that seeds meet the specific size requirements of the plate used. In the last decade fairly sophisticated kernel pickup and discharge mechanisms have been developed using air pressure. These systems have several advantages in that: (i) they do not require the narrow range of seed size that the previous systems did; (ii) the amount of mechanical damage to the seed in planting has been reduced; and (iii) improved accuracy of seed placement is achieved at higher speeds.

The planting operation must be completed over a short period of time. The primary objective in planting is very rapid precision planting. To ensure optimal yields, timeliness of planting is very important. To increase the number of acres planted over a short period of time, both the speed of the planting equipment and the number of rows planted are of importance. Precision planting at high speeds has been accomplished through the use of: plateless metering, a reduction in the weight of implements, and minimizing

the amount of soil contact. There has also been an increase in the number of rows planted. The size of planters has increased from the 2 and 4 row planters of the mid-1940s to the 8 and 12 row planters available today. The average size of planters reported on the farms with dryland corn in the Lagrone and Krenz study (1980) for the five states listed in Appendix Table VIII-3 was between 15.8 and 18.8 feet, or 6 to 8 row planters.

To illustrate the influence larger planters have on the number of acres which one farmer can plant in a season, the number of acres planted per hour for different sized planters may provide some insight. A 4 row planter using a 38 inch spacing of rows and pulled by a 50 HP tractor can plant 5.4 acres per hour whereas an 8 row pulled by a 100 HP tractor with the same row spacing can plant 10.3 acres per hour (a 12 row planter planting 30 inch rows can cover 11.8 acres per hour). So that by doubling the size of the planter the producer almost doubles the number of acres which can be timely planted in a season (thus facilitating an increase in corn acreage per farm).

Harvesting

The two major developments in corn harvesting since 1945 have been the adoption of field shelling and the corn combine. Prior to the adoption of field shelling, corn was picked and shelled in two separate operations. Although field shelling equipment had been introduced by 1935, the move towards field shelled corn was delayed until grain drying technology was developed. The portable corn dryer appeared around 1949 (Schelbecker, 1975). This introduction of heated air grain dryers made field shelling feasible. During the 1950s and 1960s there were a number of incentives which encouraged the adoption of field shelling: (i) the ability to handle larger volumes of grain; (ii) the shift to off-farm sale of corn; (iii) earlier and more rapid harvesting; and (iv) reduced labor requirements. The adoption of field shelling took place in the late 1950s and 1960s. In 1956 only 3 percent of the corn in the Corn Belt was field shelled (2% nationwide); by 1962 this had increased to 16 percent (also 16% nationwide); by 1966, 57 percent of the corn in Illinois was field shelled and by 1973 more than 80 percent (Scott and Capley, 1968; Minnesota Crop and Livestock Reporting Service, 1974).

The move to combines took place rapidly as ear corn was phased out in the 1950s and 1960s. By 1970, nearly 70 percent of corn produced in the five principal Corn Belt states was harvested by combines (Kepner et al., 1978). The development of the corn combine began as early as the 1920s when attempts were made to adapt the small grain combine to corn. These early efforts in-

volved feeding the entire plant into the combine, but it was clear that successful use of the combine would require a method of excluding the stalks from entering the machine (Kepner et al., 1978). In the early 1950s successful types of stalk gathering equipment and shellers were developed for the combine (rasp-bar cylinder), followed by the introduction of snapping units which snapped the ears from the corn sending them through the machine and omitting the stalks.

Initially combines were pull type, powered by power take-off from the tractor. Self-propelled combines represented an advance in corn combines. These combines offered such advantages as improved visibility, ease of handling, and other features which improved the machine's performance. Recent developments have been increased size of combines to handle more rows in one sweep, electronic monitoring equipment (i.e., grain loss indicators, level of grain in the hopper, monitoring the engine function, etc.), improved methods of moving the grain inside the combine and increased comfort for the operator.

Appendix Tables VIII-1 through VIII-3 appear on the next two pages.

Appendix Table VIII-1. Average Total Field Losses of Corn as a Percentage of Gross Corn Production, by Length of Harvest and Moisture Content at Beginning of Harvest (Ear Corn Picker)

Length of harvest (days)	Moisture content at beginning of harvest										
	30	29	28	27	26	25	24	23	22	21	20
8	3.8	3.6	3.4	3.2	3.1	3.2	3.3	3.5	3.9	4.5	5.5
10	3.7	3.5	3.3	3.2	3.2	3.2	3.4	3.6	4.0	4.7	5.7
12	3.6	3.4	3.3	3.2	3.2	3.3	3.5	3.8	4.2	4.9	5.9
14	3.5	3.4	3.3	3.2	3.3	3.4	3.7	3.9	4.4	5.1	6.1
16	3.5	3.4	3.3	3.3	3.4	3.6	3.8	4.1	4.6	5.3	6.3
18	3.5	3.4	3.4	3.4	3.5	3.7	4.0	4.3	4.8	5.5	6.6
20	3.5	3.5	3.5	3.5	3.7	3.9	4.2	4.5	5.0	5.7	6.8
22	3.6	3.6	3.6	3.6	3.8	4.0	4.3	4.6	5.2	5.9	7.1
24	3.7	3.7	3.7	3.8	4.0	4.2	4.5	4.8	5.4	6.2	7.3
26	3.8	3.8	3.8	3.9	4.1	4.4	4.7	5.0	5.6	6.4	7.6
28	3.9	3.9	3.9	4.1	4.3	4.6	4.9	5.2	5.8	6.7	7.9
30	4.0	4.0	4.1	4.2	4.5	4.8	5.1	5.4	6.0	6.9	8.2
32	4.1	4.2	4.2	4.4	4.6	5.0	5.3	5.7	6.3	7.2	8.4
34	4.3	4.3	4.4	4.6	4.8	5.2	5.5	5.9	6.5	7.5	8.8
36	4.4	4.5	4.6	4.8	5.0	5.4	5.7	6.1	6.8	7.7	9.1
38	4.6	4.6	4.7	5.0	5.2	5.6	6.0	6.4	7.0	8.0	9.4
40	4.7	4.8	4.9	5.2	5.5	5.8	6.2	6.6	7.3	8.3	9.7
42	4.9	5.0	5.1	5.4	5.7	6.1	6.5	6.9	7.3	8.6	10.1
44	5.1	5.2	5.3	5.6	5.9	6.3	6.7	7.2	7.9	9.0	10.4
46	5.3	5.4	5.5	5.8	6.2	6.6	7.0	7.5	8.2	9.3	10.8
48	5.5	5.6	5.8	6.1	6.4	6.8	7.3	7.8	8.5	9.6	11.1

Source: Davis (1963)

Appendix Table VIII-2. Field Machinery Required
    on a Typical 640 Acre Corn-Soybean Farm in
    the Corn Belt[a]

	New Costs[b] ($)	Average Investment[c] ($)
Anhydrous applicator	4,334	2,384
5 bottom moldboard plow	7,200	3,960
Disk 21 ft.	10,896	5,993
Field cult. 18	4,497	2,473
Spring tooth drag 48	7,952	4,374
Corn planter 8-30"	17,281	9,505
Cultivator 8-30	4,675	2,571
Sprayer 50 ft.	4,380	2,409
Tractor (1) 75 HP	22,069	12,138
(2) 110 HP	40,925	22,509
Combine	76,927	42,310
Corn head 8-30	20,527	11,290
Soybean head	8,919	4,905
Truck	22,500	12,375
Wagon	2,580	1,419
Total	$255,662	$140,615

[a] Machinery requirements were calculated with the
aid of Dr. F. Benson, Department of Applied and
Agricultural Economics, University of Minnesota,
using the "What to Grow" probram from DECAIDS -
Catalog of Computer Decision Aids for a 640 acre
farm with 340 acres of corn and 300 acres of
soybeans. Total fuel use was estimated at 10.03
gal/ac and total labor required for field opera-
tions was 1.76 hours per acre.

[b] Projected 1982 costs.

[c] 55% of new cost.

Appendix Table VIII-3. Tractors on Dryland Corn
    Farms, 1978

	Number of tractors per farm		
	(Over 50 HP)	(Over 95 HP)	Number of Gasoline Tractors (Over 50 HP)
Iowa	3	1.2	.67
Missouri	3.2	1.3	.60
Ohio	2.3	.9	.40
Minnesota	2.5	1.0	.42
Nebraska	2.7	1.3	.02

Source: Lagrone and Krenz (1980).

1. Definition and Description

Artificial drying of corn (corn drying) is defined as the process of reducing the moisture content of harvested, shelled corn to a level at which it can be stored and/or transported without significant deterioration in quality or grade. Number two yellow corn (No. 2 yellow) is the quality grade standard on which most corn grain is marketed. Although this grade standard permits a moisture content (wet weight basis) of up to 15.5 percent, shelled corn cannot be stored safely in many areas of the Corn Belt at a moisture content above 14 percent during the warm humid summer months. Inadequate drying leads to the growth of molds and to the initiation of other processes which cause quality deterioration. The growth of molds exacerbates the temperature and humidity problem.

Corn kernel moisture content is generally about 32 percent when the grain reaches physiological maturity, or maximum grain yield (Hicks, 1979), but significant variations from that level have been reported (Baker, 1970). Increased field losses during harvesting generally occur when grain is harvested at moisture contents below 25 percent. Thus, there is an important trade-off between harvesting at higher moisture levels and incurring greater grain drying costs versus harvesting at lower moisture levels and incurring higher field losses. These parameters, together with the maximum moisture content for safe storage, set the general framework in which technical and economic decisions about corn drying are made.

The terminology associated with corn drying processes and systems is complex. Three broad systems of corn drying are employed (Morey, 1981): (i) high temperature (or high speed) systems in which corn is dried rapidly at air temperatures of around 120-125° F ; (ii) low temperature systems in which drying takes place at air temperatures which are increased only by about 2°F. by the heat of the power fan unit, or by about 5-8° F. via some supplementary heating of the circulating air; and (iii) combinations of the above two systems. One method of combination drying

utilizes a high temperature system to bring the grain moisture down to a level (usually 20-22 percent moisture) at which a low temperature system may be effectively employed to reduce the moisture content further. In another combination drying system, dryeration, hot grain is discharged from a high temperature dryer (at 16-18 percent moisture) to a bin where it steeps for 8-10 hours before being cooled by airflow and transferred to storage.

A second type of categorization of corn drying systems identifies them as: (i) "in-storage drying" systems in which the grain remains in place during drying; or as (ii) "batch" or "continuous flow" systems in which the grain is moved in and out of drying bins. Some batch facilities are equipped with devices to stir the grain. All drying facilities, including those for in-storage drying, are equipped with fans to move air through the grain for drying.

Though the drying and storage of corn grain are distinct operations, they are usually closely linked, particularly when drying is done on-farm. The corn drying systems actually employed by farmers must be coordinated with the rate at which corn is harvested. In fact, this harvest rate, together with the total volume of grain harvested and its moisture content generate the critical constraints for the specification of feasible drying systems for individual farmers. In general, a higher proportion of total corn drying has been performed on-farm in recent years and on-farm drying will continue to be important in the future.

2. Direction and Magnitude

Corn drying is a recent technology which has undergone considerable evolution. Loss in volume and quality of corn grain as the result of deterioration due to excessive moisture has always been a problem. Until the late 1950s, little effort went into preventing these losses. Then the grain drying process was mostly natural field drying, followed, if necessary, by natural air drying of the ear corn (in the crib) prior to

shelling or feeding. Only rarely was corn subjected to on-farm artificial drying after shelling. However, farmers often suffered "high moisture discounts." A common discount system for high moisture corn in the mid-1960s was 3¢/bu for each point of grain moisture above 15.5 percent and up to 20 percent and 2¢/bu for each point of grain moisture above 20 percent (Hill, 1966). Under this system, corn with 25 percent moisture would have been discounted by 23.5¢/bu – highly significant when the market price for No. 2 yellow corn was in the one dollar per bushel range. Typically, however, only about 60 percent of the high moisture discounts represented a loss for farmers since they were marketing additional water when the corn moisture content was over 15.5 percent (Aldrich and Leng, 1965).

Prior to the introduction of on-farm drying technology, excessively wet corn for on-farm use often had to be fed immediately to livestock in order to avoid spoilage. In addition, much of the stored ear corn had to be fed prior to the advent of the following humid and hot summer weather. A general rule of thumb for the Central Corn Belt was that corn stored in the crib could have a maximum grain moisture content of up to 20 percent through the fall and winter, but this had to be reduced to 18.5 percent or less by March 1 (Aldrich and Leng, 1965). A high proportion of the corn was fed as ear corn, with or without grinding, on the farm where it was produced. Where dairy or beef cattle were present, some excessively wet or immature corn originally intended for harvesting as grain had to be diverted to the silo.

The shift from utilizing corn as feed, on the farm where it was produced, to marketing it, has had an influence on the adoption of artificial drying technology. As recently as 1949, less than 25 percent of the corn grain was sold from the farm where it was grown. This percentage had increased to almost 65 percent by 1978. Almost all corn sold from the farm must meet the 15.5 percent maximum moisture standard for No. 2 corn. In recent years, about 30 percent of the corn grain has been shipped to export markets in which case strict adherence to maximum moisture standards is necessary.

As recently as 1962, 79 percent of the corn in the Corn Belt was harvested as ear corn by use of mechanical pickers. This resulted in field losses ranging from 3.1 to 11.1 percent depending on length of harvest period and grain moisture content at harvest (Davis, 1963). Losses were particularly high for those farmers who had a large acreage, and, who therefore had to extend their harvest period beyond that suitable for harvesting under near optimal conditions.

The development and use of large capacity, rapid corn harvesting equipment which both picked and shelled corn in the field, coupled with the

need to meet stringent moisture requirements in order to sell corn off-farm or store it in the shelled form for extended periods, pressured many farmers to adopt on-farm corn drying technology. Jensen et al. (1979) summarized the reasons why this technology was adopted by individual farmers:

"Thus, the farmer adoption of high speed, large capacity harvesting systems, the inability of the local elevator and the transport system to handle the large grain supplied at harvest without farmer delays, along with relatively inexpensive fuels for corn drying have been important reasons why many corn producers now have their own drying systems. But other factors also have provided an incentive for early corn harvesting and artificial drying.

Early harvesting of soybeans and corn makes it possible to complete fall plowing so as to assure more timely field operations in the spring, and to take advantage of yield increases associated with fall over spring plowing on the heavy silt loams of the northern Corn Belt. Moreover, early fall harvesting reduces the risk of unfavorable weather for corn harvesting and fall plowing and decreases field losses from harvesting drier corn."

One can add the fact that longer-growing, later maturing hybrid corn varieties have rather consistently outyielded the earlier-maturing varieties (which, because of their earlier maturity, have added capability for in-field dry-down without the application of artificial drying). Farmers have preferred to plant the later maturing varieties despite their greater requirements for artificial drying.

By the early 1970s the shift to the use of field picker-shellers and corn head-on-combines for harvesting had been largely completed in the Corn Belt. In 1973, for example, about 80 percent of the corn acreage in Illinois and Indiana, and about 70 percent in Iowa was harvested with this equipment (Minnesota State Crop and Livestock Reporting Service, 1974). Simultaneously, the rapid adoption of artificial corn drying technology was taking place, and by 1978 at least 68 percent of the farms harvesting corn for grain in the Corn Belt states, except Missouri, used artificial drying (Lagrone and Krenz, 1980). An even higher percentage of "field shelled" corn was artificially dried.

The adoption of artificial corn drying technology in commercial corn production (either on-farm or in elevators) is now well advanced.

Nevertheless, a number of interesting and important questions remain concerning this technology and its possible future modification(s). By far the most prominent of these questions centers on methods by which the energy intensiveness and costs of drying can be reduced. Our assessment of corn drying centers on these topics.

3. Direct Effects of Technology

3.1 Yield Response and Aggregate Production Capacity

The adoption of corn drying technology does not, in itself, increase corn production since it is applied only after the corn is harvested. However, ceteris paribus, it does permit farmers to make more extensive use of later maturing, higher yielding hybrids. In addition, it results in reduced "field" and "in-storage" losses. Thus, corn drying technology does have an impact on aggregate corn production capacity. Moreover, compared to the use of natural drying, it permits utilization by farmers of a broadened set of production, storage and marketing strategies for corn and other grains.

It is impossible to measure precisely the increase in corn production capacity which is attributable to corn drying technology. Trade-offs occur between maturity rates,1/ yields, moisture contents and harvesting losses, making generalization difficult. However, some general assessments can be made.

Using a large number of Minnesota trials, Hicks (1979) estimated a 0.7 to 1.0 bu/ac increase in yields per relative maturity (RM) unit. Earlier maturing varieties have a 0.3 to 0.4 percent lower moisture content per RM unit. Thus, a reduction in RM from 110 to 100 days results in a yield reduction of 7 to 10 bu/ac and a reduction in moisture content of 2.1 to 4.0 percent.

On average, existing corn drying technology probably makes it feasible to increase the RM by an average of 12 or 13 days on about 60 million acres of U.S. corn.2/ Using Hicks' Yield-RM trade-off formula, this represents a total annual increase in production capacity on this acreage, of about 500 million bushels. There are, however, adjustments which farmers could make to partly offset the reduction in production capacity which would occur if corn drying technology (or capacity) was not available. So the above estimate must be regarded as being a rough approximation only.

Corn drying technology has reduced the field loss and in-storage spoilage of grain. Full implementation of drying technology permits the harvesting of most corn with high capacity field shelling equipment, at a moisture content of 25 percent or more. This probably reduces average field losses by as much as 2 to 3 percent (160-240 million bushels on an 8 billion bushel crop) compared to having to handle the crop without drying technology.

3.2 Costs and Profitability

As mentioned above, most on-farm corn drying technology is highly linked to on-farm storage facilities. Investments for corn drying and storage are not easily separated. In addition, a portion of the benefits accruing to farmers from drying technology are in the form of indirect benefits from more timely field operations, added flexibility in the farm production system and increased volume capacity. Even though it is difficult to establish an absolute value of returns from corn drying technology, one can identify the costs and energy requirements for alternative corn drying systems and match them informally against the set of general benefits accruing to farmers.

Several comprehensive cost studies (Schwart and Hill, 1977; Jensen et al., 1979) have been done to estimate investment and operating costs for alternative corn drying systems. The Schwart and Hill study estimates costs for annual volumes of 5,000 to 100,000 bushels, while the volume range considered by Jensen et al. was from 10,000 to 200,000 bushels. A summary of investment and operating costs for the latter study are reported in Appendix Tables IX-1 and IX-2.

Jensen et al. report 1977 investment costs for the alternative drying and storage systems ranging from about $2 to $4 per bushel for 10,000 bushel volume and from $1.10 to $1.75 for a volume of 200,000 bushels. Both studies indicate that most economies of size have been realized at an annual volume of 60,000 bushels,3/ which corresponds roughly to 500 to 650 acres of corn. Jensen et al. projected after-tax, real annual costs per bushel for least-cost corn drying and storage systems assuming a 5 percent level of general inflation and modest, significant and drastic price increases for energy (Appendix Table IX-2).4/ Somewhat surprisingly, even with the highest energy cost projections, the real, after-tax, per bushel drying costs for least-cost systems were $.21 or less for all volumes between 10,000 and 200,000 bushels.5/ Even after an adjustment for higher (current) interest costs, this cost level is significantly less than the combined value of higher field losses and market price discounts for high moisture corn which would generally be incurred without drying technology. Therefore, our expectation is that drying technology will remain highly profitable for all but the small volume corn producers (less than 10,000 bushels per year). Moreover, we conclude that the adoption of new drying technology will continue, although farmers will adopt the most cost-effective technology possible.

3.3 Resource Use and Productivity

Adoption of corn drying technology increases investment costs and operating expenses (mainly energy costs) for farmers, but simultaneously enhances the productivity and flexibility of other farm resources. As indicated in Appendix Table IX-1, the least-cost 1977 investment costs of drying and storage systems ranged from a low of about $20,000 for 10,000 bushel capacity to over $215,000 for 200,000 bushel capacity. The size of the investment may adversely affect the ability of some smaller-scale farmers to remain competitive in corn production. Otherwise, aside from its heavy energy use, drying technology has enhanced the productivity of most other resources used in corn production.

3.4 Aggregate Input Demand

Corn drying technology has mainly increased producer demand for facilities, equipment, LP gas and electricity. In 1974, corn drying used an estimated 50,037 billion BTU's in energy including 450 million gallons of LP gas and 378 million kilowatt-hours of electricity (USDA, 1977). The present amount of energy used in corn drying is much higher since there has been a substantial increase in grain drying since 1974. Appendix Table IX-3 illustrates some of the tradeoffs between energy sources for various types of drying systems. One advantage of the low temperature drying systems is its independence from liquid fuel. (However, it requires additional electricity to meet high air flow requirements.) As of 1978, LP gas was used as a fuel source on a high percentage of farms with on-farm corn drying technology (Appendix Table IX-4). A high priority research topic for engineers is to reduce the dependence of drying technology on liquid fuels.

4. Other Aspects of the Technology

Corn drying technology has been induced largely by the development of technologies for high-volume rapid harvest of field shelled corn. The current technology, using electricity for air circulation and LP gas for supplemental heat, is environmentally clean.
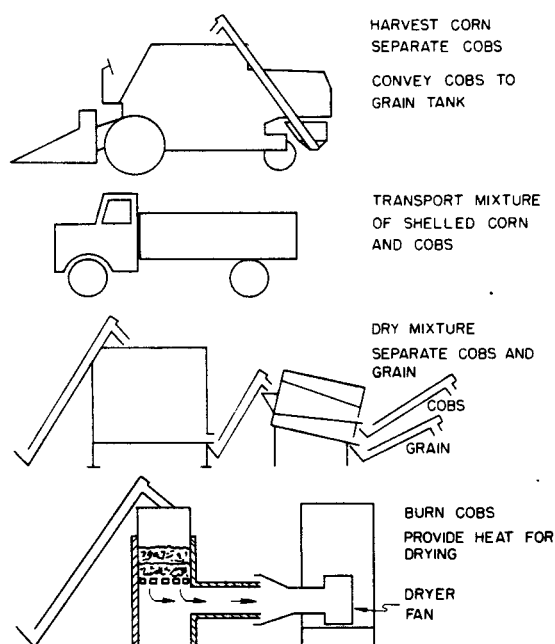
4.1 Vulnerability of the Technology

The almost sole vulnerability of drying technology is its heavy dependence on liquid fuels for the production of supplemental heat for drying. Conventional high temperature drying of corn grain from 25.5 to 15.5 percent moisture requires about 0.2 gallons of LP gas per bushel (Morey, 1981). Multiplying this quantity by the price of LP gas (about $.63 per gallon in fall 1980) indicates a cost of about $.126 per bushel for drying energy. (At $.75 per gallon, this cost would be $.15 per bushel, etc.)

Researchers in agricultural engineering are currently working on the development of technology which will permit the economic use of waste materials (particularly corn cobs) as a fuel source for heating (Loewer et al., 1980; Peart et al., 1980; Morey, 1981). One concept being researched is that of the simultaneous harvest and subsequent drying of corn grain and cobs with the subsequent recycling of the dried cobs to use as the fuel source for generating heat for drying (Figure IX-1). Since only about 50 percent of available wet cobs are needed to dry corn with 30 percent moisture (Peart et al., 1980), these waste materials represent an ample energy source for drying. Such technology would, however increase somewhat the labor requirements and other costs of corn harvest in exchange for a reduced dependence on liquid fuels. Some small equipment manufacturers are now offering prototype equipment designed to use waste materials as a fuel source.

A second area of research aimed at saving liquid fuel is that pertaining to solar-assisted grain drying systems. Two problems, however, make an economically feasible single purpose solar system for corn drying difficult to achieve. One is the high cost of solar collectors. A second is the peak volume of drying capacity which is required during the relatively short harvesting period. Heid (1980) indicates also that although

Figure IX-1.   Residue System for Drying Corn

HARVEST CORN
SEPARATE COBS

CONVEY COBS TO
GRAIN TANK

TRANSPORT MIXTURE
OF SHELLED CORN
AND COBS

DRY MIXTURE
SEPARATE COBS AND
GRAIN

COBS

GRAIN

BURN COBS
PROVIDE HEAT FOR
DRYING

DRYER
FAN

Source: Morey, 1981.

solar-assisted grain drying can reduce the requirements of LP gas by half or more, additional electrical energy is required for operation of the solar collector fan.

It appears likely that some future substitution of both waste materials burning and solar assisted systems will reduce the per bushel dependency on LP gas. For the near term, burning of waste materials is the technology most likely to be economically feasible if the cost of LP gas increases substantially in the future.

5. Feasibility of the Technology

Corn drying technology is being rapidly adopted and it appears that the liquid fuel requirements of the technology will be reduced with future modifications.

6. Alternatives to the Technology

The major alternatives to artificial corn drying technology are: (i) storage in oxygen-free (air tight) silos; (ii) acid treatment of grain; and (iii) breeding hybrid varieties with earlier maturity and/or more rapid natural dry-down capacity in the field.

Oxygen-free storage has two disadvantages. First the per bushel investment costs for equipment and storage facilities are high. Second, the corn must be fed on-farm to livestock. Thus, this is not a viable technology for corn which is to be marketed off-farm and is feasible only when compatible with the on-farm livestock system.

Acid treatment of corn to prevent its spoilage in storage is only competitive, in terms of cost, with drying technology at small volumes (less than 10,000 bushels). This alternative also has other disadvantages; acid treated corn can only be used for livestock feed and the corrosive action of acid reduces the effective life of metal storage bins. Thus, it is unlikely that acid treatment technology will compete economically with corn drying.

The tradeoffs between maturity rates and yields will continue to receive the attention of corn breeders and some improvement in the rate of natural dry-down capacity of varieties which producers grow can be expected. This will not, however, eliminate the need for artificial drying of corn grain, although it may reduce the initial moisture content from which artificial drying must begin. This should reduce the vulnerability of producers to shortages of, and higher prices for, liquid energy.

Farmers will continue to use drying capacity at commercial elevators. Indeed, elevators will try to provide effective drying capabilities in order to compete effectively for farmers' grain.

However, use of elevator facilities for drying reduces the farmers' marketing and storage options and often disrupts harvesting schedules when the demand for elevator facilities exceeds the supply.

7. Managing the Technology

Drying technology and capacity must be effectively matched with harvesting rates and volumes. Hill and Vercimak (1979) found that many Iowa and Illinois farmers left their dryers idle despite having made substantial investments in this technology. For others, inadequate management of drying technology results in "overdrying" with attendant energy waste and/or reduced product value. Drying beyond requirements for grade and storability reduces weight volume of corn, thus constituting an economic loss to farmers. Excessively rapid drying and cooling results in kernel stress and quality reduction. Moreover, such stress can be expected to have an impact not only on grain quality at first marketing, but also on the resulting quality of grain during subsequent stages of marketing and handling (Hill et al., 1979). Whenever feasible, systems which use natural air drying and in-storage cooling appear to have distinct advantages.

<center>Footnotes</center>

1/This situation is complicated by the existence of more than one measure of physiological maturity (e.g., moisture content, days after silking and black layer) and of maturity (e.g., days from planting to maturity, RM; and growing degree days, GDD).

2/This is based on a somewhat ad hoc application of varietal maturity rate designations to the length-of-growing season climatic zones shown in Chapter III. Calendar days associated with growth stages do not correspond to the relative maturity designations. However, when there are 5 days difference between ratings the earlier hybrid should reach physiological maturity about 5 days before the later hybrid (Peterson and Hicks, 1973). Extension of maturity rates as a result of drying technology availability is assumed to be greater in the Northern regions than the South.

3/Schwart and Hill suggest that "in bin" dryers provide the least costly drying across the greatest range of annual volumes and that at volumes above 20,000 bushels the addition of a stirring device reduces the cost per bushel by providing greater drying capacity with any given size of heating components. Automatic-batch or continuous-flow dryers become economically competitive mainly at annual volumes of 60,000 bushels or more.

4/Modest = energy price increases of 1 percentage point above the inflation rate for electricity and 2 percentage points above the inflation rate for propane. Significant = the real price of electricity increases 45 percent and the real price of propane increases 150 percent over 20 years. Drastic = the real price of electricity increases 154 percent and real price of propane increases 517 percent over 20 years.

5/Before-tax costs for different drying systems estimated by Schwart and Hill are significantly higher than the after-tax costs of Jensen et al. Tax adjustments would place both estimates in a similar range. Both estimates found annual operating costs to be a much smaller component of total costs than were the annualized costs of investment.

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Appendix Table IX-1. Investment Costs for Selected Alternative Drying and Storing Systems for Corn[a]

| System | Capacity (in bushels) | | | | | |
	10,000	20,000	40,000	60,000	100,000	200,000
	Investment Cost (dollars)					
High Temperature Continuous Flow	30,748	36,592	52,610	63,756	131,026	235,659
High Temperature Automatic Batch Dryer	24,436	30,768	50,332	65,297	b/	b/
High Temperature Batch-In-Bin	20,401	28,212	44,880	52,389	b/	b/
Low Temperature	22,003	41,001	65,019	106,326	b/	b/
Combination High/Low Continuous Flow Dryer	39,948	54,705	75,842	99,231	175,976	332,240
High/Low Temperature Automatic Batch Dryer	33,085	48,397	70,017	93,406	182,609	348,198
Dryeration-Continuous Flow Dryer	37,877	43,721	58,115	70,845	128,507	215,527
Dryeration-Automatic Batch Dryer	32,149	38,031	52,425	74,180	133,614	222,924

[a] 1977 Price Basis.

[b] Not evaluated

Source: Jensen et al., (1979).

Appendix Table IX-2. Real Average Annual Costs[a] (in cents) per Bushel for the Lowest Cost Drying and Storing System(s)[b] for Seven Case Farm Situations Under "Modest," "Significant," and "Drastic" Energy Price Increases[c] in Combination with a 5 Percent Rate of General Rate of Inflation Assuming a 35% Income Tax Bracket for Each Case Farm.

Case farms: bu/yr stored and dried	Rank	Modest	Significant	Drastic
10,000	1	Low temp. 16.8	Low temp. 17.3	Low temp. 19.4
	2	Batch-in-bin 19.9	Dryer-AB 22.2	Combination-AB 28.0
	3	Dryer-AB 20.1	Batch-in-bin 22.5	Dryer-AB 28.0
20,000	1	Batch-in-bin 14.8	Low temp. 16.1	Low temp. 18.1
	2	Dryer-AB 15.3	Dryer-AB 17.4	Combination-AB 22.5
	3	Low temp. 15.6	Batch-in-bin 17.4	Dryer-AB 23.2
40,000	1	Dryer-AB 12.4	Dryer-AB 14.5	Low temp. 16.6
	2	Dryer-CF 13.2	Low temp. 14.6	Combination-AB 19.6
	3	Batch-in-bin 13.3	Dryer-CF 15.3	Dryer-AB 20.3
	4	Low temp. 14.0		
60,000 without bucket elevator	1	Dryer-CF 11.9	Dryer-CF 14.0	Low temp. 16.4
	2	Dryer-AB 12.3	Low temp. 14.3	Combination-AB 18.1
	3	Batch-in-bin 12.4	Dryer-AB 14.4	
60,000 with bucket elevator	1	Dryer-CF 14.9	Dryer-CF 16.9	Combination-AB 21.1
	2	Dryer-AB 15.3	Dryer-AB 17.4	Combination-CF 21.7
	3		Combination-AB 17.5	
80,000 without bucket elevator	1	Dryer-CF 11.3	Dryer-CF 13.4	Combination-CF 18.0
	2	Dryer-AB 11.5	Dryer-AB 13.6	Combination-AB 18.3
80,000 with bucket elevator	1	Dryer-CF 13.3	Dryer-CF 15.3	Combination-CF 20.8
	2	Dryer-AB 13.6	Dryer-AB 15.7	Dryer-CF 21.1
	3			Combination-AB 21.2
100,000	1	Dryer-CF 12.9	Dryer-CF 15.0	Combination-CF 20.1
	2	Dryer-AB 13.1	Dryer-AB 15.2	Combination-AB 20.5
	3			Dryer-CF 20.8
200,000	1	Dryer-CF 11.7	Dryer-CF 13.7	Dryer-CF 19.5
	2	Dryer-AB 11.7	Dryer-AB 13.8	Dryer-AB 19.6
	3			Combination-CF 19.6
	4			Combination-AB 20.1

Low temp. = low temperature. Dryer-AB = Dryeration-automatic batch. Dryer-CF = Dryeration-continuous flow. Combination-AB = Combination high temperature-low temperature-automatic batch. Combination-CF = Combination high temperature-low temperature-continuous flow.

[a] Assumes 90 percent debt financing of investment at 9 percent interest rate. Some mechanical components of each drying and storage system are replaced on a 10-year schedule.

[b] Assumes drying for a reduction in grain moisture content of about 10 percentage points.

[c] Modest, significant, and drastic price increases for energy correspond roughly to 10 percent, 45 percent, and 154 percent real increases for electricity and 20 percent, 150 percent and 517 percent for propane respectively over a 20-year period.

Source: Jensen et al., 1979.

Appendix Table IX-3. Capital Investment (Initial and Replacement),[a/] Gallons of LP Gas and Kilowatt Hours of Electricity Per Bushel for Alternative Drying and Storing Systems[b/] and Case Farm Situations (Investment Costs are Based on 1977 Prices)

Drying and storing systems	CASE FARM SITUATIONS						
	10,000 bu.	20,000 bu.	40,000 bu.	60,000 bu.[c/]	80,000 bu.[c/]	100,000 bu.	200,000 bu.
High temperature continuous flow	$2.60 (1.61) .186 gal. .123 kwh.	$1.65 (.89) .186 gal. .150 kwh.	$1.15 (.46) .186 gal. .156 kwh.	$1.00 (.34) .186 gal. .156 kwh.	$ .99 (.30) .186 gal. .112 kwh.	$1.31 (.35) .186 gal. .174 kwh.	$1.17 (.30) .186 gal. .147 kwh.
High temperature automatic batch	$2.07 (1.12) .186 gal. .168 kwh.	$1.39 (.83) .186 gal. .201 kwh.	$1.21 (.51) .186 gal. .233 kwh.	$1.02 (.35) .186 gal. .232 kwh.			
High temperature batch-in-bin	$2.12 (.51) .148 gal. .173 kwh.	$1.32 (.24) .148 gal. .147 kwh.	$1.08 (.16) .148 gal. .155 kwh.	$ .91 (.12) .148 gal. .170 kwh.			
Low temperature	$2.02 (.54) 0 1.88 kwh.	$1.88 (.41) 0 1.88 kwh.	$1.56 (.38) 0 1.97 kwh.	$1.53 (.35) 0 1.97 kwh.			
Combination high/low temperature continuous flow	$3.60 (1.84) .048 gal. .99 kwh.	$2.51 (1.00) .048 gal. .99 kwh.	$1.82 (.57) .048 gal. 1.13 kwh.	$1.47 (.39) .048 gal. 1.23 kwh.	$1.38 (.33) .048 gal. 1.24 kwh.	$1.74 (.38) .048 gal. 1.25 kwh.	$1.61 (.31) .048 gal. 1.34 kwh.
Combination high/low temperature automatic batch	$3.02 (1.28) .048 gal. 1.00 kwh.	$2.22 (.72) .048 gal. 1.00 kwh.	$1.68 (.43) .048 gal. 1.17 kwh.	$1.39 (.31) .048 gal. 1.25 kwh.	$1.42 (.35) .048 gal. 1.25 kwh.	$1.81 (.38) .048 gal. 1.25 kwh.	$1.69 (.32) .048 gal. 1.36 kwh.
Dryeration continuous flow	$2.75 (1.38) .118 gal. .084 kwh.	$1.72 (.81) .118 gal. .111 kwh.	$1.25 (.43) .118 gal. .113 kwh.	$1.05 (.31) .118 gal. .116 kwh.	$ .96 (.23) .118 gal. .106 kwh.	$1.23 (.26) .118 gal. .157 kwh.	$1.03 (.19) .118 gal. .139 kwh.
Dryeration automatic batch	$2.33 (.96) .118 gal. .108 kwh.	$1.50 (.57) .118 gal. .139 kwh.	$1.13 (.31) .118 gal. .132 kwh.	$1.10 (.33) .118 gal. .136 kwh.	$1.00 (.25) .118 gal. .115 kwh.	$1.27 (.25) .118 gal. .163 kwh.	$1.05 (.17) .118 gal. .146 kwh.

[a/] Assumes a 20-year period of operation. Thus, replacement investments are for those components of the system with an expected life of less than 20 years.

[b/] Assumes drying for a reduction in grain moisture content of about 10 percentage points.

[c/] Without bucket elevator.

Source: Jensen et al., (1979).

Appendix Table IX-4. Drying Practices on Farms Producing Corn for Grain, 1978

State	Percentage of corn dried		Percentage on farms by dryer type used			Percentage by type of fuel used			
	Total	On Farm	Batch	Bin	Continuous Flow	LP gas	Electricity	Natural Gas	Other

<div align="center">Dryland</div>

State	Total	On Farm	Batch	Bin	Continuous Flow	LP gas	Electricity	Natural Gas	Other
Cornbelt									
Illinois	68.3	53.6	8.2	70.9	20.8	61.2	9.7	15.3	13.8
Indiana	73.8	64.9	28.1	42.7	29.2	80.5	4.5	10.9	4.1
Iowa	68.6	57.2	28.5	52.9	18.7	82.8	7.6	0.0	9.6
Missouri	56.5	50.5	28.9	41.1	30.0	74.2	2.6	0.0	23.2
Ohio	71.8	51.2	29.0	53.0	18.0	85.8	5.2	0.7	8.3
Lake States									
Michigan	65.1	30.8	65.3	8.8	25.9	100.0	0.0	0.0	0.0
Minnesota	67.7	51.3	41.3	37.0	21.8	97.1	2.9	---	---
Wisconsin	33.5	22.1	35.2	28.3	36.5	63.5	---	36.5	---
Great Plains									
Kansas	22.0	19.1	46.1	29.9	24.1	85.1	7.0	---	7.9
Nebraska	34.7	26.9	0.6	41.9	57.6	69.9	0.1	0.4	29.6
Texas	24.9	13.5	25.1	37.9	36.9	42.1	21.0	36.9	---
South									
Alabama	32.8	29.4	45.5	44.0	10.5	95.2	4.8	---	---
Georgia	28.2	17.1	48.3	51.7	0.0	69.1	18.3	---	12.6
Kentucky	53.0	50.1	22.0	51.9	26.1	68.8	0.7	10.3	20.2
North Carolina	52.7	44.4	17.3	82.7	0.0	68.7	11.5	3.5	16.3
South Carolina	61.5	41.8	38.3	46.7	21.0	70.5	11.5	---	18.0
Tennessee	20.1	20.1	0.0	97.5	2.5	----	3.7	---	96.3
Northeast									
New York	46.6	32.7	49.2	18.4	32.4	86.5	3.2	10.3	---
Pennsylvania	38.3	22.7	35.1	28.5	36.4	96.5	---	---	3.5
				Irrigated					
Colorado	14.6	11.2	17.3	33.4	49.3	40.7	---	48.1	11.2
Kansas High Plains	38.6	22.1	14.8	0.0	85.2	14.8	---	85.2	---
Nebraska	68.0	54.4	0.3	49.1	50.6	66.1	0.3	29.6	4.0
Texas High Plains	61.5	9.5	31.4	0.0	68.6	----	---	100.0	---

Source: Lagrone and Krenz (1980).

This chapter examines the potential application to corn of a number of biotechnologies which are not yet fully developed technically for application in commercial corn production. These technologies are: photosynthetic enhancement, plant growth regulators, cell and tissue culture, gene transfer at the cellular level, and biological nitrogen fixation. The technologies were identified by reference to the Competitive Grants Program of USDA (1980), from literature review and from discussions with agricultural scientists from a wide range of disciplines.

Since all of these emerging biotechnologies are not fully developed at present, their assessment necessarily involves a different approach from those technologies which are already operational. Scientists who are developing the emerging biotechnologies are in the best position to assess the likelihood of their ultimate success. Their opinions were solicited through a survey. Individuals to be surveyed in relation to each emerging biotechnology were identified through USDA (1980) and through colleagues at the University of Minnesota, Iowa State University and and Pioneer Hi-Bred International. The number of people surveyed in regard to each technology and the number of responses received are shown in Appendix Table X-1. The surveys and summaries of the results are also shown in the Appendix.

When the expected gross benefits identified in the survey were converted into present value terms (using a real interest rate of 7 percent) the expected benefits per acre resulting from each technology were $70 for plant growth regulators, $24 for photosynthesis, $14 for cell and tissue culture and $7 for biological nitrogen fixation. Benefits were only taken into account through to the year 2000. No quantification of benefits was attempted for gene transfer because of its early stage of development.

As will be seen later in the Chapter, the application of plant growth regulators are expected to add significantly to costs of corn production. However, the other emerging biotechnologies are expected to be embodied, at least in part, in

(the production of) improved hybrid seeds. When spread over 80 million acres of corn, research and development costs per acre are likely to be small. Also, the fact that the adoption of the biotechnologies (other than plant growth regulators) would be by seed companies, rather than by farmers themselves, means that there should be little time lag between development and adoption. The hybrid seed industry is generally regarded as being competitive (see Chapter III), which is an additional factor suggesting rapid adoption of most of these biotechnologies, subsequent to their development.

This chapter makes no claim to being a comprehensive technical review of the five emerging biotechnologies. Rather an attempt has been made to provide the non-specialist reader with sufficient technical detail to follow the discussion of the likely general magnitude of the impact from these biotechnologies and the likely time schedule of that impact.

Photosynthetic Enhancement

1. **Definition and Description of Photosynthetic Enhancement Technology**

This section examines the possibility of corn yield increases via an increase in the photosynthetic rate, as measured by net carbon dioxide exchange per unit of leaf per unit of time. Plants fall into one of two groups - one group with rates of 50-60 mg CO_2 dm^{-2} hr^{-1}. the other group at 20-30 mg CO_2 dm^{-2} hr^{-1}. Corn is in the higher rate group.

Total crop photosynthesis can also be increased in ways other than by increasing the photosynthetic rate (per unit of leaf area per unit of time), for example, by altering planting pattern or leaf arrangement and by prolonging leaf life. However, with these other methods, it is difficult to distinguish whether resulting yield increases are due to changes in photosynthesis or in some other factor. Therefore, in this assessment, concentration is on the narrow, but more tangible, definition of photosynthetic enhancement given in the first paragraph.

2. Direction and Magnitude of Photosynthetic Enhancement Technology

Photosynthesis is the source of dry matter accumulation in plants. One might expect that increasing the rate of photosynthesis would increase dry matter accumulation directly. There are a number of complicating factors, however, (see Section 5) and "a direct cause and effect relationship between yield and photosynthesis has yet to be established" (Moss and Musgrave, 1971). There have been no recorded increases in commercial corn yields via increasing the rate of photosynthesis.

Despite the obscurity of the relationship, there is considerable indirect evidence that photosynthesis has an important influence on yield. Shading experiments almost always result in yield reductions, while fertilizing plants with carbon dioxide gas almost always increases yields. It is presumed that, in each case, the influence occurs via a change in the photosynthetic rate. Although fertilization with carbon dioxide gas has increased yields, it would be prohibitively expensive on a large scale. Direct manipulation of the photosynthetic pathway by chemicals or plant breeding has been suggested as a possibility, but the present inadequate knowledge of the system makes this an extremely long-term prospect, at best.

The survey results (Appendix) indicated that the only mechanism likely to bring about increased photosynthetic rates in corn by the year 2000 is direct selection for high carbon dioxide exchange rate within traditional plant breeding programs. Some progress has already been made: Crosby et al. (1978) found large differences among eight lines of corn inbreds developed from Iowa Stiff Stalk Synthetic. They also found significant heterosis in these lines and concluded that selection for high photosynthetic rate should be possible.
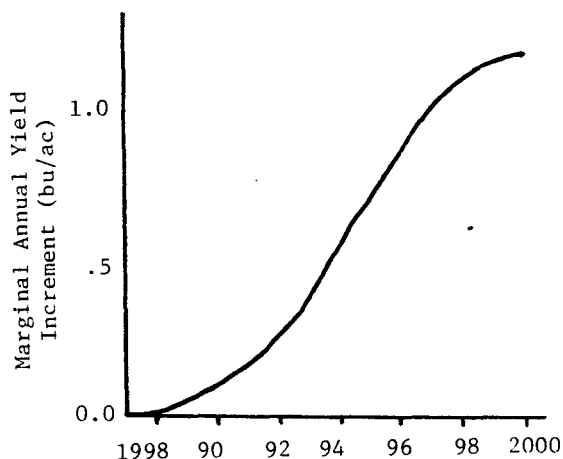
3. Direct Effects of Photosynthetic Enhancement Technology

A majority of respondents to the questionnaire felt that no yield increases in corn would come about via increases in photosynthetic rate by the year 2000. A number of respondents specifically stated that photosynthetic rate gains would be possible, but that these would not translate into yield increases. The overall expectation was for a yield increase of 8 bu/ac by the year 2000.

In addition to knowing the expected yield increase in the year 2000, it is also of interest to know the expected yield gains leading up to that time. An estimate of the marginal annual yield increase was made (Appendix Table X-2), based upon answers to questions about when the first significant yield increases could be expected and by assuming that an S-shaped curve

approximates the annual marginal yield increment over time due to photosynthetic enhancement. The results, which must be regarded as a rough approximation only, are shown in Figure X-1.

Figure X-1. Expected Marginal Annual Yield Increment Due to Photosynthetic Enhancement.

4. Environmental Aspects of Photosynthetic Enhancement Technology

Increasing the photosynthetic rate for corn has no obvious adverse environmental consequences. It is the prospect of getting "something for nothing" (virtually no additional farm inputs, no direct or indirect environmental consequences) which makes the technology attractive.

5. Feasibility of Photosynthetic Enhancement Technology

There are a number of reservations about the feasibility of corn yield increases occurring through increases in photosynthetic rate. These reservations, both theoretical and empirical, were reflected by the majority of respondents anticipating no yield gains by the year 2000. Of the 6 people who responded that they expected a positive yield gain, 3 of these were highly optimistic, expecting minimum yield gains of 25, 10 and 15 bu/ac by 1986. The most likely yield response estimates are heavily influenced by these three people.

Some of the reasons for being skeptical about yield increases by photosynthetic enhancement are given below. First, plants with a higher photosynthetic rate may also respire faster (Moss and Musgrave, 1971), thus negating the potential gain. Second, an increase in rate of photosynthesis will not increase dry matter accumulation if the demand for photosynthate (the product of photosynthesis) is already being met (Nasyrov, 1978).

Even if photosynthetic rate was directly related to dry matter production, the relationship

between dry matter production and corn grain yield is not simple. Corn yield is limited by environmental factors (water, nutrients, etc.) in addition to factors such as photosynthesis. Johnson (1980) calculated that present rates of photosynthesis are sufficient to achieve 500 bu/ac corn. A comprehensive study on wheat by Evans and Dunstone (1971) suggests that photosynthetic rate has not been an important factor in the evolution of modern wheat. Indeed, the photosynthetic rate of wheat has fallen as modern wheats have evolved from primitive types (Radmer and Kok, 1977). It must be remembered that the whole evolutionary process in plants is based upon sur-vival, not the conversion of energy. Thus, a shift toward the latter objective might be expected to require quite radical changes in plant morphology/physiology which may be difficult to achieve.

6. Alternatives to Photosynthetic Enhancement Technology

Increasing the photosynthetic rate potentially offers "something for nothing," at least insofar as farmers are concerned, and there are no known adverse environmental consequences. However, the potential yield increases look relatively small, (at least prior to 2000) and from a research re-source allocation viewpoint, the same investment elsewhere might yield greater returns.

7. Managing Photosynthetic Enhancement Technology

Photosynthesis technology is in the development stage. Questions relating to its management are mostly those concerning research funding and pri-orities. Almost all respondents to the question-naire (13 out of 15) felt that lack of research funding was limiting progress. Most stressed the need for more understanding of the physiology of photosynthesis and for a team approach to breeding for a higher photosynthetic rate.

Plant Growth Regulators

1. Definition and Description of Plant Growth Regulator Technology

Plant growth regulators (synthetic or natural) are organic compounds, other than nutrients, which promote, or otherwise modify, any physiological process in plants.

2. Direction and Magnitude of Plant Growth Regu-lator Technology

Plant growth regulators (PGRs) are not recent discoveries. Ethylene has been used for coloring oranges since the 1920s; auxins have been used to speed the rooting of cuttings since the 1930s. The first active, selective herbicide, 2,4-D, was introduced in the 1940s and is a synthetic copy of a natural plant hormone. There are a

multitude of examples of the application of growth regulators to horticulture (e.g., Morgan, 1979). Defoliants are applied to about one-half of the total U.S. cotton crop to facilitate mechanical harvesting (Morgan, 1979). There have been appli-cations of regulators to wheat and barley in Europe for the prevention of lodging (Wareing, 1976). With sugarcane, a useful role has been found for growth regulators at every stage of crop growth (Hudson, 1976). Cycocel is an impor-tant growth regulator in wheat (O'Neal, 1981). There is no widespread application of growth reg-ulators to corn for yield enhancement in the U.S. One compound, Dinoseb, was used to some extent in the mid-1970s, but it is virtually unused today.

In principle, the availability of exogenous regulators (often hormones), offers great oppor-tunity, since according to Wareing (1976): (i) there is a potential effect on virtually all aspects of plant growth and development; (ii) it is often possible to obtain relatively specific responses without undesirable side-effects; and (iii) active hormones offer favorable cost con-siderations if they can work at low concentrations.

A majority of respondents to the survey thought that a yield increase would come about by an in-crease in the harvest index of corn (the propor-tion of total dry matter which is incorporated in the grain). Some respondents specifically men-tioned the possibility of delaying the onset of leaf senescence during the grain filling stage and some suggested the use of PGRs to enhance photosynthetic efficiency. Delaying leaf senes-cence appears attractive since PGRs have been successful in delaying the onset of physiological processes in non-corn applications, and there is some evidence available relating delay of leaf senescence to increased yield. Furthermore, delaying leaf senescence is a measurable phenome-num, and thus, it is amenable to effective moni-toring for progress (Morgan, 1979). In summary, while most respondents referred to the general objective of increasing the harvest index, this objective might specifically be achieved by de-laying leaf senescence during grain filling.

3. Direct Effects of Plant Growth Regulator Technology

Because no PGR is at present, or ever has been, widely applied to corn, estimates of yield effects are not possible from historical data. Yield response estimates, therefore, relied upon responses to a questionnaire (Appendix), which indicated an expectation that the use of PGRs will result in yield increases of 16 bu/ac by the year 2000. (Only 2 of 19 respondents expected zero yield increase by the year 2000.)

It is also of interest to know the expected yield gains leading up to the year 2000. These were estimated in Appendix Table X-3, and the results are shown in Figure X-2.

Figure X-2. Expected Marginal Annual Yield Increment Due to Plant Growth Regulators
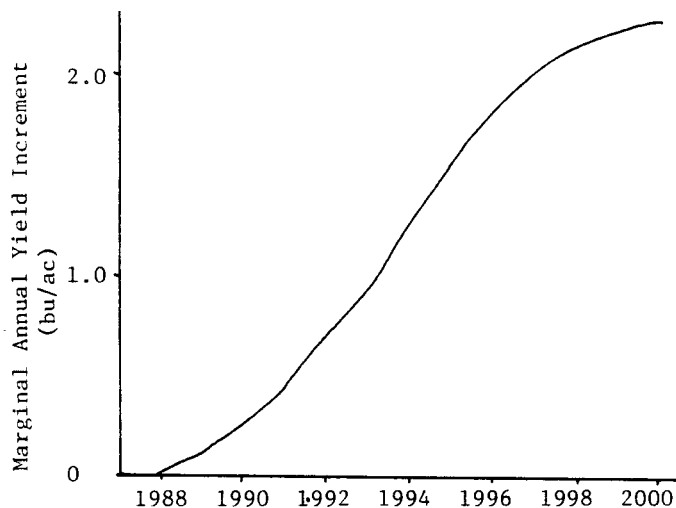
The expected increase in yield of 16 bu/ac in the year 2000 is in the range quoted by industry sources (Anonymous, 1981), as being necessary to make commercial PGR production and sales viable. In fact, development and testing of PGRs for corn is widespread in the private chemical industry.

There is little basis for making an estimate of the price likely to be charged to farmers of PGRs for corn, since at present none are in widespread use, nor apparently have any experimental use permits been issued by EPA (Anonymous, 1981). There are reasons to expect that PGR prices will be sufficiently low to encourage commercial application. Generally speaking, PGRs are highly active and only low concentrations are required to elicit a response (although Cycocel, a PGR used on wheat, is applied at a relatively heavy rate of 2 lb/ac). Another factor likely to keep prices down is the strong competition for the PGR market (Anonymous, 1981). However, in the short-run, one or two companies may be able to capture the whole market prior to other companies developing a competitive product. Overall, a price in the $10-$15 (1981 prices) per acre range might be expected (confidential industry sources).

It is not envisioned that PGRs would require additional amounts of other inputs (except for the direct cost of application) but rather they would enhance the efficiency with which available inputs are converted into economic yield.

4. Other Aspects of Plant Growth Regulator Technology

4.1 Environmental, Legal and Institutional Impacts

These are generally expected to be similar to those of herbicides used in corn production (see Chapter VI). The major difference is that PGRs on corn may be used in small concentrations and may be natural compounds or analogues of natural compounds. Overall, environmental problems should be no more severe, and possibly less severe, than with herbicides.

4.2 Vulnerability of the Technology

PGRs are not particularly energy intensive to produce and are not a concern in this regard. It is possible that corn yield variability might be increased by the application of PGRs (if, for example, yield response to PGRs is a function of weather).

5. Feasibility of Plant Growth Regulator Technology

Questions about the feasibility of yield-enhancing PGRs remain. The yield increases in Appendix Table 1 are expected by people highly knowledgeable in the area, but they may not, in fact, occur. Basic mechanisms are not well understood (most progress to date in the plant regulator area has been "empirical"). A flowering hormone is thought to exist, but has never been identified. Even if it were possible to hasten or delay flowering, it is not clear which alternative would most likely lead to yield gains.

Each type of regulator has a wide spectrum of potential physiological effects: the same substance may produce contrasting effects at different stages in the plant life cycle. The level of hormone is a factor in eliciting response, as is the hormonal balance (comparative levels of various hormones within the system). Variations in hormonal balance at different locations within the plant and over time can have far-reaching effects. Most responses to PGRs so far have involved the triggering of growth processes, such as germination or fruit set, or accelerating or retarding the rates of existing processes.

Two particular problems with PGR development and applications on corn are (Hanson, 1978):
(i) The development processes of the corn ear, which are most closely associated with yield, are in progress over a long period. It is difficult to judge when attempts at modification with PGRs should be made.
(ii) There is substantial compensation between the components of yield in corn. Artificially stimulating one component may depress another component.

6. Alternatives to Plant Growth Regulator Technology

PGRs provide a potential mechanism for increasing yield without implying the need for additional inputs, other than the PGR itself. They are somewhat akin to improved seeds in that they operate via increasing the efficiency of available inputs. PGRs are also similar to improved seeds in that they might be expected to cost roughly the same per acre as seed and would be supplied directly

to farmers by private companies. Thus, in a sense, plant breeding might be viewed as an alternative technology. Plant breeding has the advantage of having no direct environmental consequences.

On the other hand, plant breeding might be viewed as being complementary with PGRs in that breeding programs could select for hybrids exhibiting a strong response to PGRs (not practiced at present). There have been some acquisitions of corn breeding companies by major chemical companies in recent years (see Chapter III) which facilitates the joint development of PGRs and new corn varieties. It would be attractive for these companies to supply both the PGRs and the varieties which responded best to their application. It should be noted however that the two technologies are totally different in form and mode of operation.

7. Managing Plant Growth Regulator Technology

There do not appear to be any unique problems associated with the PGR technology, nor any special need for public involvement, except in relation to the environmental aspect. Even here, the potential impact is less than with other chemical applications on corn.

A majority of respondents to the questionnaire (mainly private sector) felt that research funding was not limiting progress. Yet university and government sector respondents felt that it was. The divergence of opinion over research funding limitations seems to reflect the different perspectives of the private and public sector. Nevertheless, both groups stressed the need for a better basic understanding of the physiology of yield, as a pre-requisite for successful PGR development. Basic research into the physiology of yield is more the role of the public sector where research funds do appear to be limiting progress. On the other hand, private sector funding for compound development and testing (within the bounds of existing knowledge), appears to be adequate.

Genetic Modification at the Cellular Level

Genetic modification refers to the modification of the genetic makeup of an organism by some process other than natural selection. In plants, this can take place at two levels: the whole plant or the cellular level. Genetic modification at the whole plant level has been taking place for thousands of years as plants have been selected on the basis of their performance as agricultural crops. Genetic modification at the whole plant level is examined in Chapter III - Conventional Plant Breeding. This chapter refers only to genetic modification at the cellular level.

Genetic modification at the cellular (or sub-cellular, e. g., gene) level is a relatively new development resulting from the interfacing of recent advances in three areas: cell and tissue culture; molecular biology; and gene transfer (Phillips, 1977).[1] In order to achieve cellular level modifications, plant cells are first established in tissue culture. Modifications are then made to the cells themselves. Finally the modified cells are regenerated to become whole plants. There are two forms of genetic modification - direct and indirect. Indirect modifications involve techniques such as screening for desired traits at the cellular level. (These are discussed in this Chapter under the heading of cell and tissue culture.) Direct modification involves the insertion of new genetic information into the cell. (These are discussed in this Chapter under the heading of gene transfer.)

Genetic Modification at the Cellular Level - Cell and Tissue Culture

1. Definition and Description of Cell and Tissue Culture Technology

Cell and tissue culture is the maintainance and multiplication of cells in a culture or medium. A single cell or group of undifferentiated cells from a plant are introduced into a medium where they undergo division. The development of cell and tissue culture has facilitated many advances including: the regeneration of plants from undifferentiated cells; the transfer of genetic material from one species to another; haploid and anther culture techniques; screening for desired traits at the cellular level; and mass propagation.

2. Direction and Magnitude of Cell and Tissue Culture Technology

The ability to successfully culture plant cells has been available since the late 1930s. Since that time, there has been a great deal of research refining the nutritional and environmental requirements of plant cells in culture. To date, a large number of species have been cultured successfully.

Although successfully culturing plant cells was an important development, the crucial step towards using cellular modifications in plant breeding programs was the ability to regenerate plants from cultured cells. The regeneration of whole plants from tissue culture is important because genetic modifications at the cellular level can then be evaluated in mature plants and subsequently used in breeding programs. The first regeneration of corn from tissue culture was reported by Green and Phillips (1975).

There are many potential applications of cell and tissue culture to crop development. Some of these applications serve to reduce the cost and/or time required to accomplish the same tasks as compared to conventional breeding. In other cases, cell and tissue culture increases the scope of plant breeding through achievements which are not possible using conventional breeding techniques (e.g., the transferring of genes between species).

The responses to the questionnaire (Appendix) indicated the following major categories of potential applications of cell and tissue culture to corn production.[2]/

(i) Screening varieties for disease or other stress resistance. Some plant diseases are associated with toxins; these toxins can be applied to tissue cultures of a susceptible variety to obtain disease resistant mutants. This can be a relatively inexpensive method to search for disease resistance within varieties which otherwise have desirable qualities.

(ii) Developing inbred lines using anther culture. Anther culture is a cell culture which is produced using anthers (containing the haploid sex cells of a plant). Haploids can be of value to breeding programs in the production of homozygous inbreds for hybrids.[3]/

(iii) Reducing the time required to develop new varieties. (This broader category may include one or both of the above applications.)

The respondents were divided over the potential of the various commercial applications of cell and tissue culture. Of the 31 respondents, 11 indicated that the most likely application would be to screen varieties for disease/stress resistance. (Eight specified disease resistance and three specified other forms of stress resistance.) Seven suggested that anther culture would be used for developing inbred lines. Another seven respondents indicated that cell and tissue culture would increase the rate at which new varieties would be developed. Eight responses referred to applications similar to those listed above, however, it was difficult to place their responses into any particular category. (Some individuals listed more than one application.)

3. Direct Effects of Cell and Tissue Culture Technology

The survey results indicated that 71 percent of the respondents believe that cell and tissue culture will make a significant contribution to corn breeding by the year 2000. Fifty-five percent of the respondents indicated that corn yields would increase as a result. The first commercial application is expected to be in 1988 and a 3 bu/ac yield increase is expected in the year 2000. To illustrate how this yield increase is distributed over the 12-year period, from 1988 to 2000, the expected marginal annual yield increment is shown in Figure X-3.

Figure X-3. Expected Marginal Annual Yield Increment from Cell and Tissue Culture.
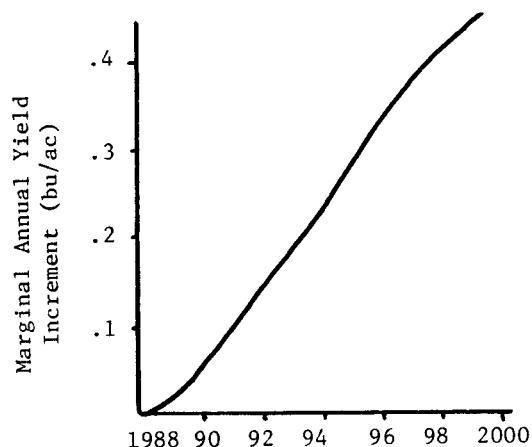
Source: Appendix Table X-4.

Many of the respondents who did not anticipate any yield increase, selected screening varieties for disease resistance as the most likely application. Although such an application may not translate directly into an increase in yield, it would do so indirectly through a reduction in yield losses. This method of screening may also be regarded as reducing the cost of production due to disease resistant varieties becoming available at an earlier date than would be possible utilizing present techniques.

The questionnaire focused on the potential yield increases by the year 2000. There may also be some non-yield impacts such as improved nutritional quality. For example, at the University of Minnesota, tissue culture is currently being used to screen for high lysine corn.

4. Other Aspects of Cell and Tissue Culture Technology

No significant environmental, legal or institutional impacts of the technology were identified.

5. Feasibility of Cell and Tissue Culture Technology

Tissue culture has not yet been systematically integrated into commercial systems of corn breeding. Commercial firms are presently establishing programs and personnel in an attempt to integrate these new techniques into their established breeding systems. Two major kinds of problems may influence the technical feasibility of doing this.

The first type of problem involves the logistics of incorporating techniques, which have been used at an experimental level, into large scale programs.

The second type of problem, relating to the techniques themselves, may limit their usefulness in commercial breeding programs. Some examples of this second type of problem are discussed below.

Tissue culture techniques may provide a relatively inexpensive method of searching for disease resistant varieties, but this particular application may be limited. It requires that a toxin be associated with the disease. The toxin can be applied to tissue culture of disease susceptible (but otherwise desirable) varieties. Consequently, this technique would be of use in producing disease resistant varieties only if the disease produced a toxin. As one respondent to the survey pointed out, many diseases do not produce toxins.

The use of tissue culture to identify strains of corn with desired characteristics (e.g., stress resistance) potentially reduces the cost of obtaining those characteristics relative to conventional methods. However, desirable characteristics at the cellular level may not translate into the same characteristics at the whole plant level (Scowcroft, 1977), although there have been some reported successes (Phillips, 1977). In addition to the concern discussed in the previous paragraph, it may be necessary to check that desirable characteristics already possessed by the plant (e.g., yield), prior to undergoing cellular level selection, are retained. This may considerably reduce the advantages gained, in terms of time and cost savings, from using this method of selection.

Other uncertainties which should be considered are the failure or success rate (90%, 50%, 25%?) of regeneration of cells and of regenerated plants to mature and produce seed in laboratory conditions in both the commercial and public sector settings.

6. Alternatives to Cell and Tissue Culture Technology

Although tissue culture cannot be thought of as alternative to present methods of plant breeding, these new techniques could replace or supplement some techniques presently used in conventional plant breeding. In this sense the alternative to using cell and tissue culture is to use the present methods of plant breeding (Conventional Plant Breeding is discussed in Chapter III of this report.)

7. Managing Cell and Tissue Culture Technology

In managing the technology, tissue culture should be considered in the context of conventional plant breeding and also as a laboratory technique which will be utilized to advance the basic knowledge of living organisms including commercial crops such as corn. Tissue culture techniques and other new biotechnologies such as genetic engineering cannot be considered as an alternative to conventional breeding. If they are used, they will be used in conjunction with conventional breeding programs, not in place of them. These new biotechnologies represent tools to be utilized within established breeding programs.

Cell and tissue culture techniques in corn have been developing along with basic knowledge in plant and cell physiology. The need to utilize the techniques in exploring other areas such as genetic engineering have hastened their development.

A question was included in the survey to establish whether or not any particular area(s) of knowledge is constraining further development (see Appendix). From the response it appears that no one area, but rather many areas are currently limiting the development of the technology. Respondents indicated that research funding is required to increase the number of corn varieties regenerated from tissue culture and to regenerate plants from suspension culture and protoplasts. Respondents also indicated that basic work in tissue culture, screening and selection schemes and protoplast work is required.

Genetic Modifications at the Cellular Level – Gene Transfer

1. Definition and Description of Gene Transfer Technology

Direct genetic modification at the cellular level currently involves two approaches: protoplast fusion and DNA transfer via a DNA carrier (foreign vector).

The first approach (protoplast fusion) refers to the fusion of two protoplasts, or the fusion of a single protoplast with cell components from another cell.4/ The resulting cell contains a combination of the genetic material from both cells.

The second approach to direct genetic manipulation (also known as "recombinant DNA" and "gene cloning"), utilizes foreign vectors to transfer DNA into a host plant cell. Foreign vectors are nonplant materials such as bacterial plasmids or phages (viruses). In simplified terms, these vectors act as intermediaries transferring segments of DNA, which have been isolated from one cell, to the protoplast of another.

2. Direction and Magnitude of Gene Transfer Technology

The development of protoplast fusion has been facilitated by developments in the areas of protoplast isolation (removal of the cell wall), tissue culture, and the regeneration of plants from tissue culture.

The work on genetic transfers using foreign vectors has been facilitated by developments in tissue culture and in the understanding of the basic mechanism by which genetic material of bacteria is sometimes transferred to another bacteria.

Molecular genetic modifications using protoplast fusion and foreign vector techniques offer the potential for transferring genes across the barriers of species (and possibly genus and kingdom). This concept of transferring genes across species has led to the proposal (which would have enormous impact, if successful) for transferring the nif (nitrogen fixing) genes to cereals. These techniques also offer the potential of reducing or eliminating the number of crosses presently required to transfer characteristics.

3. Direct Effects of Gene Transfer Technology

Gene transfer technology is less developed than the other four emerging biotechnologies. Consequently, no quantitative estimates on its impact were solicited in the survey. Rather, the survey focused on the most likely applications of this technology on commercial corn production by the year 2000. Eighty percent of the respondents indicated that there would be an impact by the year 2000. Some of these respondents indicated that the impact would be indirect in that research in this area would lead to a greater understanding of the genetics of corn. The types of direct impacts which respondents listed were: the efficient transferring of selected traits controlled by a single gene (e.g., disease or herbicide resistance) without also transferring other less desirable traits; changing the chemical composition of corn (e.g., protein content and type, oil and starch content); and extending the genetic base to include other cereals. Increased yields and other more complex genetically controlled attributes were _not_ among those applications listed.

4. Other Aspects of Gene Transfer Technology

4.1 Environmental, Institutional and Legal Impacts

4.1.1 Environmental

The creation of previously nonexistent organisms raises the concern that their effects on the environment and other organisms is unknown. As the OTA report (1981) points out, organisms, unlike chemicals, may reproduce and might be impossible to control. This concern could be partly alleviated by extensive testing. However, blanket testing for genetically engineered organisms could result in eroding the potential time advantages to be gained from using genetic engineering techniques (rather than conventional breeding techniques). An example is disease resistance, where the same resistance could be

accomplished by utilizing more time-consuming conventional breeding methods which would not be required to submit to regulatory tests. In order to profit from gene transfer techniques, selective, rather than blanket, regulations should be applied. The types of modified organisms that would likely be produced in connection with corn would be new varieties of corn and biological nitrogen fixing organisms.

4.1.2 Institutional

One of the concerns with genetically modified organisms developed by the private sector has been the controversy over patenting living organisms. If private industry is to develop these organisms they require a method of capturing the returns to their investment. One method of protecting their investment is through the use of patents. In June 1980, the U.S. Supreme Court ruled that man-made organisms are patentable under the current patent statutes. For several years the uncertainty of whether or not living organisms would be patentable resulted in hesitation by firms to invest in the developing of such organisms.

The Supreme Court decision should have two effects on the area of genetic modification in corn. First, general efforts to develop biotechnologies useful for corn should increase, thereby expanding the knowledge base which should in turn facilitate future advances. Second, firms which develop specific biotechnologies, such as N_2-fixing microbes via genetic modifications, will be able to patent them.

4.1.3 Legal

The possibility exists that genetically engineered organisms intentionally released into the environment may cause some sort of damage. Organizations which develop or release these organisms could be liable for that damage. This threat of liability may result in hesitation by private industry in utilizing these new technologies.

5. Feasibility of Gene Transfer Technology

Gene transfer in corn, as for many other crops, is in its conceptual stages. The majority of the surveyed scientists indicated that by the year 2000, genetic modification is expected to contribute significantly to corn production, either directly through the transfer of genes, or indirectly by increasing the basic understanding of corn genetics.

Those scientists expecting gene transfers to take place expect traits such as disease resistance to be affected, but not the more complex traits, such as yield. From the literature it appears that the actual physical transfer of genes

from one cell to another will be less difficult than identifying which genes to transfer. Also, the transferring of genes may be a relatively simple task compared to getting the genes to be properly expressed and remain functional throughout a number of generations.

One possible limitation to the practical use of gene transfers, initially at least, is that cells which have been altered must be regenerated and tested to examine whether or not alterations at the cellular level have also occurred at the whole plant level. Also they may require testing to check that the genetic alterations have not affected other traits such as yield and productivity capacity. In some cases, the necessity to test genetically altered cells before releasing them may erode some of the gains (in terms of time and cost) originally gained by utilizing the techniques.

6. Alternatives to Gene Transfer Technology

The alternative to using gene transfers at the cellular level is to use conventional plant breeding. Conventional techniques can produce the same results with the exception of introducing genetic material from outside the species.

7. Managing Gene Transfer Technology

Gene transfer is being developed in line with advances in basic knowledge in this and related areas. Questions were included in the survey to establish whether or not any particular research area in either genetic engineering of corn or in a related basic science was constraining development in this area. From the responses it appears that additional research funding is required in many areas (see Appendix).

One of the concerns of scientists working in the area of conventional plant breeding is that genetic engineering, cell and tissue culture and other developing biotechnologies will be funded at the expense of conventional plant breeding programs. It should be emphasized that conventional and emerging techniques are complementary rather than competitive. The funding of one area at the exclusion of the other would be a mistake; developments in any of the areas will enhance the other areas and the new techniques will make a valuable contribution to commercial corn production by being utilized in conventional plant breeding programs.

Biological Nitrogen Fixation in Corn

In recent years there has been renewed interest in biological nitrogen fixation as a source of nitrogen for crop production. This interest has resulted both from a search for alternative sources of nitrogen (due to increasing energy prices) and from advances in basic research.

As a result of the research efforts in this area there is a possibility that non-legume crops may, in the future, supply a portion of their nitrogen requirements through N_2-fixation. This section of the report focuses on developments in the emerging technology of biological nitrogen fixation in corn.

1. Definition and Description of Biological Nitrogen Fixation Technology

Nitrogen fixation (N_2-fixation) refers to the conversion of atmospheric nitrogen (N_2) to fixed forms of nitrogen, in which nitrogen is combined with at least one other atom (e.g., NH_4^+). Biological nitrogen fixation (BNF) is nitrogen fixation by living organisms. BNF involves microbial activity in which atmospheric nitrogen in the soil air (air within the soil) is transformed into a form which is directly usable by the plant.

Microbial N_2-fixation can be divided into two categories—symbiotic and nonsymbiotic.[5] In nonsymbiotic fixation, nitrogen is fixed by free living microorganisms which exist independent of a host plant. These microbes derive their source of energy either from photosynthesis (e.g., blue-green algae) or from organic matter in the soil.

In symbiotic fixation, the bacteria obtain their energy from the photosynthate of higher plants with which they are associated (e.g., legumes). Photosynthate is the product of photosynthesis in plants. Symbiotic relationships have been divided into two groups: the associative and the obligatory. In the associative symbiotic relationship, free living bacteria in the rhizosphere (root zone) associate with plants without nodule formation. The plant produces photosynthate, releasing some of it into the rhizosphere. The microbes fix nitrogen by utilizing the photosynthate as an energy source.

An example of the obligatory symbiotic system occurs with Rhizobium bacteria and legumes. The bacteria invade the root hairs of the plant causing the formation of nodules on the host plant. The Rhizobia fix nitrogen in the nodules utilizing photosynthate. Neither the plant nor most Rhizobium bacteria will fix nitrogen independently. The Rhizobium-legume combination has been the major source of fixed nitrogen in crop production for centuries. Since the question of using legumes as a source of nitrogen is not one of technical feasibility, legumes are excluded from this discussion and are considered under crop rotations in Chapter VII.

2. Direction and Magnitude of Biological Nitrogen Fixation Technology

Although legumes have been utilized in crop rotations for centuries and their benefits recognized, the mechanism of N_2-fixation remained obscur

Recently a number of developments have increased the understanding of this area and have led to various proposals for extending N$_2$-fixation to crops which currently do not fix nitrogen.

There are a number of alternative potential strategies for utilizing BNF to achieve total or partial nitrogen self-sufficiency in commercial corn production. The respondents to the questionnaire indicated the following as the most likely mechanisms for bringing about N$_2$-fixation in corn.

(i) Forming an associative symbiotic relationship (non-nodular) between free-living microbes and the corn plant. The concept of forming non-nodular associative relationships between cereals and N$_2$-fixing microbes has been encouraged by the discovery in 1975 by von Burlow and Dobereiner of this type of association in monocots and the bacterium Sprillum lipoferrum. This type of relationship has since been reported in corn.

(ii) Transferring the nif (nitrogen fixing) genes to corn. This approach involves inserting the nif genes into the plant cell so that the corn plant fixes nitrogen in the absence of microbes. Until the early 1970s it was thought that Rhizobia fixed nitrogen only when associated with a legume host. It was believed that the legume provided essential genetic information for the synthesis of the N$_2$-fixing enzyme, nitrogenase. However, a number of experiments in 1975 demonstrated that the necessary genetic information is present in the Rhizobia itself (see Scowcroft, 1977). This discovery opened up the possibility of transferring the nif genes to higher plants. In 1976 a transfer of the nif genes to non-nitrogen fixing bacteria was reported (Cannon and Postgate, 1976), although to date there is no record of a successful transfer to higher plants.

(iii) Establishing a legume-like relationship by inducing corn to form nodules. This would involve inducing cereals to form nodules in response to infection by Rhizobia (NRC, 1977). This approach would require that the barriers to infection be removed and that the environment within the nodules be conducive to the nitrogen fixation reaction.

Ten of the respondents indicated that the most likely mechanism for bringing about N$_2$-fixation in corn was through the associative symbiotic relationship of corn with free-living microbes. Three selected the transfer of the nif genes to corn and two favored establishing a legume-like relationship (nodule formation).

3. Direct Effects of Biological Nitrogen Fixation Technology

The survey results indicated that 66 percent of the respondents believe that at least one of the mechanisms discussed above will provide nitrogen for commercial corn production by the year 2000. The respondents expected that the date of the first significant N$_2$-fixation in corn would be 1990 and that, in the year 2000, corn is expected to be capable of fixing 32 lbs of N/ac.

In addition to knowing the expected nitrogen contribution in the year 2000, it is also of interest to know the expected nitrogen contribution during the period leading up to that time. Figure X-4 illustrates the expected yearly contribution (total amount of nitrogen produced each year) by BNF in corn. The marginal annual contribution was also calculated to illustrate the expected annual increment in nitrogen contribution over this same period (Figure X-5). (This figure corresponds to the figures illustrating marginal annual yield increases in the other four emerging biotechnologies.)

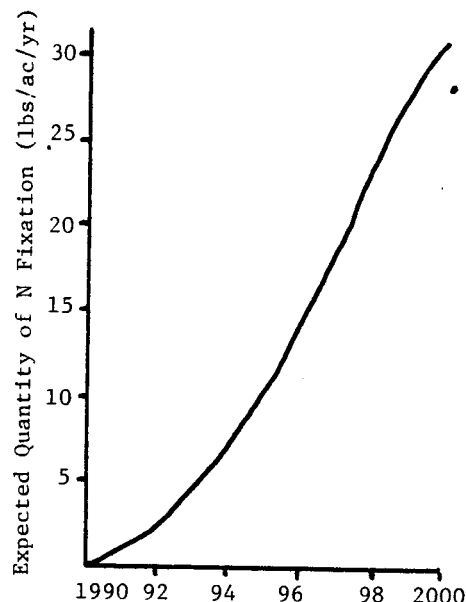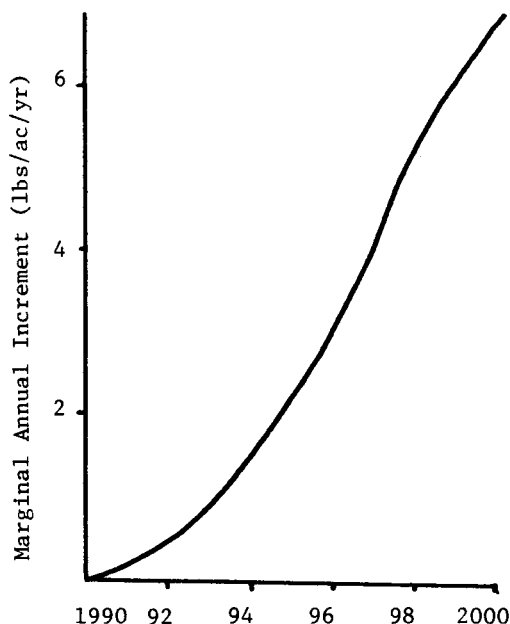Figure X-4. Expected Amount of Biological Nitrogen Fixation in Corn.

Figure X-5. Marginal Annual Increment in Nitrogen Contribution from BNF.

Although the expected contribution of 32 lbs/ac is only one-fourth of the present nitrogen application rate, this does not necessarily mean that this source of BNF will only replace one quarter of the present nitrogen application. It has been estimated that only about 50 percent of the nitrogen applied to crops is, in fact, utilized by the crop (Ausubel, 1981). The remainder of the nitrogen is: leached below the root zone, is lost to the atmosphere through denitrification, or remains in the soil. These losses can be reduced by coordinating the crop's requirement and the timing of application. Since the crop's requirements closely match the supply of nitrogen from N_2-fixation in the crop, the expected 32 lbs of N/ac may represent closer to one-half of the nitrogen required to maintain present yields. (N_2-fixation by legumes grown in rotation with corn do not have this advantage.)

In the introduction to this chapter, the present value of the expected future benefit from BNF in corn, for the period 1990 to 2000, was calculated to be $7/ac. This represents the value of the nitrogen produced by the crop over the ten year period, in present value terms. This may represent only a portion of the real savings for the reason discussed in the previous paragraph. To provide an indication of the magnitude of the potential saving to producers, the likely reduction in the quantity of nitrogen fertilizer, is between one-third to one-half of the present 130 lbs/ac (i.e., 43 to 65 lbs/ac). If producers were able to reduce their nitrogen applications by this amount, this would represent an annual saving of between $8.60-$13.00/ac (43 lbs/ac x 20¢/lb of applied N = $8.60). This calculation however, assumes that there would not be a yield loss due to additional energy requirements of the plant for N_2-fixation. It also ignores the problem of a reduction in N_2-fixation by the crop if nitrogen fertilizer were added (to maintain present nitrogen and yield levels).

4. Other Aspects of Biological Nitrogen Fixation Technology

The environmental impact of nitrogen self-sufficiency in cereals would be favorable. The present high levels of N fertilizer application are causing concern (Chapter IV). As was mentioned in the previous section, nitrogen fixed by the crop is more likely to be utilized by that crop than is nitrogen applied as fertilizer. As a result of this higher utilization rate, less of the applied nitrates would leach into the ground water.

Another environmental concern associated with the use of high levels of fertilizer N, is that nitrous oxides produced by denitrifying bacteria may be damaging to the ozone layer of the earth's atmosphere. The use of biological nitrogen fixation in corn may result in a reduction in the amount of nitrous oxides produced since there would be a higher rate of utilization of the fixed nitrogen by the crop (Ausubel et al., 1977).

5. Feasibility of Biological Nitrogen Fixation Technology

The technology of BNF in corn is at a developmental stage, and there remain many unanswered questions about its technical feasibility. In most cases it is not a question of improving an existing N_2-fixation system (such as in legumes) but rather of creating a new one.[6]

The survey of scientists indicated that they expected at least partial nitrogen self-sufficiency in corn by the year 2000. The method chosen as the most likely method of N_2-fixation, that of a nonnodular associative symbiotic relationship between free-living microbes and the corn plant, presently exists to a limited extent. Some of the respondents to the questionnaire pointed out that, since this method is already in existence, it is logical to expect improvements to it at an earlier date (compared with the other approaches). Three of the respondents indicated that the most likely mechanism for bringing about N_2-fixation in corn was by developing corn plants which fix nitrogen. The success of this method depends not only on the successful transfer (and subsequent heritability) of the nitrogen fixing genes, but also depends upon whether or not the transferred genes will actually fix nitrogen (Ausubel, 1980).

The technical feasibility of N_2-fixation in corn will not ensure its economic feasibility in U.S. commercial corn production. At present, there are concerns which, if verified, may reduce the attractiveness of nitrogen self-sufficiency in corn. One of these concerns is that there will be a trade-off between yield and N_2-fixation in the plant. N_2-fixation requires high levels of energy which must be provided by the plant. At present, this concern remains unresolved. There may also be problems with corn's ability to provide energy at the appropriate location (e.g., rhizosphere). Another concern for U.S. commercial corn production is that, with present BNF systems, in legumes the presence of high levels of nitrogen suppresses fixation by microbes. If the corn plant is less than totally self-sufficient in N_2-fixation, nitrogen added as fertilizer to maintain high yield levels, may suppress N_2-fixation by the crop.

6. Alternatives to Biological Nitrogen Fixation Technology

The alternatives to nitrogen self-sufficiency in corn, are other sources of nitrogen such as: fertilizer nitrogen, organic wastes, and rotations with legumes. These alternate sources of nitrogen are discussed in Chapters IV and VII in this report.

7. Managing Biological Nitrogen Fixation
   Technology

Although the associative symbiotic relationship
of corn and free-living microbes was identified
as the most promising method for bringing about
nitrogen self-sufficiency in corn, at this early
stage not enough is known about the alternatives
to eliminate any from consideration (including
the enhancing of legume N_2-fixation as an indirect
method of providing N for corn). Development of
the technology depends upon advancing the under-
standing of the process of BNF itself.

To establish whether or not any particular
areas of knowledge are constraining the develop-
ment of this technology, a question was included
in the survey (see Appendix). No single research
area was identified as the area which should be
given highest priority but various areas were men-
tioned, including the basic sciences (biochem-
istry, physiology); genetic engineering and
tissue culture work; understanding the process of
BNF; and methods of measuring N_2-fixation.

One suggestion put forward was that of estab-
lishing mission-oriented research teams comprised
of a plant breeder, physiologist-agronomist, bio-
chemist and microbial geneticist. This approach
has met with considerable success in other areas
such as plant cell and tissue culture.

Footnotes

1/Molecular biology is not specifically exam-
ined because, as a more basic research area, it
is outside the scope of this study.

2/Another potential application, not specifi-
cally addressed in the questionnaire is long-term
storage of germplasm. There are two procedures
currently under development, freeze preservation
of: (i) tissue culture, and (ii) cultured excised
shoot meristems. Freeze preservation involves
slow freezing of the culture and storing in liquid
nitrogen. Later, the cells are rapidly thawed.
This process, although still in the development
phase, could provide a means of preserving genetic
stocks at a relatively low cost.

3/Normally, five to six generations of selfing
are required to produce a homozygous line. The
use of double haploid cells represents an advan-
tage in that a shorter period of time is required
to produce homozygous cells which can be regener-
ated into plants (the haploid cells can be induced
to double their chromosome number; thus the term
double haploid).

4/A protoplast is that part of the cell that
lies within the cell wall or, for the purposes of
discussing protoplast fusion, it refers to a cell
from which the cell wall has been removed.

5/The basis for this division is the source
from which the N_2-fixation organism derives its
energy: whether or not it is dependent upon
plants.

6/Although it has been demonstrated that a
small quantity of nitrogen is fixed in corn crops,
as for many other crops, in an associative type
of system, the system is not well developed nor
has it been shown to fix significant quantities
of nitrogen in field conditions.

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Appendix

Questionnaires were sent to leading scientists working in each of the emerging biotechnology areas. The names of these leading scientists were solicited from the Department of Agronomy and Plant Genetics, University of Minnesota and Iowa State University and Pioneer Hi-Bred International, Des Moines, Iowa. The number of questionnaires sent and the number of responses received are shown in Appendix Table X-1.

Appendix Table X-1. Questionnaires Mailed and Responses Received

Biotechnology	No. Questionnaires Mailed	No. Questionnaires Received
Biological Nitrogen Fixation	20	15
Photosynthetic Enhancement	22	18
Cell or Tissue Culture	37	31
Plant Growth Regulators	22	19
Genetic Engineering	32	27

In the remainder of the appendix we present the questionnaires and a summary of the results for each technology. Appendix Tables X-2 through X-5 are at the end.

Yield Gains to the Year 2000

Among other things, the questionnaires requested information on scientists' expectations about corn yields in the year 2000. It is also of interest to know the expected yield gains in years prior to that time, but to ask direct questions about this was thought to entail too much "subjectivity" to elicit satisfactory responses. The method used to estimate the annual expected yield gains (1981-2000) from each emerging biotechnology is explained below with reference to the photosynthetic enhancement questionnaire (p. X-15 and Appendix Table X-2). The method used was the same for each biotechnology.

In general terms, the answers to the questions about first commercial applications of the technologies were used to approximate a time path for yield gains between 1981-2000. In particular, for photosynthetic enhancement, the triangular frequency distribution embodied in the responses to question 3, was used to determine the cumulative probability of a significant yield increase for each year 1981-2000 (Appendix Table X-2, column 2). Then, this cumulative probability distribution was used to weight the most likely yield gain in the year 2000 (question 2). The result was taken to be an estimate of the marginal annual yield increase (e.g., Appendix Table X-2, column 3). From this, the total yield increment over 1980 can be calculated (Appendix Table X-2, column 4).

Photosynthetic Enhancement Questionnaire

Q.1 Which do you think is the most likely mechanism for bringing about photosynthetic rate increases (net CO_2 uptake per unit of leaf per unit time) of commercially grown corn by the year 2000?
(check one only)
_____(a) direct application of chemicals to the plant in order to alter photosynthesis or photorespiration.
_____(b) traditional breeding programs based upon direct selection for high CO_2 exchange rate, or reduced photorespiration, etc.
_____(c) genetic engineering techniques which modify cells within the corn plant.
_____(d) As these 3 mechanisms (a,b,c) do not exhaust the possibilities, please feel free to add your own suggestions here.

Questions 2 and 3 request information which, because of the undeveloped state of the technology, is of a subjective nature. Please answer according to your best judgment. If you are absolutely unable to express an opinion, leave the question unanswered.

Q.2 (a) Do you think that there will be increases in the photosynthetic rate of corn and that significant grain yield increases will result by the year 2000?
_____Yes _____No

(b) If yes, what commercial corn yield increases do you expect to have resulted from photosynthetic enhancement by the year 2000 (given current levels of research expenditure)?

	Total yield increase by the year 2000 (bu/ac)
(please fill each box) Minimum	
Most likely	
Maximum	

Q.3 In what year do you expect to see the first significant commercial yield increases due to photosynthetic enhancement?

	Year
(please fill each box) Earliest	
Most likely	
Latest	

Q.4 (a) Are current levels of research funding constraining the achievement of corn yield gains through photosynthetic enhancement?
_____Yes _____No

(b) If yes, which research areas should be given highest priority for receipt of additional funds in order to lift this constraint?

Summary of Results:

Q.1 All respondents to this question (11) selected traditional plant breeding programs as being the most likely mechanism for bringing about photosynthetic rate increases of commercially grown corn.

Q.2 Opinion was divided as to whether corn yield gains could be achieved through photosynthetic rate enhancement by the year 2000 (7 yes, 9 no). Of those saying no, a number explicitly said that photosynthetic rate increases would be possible, but would not translate into yield increases.

Q.3 The most likely expected yield response by the year 2000 was 7.9 bu/ac (average across all respondents including those expecting zero response). The 7.9 figure represents the expected yield increase in the year 2000 due to photosynthetic enhancement.

Q.4 The earliest expected date to see a significant yield increase from this source was 1987, while the most likely date was 1995 and the latest date, 2000. (Again including only those people who expect an increase.)

Q.5 All but one of the 14 respondents to this question felt that lack of research funds were constraining progress. Most mentioned better understanding of basic physiology and integration of that knowledge into breeding programs as requiring more research.

Plant Growth Regulator Questionnaire

Q.1 What is the most likely mechanism for in-
creasing corn grain yields through the appli-
cation of plant regulators by the year 2000?
(check one only)
_____(a) delaying the onset of leaf senes-
cence.
_____(b) altering the harvest index.
_____(c) altering photosynthesis or photo-
respiration rate.
_____(d) altering duration of growth stages.
_____(e) As these 4 mechanisms (a,b,c,d) do
not exhaust the possibilities,
please feel free to add your own
suggestions here.

Q.2 Do you think that it is more likely that
future commercial applications of plant reg-
ulators to corn will be:
_____(a) Dinoseb.
_____(b) other regulators (specify if you
wish).

Questions 3 and 4 request information which, be-
cause of the undeveloped state of the technology,
is of a subjective nature. Please answer accor-
ding to your best judgment. If you are absolute-
ly unable to express an opinion, leave the ques-
tion unanswered.

Q.3 Do you think that the use of plant regulators
will result in an increase of commercial corn
yields by the year 2000? _____Yes _____No

If yes, what commercial corn yield increases
do you expect to have resulted from plant
regulator applications by the year 2000?

	Total yield increase by the year 2000 (bu/ac)
Minimum	
(please fill each box) Most likely	
Maximum	

Q.4 In what year do you expect to see the first
significant and consistent commercial corn
yield increases due to plant regulator appli-
cation?

	Year
Earliest	
Most likely	
Latest	

Q.5 (a) Are current levels of research funding
constraining the achievement of corn
yields gains from plant regulator appli-
cation? _____Yes _____No

(b) If yes, which research areas should be
given highest priority for the receipt
of additional funds in order to lift
this constraint?

Summary of Results:

Q.1 Eight respondents said that the most likely
mechanism for obtaining a corn yield increase
was by altering the harvest index. Five
people suggested increases in photosynthesis
(but did not specifically mention increases
in the rate of photosynthesis per unit of
leaf per unit of time).

Q.2 Everyone who forecast increases in photosyn-
thesis felt that such success would come from
growth regulators which have not yet been
developed.

Q.3,4 Seventeen of the nineteen respondents
thought that there would be significant yield
increases in corn from the application of
growth regulators by the year 2000. The most
likely expected increase was 15.7 bu/ac in
the year 2000. The earliest date by which
people expect to see the first measurable
and consistent yield increases from plant
growth regulators is 1988, with the most
likely date being 1994 and the latest date
being 2000.

Q.5 Ten people thought research funds were limit-
ing progress while eight thought otherwise.
Understanding the physiological basis for
yield was the only area mentioned more than
once (5 times) as requiring further research.

Cell and Tissue Culture Questionnaire

Q.1 Cell and tissue culture has many potential
applications in plant breeding and genetics.
What do you think the <u>most likely</u> application
of <u>plant cell and tissue culture</u> will be to
plant breeding in corn?
(check one only)
_____(a) developing inbred lines using anther
culture.
_____(b) screening varieties for disease
resistant mutants.
_____(c) using tissue culture to increase
the rate at which new varieties are
developed.
_____(d) As these three applications (a,b,c)
do not exhaust the possibilities,
please feel free to add your own
suggestions here.

Q.2 Do you believe cell and tissue culture will
make a significant contribution to commer-
cial corn breeding by the year 2000?
_____Yes _____No

Questions 3 and 4 request information, which be-
cause of the undeveloped state of the technology,
is of a subjective nature. Please answer accor-
ding to your best judgment. If you are absolute-
ly unable to express an opinion, leave the ques-
tion unanswered. (Assume current levels of re-
search expenditure will continue in the future.)

Q.3 In what year would you expect to see the use
of cell and tissue culture incorporated into
commercial corn breeding?

		Year
(please fill each box)	Earliest	
	Most likely	
	Latest	

Q.4 Do you think that the use of cell and tissue
culture will result in an increase in the
yield of commercial corn production by the
year 2000? _____Yes _____No

If yes, what increase in the yield of commer-
cial corn production would you expect the
influence of cell and tissue culture to have
by the year 2000?

		Total yield increase by year 2000 (bu/ac)
(please fill each box)	Maximum	
	Most likely	
	Minimum	

Q.5 Are current levels of research funding con-
straining progress in the application of
cell and tissue culture to corn breeding?
_____Yes _____No

If yes, which research area should be given
highest priority for additional research
funds in order to lift this constraint?

Summary of Results:

Q.1 Respondents were divided in their response
to the question on the most likely applica-
tion of cell and tissue culture to corn pro-
duction.
-8 indicated screening varieties for disease
resistant mutants.
-7 indicated developing inbred lines using
anther culture.
-7 indicated using tissue culture to in-
crease the rate at which new varieties are
developed.
-6 respondents indicated other applications.
-3 indicated selection of stress resistant
varieties.
-2 indicated all applications of plant tis-
sue culture.

Q.2 Twenty-two respondents indicated that they
believed cell and tissue culture will make
a significant contribution to corn breeding
by the year 2000, eight respondents said no,
one respondent said possibly.

Q.3 In response to the question as to what year
respondents expected to see the use of cell
and tissue culture incorporated into commer-
cial corn breeding, the earliest expected
date was 1988, the most likely date was
1990, and the latest date was 2008.

Q.4 Seventeen respondents thought that the use
of cell and tissue culture would result in
an increase in the yield of commercial corn
production by the year 2000, thirteen res-
pondents said no, one said possibly.

The most likely increase in yield by 2000
due to influence of cell and tissue culture
was 3.09 bu/ac.

Q.5 Nineteen respondents indicated that research
funds were constraining progress in the
application of cell and tissue culture to
corn breeding.

No one research area was emphasized as an
area which should be given highest priority
for additional research funds. The areas
frequently mentioned were:

-protoplast work.
-regeneration of plants from tissue culture,
suspension culture and protoplasts.
-others indicated basic work in tissue cul-
ture (and combined tissue culture and gene-
tic work) and mutant selection schemes.

Gene Transfer Questionnaire

Q.1 What applications do you foresee for genetic engineering techniques which will have a significant impact on corn production by the year 2000?

Q.2 Are current levels of research funds constraining progress in genetic engineering in corn?
_____Yes   _____No

If yes, which research area should be given highest priority for additional research funds in order to lift this constraint?

Q.3 Consider the broader question of fundamental knowledge required for advances in genetic engineering. Is knowledge in any basic science area seriously constraining progress in genetic engineering?
_____Yes   _____No

If yes, in which area of basic science are advances required?

Summary of Results:

Q.1 What application do you foresee for genetic engineering techniques which will have a significant impact on corn production by the year 2000? No single application was emphasized. The most frequent responses were:

-transferring single gene traits (i.e., disease or herbicide resistance) from undesirable varieties to varieties that have desirable characteristics.
-changing the chemical composition of corn (i.e., protein content and type, oil, and starch).
-expanding the genetic base of corn to include other cereals.
-others indicated that research in this area would lead to a greater understanding of genetics of maize (e.g., factors involved in gene expression).
-4 respondents indicated that there would be no application which would have significant impact by the year 2000.

Q.2 In response to the question as to whether or not current research funds are constraining progress in genetic engineering in corn, 21 respondents said yes, 5 said no, and 1 had no opinion.

There was no single research area that was emphasized for receiving the highest priority for additional research funds. To summarize the most frequent responses:

-5 indicated basic genetics.

-3 respondents indicated all areas required research funds.
-other respondents indicated molecular biology of plants, corn biochemistry, tissue culture, protoplast techniques, identification of genes and vectors which transfer DNA in plants.

Q.3 In response to the question as to whether or not knowledge in any basic science area is seriously constraining progress in genetic engineering, 25 respondents said yes.

No specific research area in the basic sciences was emphasized as the area in which advances are constraining genetic engineering advances. To summarize the areas frequently mentioned:

-genetics - these respondents included the general area of genetics, plant genetics, identifying genes (mentioned by several), gene regulation, mechanisms for gene expression, and physical size of specific genes.
-plant physiology.
-molecular biology (plants and other), biochemistry, cell biology, chemistry (both pure chemistry and chemistry of nucleic acids).
-tissue culture, protoplast technology, regeneration from single cells.
-gene transfer.

Biological Nitrogen Fixation Questionnaire

Q.1 Proposals have been made to develop nitrogen fixation in cereal crops. What do you think is the most likely mechanism for bringing about nitrogen fixation in corn?
(check one only)
_____(a) forming associative symbiotic relationships (nonnodular) between free-living microbes and the corn plant in the rhizosphere.
_____(b) establishing a legume-like relationship between corn and nitrogen-fixing bacteria by inducing corn to form nodules and to establish a symbiotic relationship with nitrogen-fixing bacteria.
_____(c) transfering nitrogen-fixing genes to corn so that the corn plant fixes the nitrogen without the aid of bacteria.
_____(d) introducing highly efficient nitrogen-fixing genes into photosynthetic free-living nitrogen-fixing microbes (e.g., blue-green algae).
_____(e) As these four applications (a,b,c and d) do not exhaust the possibilities, please feel free to add your own suggestions here.

Questions 2 and 3 request information, which be-
cause of the undeveloped state of the technology,
is of a subjective nature. Please answer accord-
ing to your best judgment. If you are absolutely
unable to express an opinion leave the question
unanswered.

Q.2 Do you believe the above mechanism will be
     successful in providing nitrogen for commer-
     cial corn production by the year 2000?
     _____Yes   _____No

     If yes, in what year would you expect to see
     the first significant biological nitrogen
     fixation in commercial corn production?

		Year
	Earliest	
(please	Most likely	
fill each		
box)	Latest	

Q.3 What annual quantity of nitrogen would you
     expect these mechanisms to contribute in
     commercial corn production by the year 2000?
     (given the current level of research expen-
     diture)?

		Pounds/acre/year
	Minimum	
(please	Most likely	
fill each		
box)	Maximum	

Q.4 Are current levels of research funding con-
     straining progress with biological nitrogen
     fixation in corn production?
     _____Yes   _____No

     If yes, which research area should be given
     highest priority for additional research
     funds in order to lift this constraint?

Summary of Results:

Q.1 Ten respondents selected forming an associ-
     ative symbiotic relationship (non-nodular)
     between free-living microbes and the corn
     plant, as the most likely mechanism for
     bringing about nitrogen fixation in corn.
     Two selected establishing a legume-like rela-
     tionship, by inducing corn to form nodules.
     Three selected the transfering of nif genes
     to corn. One respondent indicated that
     these were long range alternatives (if not
     impossible) and that growing legumes in
     close association with corn may be better.

Q.2 In answer to the question of whether or not
     these mechanisms would provide nitrogen for
     commercial corn production by the year 2000,
     10 said yes, 3 said no and one indicated
     that an effort must be made to try.

Of those who answered yes, the earliest expec-
ted date of significant biological nitrogen
fixation in commercial corn production was
1990, the most likely date was 1996, and the
latest date was 2009.

Q.3 The most likely quantity of nitrogen contri-
     buted by these mechanisms in commercial corn
     production in the year 2000 was estimated to
     be 31.7 lbs/ac, the minimum estimate was
     13.5 lbs/ac and the maximum was 62.5 lbs/ac.

     Calculation: To calculate the quantities of
     nitrogen contributed the quantities listed
     by the respondents were averaged. If the
     respondent left this section blank and also
     indicated that these mechanisms would not
     contribute by the year 2000 (Q.2), 0 lbs/ac
     was used. If the respondent indicated that
     these mechanisms would contribute by the
     year 2000 (Q.2), but left this section blank,
     their answer was assumed to be represented
     by the average.

Q.4 Eight respondents felt that research funds
     are constraining progress of biological
     nitrogen fixation in corn production. In
     addition, one respondent indicated that the
     constraint is the number of researchers
     willing to undertake a project as well as
     the difficulty in obtaining funding.

     In response to the question on which research
     area should be given highest priority, there
     was no single area that was emphasized. To
     summarize the answers, respondents indicated
     that priority areas for additional research
     funds should be (without regard to order of
     emphasis in the survey):

     -concentration on the actual BNF process it-
     self (in legumes and other, i.e., grass and
     N-fixing bacteria).
     -training (graduate level) and research pro-
     grams which interface agricultural and bio-
     logical sciences.
     -genetic engineering of nif genes (trans-
     fering to cereals).
     -increasing the efficiency in N-fixation
     (genetic manipulation of both bacteria and
     plants involved).
     -increased funding in corn biochemistry and
     physiology, and in plant cell culture work.

Appendix Table X-2. Expected Yield Increases from Photosynthetic Enhancement in Corn, 1980-2000

Year	Probability of Significant Yield Increase by That Year [a]	Expected Marginal Annual Yield Increment [b] (bu/ac/yr)	Total Yield Increase Over 1980 [c] (bu/ac)
1987	0.00	0.00	0.00
1988	0.01	0.01	0.01
1989	0.04	0.05	0.06
1990	0.08	0.10	0.16
1991	0.15	0.18	0.34
1992	0.24	0.29	0.63
1993	0.35	0.42	1.05
1994	0.48	0.58	1.63
1995	0.63	0.76	2.39
1996	0.77	0.93	3.32
1997	0.87	1.05	4.37
1998	0.94	1.14	5.51
1999	0.98	1.19	6.70
2000	1.00	1.21	7.91
Total	6.54	7.91	

Appendix Table X-3. Expected Yield Increases from PGR Application to Corn, 1980-2000

Year	Probability of Significant Yield Increase by That Year	Expected Marginal Annual Yield Increment (bu/ac/yr)	Total Yield Increase Over 1980 (bu/ac)
1987	.00	.00	0.00
1988	.01	.02	0.02
1989	.05	.11	0.13
1990	.11	.25	0.38
1991	.19	.43	0.81
1992	.29	.66	1.47
1993	.41	.93	2.40
1994	.55	1.25	3.65
1995	.69	1.56	5.21
1996	.80	1.81	7.02
1997	.89	2.02	9.04
1998	.95	2.15	11.19
1999	.99	2.24	13.43
2000	1.00	2.26	15.69
Total	6.93	15.7	

[a] Cumulative probabilities derived from triangular frequency distribution embodied in answers to Q.4 (i.e., the parameters of the triangular distribution are completely specified by the minimum, maximum and most likely dates).

[b] Total increment by 2000 (7.9 bu/ac), weighted by Column 2 figures (e.g., year 2000 figure) of:

$$7.9 \times \frac{1.00}{6.54} = 1.21, \text{ where } \sum \text{ column 2} = 6.54;$$

year 1999 figure of: $7.9 \times \frac{0.98}{6.54} = 1.19$, etc.

[c] Cumulative numbers from column 3.

For method of calculation, see Appendix Table X-2 and discussion on "Yield Gains to the Year 2000" on p. X-14.

Appendix Table X-4. Expected Yield Increases from Cell and Tissue Culture, 1980-2000

Year	Probability of Significant Yield Increase by That Year	Expected Marginal Annual Yield Increment (bu/ac/yr)	Total Yield Increase Over 1980 (bu/ac)
1988	0.00	0.00	.00
1989	0.02	0.01	.01
1990	0.09	0.04	.05
1991	0.21	0.10	.15
1992	0.32	0.15	.30
1993	0.43	0.20	.50
1994	0.53	0.25	.75
1995	0.62	0.29	1.04
1996	0.71	0.34	1.38
1997	0.79	0.37	1.75
1998	0.87	0.41	2.16
1999	0.94	0.44	2.60
2000	1.00	0.47	3.07
Total	6.53	3.07	

For method of calculation, see Appendix Table X-2 and discussion on "Yield Gains to the Year 2000" on p. X-14.

Appendix Table X-5. Expected Quantity of Biological Nitrogen Fixed by Corn, 1980-2000

Year	Probability of Significant Contribution from BNF by Year	Expected Marginal Annual N Contribution (lbs/ac/yr)	Total Contribution Over 1980 (lb /ac)
1990	0.00	0.00	0.00
1991	0.01	0.07	0.07
1992	0.06	0.43	0.50
1993	0.13	0.92	1.42
1994	0.22	1.56	2.98
1995	0.33	2.34	5.32
1996	0.46	3.27	8.59
1997	0.60	4.26	12.85
1998	0.76	5.40	18.25
1999	0.89	6.32	24.57
2000	1.00	7.10	31.67
Total	4.45	31.67	

For method of calculation, see Appendix Table X-2 and discussion on "Yield Gains to the Year 2000" on p. X-14.

Most corn production technologies require management decisions by individual corn producers when they are applied. Even in the use of hybrid seed, for example, the producer must choose, from among available alternatives, which variety (or varieties) to purchase and plant. As technologies multiply in number and complexity, their implementation by producers requires both more information and more timely information.

Historically, corn producers have been hesitant to subscribe to technology management services although they have used the information services of both the public sector (e.g., the Cooperative Extension Service) and the private sector (e.g., seed companies, fertilizer dealers and machinery dealers) to answer technical questions. However, the complexities of production technology, its high cash cost and the importance of its correct implementation on a timely basis have combined to increase the value of technology management services. A broad range of such services are now being provided and used, and the list is growing rapidly.

The following is a partial list of the corn production decisions for which appropriate technological information is important:
  (i)   seed variety and plant population rates;
  (ii) fertility programs;
 (iii) pest management programs;
  (iv) soil moisture control and management;
  (v)   tillage, planting and harvesting programs, including their calendarization; and
  (vi) corn drying and storage programs.

In addition to the previous list, many producers use formalized information systems as a basis, or partial basis, for determining cropping systems, and for planning input acquisition, product marketing and financial management. Moreover, several of the above activities must be effectively coordinated, both within production activities and between them. For example, planting machinery must be coordinated with harvesting machinery for compatibility of row numbers and width between rows. Maturity rates for seed varieties used, and their planting dates, must be

consistent with the time schedule and equipment available for planting, harvesting and grain drying. With these complexities, the development of information and decision systems for managing corn production technologies has become virtually a technology of its own. These systems can be adapted for use in a multitude of ways to meet the individual decision-making needs of producers. We do not, however, undertake to examine such potential adaptations in any detail.

1.   Definition and Description of Systems of Technology Management

These systems include any technical information provided to farmers for the management of the technology which they use in corn production. The digital computer has become a central component in some technical services, information systems and decision aids, but it is still absent from many others. Moreover, some computerized management information systems provide for user interaction and/or system modification, while others do not.

In an effort to achieve effective technology management, many commercial corn producers now use formalized technical information systems pertaining to the following:
  (i)   varietal performance (yields, maturity rates, insect and disease resistance and optimal plant populations);
  (ii) plant nutrition (soil tests, plant sample analysis, fertilizer-yield response, alternative fertilizer formulations, fertilizer application methods and timing, costs, etc.);
 (iii) water management (irrigation scheduling, crop water demand, irrigation system efficiency, energy efficiency, soil – water – plant relationships, etc.);
  (iv) pest control (monitoring of insect, disease and weed populations, assessment of chemical pesticide performances, recommendations on chemical pesticide treatments and integrated pest control methods, etc.); and
  (v)   grain moisture management (evaluation of corn grain moisture for implementation of

harvesting and drying technologies and information on capacities, costs and performances of alternative drying systems).

Many commercial corn producers also use technical information on costs, cash flows, present value analysis, etc. Some of the latter information is, however, not uniquely applicable to the corn enterprise but is used for production management of all enterprises. Both high investment costs and high operating costs (including high interest charges) require farmers to implement effective procedures for financial management and control.

2. Direction and Magnitude of Technology

Until they began using hybrid seed varieties, most corn producers either selected seed from their own fields, or purchased a single approved seed variety from a local dealer. As indicated elsewhere in this report, the extensive use of chemical fertilizers and pesticides is mainly a post World War II phenomenon. Sprinkler irrigation and grain drying technologies are even more recent. Thus, the effective demand for information on technology management is mainly a product of the last three decades.

On the supply side, private consultant services have emerged quickly in response to demand. The necessary software for effective computerized decision aids is only now being generated for some of the more recent corn production technologies. The availability of such computer software (Strain, 1980) and the availability of micro- and mini-computers for its widespread application are both in a period of rapid change (Fuller, 1981). In many states, the Cooperative Extension Service is providing development services and is also providing leadership in implementation to the private sector.

2.1 Sources of Technical Information

Information for technology management is currently being made available by a variety of sources including:
(i) industry, particularly those firms engaged in sale of seeds, fertilizers, pesticides, machinery, and equipment;
(ii) public sector agencies, including USDA, state agricultural experiment stations and the Cooperative Extension Service; and
(iii) agricultural consultants, including independent consulting services as well as those associated with cooperatives and other agribusinesses.

Some information regarding corn production technology must be provided on a highly time-specific basis in order to be effective for decision making. Examples include diagnostic-type information pertaining to on-farm management of

irrigation and pest control programs. In the latter case, for example, one needs to have timely information on those pest species present in the individual fields and their populations and development stages. This is necessary in order to implement control programs which use the appropriate amounts of the appropriate pesticides on the appropriate time schedule.

2.2 Technical Information Services

The critical need of producers for information inputs for technology management has been the major impetus for the rapid growth in number of professional agricultural consultants. Moreover, the complexity of current technologies has created a demand, not only for professional personnel as consultants, but also for sophisticated electronic and mechanical monitoring devices and for a variety of computerized information systems and decision aids.

Individual agricultural consultants provide a range of services to corn producers at various prices. The following is an illustrative listing of services provided by one farm management cooperative either in its base corn management plan or as an addition to it (CENTROL, 1981):
(i) crop planning (including plant population, row spacing, and variety recommendations);
(ii) soil sampling and testing;
(iii) fertility recommendations;
(iv) stand evaluation at crop emergence;
(v) early insect, disease and weed evaluations;
(vi) pest control recommendations;
(vii) plant samples (early and at reproductive stage of plant);
(viii) corn borer count;
(ix) corn rootworm evaluation;
(x) final stand count;
(xi) late weed and disease evaluations; and
(xii) for irrigated corn: water scheduling, an extra plant sample and infra-red photography; the latter to monitor the crop for plant stress.

The general plan for this service is to monitor field conditions on a 7-10 day schedule during the growing season, with more frequent visits during critical stages of plant growth and/or during special problem periods.

Other services provide technical information centering mainly on integrated pest management or on irrigation scheduling. Although formal technical information services are currently used by only a minority of corn producers, it appears likely that many more producers will be utilizing some formalized technical information services by the mid-1980s.

2.3 Role of Computers

Digital computers have been in widespread use in farm planning for over two decades. Only recently, however, have they been used extensively

as a decision aid for the management of complex agricultural technologies. Computers are also being used to record and store voluminous data on variety performance, weather, pest populations, efficacy of chemical pesticides, yield response to fertilizer and water, etc. This data, when analyzed, will provide an additional information base for future technology management.

The current list of computerized information systems and decision aids is excessively long to report here. Moreover, the systems are changing rapidly. Some brief examples are included for illustrative purposes.

A computerized information system used in pest control management is that of WEEDREC, a computer assisted herbicide recommendation program developed at Kansas State University (Nilson, 1981). Program users may specify up to five important weed species, the infestation situation for each and the preferred method of herbicide application. The computer printout provides an array of herbicide materials, their performance for the listed weeds and current recommendations relative to restrictions on their use. This decision aid can be readily augmented to include current cost information as well.

To predict potential evapotranspiration rates, other Kansas State University analysts adopted a modified Penman equation and the Jensen equation for utilization on programmable calculators in order to predict potential evapotranspiration for crops. A crop coefficient curve (which describes the stage of plant development) is then used to correct to the actual water useage by the stage of the corn crop (Thomas, 1981).

A third widely used type of computerized decision aid is the corn enterprise budget generator (Benson, 1981; FEDS, 1981). These budget generators provide detailed, area specific compilations of per acre (and sometimes per bushel):
   (i)   input requirements;
   (ii) expected yields;
   (iii) cost category breakdowns, and
   (iv) returns above costs.
The FEDS corn budget generator, for example, provided the production costs per bushel shown in Chapter XII of this report. A sample FEDS corn budget is shown in Appendix Table XI-1.

Other computerized decision aids now available include those pertaining to grain drying and storage decisions, machinery selection and costs, optimal fertilizer programs, insect and disease control programs and many others. In response to the widespread availability of computerized decision aids, a major farm magazine (Successful Farming) recently initiated a publication called Farm Computer News. This and other communication devices will surely speed the development and use of computerized information systems and decision aids for technology management.

3. Direct Effects of the Technology

The effectiveness in use of improved information systems for capturing potential benefits depends on both (i) the quality of the information system(s); and (ii) the effectiveness with which producers use this information for decision making. No quantitative assessment of either is currently possible. It is clear, however, that effective information services are now an integral component of the technology utilized by many leading commercial corn producers. The relative importance of these services is expected to increase greatly in the future.

3.1 Impact on Yields

Overall, it is unlikely that this technology (mainly technical consultants, formal information systems and computerized decision aids) currently makes a contribution of more than 1.5-2 bu/ac to average U.S. corn yields. But, they have the potential by 1990 to reduce by as much as 20-25 percent (perhaps a maximum reduction of 40 percent by 2000) the existing gap between average farm yields and those on farms with top technology management. This probably translates into a weighted annual yield increase of .25 to .3 bu/ac/yr during the 1980s and .2 bu/ac or so from 1990 to 2000.1/

3.2 Costs and Profitability

Costs of services for technology management vary depending on the scope and source of services provided. The 1982 cost schedule for the comprehensive crop management service referred to earlier (CENTROL, 1981) will be approximately as shown below:

Dryland Corn

   First 40 acres in field - $260.00
   Additional acres - $5.00 per acre

Irrigation Corn

   First 40 acres in field - $360.00
   Additional acres - $6.50 per acre

It can be seen that larger acreage producers achieve some cost economics of size (reflecting the overhead costs of travel time by consultants), but these economics are very modest. Comprehensive technology management services can be profitable for producers if they result in yield gains of about 2.5 to 3 bushels per acre, or even smaller yield gains if coupled with cost savings. The most likely areas for cost savings appear to be reduced pesticide applications and reduced use of irrigation water. Costs of up to $15.00 per acre have been reported for a comprehensive package of field monitoring, irrigation scheduling and other formalized information system services. This appears to represent an upper limit to the feasible cost structure for such services.

3.3 Resource Use and Productivity

Technology management services mainly require the use of additional trained technical personnel and the development of effective data systems and computer software. In the near term, trained personnel are in short supply. However, this supply can be augmented rather quickly (by the mid-1980s) via adjustments in employment and/or additional technical training. Impacts of management technology on conservation and productivity of other resources is expected to be strongly positive.

4. Other Aspects of the Technology

Environmental impacts of this technology appear to be minimal. A net reduction in use of chemical pesticides in the U.S. appears to be a likely result as does some conservation in the use of irrigation water. Both adjustments are ecologically positive.

5. Alternatives to the Technology

Demand for management technology is induced by the complexity of the production technologies available, and in use. Future corn production technologies are expected to be at least as complex as those currently employed. There is no obvious alternative to the development of improved management technology except the reversion to simpler production technology and this appears very unlikely.

6. Managing the Technology

Since the technology is ecologically positive there are no substantial management problems. Continued public sector inputs will be needed, however, to:

(i) continue the development of more effective technology management services;
(ii) train technical personnel;
(iii) monitor the quality of services being provided to producers; and
(iv) provide management training programs for producers.

Footnotes

1/Swanson, Smith and Nyankori (1979) estimate the yield differential between average county yields (Piatt County, Illinois) and those on well managed (Allerton Trust) farms to be about 13 percent. Thus, if one assumed a 12-13 percent differential to corn yields of 100 bu/ac for average U.S. corn production, a 20 percent reduction in the differential would be about 2.5 bushels, or .25 bu/ac/yr, if the reduction occurred over a 10 year period, and a 25 percent reduction would be about .3 bu/ac/yr.

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Appendix Table XI-1. Corn for Grain - Illinois - Area 300, 1979.

	Unit	Price or Cost/Unit	Quantity	Value or Cost Per Acre	Cost Per Unit of Production
1. Gross Receipts from Production:					
Corn	bu	2.500	134.200	335.50	
Total Receipts				335.50	
2. Variable Costs:					
Preharvest:					
Herbicide	ac	11.440	1.000	11.44	0.09
Insecticide	ac	3.060	1.000	3.06	0.02
Herbicide Appl.	ac	2.300	0.040	0.09	0.00
Seed	lbs	0.893	16.600	14.82	0.11
Nitrogen	lbs	0.145	162.100	23.50	0.18
Phosphate	lbs	0.189	88.000	16.63	0.12
Potash	lbs	0.093	107.400	9.99	0.07
Lime	tn	8.390	0.190	1.59	0.01
Fertilizer Appl.	ac	2.240	0.280	0.63	0.00
Tractor Fuel & Lube	ac			4.47	0.03
Tractor Repairs	ac			1.89	0.01
Mach Fuel & Lube	ac			1.30	0.01
Mach Repairs	ac			2.41	0.02
Machinery Labor	hrs	3.610	1.846	6.66	0.05
Interest on Op. Cap.	$	0.105	47.954	5.04	0.04
Total Preharvest				103.53	0.77
Harvest:					
Corn Shelling	bu	0.109	10.000	1.09	0.01
Custom Combining	ac	15.250	0.100	1.52	0.01
Tractor Fuel & Lube	ac			0.25	0.00
Tractor Repairs	ac			0.10	0.00
Mach Fuel & Lube	ac			5.55	0.04
Mach Repairs	ac			6.29	0.05
Machinery Labor	hrs	3.610	1.930	6.97	0.05
Drying Cost	bu	0.103	93.940	9.66	0.07
Interest on Op. Cap.	$	0.105	0.908	0.10	0.00
Total Harvest				31.53	0.23
Total Variable Costs				135.07	1.01
3. Income Above Variable Costs				200.43	1.49
4. Ownership Costs (Replacement, Taxes, Interest, Ins.)					
Tractors				6.26	0.05
Machinery				39.31	0.29
Total Ownership Costs				45.57	0.34
5. Other Costs					
Land Charge (Share Rent)				121.75	0.91
Gen Farm Overhead				7.94	0.06
Management Charge (10.0% of Total Non-Land Costs)				18.86	0.14
Total Other Costs				148.54	1.11
6. Total of Above Costs				329.18	2.45
7. Return to Risk				6.32	0.05

This chapter has two prime objectives. The first major section of the chapter presents an aggregation and integration of key findings from the assessments of individual technologies for the overall U.S. corn production system. In the second section, the impacts of these technologies are projected to the year 2000 and the major implications of these projections are discussed.

The analysis presented here is a partial one, since a complete analysis would require assessment of the interaction of technologies across commodities within a general equilibrium (supply-demand) framework. Such a complete analysis would require resources beyond the level available for the study. Two basic assumptions are made: (i) the demand for corn relative to other products will remain at about its present level;1/ and (ii) total U.S. corn acreage will also remain at about its present level.2/

Assessment of Overall Corn Production System

Acreage, Yields and Production Capacity

Annual average yield increases of 1.5 bu/ac can be expected through most of the next decade. The major gains will come from improved hybrids, but irrigation, drainage, crop rotations and improved technology management systems will also make contributions. (This will be discussed in more detail later under "Production Impacts Of Technologies by the Year 2000.")

Future production capacity changes may come from either yield or acreage changes, but yield increases will probably be the most important. The roughly five-fold increase in corn production capacity since 1930 has come mainly from increased yields. The land inputs used in achieving these yields have been augmented substantially by irrigation, drainage and other technological improvements. Should effective demand warrant doing so, corn production in the U.S. could be quickly expanded by another 10 million acres or so, mainly by substituting corn for other crops. Much of this expansion potential is due to available

technologies which now provide improved control of soil moisture and fertility, more widely-adaptable hybrids (e.g., shorter maturity rates), more effective pest control systems, more timely production operations and reduced labor requirements.

Resource Use

This discussion on resource use is limited to the major resources involved in corn production.

(i) Energy

The nature of energy use in corn production changed greatly as production practices shifted from the use of draft animals and labor intensive production technologies, to the use of highly mechanized technologies with large inputs of chemical fertilizers and pesticides. Prior to this change, corn production used very little fossil fuel energy. The system drew heavily on land to produce hay and grain as an energy source for draft animals, mainly horses. By 1950, horse and mule numbers had been reduced by 70 percent from World War I levels, and the substitution of tractors for draft animals was virtually complete. The use of chemical fertilizers and pesticides in farm production, on the other hand, is mainly a post-World War II phenomenon. The energy output/input ratio has remained fairly constant since 1945 - energy inputs per acre have risen in roughly the same proportion as energy outputs (yields/ac), as is illustrated in Figure XII-1.

Although the energy intensiveness per bushel of corn does not appear to have increased since World War II, corn has become more energy intensive on a per acre basis (particularly when produced with pump-sprinkler irrigation technology). At present, corn is energy intensive relative to other field crops. It requires three times more energy per acre than soybeans (in the Corn Belt), and twice as much energy per dollar of output (Johnson, 1981). Thus, increases in real energy prices will enhance the competitive position of

Figure XII-1. Energy Output/Input Ratio for U.S. Corn Over Time, 1945-79

Kcal Output
Kcal Input
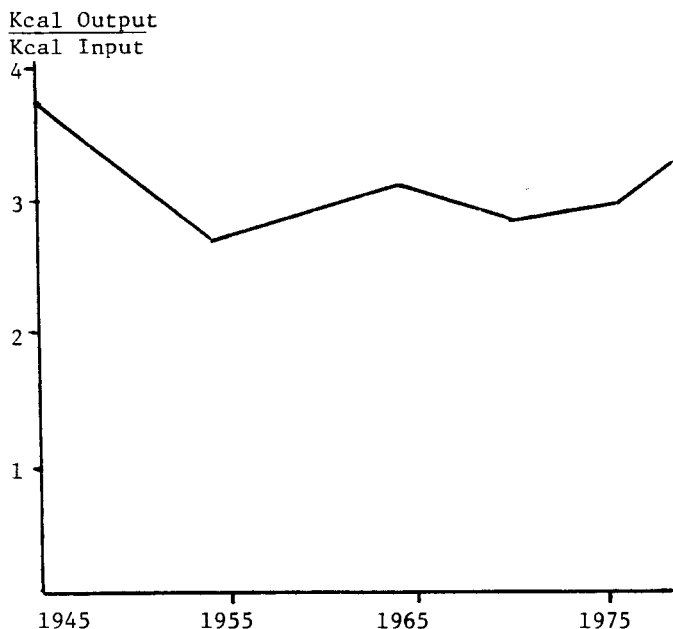
Source: Pimentel et al. (1973); Pimentel and Pimentel (1979); and Pimentel (1980).

soybeans (and some other crops) vis-a-vis corn. The major energy intensive inputs in dryland corn production are fertilizers (over 50% of the total) and grain drying (13%). Irrigated corn is more energy intensive than dryland production, with the irrigation process itself being the major user of energy (at 30% of the total). Where deep well pumping of water is involved, energy costs for pumping may be 60 percent of total energy costs (Wittmus et al., 1975; Jensen and Kruse, 1980).

Dramatic increases in energy prices relative to those for corn could have severe adverse impacts on the cost structure of corn production. A critically important criterion for future corn production technology is that of increased energy efficiency. Low energy prices have induced energy-intensive production technologies for corn. However, the overall energy output/input balance remains highly favorable (Figure XII-1).3/ In the future, improved energy efficiencies in irrigation and corn drying are likely. There are also indications of a leveling off in the use of agricultural chemicals.

(ii) Land

. The amount of land required to produce one bushel of corn has fallen rapidly, corresponding to increases in corn yields (Table XII-1). In 1945-49, 0.028 acres of land were required to produce one bushel of corn. During 1975-79, this fell by two-thirds to 0.010 ac/bu. Thus, changes

in technology have resulted in a lower land requirement for a given amount of corn production.

Table XII-1. Land Requirement to Produce Corn

Year	Total Corn Acres Harvested for Grain (m. acres)	Yield of Corn (bu/ac)	Acres of Land Per Bushel of Corn Grain Harvested
1945-49	86	36.1	0.028
1955-59	76	48.7	0.021
1965-69	57	78.5	0.013
1975-79	70	95.1	0.010

Source: USDA, Agricultural Statistics, various years.

As of 1981, the potentital for some major land augmenting technologies (agricultural chemicals in general, and nitrogen fertilizer in particular) appear to have been almost fully exploited. Mechanical technologies have made modest contributions to land augmentation in the past (more effective tillage, planting and harvesting technologies) and, can only be expected to make modest (at best) contributions in the future. Thus, conventional plant breeding, irrigation and improvements in technology management procedures appear to be the major sources of land augmenting technology in the near term. (Contributions from the emerging biotechnologies are still some years away.)

(iii) Labor

A century ago (in 1880) corn production required about 1.8 hours of labor per bushel. Corn production remained labor intensive throughout the early decades of the 20th century. Since World War II, the labor required to produce one bushel of corn has fallen even more dramatically than the land requirement (Table XII-2). In 1975-79, labor required was less than 10 percent of that in 1945-49. A modest decline in labor input per unit of output is continuing.

Table XII-2. Labor Required to Produce Corn

Year	Labor Requirement (hrs/ac)	(hrs/bu)
1945-49	19.2	0.53
1955-59	9.9	0.20
1965-69	5.8	0.07
1975-79	3.6	0.04

Source: USDA, Agricultural Statistics, various years.

The major labor efficiencies in corn production resulted from the mechanization of tillage, planting and harvesting operations, combined with the extensive use of herbicides for weed control. Improved labor efficiency, coupled with per acre yield increases have reduced the labor input in corn production to less than 5 percent of total production costs (Table XII-5). Moreover, at the present level of less than 0.04 hrs/bu, the scope for further substantial increases in labor efficiency appears remote.

(iv) Capital

Expenditures for corn production - both those for investments in durable items (e.g., land, machinery and equipment) and those for servicing annual production inputs (e.g., fertilizer, fuel, seed, machinery repairs, etc.) - have grown rapidly in recent years. The cost of credit required to finance these expenditures has, along with interest rates, exploded to much higher levels. Annual costs of servicing all production inputs (including capital investments) are illustrated in Table XII-5 for the period 1975-80. Some additional perspective on capital investments for corn production is presented below.

In terms of capital investment costs for corn production, several items dominate. Foremost is real estate capital. Field machinery and equipment, along with grain drying and storage facilities, are also expensive investment items. Where applicable, irrigation and drainage systems are also of key importance. Table XII-3 presents an illustrative, and somewhat simplified, perspective on the per acre and per bushel investment requirements for these durable capital items. Actual per unit investments vary greatly between farms depending on size of farm, location and technology used. One impact of these high capital investments is to drive the per bushel differential between costs and revenues to a very low level (see section on costs later in this chapter). Another impact is that of limiting entry into commercial corn production to those with substantial capital or access to capital. For example, the investment costs of Table XII-3 indicate that 300 acres of corn require a capital investment of $1 million.

(v) Water

With the major expansion in the irrigation of corn that has taken place, water has become a critical input on more than 11 million acres of corn. This acreage is continuing to grow, and compared to other irrigated field crops, corn is a heavy user of water. Until recently, water consumption withdrawals in the U.S. for agriculture (77% of total withdrawals in 1975) dwarfed all other uses. However, non-agricultural water use is increasing rapidly, and future competition between water for corn production and other uses will be much more intense.

Table XII-3. Illustrative Investment Costs for New Durable Capital Used in Corn Production (1981 Basis)

Capital Investment Item [a]	Approximate Investment/Acre	Approximate Investment/Bushel [b]
Cropland (Corn Belt)	$2,000+	$20.00
Field Machinery and Equipment	$ 400	$ 4.00
Drying and Storage Facilities	$ 150+	$ 1.50
Irrigation Facilities	$ 500-$650	$ 5.50
Subsurface Drainage System	$ 300-$500	$ 4.00
Total	$3,350+	$35.00

[a] Not all of these investment costs are incurred by all producers. For example, many, though not all, Corn Belt farmers invest in drying and storage facilities and in land drainage systems. Few, however, invest in irrigation systems.

[b] For investment decision purposes, investment per additional bushel produced is a more relevant measure than these average investments across the whole corn enterprise.

Currently, the rapidly declining water table in the Southern Plains portion of the Ogallala aquifer constitutes an issue of particular concern. In general, the intertemporal trade-off in water use is becoming a critical issue in the application of irrigation technology, since current use from some aquifers exceeds their recharge capacity. Aside from the Southern Plains however, most current use of water for corn irrigation is not in intense competition with other present or "near future" water uses. This is partly because corn is not a major crop in the arid regions of the Mountain or Western States.

(vi) Chemicals

Use of agricultural chemicals increased ten-fold in the Corn Belt between 1950 and 1979 (USDA, 1981). In recent years, the aggregate use of both fertilizers and pesticides in corn production has levelled off substantially. This levelling off is the result of both: (i) a very high proportion of corn acreage now receiving treatment

(96% of all corn acreage now receives fertilizer and 98% receives herbicide); and (ii) fertilizer applications have now reached near optimal levels from a marginal cost-marginal returns perspective. One can conclude that the leveling off of fertilizer application rates on corn (and consequently in the yield increase from fertilizer) is probably a rather permanent phenomenon because, at currently high application rates (125-130 lbs/ac), the marginal product from additional nitrogen is relatively low (.12 bu/lb of N).

Chemical fertilizer is a land augmenting technology since it has generated major increases in per acre yields. While pesticides are land augmenting (yield increasing), herbicides also substantially reduce the labor and mechanical inputs required for effective weed control. Both fertilizer and pesticides are energy intensive inputs. It is this characteristic, plus their potential for environmental pollution, which gives them an element of vulnerability.

Continued use of herbicides at, or near, current levels is probably necessary if soil erosion is to be contained or reduced via reduced tillage technologies. Environmental damage from herbicides could be minimized by using less persistent chemicals. Insecticides are currently used on corn, particularly for controlling corn root worm. Use of insecticides can be minimized by reducing the incidence of corn following corn and by scouts to monitor insect populations and to optimize the timing of insecticide treatments.

In summary, agricultural chemical technologies are a key component of current corn production technology, reducing labor and machinery field operations substantially. Their continued use is of critical importance, but improved management practices have the potential to reduce application rates, thus also conserving energy and minimizing environmental damage.

Costs

Obtaining consistent, historical cost of production data on corn proved difficult. No U.S.-wide data were available prior to 1975, but useful historical data for Illinois were obtained from the Department of Agricultural Economics, University of Illinois.[4] Even with these data (Table XII-4), there are problems of comparability over time. Thus, no strong inferences can be drawn about trends in the real costs of producing corn. The data of Table XII-4 do not indicate any clear trend in real producton costs per bushel of corn prior to the mid-1970s.[5] During most of this period, machinery inputs were replacing labor, and chemical inputs were becoming major components of the corn production system. In general, farm labor was being replaced by capital intensive inputs purchased from the industrial sectors.[6] Fortunately, yields increased

Table XII-4. Real Corn Production Costs - Central Illinois, 1931-80

Period	Real Cost ($/bu)[a]
1931-32	$2.57
1941-42	$1.61
1951-52	$1.98
1959-60	$1.88
1964-73	$2.01
1974-80	$2.30

[a] The first four figures in this column were obtained by dividing the real costs for the period by the average yield for six years surrounding and including that period (to smooth out yield fluctuations due to weather). The final two figures were obtained directly from yield and cost figures for each year within the relevant period. Real cost is nominal cost deflated by Prices Paid index (1977=100).

dramatically during the 1950s and 1960s, so that real costs (per bushel) appeared to change little during this period. However, during the 1974-80 period, rising land, machinery and energy prices, coupled with a slowing of yield gains pushed real costs (per bushel) above the levels of the preceding decades. From the standpoint of the economic viability of corn production, increasing intersectoral costs (purchases of machinery, energy, chemicals, etc.) are of greater concern than are increases in (largely) intrasectoral costs, such as those associated with the capital costs due to the restructuring of land ownership.

Cost of production data for the whole U.S. are available only since 1975 (Table XII-5). From 1975-79, total variable costs averaged about $1.05 per bushel. Fixed costs, other than land, were around 55¢/bu and land (market value) almost 90¢/bu. (Each cost category, however, shows a significant jump in 1980, due to low yields, as well as continuing inflation.)

There are only small regional cost differences between the major corn producing areas. Where they do exist, they are strongly influenced by regional yield differences (Lagrone and Krenz, 1980). The greatest cost differences occur between irrigated and dryland production where the production cost structure differs substantially (Lagrone and Krenz, 1980). Moreover, individual producer costs do vary greatly within all regions, particularly with respect to the actual land costs incurred. Those producers with very high land servicing costs currently have major cash flow problems.

Table XII-5. U.S. Corn Production Costs Per Bushel, 1975-80.

	1975	1976	1977	1978	1979	1980
VARIABLE:						
Seed	0.11	0.11	0.12	0.12	0.11	0.16
Fertilizer	0.45	0.39	0.39	0.33	0.34	0.53
Lime	0.01	0.01	0.01	0.01	0.01	0.02
Chemicals[a]	0.14	0.11	0.10	0.13	0.12	0.17
Custom operations[b]	0.06	0.07	0.06	0.04	0.04	0.05
Labor	0.10	0.12	0.13	0.10	0.11	0.14
Fuel and lubrication	0.07	0.09	0.09	0.08	0.11	0.19
Repairs	0.06	0.08	0.08	0.07	0.09	0.11
Drying	0.04	0.06	0.07	0.06	0.06	0.07
Interest	0.04	0.03	0.03	0.03	0.04	0.07
Total	1.06	1.07	1.09	0.98	1.03	1.51
MACHINERY OWNERSHIP:						
Replacement	0.17	0.20	0.21	0.19	0.21	0.28
Interest	0.08	0.09	0.08	0.09	0.13	0.22
Taxes and Insurance	0.02	0.02	0.03	0.03	0.03	0.04
Total	0.27	0.30	0.31	0.31	0.37	0.54
Farm Overhead	0.10	0.11	0.11	0.07	0.07	0.10
Management[c]	0.17	0.14	0.15	0.14	0.15	0.21
TOTAL, EXCLUDING LAND	1.60	1.62	1.66	1.49	1.62	2.36
TOTAL, INCLUDING LAND[d]	2.48	2.46	2.54	2.35	2.60	3.82
TOTAL, EXCLUDING LAND, DEFLATED[e]	1.80	1.71	1.66	1.37	1.30	1.69
TOTAL, INCLUDING LAND, DEFLATED[e]	2.79	2.59	2.54	2.16	2.08	2.73
YIELD/PER PLANTED ACRE	85.7	87.1	88.8	100.5	109.6	90.5

[a] Includes herbicides, insecticides and rodenticides not otherwise included under custom operations.

[b] Includes custom application of crop chemicals, the cost of chemicals in some cases, and custom harvesting and hauling.

[c] Based on 10% of the above costs.

[d] Weighted current value composite of owned and rented land.

[e] Deflated by USDA Prices Paid Index, which in the respective years was 89, 95, 100, 109, 125, and 140.

Source: Committee on Agriculture, Nutrition and Forestry, U.S. Senate (various years), Costs of Producing Selected Crops in the United States, 1975, 1976, 1977, 1978, 1979. Data for 1980 are unpublished, USDA.

Revenue vs. Costs

The nominal values for costs of producing corn in Central Illinois were compared with the nominal corn price for the corresponding period (1931-80). The difference between nominal prices and costs for each period were then deflated by the CPI, in order to estimate changes in real net returns over time. The results of these calculations are shown in Table XII-6.

There was a negative return in 1931-32, as a result of the extremely low corn prices during economic depression, as well as the relatively high costs per bushel (Table XII-4). Aside from the 1931-32 period, there has been a steep decline in the real revenue-cost differential over time. The present low margin between revenue and cost per bushel for Central Illinois can be extrapolated to the whole U.S., by comparing costs from Table XII-5 with the corresponding U.S. corn prices.

Table XII-6. Historical Real Net Returns for
   Corn - Central Illinois

Period	Real Net Returns (Prices - Costs in $/bu)[a]
1941-42	$3.15
1951-52	$2.61
1959-60	$0.61
1964-73	$0.61
1974-80	$0.12

[a]1980 dollars (nominal prices - costs, deflated
by CPI).

Thus, new technology has been accompanied
by both (i) increased yields and production vol-
ume, and (ii) lowered profits per unit of output.

Farm Structure

With a decline over time of real net returns
per bushel of corn, total net income of producers
can be maintained only by increasing the size of
the operation. Historical data on the size of
farms growing corn, and on the size of the corn
enterprise, is available from U.S. Census of
Agriculture sources. However, such data averages
all units identified as "farms," rather than pro-
viding a more useful "operating unit" definition
of size. An operating unit measure, which is
"acreage weighted" is available from a cost of
production survey (Lagrone and Krenz, 1980).[7]

Table XII-7 illustrates the difference in size
of corn enterprise between Census farms and
acreage-weighted operating units for Minnesota,
Iowa, and Illinois in 1978. It is only by utili-
zing modern mechanization technology on these
larger operating units that commercial producers
can keep per unit investment costs to an accept-
able level. Moreover, the corn enterprise typi-
cally represents only about one-third to two-
thirds of the cropland acres for operating units
(see Table XII-8). Thus much of the machinery
and equipment technology, labor and overhead costs
are spread over enterprises other than corn.

In order to put together operating units of
adequate size, many farmers rent cropland acreage
in addition to that which they own. For example,
the percentage of land rented on the sample of
dryland operating units shown for 1978 (Table
XII-8) ranged from about one-third in Minnesota
to almost 60 percent in Illinois (Lagrone and
Krenz, 1980). In summary, among the impacts of
technological change in corn production have been
increases in farm operating size, and in the inci-
dence of land renting, in order to increase in-
comes and to spread overhead.

Table XII-7. Comparison of Corn Enterprise Size
   (Census vs. Operating Unit Definitions) for
   Three States, 1978

State	Cornland (acres)	
	Census Units	Acreage Weighted Operating Units[a][b]
Minnesota	91	218
Iowa	125	262
Illinois	140	372

[a]Data are from statistical samples ranging from
48-73 farms per state. Sample stratification
sought to provide equal probability of including
each acre of corn. Thus it is an acreage weighted
sample of corn producing units which is depicted
by the data.

[b]The corn acreage weighted operating units in
Minnesota and Iowa farms each had 131 acres of
soybeans and the Illinois farm 174 acres.

Source: 1978 Census of Agriculture and 1978
       survey by Lagrone and Krenz (1980).

Table XII-8. Operating Unit Sizes of Total
   Cropland and Total Cornland, Various States,
   1978

	Cropland (ac)[a]	Cornland (ac)
Dryland		
Illinois	605	372
Indiana	515	326
Iowa	459	262
Missouri	799	294
Ohio	489	230
Michigan	447	233
Minnesota	505	218
Wisconsin	403	212
Kansas	535	177
Nebraska	556	352
Texas	1,149	382
Irrigated		
Colorado	2,403	1,139
Kansas (High Plains)	1,537	455
Nebraska	756	450
Texas (High Plains)	1,979	655

[a]Soybeans are the major non-corn field crop in
the Corn Belt, whereas both wheat and sorghum
are the major non-corn irrigated field crops in
the High Plains.

Source: Lagrone and Krenz (1980).

No direct observations on the historical
acreage of corn per acreage weighted operating
unit are available. The Agricultural Census does
give the acreage of corn land per census defined
farm. (Table XII-9 shows data from Iowa which
is used here as an example.)

Table XII-9. Census Data on Amount of Corn Land
Per Farm in Iowa, 1945-78

Year	Corn Land (ac)
1945	56
1954	56
1964	72
1974	112
1978	124

One could assume that these same rates of
change over time apply to the amount of corn land
actually farmed per operating unit. However,
this would result in an underestimate of the real
rate of change, since the proportion of corn land
rented per operating unit is thought to have
risen substantially over time. Consequently,
the historical size change of operating units in
Iowa is probably better represented by the upper
line in Figure XII-2.

Environmental Externalities

Environmental externalities are discussed in
detail within the chapters dealing with specific
technologies and are only highlighted below.

If soil erosion on corn land continues at pre-
sent rates, the long-run yields of corn will be
severely affected, perhaps by 15-30 percent by
the year 2030 (USDA, 1980). Thus, changes in the
technology of producing corn are necessary - and
in fact, are already underway. One-third of corn
land is presently under reduced tillage and this
proportion is expected to double by 2000. Not
only will this conserve soil but short-term pro-
duction costs will be reduced. Many corn farmers
have, and will continue to adopt reduced tillage
voluntarily. In other cases, small economic
incentives may be necessary. On steeper slopes
(especially in Iowa), reduced tillage will have
to be augmented by other forms of erosion control
and stronger economic or legislative inducements
may be necessary.

Nitrate contamination of groundwater is a po-
tential problem which could result from nitrogen
applications to corn and from release of nitrogen
from organic matter. Problems so far have been
of a localized nature. Although this is not to
discount its importance in those areas, it does
mean that local adjustments (deeper wells,

Figure XII-2. Estimate of Historical Corn Acreage
Per Unit, Iowa, 1945-78.
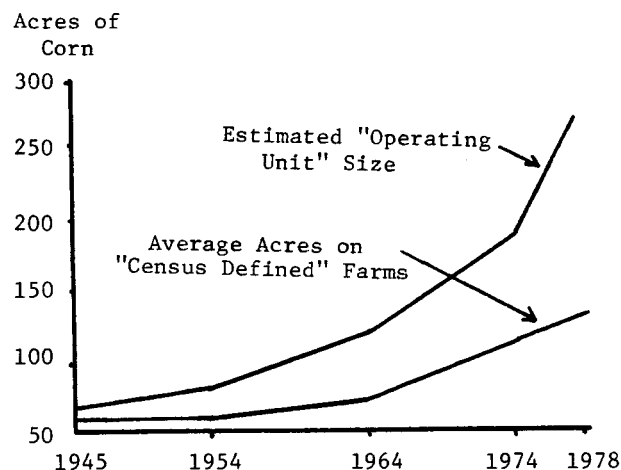
Source: Lower line is from Table XII-9. Upper
line estimated by adjusting the lower
line by: (i) a factor representing the
proportion of operating acres rented
(assumed to have risen linearly from 10%
to 50% over the period); (ii) an addi-
tional small modification in order to
bring the 1978 estimate to the level
found in the survey by Lagrone and Krenz.

improved management of water applications, etc.)
may provide solutions. Future real energy price
rises should ensure a more efficient use of ni-
trogen fertilizer and consequently reduce the
problem. Effective monitoring of nitrate levels
would also be beneficial. Based upon present
knowledge, this does not look like an area re-
quiring major public sector intervention, or
major changes in production technology.

Phosphorus, unlike nitrogen, strongly adheres
to soil and is thus not a problem in groundwater.
It is more likely to be a problem in relation to
eutrophication of lakes. Reductions in soil ero-
sion from reduced tillage are also reducing losses
of soil-borne phosphorus. The general problem of
phosphorus in relation to eutrophication is not
in relation to corn particularly, but to all of
agriculture.

Herbicides used on corn are generally non-per-
sistent and non-toxic to humans. However, herbi-
cides have been linked with known carcinogenic
compounds and monitoring of herbicides for pos-
sible subtle or obscure effects should be contin-
ued. Tillage is the only viable technological
alternative to herbicides, but tillage on corn
has strong negative consequences in terms of soil
erosion. Heavy reliance on herbicides well

into the future seems likely. A number of families of effective herbicides are available, thus the removal of one or two families of compounds from the market poses no serious threat to corn production. A total ban on all herbicides would reduce yields, however, a total ban seems a remote possibility.

Insecticides pose a more serious threat to human health. In addition, insect resistance, along with the lack of a set of "back-up" chemicals means that the insecticide technology is somewhat vulnerable. However, alternative (or at least partially alternative) control measures are available - crop rotation, scouting and hybrid resistance. Overall there seems no strong reason to predict environmental/health problems of sufficient magnitude to remove corn insecticides from the market. If this did happen, alternative control techniques could substitute, with little overall loss in efficiency. (Indeed, there appear to be sufficient economic incentives at present, to diminish insecticides use on corn.)

In addition to the problem of mining groundwater resources discussed earlier in this chapter, irrigation of corn contributes in a minor way to water erosion on some fragile soils. However, a greater environmental problem will exist via wind erosion, if and when irrigation is abandoned on some land due to the depletion of water supplies and/or excessively high energy/corn price relationships. In this regard, public policies should be directed to the development of appropriate environmental impact studies and to the provision of appropriate soil protection mechanisms in connection with new irrigation developments.

Supply Vulnerability

The vulnerability of individual crop production technologies has been discussed in some detail in previous chapters. Our purpose in this section is to discuss briefly the implications of these vulnerabilities for the aggregate supply of U.S. produced corn over the period between now and the year 2000. Though it is not derived from our technology assessment directly, a very brief discussion of supply vulnerability due to weather and climate is included.

In order to place the following discussion of supply vulnerabilities in perspective, it is important to keep in mind that aggregate corn acreage harvested for grain is expected to remain generally in the 70-80 million acre range. Also, average annual marginal yield increases of around 1.5 bu/ac/yr can be expected through the 1980s. This expected increase represents two-thirds of the average yield increase over the period from 1954-80. From 1990-2000, significantly higher yield increases are expected, as some emerging biotechnologies are commercially applied. (See second part of this chapter for more details.)

(i) Weather and Climate

Plant breeding, irrigation, drainage, grain drying and mechanization technologies have all reduced the vulnerability of corn production to both intra-season and inter-season weather fluctuations. Yet, weather variability continues to have a major impact on aggregate production mainly via variance in average annual yields. A recent study (Research Directorate of the National Defense University, 1980) reported a standard deviation in corn yields of 10 bu/ac for a historical base period when adjusted to 1976-levels of technology. That study did not account for "price induced" yield effects, principally via fertilizer and corn prices. Our own analysis, which used the results of equation III-1 to do this, resulted in a standard deviation of about 5 bu/ac over the past 27 years.[8]

With respect to climatic changes (longer-term changes in weather patterns) there is no strong consensus regarding what changes are likely or what their impact on corn yields might be. However, indications are that, "to the year 2000 at least, climate (long-term changes) will probably be a much weaker determinant of crop yields than agricultural technology" (Research Directorate of the National Defense University, 1980). Moreover, should systematic climatic changes occur, plant breeding technology, particularly, can be employed to minimize the adverse impacts of modest changes in climate.

(ii) Genetic Resources

There may have been some improvements in increasing the genetic diversity of corn in the ground in a given year (Duvick, 1981) and such improvement may continue as more private sector resources are devoted to the development of parent inbred lines. Nevertheless, disease or insect pest attack of the magnitude of the 1971 corn blight could reoccur. The prospect of such a problem existing for a period of more than one to two years appears remote, since genetic resources in breeding pools and in gene banks appear to be adequate.

Taking a longer-term view of the situation, however, it appears that the total world supply of genetic resources is diminishing. Yet there will be a continuing demand for new and exotic germplasm. Present government efforts to collect, preserve and describe corn germplasm appear to be inadequate. This poses a threat to corn supply in the long-term.

(iii) Environmental Externalities

In the short-term, environmental considerations are not likely to pose any major threats to the supply of corn.[9] In the long-term, soil erosion from water runoff could pose a serious threat, if unchecked. However, voluntary changes in tillage systems by farmers, assisted by modest

incentives from government, can greatly reduce this threat.

Other adverse environmental externalities associated with current production technologies (principally nutrient and toxic pollutants) can probably be controlled at acceptable levels by improved management and local regulation. Eventual reversion of some irrigated cornland to dryland farming upon depletion of local water supplies and/or because of high energy prices will constitute a problem of significant adverse environmental impact when it occurs. But, it will probably not greatly jeopardize the aggregate supply of corn.

(iv) Resource Supplies and Prices

Of the important resources used in corn production, only the supplies of energy (including agricultural chemicals with their high energy embodiments), and water appear vulnerable to short supplies in the near term.

Corn yields are now less responsive to changes in nitrogen fertilizer prices compared to the period from the mid-1950s to 1970 (Menz and Pardey, 1981). Although the rates of nitrogen application may change with a change in the corn/nitrogen price ratio, this will not result in large corn yield changes. (At the lower nitrogen application rates which prevailed during the 1950s and 1960s, corn yields were much more responsive to changes in the nitrogen/corn price ratio.)

Although fuel for field machinery and grain drying may be in short supply and experience price rises in the future, the conservation of fuel in field operations and the use of substitute fuels for grain drying will probably avoid vulnerability for aggregate corn production. Of the several intensive energy using technologies, only deep well irrigation appears seriously threatened by "high price" energy. Even in this case, a combination of energy conservation, adoption of more energy efficient technology and a shift to shallower well water supplies (principally in Nebraska) will likely postpone the vulnerability of aggregate corn supplies to energy prices until the year 2000. In fact, aggregate irrigated corn acreage is expected to increase over the short term.

In the near term, water resources will limit corn production below current levels only in the Southern Plains. This vulnerability to aggregate corn supplies will be more than offset by expanded water use for irrigating corn in other areas. Though competition from non-agricultural water uses is rising rapidly, it does not appear that this competition will be intense with most water use for corn irrigation before the year 2000. This situation could change, however, with an extended drouth in the Central portion of the U.S.

(v) Farm Structure

Concern has been expressed regarding the impact of large farms (particularly corporate farms) on the vulnerability of supply for farm products. Although this may well be a legitimate concern in the long-term, it does not appear to be a source of short-term vulnerability for aggregate corn production. Only a small portion (about 5% in 1978) of U.S. corn production was from farms with annual sales of $500,000 or more (Coffman et al., 1981).10/

Probably of significant vulnerability is the current and future financial solvency of some corn producers who have borrowed heavily to invest in durable capital for corn production (land, machinery, irrigation equipment, drying and storage facilities, etc.) at high prices. However this financial vulnerability for individual producers does not translate into vulnerability for aggregate corn production. Corn land will likely continue in production under a high level of technology even though individual producers experience financial problems severe enough to create business insolvency. There is a strong incentive for remaining producers to absorb any available cropland.

Production Impacts of Technologies by the Year 2000

In this section, we take a longer-term (year 2000) view of the technologies which are expected to have significant impacts on production capacity. This is done in a ceteris paribus framework, where intercrop price and production relationships are not evaluated. Moreover, we continue our assumption that, on average, real corn prices will continue at current or higher levels to the year 2000. Since we do not consider acreage changes, our projection of future technological impacts is mainly in terms of changes in per acre yields, subject to informal feasibility constraints on production costs and permissable environmental impacts.

An initial set of yield projections is made which reports the "average" future impacts expected by survey respondents for the emerging biotechnologies. A set of "adjusted projections" is then developed which, in our judgment, better reflects the impacts from these emerging technologies after taking uncertainty into account.

Yield Impacts to the Year 2000

Impacts of the technologies expected to have a significant effect on corn yields are presented in Table XII-10. The figures in this table are taken directly, or derived from, earlier chapters of this report. Columns two and three were

Table XII-10. Yield Impacts of Various Technologies, 1981-2000

Year	Technology Trend [a]	Additional Nitrogen	Production Management Technologies	Emerging Biotechnologies	Total [b]
	Marginal Annual Yield Increases (bu/ac/yr)				
1981	1.0	.4	.2		1.5
1982	1.0	.3	.2		1.5
1983	1.0	.3	.3		1.5
1984	1.0	.2	.3		1.5
1985	1.0	.2	.3		1.5
1986	1.0	.2	.3		1.4
1987	1.0	.2	.3		1.4
1988	1.0	.1	.3		1.4
1989	1.0	.1	.3	.2	1.5
1990	1.0	.1	.3	.4	1.8
1991	1.0	.1	.2	.7	1.9
1992	1.0	.1	.2	1.1	2.3
1993	1.0	.1	.2	1.6	2.8
1994	1.0	.1	.2	2.1	3.3
1995	1.0		.2	2.6	3.8
1996	1.0		.2	3.1	4.3
1997	1.0		.2	3.4	4.6
1998	1.0		.2	3.7	4.9
1999	1.0		.2	3.9	5.0
2000	1.0		.2	3.9	5.1
		Total Increase Over 1980			53.0

[a] See text.

[b] May not add due to rounding.

derived using the coefficients of Equation III-1. The components of the technology trend variable are expected to contribute the same one bu/ac/yr as they have done in the past. These components are plant breeding, irrigation, drainage and perhaps some other technologies, such as plant population, whose contributions to corn yields have been strongly correlated with the contribution of plant breeding.[11] The yield contribution from additional nitrogen fertilizer is expected to decrease over time.[12] However, the expected increase in the 1980s, while extremely small compared to the decades of the 1950 and 1960s, is only slightly below its contribution during the 1970s.[13] Columns four and five in Table XII-10 derive directly from the analyses presented in Chapter XI and X, respectively.

The expected average annual corn yield increase for the decade of the 1980s (1.5 bu/ac/yr) is substantially below the average increase from 1954-80 (2.3 bu/ac/yr). However, technology-induced corn yield increases are expected to be approximately 0.2 bu/ac/yr higher in the 1980s compared to the 1970s, due mainly to new production management technologies.

The exhaustion of yield gains from other sources may provide an impetus for the development of the emerging biotechnologies, which are expected to begin making a significant contribution to yield increases around 1990. Mainly as a result of this, annual yield increases of 4 to 5 bu/ac/yr could be expected as the year 2000 approaches, resulting in a total increase by the year 2000, of 53 bu/ac from all sources. This estimated increase is double that of the Research Directorate of the National Defense University (1980). However, we believe that the estimate of total yield increase, shown in Table XII-10, is biased upward since it embodies scientists' opinions about emerging biotechnologies which do not yet exist.[14]

Adjusted Yield Impacts to the Year 2000

The yield impacts of the emerging biotechnologies are not known with certainty. Indeed, there was considerable variability in the scientists' estimates (as indicated in the Appendix to Chapter X). In order to reflect this uncertainty, the average yield increase estimates derived from the surveys were adjusted downward by one-third for plant growth regulators and cell and tissue culture. For photosynthetic enhancement, the expected yield increase was put at zero.[15] The adjusted contributions from the emerging biotechnologies, and the corresponding adjusted total contributions, are shown in Table XII-11. Under this adjusted regime, yield gains are estimated to range around 1.5 bu/ac/yr during the period 1981-90, rising to 3 bu/ac/yr by 2000.

Table XII-11. Adjusted Yield Impacts, 1989-2000

Year	Marginal Annual Yield Increase (bu/ac/yr)	
	Emerging Biotechnologies	Total [a]
1989	.1	1.5
1990	.2	1.6
1991	.3	1.5
1992	.5	1.7
1993	.8	2.0
1994	.9	2.1
1995	1.2	2.4
1996	1.4	2.6
1997	1.5	2.7
1998	1.7	2.9
1999	1.7	2.9
2000	1.7	2.9
	Total Increase Over 1980	38.5

[a] No contributions are expected from the emerging biotechnologies prior to 1989. Therefore, expected yield increases prior to 1989 are as indicated in Table XII-10. Components of the total annual yield increases, other than emerging biotechnologies, are as shown in Table XII-10.

Footnotes

1/The secular demand for feed grains is expected to be strong, both domestically and internationally, and the U.S. is expected to be the major supply source in world trade. Annual export demand for corn may, however, fluctuate by 10-15 percent. Thus, short run corn prices could decline in both nominal and real terms. Demand is not expected to change so as to induce major changes in the price of corn relative to substitute field crops or relative to other livestock feeds.

Our analyses indicate that the use of many corn production technologies are not highly sensitive to corn price changes, therefore, the assumption about the relative demand for corn remaining high is probably not a critical one to the conclusions of this chapter.

2/Relative to yields, corn acreage has remained fairly stable, ranging between 55-80 million acres over most of the period since 1945. The advantages inherent in rotating corn with soybeans should help to stabilize the proportion of corn land within a range about its present level (73 million acres harvested for grain).

Pasture and other non-cropland exists which, under a regime of rising real prices for corn, could be converted to corn production. Much of this unused potential cropland is outside the Corn Belt. However, an estimated 5 million acres of prime farmland not presently used as cropland exists within the five-state Corn Belt Region (Larson, 1981). This land has withstood earlier price incentives for conversion to cropland. On some acreage, conversion costs are too high to be profitable. In other cases, the land use objectives of owners and other factors make conversion unlikely (Lee, 1978; 1981). Thus, it would probably take high corn prices to induce the conversion of as much as two million acres of non-cropland to corn over the next decade.

3/The data (presented in Figure XII-1) must be regarded as being approximate only, although a comparison between Pimentel's figures for 1975 and those of USDA (1977) for 1974 showed a close correspondence.

Furthermore, these data should not be applied to specific corn production systems. Energy inputs per unit of output vary greatly between production systems. Production systems using deep well irrigation, for example, are much more energy intensive than dryland systems (Chapter V).

4/Costs and yields for Central Illinois for selected years since 1930 (and all years since 1964) were obtained. Total per acre costs were divided by yields to obtain costs per bushel. In order to determine what has happened to real costs over time, it is necessary to further adjust these nominal historic costs by a deflator. Ideally this deflator would be a price index relating specifically to inputs used in corn production. Such a deflator was not available for the whole period, but was available from 1965 to the present (Houck, 1981). A comparison between the Houck deflator and the general "Prices Paid" index from USDA revealed only small differences, however, and the Prices Paid index was deemed adequate as a deflator for our purposes. This deflator was used to obtain an estimate of real costs per bushel of corn over time.

5/The high cost in 1931-32 was due to low yields since hybrids were not available, and higher land prices relative to later periods.

6/Not surprisingly, in the U.S. this was a period of rapid movement of labor out of production agriculture since wage rates in other economic sectors were well above earnings achievable via employment on small unmechanized farms.

7/In assessing the impacts of production technology we believe that, of the two measures, an "acreage weighted" operating unit is the more appropriate unit of observation. This is true because it is the unit to which production technology is actually applied. And, these operating units tend to gravitate toward a size which: (i) effectively utilizes a rather complete complement of modern production technology (e.g., 8-row planting and harvesting equipment, efficient sizes of tractor and tillage equipment and cost-effective grain drying technology); (ii) effectively uses a 2-person labor complement, often available from the family labor supply; and (iii) effectively exploits most available cost economies of size (see Chapter VIII).

8/The maximum yield deviation of 15.8 bu/ac between actual and expected yields (the latter based upon average weather conditions using equation III-1) in 1974 is indicative of the strong impact which weather has on corn production, even with modern technology.

9/The current situation with respect to soil erosion in the U.S., though serious, is not as bad as represented by some. Mayer (1981), while warning that the methodology differs somewhat between the two surveys, compares results of a survey conducted in 1934 with the 1977 National Resources Inventory. "The 1977 survey found 77 percent of cropland with only slight erosion compared to 47 percent in the 1934 survey, 13 percent with moderate erosion compared with 38 percent in the 1934 survey and 10 percent with severe erosion compared to 15 percent in 1934." Moreover, in order for corn yields to increase as dramatically as they have over the past several decades, one concludes that soil resources used for corn production are still in fairly good condition.

10/Moreover, only 40 percent of U.S. farms with sales of $500,000 or more were operated by corporations in 1978. And, these units were concentrated in fed cattle, sugarcane, poultry, canning crops and nursery stock (Coffman et al., 1981). Thus, corn production is now mainly on non-corporate farms of moderate size.

11/This correlation is expected to continue in the future.

12/In order to derive the estimates in column 2, Table XII-10, it was first necessary to make a projection of nitrogen application rates through the year 2000. This was done by extrapolating from past rates of increase. In addition, a check was made to see that the projected rates did not conflict with the long-term pattern of adjustment towards optimal (profit maximizing) nitrogen application rates (see Menz and Pardey, 1981).

13/Energy shortages and high prices caused temporary reductions in nitrogen application rates on corn during 1974-75. As a consequence, the contribution of additional nitrogen to corn yield increases over the decade 1971-80 was lowered to a level which may almost be equalled during the decade of the 1980s.

14/On the other hand, no allowance has been made in Table XII-10 for any contribution from genetic modification at the cellular level. This technology is expected to be applied to corn prior to the year 2000, but early applications are not expected to result in significant yield increases (Chapter X).

15/A majority of the survey respondents expected a zero yield gain from photosynthetic enhancement by the year 2000 and the average estimate of 7.9 bu/ac was strongly influenced by the responses of only three people, whose expectations of yield gains were highly optimistic.

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The discussion in this chapter has three broad objectives:
    (i) to assess briefly the pay-off from past research and development (R&D) work on corn;
    (ii) to present a brief inventory of R&D investments currently being made in both the public and private sectors; and
    (iii) to identify some areas of R&D for corn which appear to have high future priority.

The Pay-off for Past R&D

Most analyses of the returns to agricultural research in the U.S. has been for aggregate, public sector research (Norton and Davis, 1981). Little analysis has been oriented specifically towards corn-related research since much agricultural research is not commodity specific. Also, until recently, available data did not permit an effective breakdown of research expenditures along commodity lines even for that research which was commodity-specific. Analyses of private sector R&D are hindered by lack of publicly available information about expenditures and revenues. With respect to both public and private R&D for corn, there is the problem of separating the funding and effects of research from those of education and/or market development (the latter including advertising and promotion by the private sector). Finally, not all research needs or benefits can be identified by market related measures of costs and benefits.1/ One advantage of a broad based technology assessment, such as the one reported here, is to help identify those non-market related issues.

The initial major R&D effort on corn was the development of hybrid seed. Griliches (1958), in a pioneering work, estimated joint private and public research expenditures for hybrid corn and related innovations from 1910 to 1955. He then computed the flow of net social returns (which began in 1933) from this technology. By 1955, the annual flow of research expenditures (about $2.8 million) was dwarfed by the net annual flow of social returns (about $239 million). He estimated that the average dollar invested in hybrid corn research in 1955 was earning a return of

about 700 percent per year and that, up to 1955, the social rate of return (conservatively computed as an annual internal rate of return on research) was between 35 and 40 percent.2/ This high rate of return far exceeded that available from conventional market investment alternatives.

Other Evaluations of Past Public Sector Research

Bredahl and Peterson (1976) estimated a marginal annual internal rate of return of 36 percent for public sector research investments made for cash grains (of which corn is the largest single crop) by the U.S. State Agricultural Experiment Stations.3/ Their analysis focused on measuring the pay-off from research expenditures made in the early 1960s and impacting on production in 1969. A similar, subsequent analysis by Norton (1981) concluded that the marginal internal rate of return on public research for cash grains was probably even higher (over 50%) for Experiment Station investments made in the late 1960s and impacting in 1974. (By the latter period, production volumes and nominal prices for the major grains were much higher than in the 1950s and 1960s.) Sundquist et al. (1981) developed estimates specifically for corn. They calculated the annual internal rate of return (for corn research done in the early 1970s and impacting in 1977) to be 100 percent or more.4/

In summary, available evidence indicates that the social returns to total public sector research for corn and related cash grain crops has been high and generally well in excess of the opportunity costs of alternative market options.5/ This conclusion does not automatically indicate that the combination of past public sector research investments for corn has been optimal. Some important research areas may have been underfinanced while other research expenditures may have contributed little to improved corn production technology. In any event, the agenda of research priorities changes over time, and continued efforts must be made to identify topics of high priority for future research and to ensure that they received adequate support.

Private Sector R&D

Past R&D expenditures for corn production by the private sector have centered on the development of marketable inputs. Prior to World War II, the emphasis was on machinery and equipment (see Chapter VIII). In recent decades, however, R&D by private sector chemical and seed companies has risen sharply.

Although it is virtually impossible to estimate a specific rate of return for private sector R&D investments for corn, data presented in Chapter III for Pioneer Hi-Bred International indicated that R&D expenditures for hybrid seed corn are a rather small percentage (2.25%) of total sales revenues. Thus, industry-wide expenditures for seed corn related R&D (estimated at $26 million in 1980) probably earn a very high rate of return from the $1 billion of annual corn hybrid seed sales (see Chapter III). Aggregate R&D expenditures of this magnitude appear rational as individual seed companies undertake development work in order to remain competitive in the market place for their products.

Ruttan (1981) estimates that the agricultural pesticide industry is the most research-intensive of the agricultural input industries, spending about 10 percent of the sales dollar for research. Comparable percentages are about 3 percent for the farm machinery industry, and less than 1 percent for the fertilizer industry. Compared to the public sector, private sector research is concentrated in the physical sciences and engineering (close to two-thirds of all private sector R&D), reflecting its focus on "marketable" products. Recently, however, the private sector has also become heavily involved in R&D activities pertaining to the emerging biotechnologies (Murray and Teichner, 1981). And, some of this R&D effort is focused directly on corn. The prospect of developing patentable products in this area is obviously spurring such investments.

Current R&D Expenditure Levels

Close to two-thirds of the research in support of the U.S. food system now comes from the private sector (Ruttan, 1981). It is about evenly divided between the production and the marketing-distribution sectors. Public sector research, on the other hand, is concentrated heavily on the production side.6/ In the past 15-20 years agricultural research expenditures by the private sector have increased much more rapidly than for the public sector. In fact, the real (constant dollar) level of agricultural research expenditures by USDA is virtually unchanged over the past 15 years. And, increases in real expenditures by the State Agricultural Experiment Stations have been very modest indeed (OTA, 1981).

Public Sector Research

In 1979, research expenditures for corn made by USDA and the State Agricultural Experiment Stations (SAES) totalled more than $33 million and included over 313 scientific man-years of human resources (CRIS, 1981). Though this represents a significant public research investment, it is less than 0.2 percent of the market value of corn produced in that year. (Some significant portion of other basic and applied research, not specifically targeted on corn also has impacted on corn production technology. Some other public agencies also conduct a minor amount of research for corn.)

Table XIII-1 presents a breakdown of 1979 USDA-SAES research expenditures for field crops by major research categories. Though these expenditures do not refer specifically to corn, they do provide some perspective on the current relative importance of the major public sector research endeavors which impact on corn technology. Biological research is of primary importance, followed by pest management. Soil-plant water and nutrition and other water related research also receives considerable research attention. Though mechanical research still receives some public sector funding support, most is not aimed just at saving labor.

Table XIII-1. Selected USDA-SAES Research Expenditures and Scientific Man Years (SMY) by Major Research Categories (1979)

Research Category	Expenditures ($m.)	SMY
Improved biological efficiency-field crops	89.9	800
Disease control-field crops	34.5	338
Pest (insect) control-field crops	35.2	322
Weed control-field crops	16.3	153
Soil-Plant Water and Nutrition[a]	27.4	265
Watershed Protection and Management[a]	25.3	224
Conservation in Use of Water[a]	13.7	135
Drainage and Irrigation[a]	7.1	68
Mechanization of Field Crops	7.1	66

[a] Not limited to field crops but includes all agricultural research applications.

Source: Unpublished data from CRIS (1981)

Private Sector R&D

Estimates of private sector (industry) expenditures for plant-related research (corn and non-corn) in 1979 are shown in Table XIII-2. These estimates, while not breaking out corn related research specifically (with the exception of our estimate for corn breeding), do serve to highlight the three major areas of private sector interest in plant related R&D: plant breeding; chemical pesticides; and machinery and equipment.

Table XIII-2. Estimated Private Sector Plant-Related Research in 1979

Category of Research	Research Expenditures ($m.)
Plant Breeding	60-155[a]
Pesticides	339
Plant Nutrients	3
Farm Equipment	225[b]

[a] Our previously reported estimate of annual R&D for hybrid seed corn is $26 million (see Chapter III).

[b] Includes all R&D investments by industry for farm equipment. No plant/livestock breakdown is available.

Source: Malstead (1980).

With the exception of some more basic research on emerging biotechnologies, a high portion of private sector R&D expenditure is aimed at product development.

An Agenda for Future R&D

Strong continuing public sector research efforts on corn appear to be needed. Ruttan (1981) concludes that: "even in corn breeding, where economic incentives have been strongest (for private sector R&D), the private sector companies continue to make only limited investments in the supporting sciences such as genetics, plant pathology, plant physiology and related areas." We share this conclusion and believe that similar statements can be made regarding the importance of continuing public sector research input in such areas as pest management, plant nutrition, biotechnologies, etc.

Increased labor efficiency coupled with technology to service larger production units (capable of generating larger incomes) were for many years the key forces driving R&D efforts for corn production. In more recent decades, the drive for higher yields has accelerated as market demand for corn has increased along with the need of farmers to cover much higher cash costs.

Looking to the future, further yield increasing and cost reducing production technology will continue as a high priority. This conclusion is supported by data in Chapter XII showing that the real net returns per bushel of corn have declined dramatically over time leaving only a narrow profit differential for even the more efficient corn producers.7/ In addition, ecological safety together with conservation of energy, soil and water resources will replace additional labor efficiency as major public sector goals while private sector R&D will continue to focus mainly on "marketable products." The listing of high priority research areas which follows, though targeted mainly at the public sector, should also have relevance to private sector R&D.

Technologies for Directly Manipulating the Corn Plant

Breeding

Currently the single most important source of corn yield increase over time is conventional plant breeding. These breeding programs also provide a cost-effective and ecologically safe source of much disease and insect resistance.

It would be logical to divide research responsibilities so that the public sector could concentrate on more basic research (e.g., the development of new breeding methods and procedures), while the private sector emphasizes research into marketable products, such as new hybrids. However, in order to attract research funds, the public sector is inclined to continue to develop hybrids as tangible evidence of research output. Historically, a large proportion of inbred lines used in hybrid corn production have come from the public sector. Ruttan (1981) contends that public sector breeding programs should continue at least "until it is possible to evaluate the effects of plant variety protection on the performance of private sector varietal improvement efforts." Our analysis supports this contention.

Conventional plant breeding is not replaceable by the emerging biotechnologies examined in this report. Future R&D gains from breeding-related biotechnologies will only be possible by their incorporation within more or less traditional plant breeding programs. Thus, conventional plant breeding should receive continuing high priority for future corn research funding. Funding the emerging biotechnologies at the expense of conventional breeding would appear to be foolhardy, since there is comparatively little risk associated with yield gains from conventional breeding research.

Advances in basic sciences related to tissue culture and genetic engineering are a pre-requisite to these techniques being routinely utilized in commercial corn breeding programs. Such advances will necessarily come mainly from publicly funded research, because private institutions avoid basic research unless they can capture significant benefits, which they normally cannot do. Because of the rate at which these emerging biotechnologies have developed in recent years there is an excess demand for qualified research personnel. Thus, research progress in the public sector will be slowed unless qualified scientists can be retained in public sector employment via adequate financial and other incentives.

In Chapter X, plant breeding for photosynthetic enhancement was estimated to provide an average yield increase of 8 bu/ac by the year 2000. However, since most scientists surveyed expected a zero yield gain from this source, we concluded that the 8 bu/ac estimate is probably too high (see second part of Chapter XII). We believe that a more realistic expectation is in the 0-5 bu/ac range, which is probably insufficient to justify very high levels of research funding.

Systematic collection, classification and preservation of existing germplasm is a high priority item for public sector R&D related to breeding. The potential cost of losing germplasm is too great to incur, when it can be avoided at modest public sector expenditure.

Physiology

Plant growth regulators: Sufficient funds appear to be available for the applied testing of available compounds by agricultural chemical companies. What is lacking is the basic knowledge of plant growth/physiological processes which will allow guided, beneficial intervention in those processes via growth regulators. Increased public investment in understanding the relevant aspects of plant growth/physiology has a potentially high payoff.

Biological Nitrogen Fixation (in corn): Total or partial nitrogen self-sufficiency in corn offers an appealing ecological approach to supplying nitrogen for corn production. Scientists believe that modest gains in this area can be made by the year 2000, but, at present, it is unclear which approach towards nitrogen self-sufficiency in corn will be most successful. None of the major potential approaches can yet be discarded. Again, publicly funded basic research is necessary to advance this technology. When considering research funding, global implications are relevant. A strong case for research funding for BNF can be made on development assistance grounds alone.

Interactions

Significant interactions are likely to occur witl with basic research conducted in the above areas. Research developments in one technology may find application, or may speed developments, in relation to other technologies, or other crops.

Technologies for Manipulating the Environment in Which Corn is Grown

Our assessment has indicated that improved technology management procedures can contribute significantly to future corn yield gains and to improved resource conservation. Effective R&D is needed to improve both: (i) the information available for technology management (including biological, physical, and economic relationships); and (ii) the systems for its delivery and implementation (e.g., computer software, electronic monitoring and control systems, improved scouting techniques, etc.).

Soil erosion and soil nutrient pollution are both contemporary environmental problems which are potentially solvable by modifying existing management practices. Research aimed at promoting the use of reduced tillage for corn has a payoff both for farmers (in terms of reduced production costs) and for society in general (in terms of reduced soil erosion). The main difficulty with the implementation of reduced tillage is in terms of weed control.8/

The reduced tillage system requires adaptation to specific local needs and conditions (topography, weeds, mulch cover, etc.). Farmers will do the adapting themselves in many instances, but a line of highly flexible reduced tillage machinery will be a key ingredient in the spread of reduced tillage systems for corn.

Formulation of constructive policies by the public and by farmers towards soil erosion control requires information on soil loss tolerance values (the rate of soil loss which can be endured without decreasing yields). While such values are published for all important U.S. soils, considerable uncertainty remains regarding their accuracy. The consequences of these values being inaccurate could be severe. More long-term research into gauging soil loss tolerance values (and to measure the long-run impacts of soil erosion on corn yields) is of high priority.

Since much of the nitrogen fertilizer applied to corn is not utilized by the corn plant, increasing the efficiency of fertilizer use by corn would have the same general consequence as using reduced tillage: a decrease in both production costs and environmental pollution. Additional research on accurate measurement of plant nutritional requirements, the process of nutrient

uptake by the plant and into methods of fertilizer application (including timing and form of application) can lead to this increased efficiency.

Rotating corn with legumes offers a potential alternative source of nitrogen, but one which cannot compete economically with inorganic fertilizers at present. Research into increasing the nitrogen contribution of rotations with corn should be increased.9/

Chemical pesticides are used quite heavily on .corn, and chemical companies clearly have a vested interest in promoting the use of their products, through research or other means. Thus, the information base for pest control methods which use reduced levels of chemical inputs will have to be provided by the public sector; this will include information on insect physiology and pathology and on the dynamics of pest populations.

Corn has a high water requirement. Therefore, research needs to center on conserving water while maintaining or increasing yields. One need is for a better basic understanding of plant-water-soil relationships. A second need is to develop applied technology (irrigation systems, tillage systems, moisture monitoring and control systems, etc.) to utilize available water resources as efficiently as possible.10/

Finally, nitrogen fertilizer, artificial grain drying and irrigation are the three energy-intensive technologies now used in commercial corn production. Creative research attention to conserving liquid fuel in these technologies is crucial both for corn to remain a cost-effective crop and for it to remain competitive with less energy intensive crops (e.g., soybeans).

Footnotes

1/Among those costs and benefits most commonly cited as being inadequately measured by market forces are those of environmental externalities, intertemporal trade-offs in use of resources, basic social values, and public goods generally.

2/The internal rate of return is computed as being that annual interest rate which, if charged to research investments, would just equate the cost of these investments with the discounted value of the benefits accruing from the research. Griliches warned, as have others, that any rates of return which can be calculated for research are rough and should be regarded only as approximations. Most analysts, subsequent to Griliches, have found it difficult to determine research investments by the private sector and have estimated returns to public sector research expenditures and then weighted the returns downward to adjust for the omitted private sector expenditures.

3/This marginal rate of return is appropriate for evaluating the earnings of incremental expenditures for research. It is probably an underestimation of the average rate of return accruing to such research.

4/Data unavailability somewhat reduced the reliability of estimated returns for corn research alone. This high rate of return, as in the Norton study, is attributable partly to the higher production levels and nominal prices existing for corn during the 1970s. However, without effective yield increasing (and cost reducing) research, the production volume generating these high benefit rates could not have been achieved.

5/Whether or not there have been alternative public sector investment options with comparable rates of return is an unanswered question, since extensive evaluation of such alternatives has not been conducted.

6/An excellent discussion of both the public and private sector roles in agricultural research is presented in Vernon Ruttan's book, Agricultural Research Policy, forthcoming from the University of Minnesota Press.

7/Earlier in our assessment we indicated that the major potential yield gains from fertilizer technology and the major potential productivity gains from labor saving mechanization may have already been exploited (see Chapters IV, VIII, and XII particularly). Thus, new sources of yield and productivity gains for corn must come mainly from technologies other than these.

8/Two approaches to weed control worthy of research attention are: (i) designing machinery to temporarily remove mulch material from the ground as herbicides are being applied; and (ii) using chemicals, which naturally occur in cover crops or mulches, as weed control agents. This technology is in the exploratory stage only, but the possibility which it offers for weed control without either tillage or manufactured chemicals makes it worthy of research attention.

9/The corn yield benefit resulting from rotations is well-established. However, the reasons for the yield increase are not clear (and cannot be attributed to a simple "fertilizer" effect). Research should be aimed (i) at understanding the yield increasing mechanism, and (ii) promoting the fertilizer contribution of legumes in rotation with corn.

10/Institutional reforms may be needed to deal effectively with some problems of water mining and environmental damage. But, these are not so much future research agenda items as they are items of basic value conflicts between societal groups.

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