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TECHNICAL AND ECONOMIC CAUSES OF PRODUCTIVITY CHANGES IN U.S. WHEAT
BOND, J.J. ; UMBERGER, D.E.  1 OF 2

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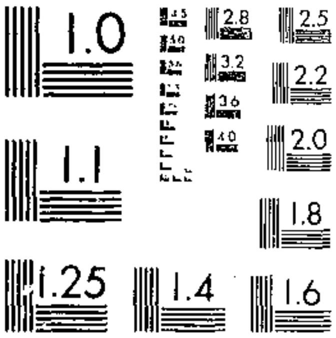

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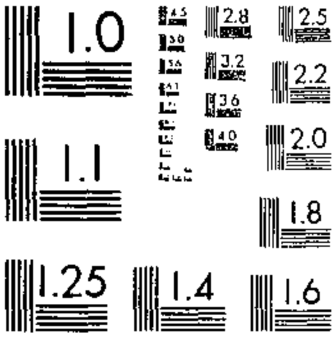

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# TECHNICAL AND ECONOMIC CAUSES OF PRODUCTIVITY CHANGES IN U.S. WHEAT PRODUCTION, 1949–76

UNITED STATES
DEPARTMENT OF
AGRICULTURE

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# ABSTRACT

Bond, J. J. and D. E. Umberger, 1979. Technical and Economic Causes of Productivity Changes in U.S. Wheat Production, 1949–76. U.S. Department of Agriculture Technical Bulletin 1598, 109 pp.

Accurate methodology to predict worldwide wheat yields has become increasingly important in the U.S. balance of payments and agricultural economy. This publication analyzes selected technical and economic factors that have caused changes in U.S. wheat production during the past quarter century. Knowledge of these factors provides a basis for predicting trends in wheat yields and developing yield models. Technical factors or inputs discussed include summer fallow, soil productivity, irrigation, varietal productivity, wheat class productivity, fertilizer, pesticides and cultural practices. Economic factors affecting the production of wheat include the domestic use and exportation of wheat, Government programs, and changes in the economics of using different technical inputs.

*Keywords:* wheat varieties, wheat yields, wheat trends, summer fallow, soil productivity, irrigation, fertilizer, pesticides, cropping sequences.

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# PREFACE

The increased importance of wheat exports in the U.S. balance of payments and the overall agricultural economy has brought to the forefront the need for accurate methodology to predict worldwide wheat yields.

This publication identifies and analyzes those wheat production inputs impacting U.S. wheat yield trend during the past quarter century. Knowledge of these production inputs provides a basis for assessing the present and possible future role of the several production inputs in wheat yield trend and for developing yield models.

The stimulus for this publication derived from the Large Area Crop Inventory Experiment (LACIE), a cooperative effort of the U.S. Department of Agriculture (USDA), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA). The purpose of LACIE, which began in 1974, was to develop, test, and evaluate the utility of satellite, meteorological, and climatological data in predicting wheat production in selected areas by combining estimates of wheat area (acres, hectares) and yield per unit of area in selected regions. This study investigated the need for utilizing another class of data, that is, information on changes in technical and economic factors affecting farming practices and, consequently, yield and production. Within LACIE, wheat acreage is estimated using satellite data, but yield estimates are derived from mathematical models using weather observations as inputs.

Present (1977) models use time as a surrogate variable to separate the effects of yield trend from weather effects in predicting wheat yields. However, models incorporating selected trend factors as independent variables are being investigated. This study contributes background material for the investigation.

# ACKNOWLEDGMENT

Much of the historical data used in this study was graciously provided by State offices of the USDA's Economics, Statistics, and Cooperatives Service (ESCS). The North Dakota Agricultural Stabilization and Conservation Service (ASCS) provided historical data on agricultural programs in that State. Lola Calvin and Don Emery of the Boone County ASCS Office in Columbia, Mo., provided much assistance in interpreting annual farm programs.

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Issued May 1979

# TECHNICAL AND ECONOMIC CAUSES OF PRODUCTIVITY CHANGES IN U.S. WHEAT PRODUCTION 1949-76

By J. J. Bond, *SEA soil scientist*,[1] and D. E. Umberger, *ESCS agricultural economist*

## SUMMARY

In 1949 an alltime high of 83.9 million acres of wheat were planted in the United States. Wheat acreage during the fifties and sixties generally declined, reaching a low of 48.7 million planted acres in 1970. After 1970 wheat acreage increased rapidly. An estimated 80.2 million acres of wheat were planted for the 1976 crop. Although wheat acreage was slightly lower in 1976 than in 1949, wheat production went from 1 billion bushels in 1949 to 2.1 billion bushels in 1976. That is, average wheat yield per acre doubled during the 1949-76 period. This publication analyzes selected natural, technical, and economic factors causing wheat production changes during this period.

Because factors affecting wheat production differ among regions, the United States is divided into five major wheat production regions based on geography and the relative acreage of different wheat classes. The five regions, listed in descending order of their contribution to U.S. wheat production, are the central and southern Great Plains States, the northern Great Plains States, the Midwest and Eastern States, the Northwest States, and the Southwest States. If these regions were ranked by yield per acre, in most years their order would be reversed. Annual changes in acreage, production, and yield differed somewhat by region. Wheat yields in the United States and in three of the five regions peaked in 1971. In the central and southern Great Plains States region, wheat yields reached a high for the period in 1973. The Southwest States region (California, Arizona, and Nevada) is the only region where yields continued their upward trend through 1976.

The technical factors contributing to increased yield after 1949 have been: (1) Changes in the share of wheat grown on summer fallow, (2)

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[1] Presently stationed in Saudi Arabia.

changes in the share of wheat grown on land with a relatively low soil productivity base, (3) changes in irrigated wheat acreage, (4) development and farmer adoption of varieties with increased yield potential, (5) changes in wheat market classes grown, (6) changes in fertilizer usage, (7) changes in pesticides usage, and (8) improved cultural practices. These factors are not ranked in any particular order of importance as the absolute and relative contribution of each factor to yield trend varied with time. Each factor's contribution also varied among (and within) regions as differing natural conditions affected technical response rates and the relative profitability of each factor.

Growing wheat on summer fallow is most often practiced in the semiarid areas of the Great Plains States and in the Northwest States of Washington, Oregon, and Idaho. In the Great Plains the proportion of wheat grown on summer fallow and the differences in yield for wheat grown after fallow and on continuous cropping generally increase from east to west corresponding to decreases in mean annual precipitation. The total acreage of summer fallow gradually increased from 26 million acres in 1949 to a high of 41 million acres in 1969. By 1974, however, fallow land had decreased to 28 million acres. Government programs and economic conditions play a major role in determining annual changes in the proportion of wheat grown on summer fallow. Restrictive acreage allotmets contributed to increased summer fallow in the 1950's and 1960's while high prices caused by high export demand led farmers to reduce summer fallow acreage after 1973.

Agricultural programs causing declining wheat acreage during the 1950's and 1960's also led farmers to divert their poorer quality land to other uses. As wheat acreage increased in the 1970's, much of the land with a lower soil productivity was returned to wheat production. Because wheat yield is directly dependent on soil productivity, this changing land use practice affected wheat yields.

Since 1949, irrigation has become increasingly important in the production of wheat in all regions except the Midwest and Eastern States. The Southwest States have the highest proportion of irrigated wheat acreage, but irrigated wheat acreage and production are largest in the central and southern Great Plains States. In areas where practiced, irrigation substantially increases yields. Since 1949, improved water management, higher yielding varieties, and increased use of fertilizer on irrigated acreage have combined to raise yields. However, irrigated wheat acreage remains responsive to water supplies and to the relationship of wheat price to the prices of other crops and to production costs.

The adoption by farmers of wheat varieties with higher yield potential also contributed to the upward wheat yield trend for each region. The semidwarf varieties that are resistant to lodging and more responsive than traditional varieties to higher levels of water and applied fertilizer have been widely adopted in the Northwest States. In the Southwest States and in the central and southern Great Plains States the semidwarf varieties are widely grown on irrigated acreage. In the Midwest and Eastern States, Arthur and Arthur 71 have contributed to higher yields. However, in the semiarid Great Plains low levels of precipitation continue to limit yields of wheat grown on dryland conditions regardless of potential varietal productivity.

Varieties grown in the United States are often grouped into five major wheat classes: (1) Hard Red Spring, (2) Hard Red Winter, (3) Durum, (4) Soft Red Winter, and (5) White. Since 1949, the development of varieties with improved yield potential has altered the wheat class grown in several regions. Development of more winter-hardy Hard Red Winter wheat varieties has encouraged their gradual movement into South Dakota and Montana. The development of the high-yielding White wheats (Gaines) led to their rapid adoption in the Northwest States in the 1960's. With the development of Arthur and Arthur 71, the Midwest and Eastern States have produced increasing amounts of Soft Red Winter wheat.

The application of commercial fertilizers to an increasing proportion of wheat acreage and increased fertilizer application rates per acre also contributed to wheat yield trend since 1949, particularly after 1954. Major fertilizer nutrients used on wheat are nitrogen and phosphorus. Potassium is important in the Midwest States and Eastern States. Fertilizer use varied substantially among and within regions throughout this period, reflecting the fact that wheat response to fertilizer depends on local differences in available water, soil fertility, cropping sequence, and varieties planted. Factors contributing to increasing fertilizer use include irrigation, adoption of more responsive varieties, acreage restrictions of government programs, and an improving wheat/fertilizer price ratio.

Cultural practices contributing to higher crop yields since 1949 include farmer adoption of better tillage equipment, which has improved the efficiency of soil water storage in summer fallow areas; grain drills allowing improved seeding methods; and more timely seeding dates.

An analysis of experimental data on yield variability under identical climate conditions indicates that when a production input raises yield level, the relative yield variability is reduced. That is, the coefficient of variation of yields declined with increased use of the several production inputs. These conclusions, however, were based on analysis of data of experiments which were limited to the climate conditions of the 1949–76 period and had limited geographic coverage. A decline in the relative yield variability implies that the changing production input combinations that have raised yield levels have also reduced the importance of changes in climate as a source of yield variability. Nevertheless, wheat yields remain quite responsive to climate conditions as the analyses indicate the absolute yield variability—as opposed to relative variability—increases with higher yields. Consequently, yield levels have become more dependent on changing economic and technical conditions while remaining responsive to changes in climate. Predicting wheat production has become more difficult as the factors influencing both wheat acreage and the productivity of that acreage have increased in number and complexity.

Although much of the annual variation in yield was caused by year-to-year variations in climate, successive years of benevolent climate do not explain the major share of yield increase with time during 1949–72 or the leveling of the wheat yield trend after 1971. The upward trend in yields was mainly caused by farmers adopting different, often new, production techniques and changing production input combinations.

Wheat is a cultivated crop, and the area planted to wheat is dependent on the decisions of farmers, who work within the constraints and with the opportunities given them by the natural environment and society. Although wheat yields depend on the area's natural resource endowment, farmers choose which soils and climatic regimes to use for wheat production. In addition, individual farmers select the farming practices and levels of other inputs such as wheat variety, fertilizer, pesticides, and irrigation water to apply to the land.

Changing technical conditions, economic forces, and agricultural policies have influenced farmers' decisions on allocating land and other inputs to wheat production during 1949–76. With the gradual adoption of production techniques that depend on the nonfarm sector for supplies of inputs, wheat yields have become increasingly dependent on the agribusiness sector. Although farmers gradually adopted many yield-increasing production techniques and increased their usage rates of nonfarm-supplied inputs that increase yields, they have kept per-acre usage of many inputs below levels necessary for maximum wheat yields per acre. Although it is possible to increase wheat yields with known techniques, future yield trends will depend on the discovery and adoption by farmers of new innovations, future agricultural policies, and economic conditions affecting utilization of land and the availability and cost of yield-enhancing inputs relative to wheat prices.

# INTRODUCTION

U.S. wheat exports increased abruptly in 1972 and since have remained at a high level. In 1975, 55 percent of the wheat produced in the United States was exported (*105*).[2]

For about two decades beginning around 1949, a fairly constant annual increase in wheat yield occurred from a combination of production inputs, often collectively termed "technology." Between 1972 and 1977, however, yield trends for wheat apparently leveled off (*36*).

The purpose of this report is to identify and to analyze those production inputs impacting U.S. wheat yield trends from 1949 to 1976. An understanding of the impact of these production inputs is a necessary condition for developing improved wheat yield models and assessing the present and possible future role of the several production inputs in wheat yield trends. Although weather remains a major determinant of wheat yields in any given year, since 1949 selected production inputs have become increasingly important in determining U.S. wheat yield. The leveling of the U.S. wheat yield trend after 1971 was partially caused by a change in the combination of production inputs used by farmers. This change reflects farmers' reaction to altered world economic conditions.

In this report, data of the Department's ESCS are used whenever possible in discussing the production inputs contributing to wheat yield over a large area rather than experimental plot wheat yields.

# WHEAT PRODUCTION TRENDS

Since 1949 the trend in U.S. wheat production has been upward, but large annual fluctuations have occurred in production, acreage, and yield. These changes in production, yield, and acreage vary by region.

## U.S. Trends

Harvested acres, yield, and production of U.S. wheats during the past century (1875–1975) are shown in figure 1 (*105*). Planted acreages were first reported in 1919. Harvested acreages of wheat reached a peak shortly after World Wars I and II. An alltime peak in wheat acreage occurred in 1949—83,905,000 acres planted and 75,910,000 acres harvested. The maximum difference between planted and harvested acreages occurred during the drought of the thirties. During the drought of the early fifties, an appreciable amount of abandoned wheat acreage occurred. For the past two decades, abandoned wheat acreage has

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[2] Italic numbers in parentheses refer to Literature Cited, p. 95.

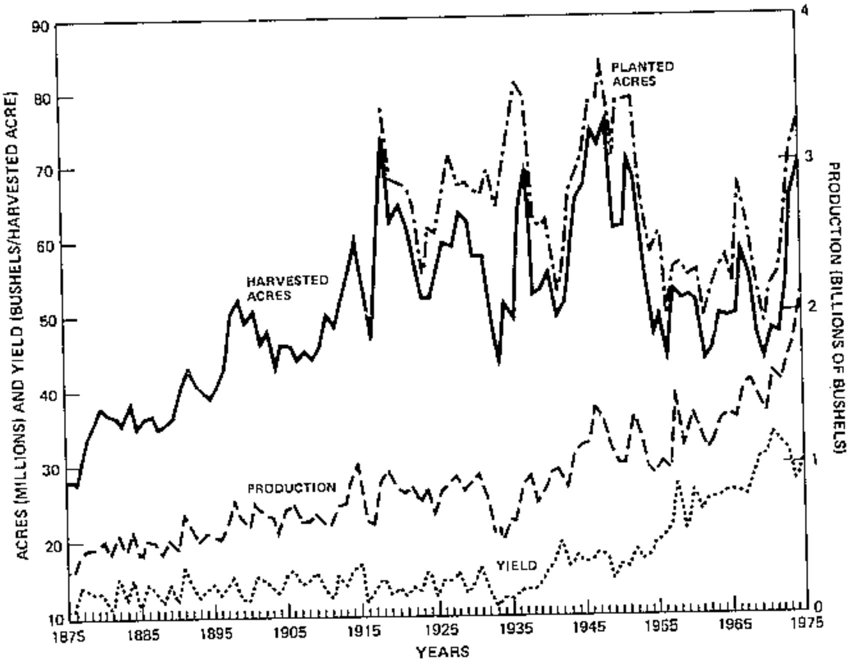

FIGURE 1.—Harvested acres, yield per harvested acre, and production of U.S. wheat, 1875–1975. (USDA–ESCS data.)

been rather small and relatively constant due to generally favorable climatic conditions.

During the first three quarters of the past century (1875–1975), annual variations in U.S. wheat yield were largely due to weather (fig. 1). Very little upward yield trend is evident except during the unusually favorable weather years of World War II. However, during this period the location of wheat growing shifted westward to the Great Plains from the more humid, north central and northeastern regions of the United States (*99*). Consequently, the upward yield trend in the older more humid areas was offset by the bringing of drier, lower yielding acreage into production.

In 1949, when the U.S. wheat acreage reached an alltime high, wheat yields were essentially the same as those 75 years earlier. However, after 1949 wheat yields per acre started to increase and wheat acreage started to decrease.

During the fifties and sixties, U.S. wheat acreage was controlled by a series of acreage allotment and crop diversion programs. With the removal of acreage restrictions beginning in the early seventies and strong export demand, wheat acreage in 1976 was again near the 1949 high with more than 80 million acres planted (*106*). Average U.S. wheat yields approximately doubled from about 15 bushels per acre in 1949 to near 30 bushels per acre in 1976. In 1971 U.S. wheat yields were 33.9 bushels per acre, an alltime high (*106*). In 1975, for the first time in history, U.S. wheat production exceeded 2 billion bushels (fig. 1). Because of significant changes occurring in both wheat acreage and yield since 1949, this publication will concentrate on those production inputs that have been involved from 1949 to 1976 and will chronologically begin where a previous publication ended (*99*).

## Regional Trends

### Definition of Regions

Because geographic characteristics often vary significantly within a State, any regional classification is somewhat arbitrary. However, the States have been divided into broad regional groups based on geographic, climatic, and wheat class differences. For the purpose of this publication, the United States was divided along State boundaries into five major wheat-growing regions (fig. 2). The five regions, based on the geographic and climatic settings and the relative acreage of different classes of wheat in a State, are as follows:

Region 1—Central and Southern Great Plains States where Hard Red Winter wheats are grown.

Region 2—Northern Great Plains States where Hard Red Spring, Durum, or Hard Red Winter wheats are grown.

Region 3—Midwest and Eastern States where Soft Red Winter or White Wheats are grown.

Region 4—Northwest States where White or Hard Red Winter wheats are grown.

Region 5—Southwest States where Hard Red Spring, White, or Durum wheats are grown.

Florida, Louisiana, and the Northeast States of Connecticut, Maine, Massachusetts, Rhode Island, New Hampshire, and Vermont are excluded from this study because annual production data for these States are unavailable for part or all of the period.

A major characteristic used in specifying wheat regions and allocating individual States to a region was the market class of wheat grown in the State. There are seven recognized classes of wheat in the United States (*58*). Wheat breeders have made many crosses between wheat classes in recent years that have tended to obliterate wheat class distinctions (*100*). For practical purposes, only five market wheat classes are of major importance (*93*). These classes are Hard Red Winter

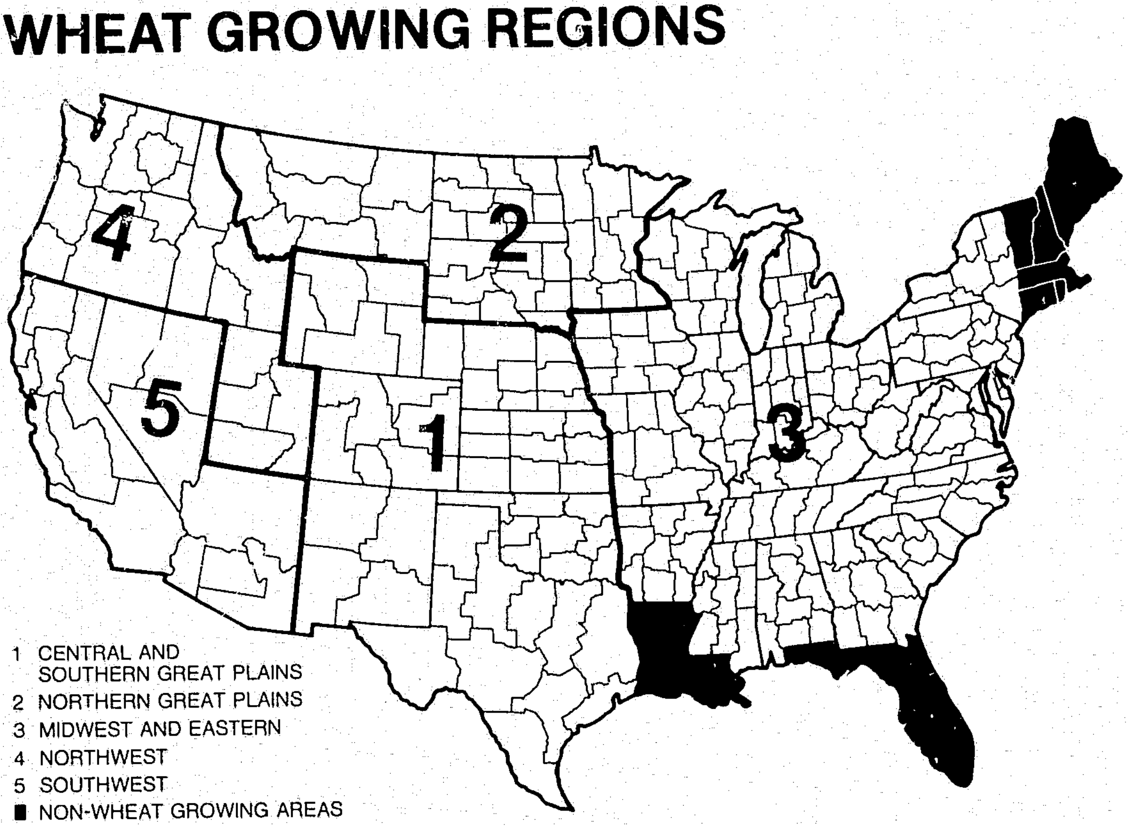

FIGURE 2.—Map of the United States showing the boundaries of the five wheat-growing regions.

(HRW), Hard Red Spring (HRS), White (W) including Club wheat, Soft Red Winter (SRW), and Durum (D).

Because several wheat classes are adaptable to wide ranges of climatic conditions, they are grown in more than one region.[3] The wheat acreages devoted to different wheat classes depend on local cropping practices and marketing conditions. As new varieties are introduced or market demands change, significant changes in the amount of acreage planted to any market class can occur in a short time interval, making any regional grouping somewhat arbitrary and subject to change. The grouping in this publication was based largely on the most recent market class data available. Table 1 shows the percentage of acreage in each wheat class by region and State.

### Regional Differences

Trends in harvested acreages since 1949 for the five wheat-growing regions are plotted in figure 3. As shown, all five regions shared similarly in the acreage decreases that occurred in the early fifties and increases that occurred since 1970. The greatest fluctuations in harvested acreage occurred in Great Plains Regions 1 and 2. Acreage fluctuations in the Great Plains (particularly Region 1) were largely attributable to weather in that abandonment of seeded wheat may be large during drought (*99*).

Figure 4 illustrates how wheat production has been shared by the five wheat growing regions since 1949 and how all five contributed to carrying U.S. wheat production above the 2-billion-bushel mark in 1975. However, the climatic uncertainty of Great Plains Regions 1 and 2 is more clearly evident in terms of the percentage of U.S. wheat production than in the harvested acreage.

Wheat yield trends (fig. 5) have been upward in all regions, but yield levels were quite different between regions. Regions 1 and 2 with the largest acreage and production usually had the lowest wheat yields of the five regions, whereas since 1969 Region 5 usually had the highest yield per acre.

Table 2 ranks the five regions and States according to their share of U.S. harvested acreage and production in 1975. The ranking of the five regions has not changed during the 1949–76 period. However, if

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[3] For a more detailed grouping of wheat by adaptation regions, see *Wheat in the United States* (*91*). Earlier studies also show a somewhat different grouping as the market demands and adaptability of varieties change over time (*70, 90*). Within States, wheat classes are also reported by Crop Reporting District (CRD). Each CRD and its number in each State is given in (*93*).

TABLE 1.—*Percentage of acreage in each wheat class by State and wheat-growing region* [1]

| Region and State | Year | Percentage of acreage in—[2] | | | | |
|---|---|---|---|---|---|---|
| | | Hard Red Winter | Hard Red Spring | Durum | Soft Red Winter | White |
| REGION 1: CENTRAL AND SOUTHERN GREAT PLAINS HRW WHEAT REGION | | | | | | |
| Kansas | 1974 | 100 | | | | |
| Oklahoma | 1969 | 100 | | | | |
| Texas | 1969 | 91 | 4 | | 5 | |
| Nebraska | 1974 | 100 | | | | |
| Colorado | 1974 | 100 | | | | |
| New Mexico | 1969 | 99 | | | | |
| Wyoming | 1974 | 92 | 8 | | | |
| Total | | 98 | 1 | | 1 | |
| REGION 2: NORTHERN GREAT PLAINS HRS-D-HRW WHEAT REGION | | | | | | |
| North Dakota | 1974 | 1 | 65 | 34 | | |
| Montana | 1974 | 55 | 40 | 5 | | |
| South Dakota | 1974 | 30 | 63 | 7 | | |
| Minnesota | 1974 | 1 | 96 | 3 | | |
| Total | | 18 | 63 | 19 | | |
| REGION 3: MIDWEST AND EASTERN SRW-W WHEAT REGION | | | | | | |
| Ohio | 1974 | | | | 100 | |
| Illinois | 1974 | 20 | | | 79 | |
| Indiana | 1974 | | | | 100 | |
| Missouri | 1974 | 18 | | | 82 | |
| Michigan | 1974 | | | | 25 | 74 |
| Arkansas | 1969 | 2 | | | 98 | |
| Kentucky | 1969 | 3 | | | 97 | |
| Pennsylvania | 1969 | | | | 100 | |
| Tennessee | 1969 | 2 | | | 98 | |
| North Carolina | 1974 | | | | 100 | |
| Virginia | 1974 | | | | 100 | |
| New York | 1969 | | | | 2 | 98 |
| Mississippi | 1969 | 1 | | | 99 | |
| Maryland | 1969 | | | | 100 | |
| South Carolina | 1974 | | | | 100 | |

TABLE 1.—*Percentage of acreage in each wheat class by State and wheat-growing region* [1]—Continued

| Region and State | Year | Percentage of acreage in—[2] Hard Red Winter | Hard Red Spring | Durum | Soft Red Winter | White |
|---|---|---|---|---|---|---|
| Alabama | 1974 | | | | 100 | |
| Georgia | 1969 | | | | 100 | |
| Wisconsin | 1974 | 1 | 19 | | 64 | |
| Iowa | 1969 | 95 | 4 | | 1 | |
| New Jersey | 1969 | 1 | | | 99 | |
| Delaware | 1969 | | | | 100 | |
| West Virginia | 1969 | 3 | | | 97 | |
| Total | | 7 | (3) | | 84 | 9 |
| REGION 4: NORTHWEST W-HRW WHEAT REGION | | | | | | |
| Washington | 1974 | 18 | | | | [4] 82 |
| Idaho | 1969 | 41 | 5 | | | [4] 54 |
| Oregon | 1974 | 7 | | | | [4] 93 |
| Utah | 1969 | 79 | 3 | | | [4] 18 |
| Total | | 24 | 1 | | | 75 |
| REGION 5: SOUTHWEST HRS-W-D WHEAT REGION | | | | | | |
| California | 1976 | | 83 | | | 7 |
| Arizona | [5] 1976 | | | 74 | | 26 |
| Nevada | 1969 | | 18 | | | 82 |
| Total | | | 62 | 23 | | 13 |

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[1] Excludes Florida, Louisiana, and Northeast States. Within regions, States are listed in order of decreasing harvested acreage in 1975.

[2] 1969 data are from *(98)*. Whenever available, more recent 1974 USDA–ESCS data are given. Percentages may not total 100 percent because of all other unidentified classes (not shown). Values less than 1 percent are omitted.

[3] Less than 0.5 percent.

[4] Includes White Club wheat.

[5] Indicated for 1976. Winter wheat assumed to be White wheat.

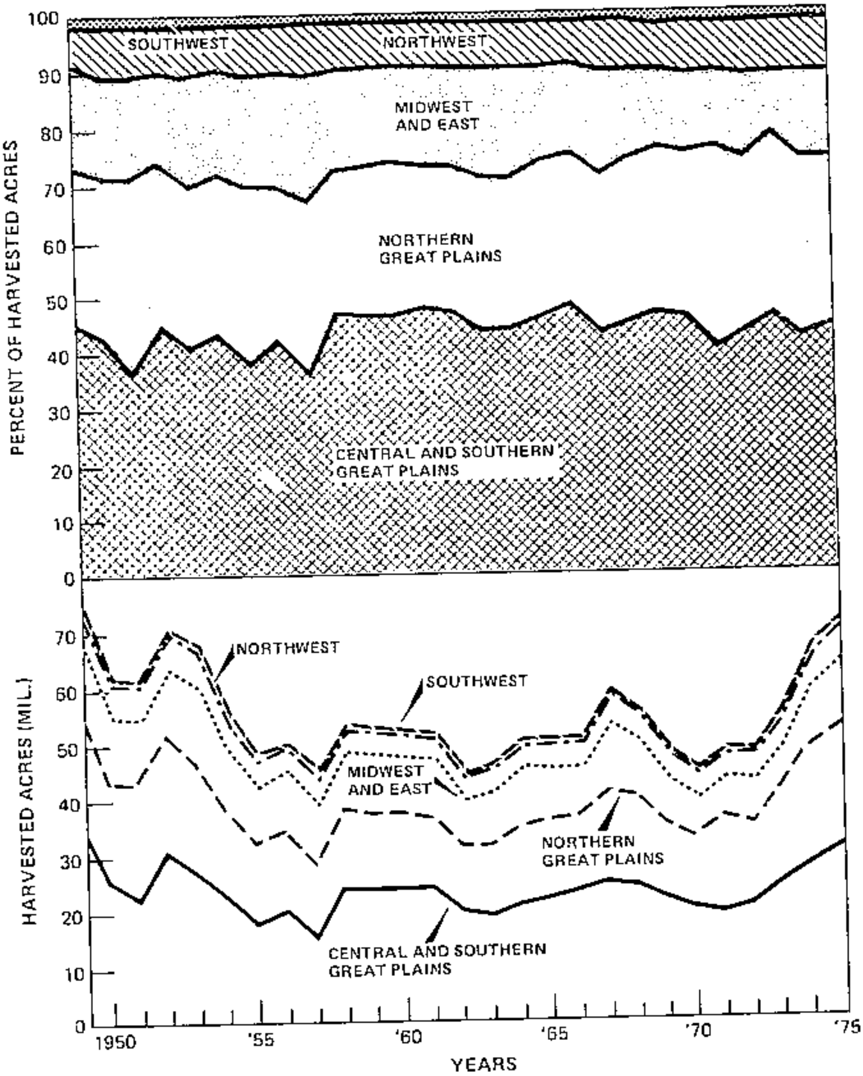

FIGURE 3.—Accumulative harvested acreages and percent of harvested acreages of all wheat by regions, 1949–75. (USDA-ESCS data.)

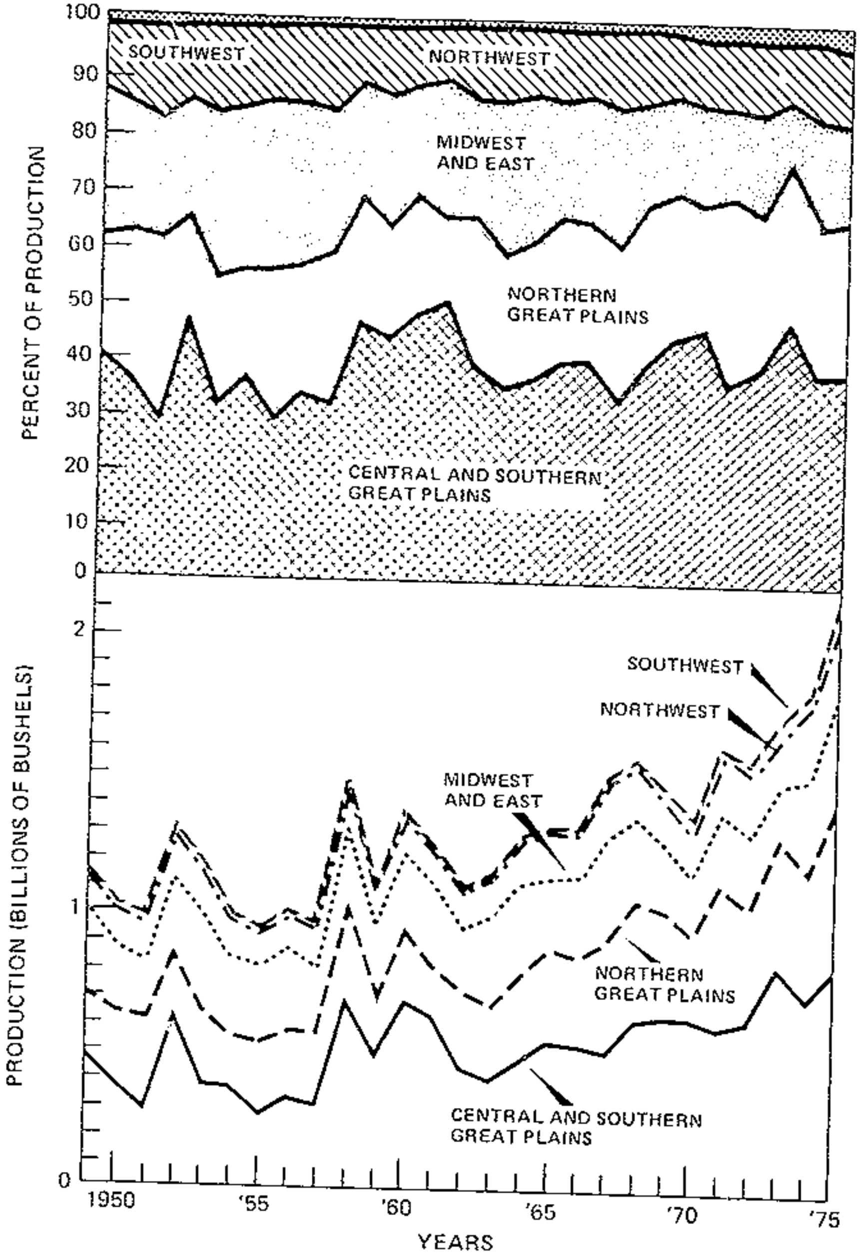

FIGURE 4.—Accumulative production and percent of production of all wheat by regions, 1949–75. (USDA-ESCS data.)

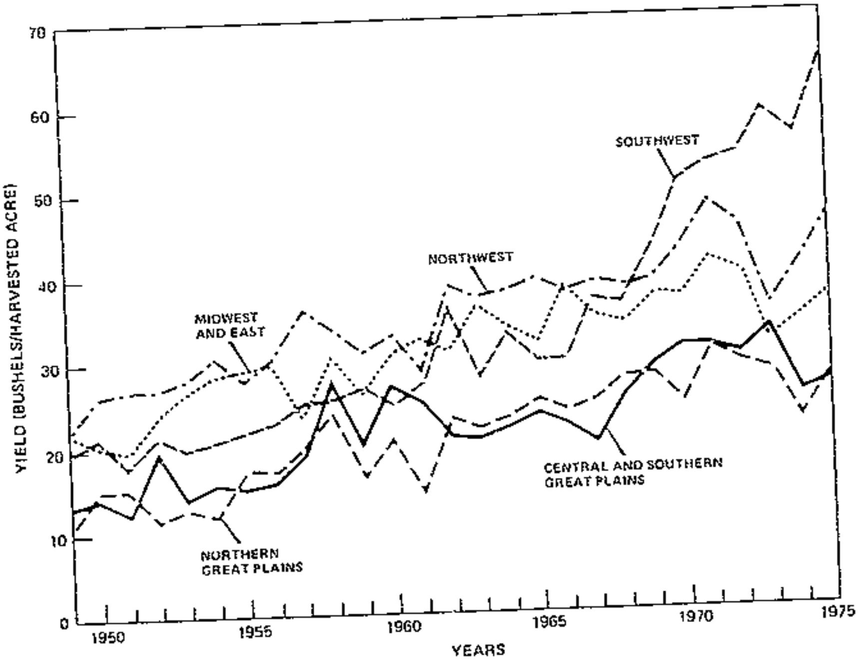

FIGURE 5.—Yield of all wheat by regions, 1949–75. (USDA-ESCS data.)

yield per acre were used to rank the five regions, their order would be reversed in most years of this period. A discussion of important regional characteristics follows.

*Region 1, The Central and Southern Great Plains States.*—In 1975, this Hard Red Winter wheat region grew 43.8 percent of the 69.6 million U.S. harvested acres; but due to yields that were below the U.S. average, the region accounted for only 37.9 percent of the U.S. production (table 2). Kansas is the largest wheat-producing State in this region (and in the United States). Region 1 varies more than any other region with respect to the percentage of production (fig. 4). This large year-to-year variation in wheat production is caused mostly by year-to-year variations in climate, particularly rainfall, but also is caused by temperature. Wyoming is included within Region 1 because 92 percent of its HRW wheat is grown in its southeastern counties. New Mexico was included because most of its wheat is grown in proximity to the Texas Panhandle.

*Region 2, The Northern Great Plains States.*—In 1975, this region accounted for 30.2 percent of the U.S. harvested wheat acreage. North Dakota accounts for almost half of all wheat acreage and production

TABLE 2.—*Harvested acreages, yield, and production of U.S. wheat by wheat-growing region, 1975* [1]

| Region and State | All wheat | | | | | |
|---|---|---|---|---|---|---|
| | Harvested | Share of U.S. total | Yield per harvested acre | Share of U.S. average | Production | Share of U.S. average |
| | *1,000 acres* | *Percent* | *Bushels* | *Percent* | *1,000 bushels* | *Percent* |
| REGION 1: CENTRAL AND SOUTHERN GREAT PLAINS HRW WHEAT STATES | | | | | | |
| Kansas | 12, 100 | 17. 4 | 29. 0 | 94. 46 | 350, 900 | 16. 4 |
| Oklahoma | 6, 700 | 9. 6 | 24. 0 | 78. 18 | 160, 800 | 7. 5 |
| Texas | 5, 700 | 8. 2 | 23. 0 | 74. 92 | 131, 100 | 6. 4 |
| Nebraska | 3, 070 | 4. 4 | 32. 0 | 104. 23 | 98, 240 | 4. 6 |
| Colorado | 2, 260 | 3. 2 | 22. 5 | 73. 29 | 50, 950 | 2. 4 |
| New Mexico | 387 | . 6 | 26. 0 | 84. 69 | 10, 062 | . 5 |
| Wyoming | 273 | . 4 | 24. 9 | 81. 11 | 6, 802 | . 3 |
| Total | 30, 490 | 43. 8 | 26. 5 | 86. 32 | 808, 854 | 37. 9 |
| REGION 2: NORTHERN GREAT PLAINS HRS-D-HRW WHEAT STATES | | | | | | |
| North Dakota | 10, 213 | 14. 7 | 25. 9 | 84. 36 | 264, 392 | 12. 8 |
| Montana | 4, 975 | 7. 1 | 31. 3 | 101. 95 | 155, 925 | 7. 3 |
| South Dakota | 2, 965 | 4. 3 | 21. 1 | 68. 73 | 62, 610 | 2. 9 |
| Minnesota | 2, 867 | 4. 1 | 30. 8 | 100. 33 | 88, 368 | 4. 1 |
| Total | 21, 020 | 30. 2 | 27. 2 | 88. 60 | 571, 295 | 26. 8 |
| REGION 3: MIDWEST AND EASTERN SRW-W WHEAT STATES | | | | | | |
| Ohio | 1, 770 | 2. 5 | 42. 0 | 136. 81 | 74, 340 | 3. 5 |
| Illinois | 1, 730 | 2. 5 | 39. 0 | 127. 04 | 67, 470 | 3. 2 |
| Indiana | 1, 500 | 2. 2 | 43. 0 | 140. 07 | 64, 500 | 3. 0 |
| Missouri | 1, 470 | 2. 2 | 33. 0 | 107. 49 | 48, 510 | 2. 3 |
| Michigan | 1, 020 | 1. 5 | 38. 0 | 123. 78 | 38, 760 | 1. 8 |
| Arkansas | 520 | . 8 | 30. 0 | 97. 72 | 15, 600 | . 7 |
| Kentucky | 352 | . 5 | 34. 0 | 110. 75 | 11, 968 | . 6 |
| Pennsylvania | 345 | . 5 | 33. 0 | 107. 49 | 11, 385 | . 5 |
| Tennessee | 310 | . 4 | 31. 0 | 100. 98 | 9, 610 | . 4 |
| North Carolina | 275 | . 4 | 31. 0 | 100. 98 | 8, 525 | . 4 |
| Virginia | 292 | . 4 | 31. 0 | 100. 98 | 9, 052 | . 4 |
| New York | 190 | . 3 | 39. 0 | 127. 04 | 7, 410 | . 4 |
| Mississippi | 185 | . 3 | 24. 0 | 78. 80 | 4, 440 | . 2 |
| Maryland | 156 | . 2 | 34. 0 | 110. 75 | 5, 304 | . 2 |
| South Carolina | 155 | . 2 | 27. 0 | 87. 95 | 4, 185 | . 2 |

TABLE 2.—*Harvested acreages, yield, and production of U.S. wheat by wheat-growing region, 1975* [1]—Continued

| Region and State | All wheat | | | | | |
|---|---|---|---|---|---|---|
| | Harvested | Share of U.S. total | Yield per harvested acre | Share of U.S. average | Production | Share of U.S. average |
| | *1,000 acres* | *Percent* | *Bushels* | *Percent* | *1,000 Bushels* | *Percent* |
| Alabama | 135 | .2 | 24.0 | 78.18 | 3,240 | .2 |
| Georgia | 135 | .2 | 27.0 | 87.95 | 3,645 | .2 |
| Wisconsin | 93 | .1 | 30.3 | 98.70 | 2,820 | .1 |
| Iowa | 100 | .1 | 34.0 | 110.75 | 3,400 | .2 |
| New Jersey | 54 | .1 | 36.0 | 117.26 | 1,944 | .1 |
| Delaware | 34 | .1 | 34.0 | 110.75 | 1,156 | .1 |
| West Virginia | 17 | ([2]) | 32.0 | 104.23 | 544 | ([2]) |
| Total | 10,838 | 15.6 | 36.7 | 119.54 | 397,808 | 18.6 |
| REGION 4: NORTHWEST W–HRW WHEAT STATES | | | | | | |
| Washington | 3,060 | 4.4 | 47.4 | 154.40 | 145,140 | 6.8 |
| Idaho | 1,350 | 1.9 | 44.5 | 144.95 | 60,050 | 2.8 |
| Oregon | 1,215 | 1.7 | 47.3 | 154.07 | 57,480 | 2.7 |
| Utah | 282 | .4 | 25.4 | 82.74 | 7,164 | .3 |
| Total | 5,907 | 8.5 | 45.7 | 148.86 | 269,834 | 12.6 |
| REGION 5: SOUTHWEST HRS–W–D WHEAT STATES | | | | | | |
| California | 1,001 | 1.4 | 62.2 | 202.61 | 62,227 | 2.9 |
| Arizona | 320 | .5 | 71.0 | 231.27 | 22,720 | 1.1 |
| Nevada | 20 | ([2]) | 58.8 | 191.53 | 1,175 | .1 |
| Total | 1,341 | 1.9 | 64.2 | 209.12 | 86,122 | 4.0 |
| U.S. Total | 69,641 | 100.0 | 30.7 | 100.00 | 2,134,833 | 100.0 |

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[1] Excludes Florida, Louisiana, and Northeast States. Within regions, States are listed in order of decreasing harvested acreage.

[2] Less than 0.05 percent.

Source: *Crop Production (106).*

in this area. Large annual climate variations also cause considerable yield variability in this region. Hard Red Spring wheat accounts for most of the wheat acreage in this region, but large amounts of Durum and Hard Red Winter are also grown (table 1).

*Region 3, The Midwest and Eastern States.*—In 1975, this region accounted for 15.6 percent of the U.S. harvested acreage and 18.6 percent of the U.S. production. Ohio, Illinois, and Indiana were major producing States in this region. Soft Red Winter was the major class of wheat in this region, although some Hard Red Winter, Hard Red Spring, and White wheats were grown. Although Michigan and New York primarily grow White wheat, these States are included in this region because of their proximity to the region.

*Region 4, The Northwest States.*—In 1975, this region had 8.5 percent of the U.S. harvested acreage and 12.6 percent of the U.S. wheat production (table 2). The dryland wheat-growing areas of this region are different from most of the other regions in that they receive much of the annual precipitation during the winter months. Average annual precipitation amounts vary widely within this region. White wheat, grown primarily in the higher precipitation areas and under irrigation, accounts for 75 percent of all wheat acreage (table 1). Hard Red Winter and Hard Red Spring wheat classes are also grown, particularly in the drier areas of the region such as the Columbia Plateau, the south central and eastern areas of Idaho, and in areas of Utah adjacent to Idaho.

*Region 5, The Southwest States.*—In 1975, this region had 1.9 percent of the U.S. harvested acreage and 4.0 percent of the U.S. production (table 2). Regional yield was 209 percent of the U.S. yield. Most of the wheat grown in this region is Hard Red Spring, but the importance of wheat class varies widely by State (table 1). Hard Red Spring is the major class grown in California; Durum is the major class grown in Arizona, and White is the major class grown in Nevada.

# TECHNICAL FACTORS AFFECTING WHEAT PRODUCTION

This section identifies how changes in production practices and production input combinations have affected wheat yield trend since 1949, discusses regional impacts of each input on yield and production, and evaluates the influence of the production input on yield stability.[4]

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[4] The effect of production inputs on the stability of wheat yields is of interest in evaluating the sensitivity of wheat yields to changing weather patterns or in evaluating the feasibility of utilizing historical yield and weather data for wheat yield models.

Production inputs impacting wheat productivity since 1949 include summer fallow, irrigation, wheat varietal productivity, wheat class productivity, fertilizer, pesticides, soil productivity base, and cultural practices. Because of limitations of data and space, the discussion of production inputs is limited to using selected wheat States or areas as examples. In each case, an attempt is made (where data are known to exist) to discuss those areas where the particular production is most important.

The stability of production will be assessed by using the statistics: Standard deviation (*s*) and coefficient of variation (*CV*). The *CV*, which is defined as *s* divided by mean yield measures of relative magnitude of yield variations. A comparison of the standard deviation with and without the production input gives an indication of the absolute magnitude of yield variations (one standard deviation including two-thirds of the sample) due to the input.

The importance of the *CV* as a measure of relative yield variability is shown by the following hypothetical example. Suppose that for a set of climatic events and a certain set of production inputs (case 1) the mean yield for a given period of years is 15 bushels per acre and the *s* is 5 bushels per acre. Now, suppose that for the same set of climatic events but a different set of production inputs (case 2) the mean yield is 30 bushels per acre while the *s* remains 5 bushels per acre. In case 1 the *CV* is 0.333; and the doubling of mean yield in case 2 reduces the *CV* by one-half to 0.167. Such a reduction in the *CV* indicates that the relative variability of yield with respect to observed climatic conditions has declined. Although no change has occurred in the absolute variability of yields (*s*), the annual variability relative to the mean yield level has been stabilized by the new set of production inputs.

Because regional yield trends and annual yield variations are typically a combination of annual changes in climate and of annual changes in production input combinations, and climate sequences have not generally repeated themselves during the 1949–76 period, area yield series are not a very usable basis for measuring changes in yield stability. Only for the summer fallow section are comparable yield data available to provide a rough indication of the impact of a change in farming practice on yield stabiltiy. The effect of changes in other input combinations is implied from experimental data that compare production input combinations under the same set of annual climatic conditions.

## Summer Fallow

Summer fallow is defined as: "a farming practice wherein no crop is grown and all plant growth is controlled by cultivation or chemicals during a season when a crop might normally be grown." (*44*, p. 1).

The total acreage of summer fallow increased from 4 million acres in 1909 (when summer fallow was first reported) to 26 million acres in 1949, reaching a high of 41 million acres in 1969 (*38*). Since 1969, summer fallow land has decreased to 28 million acres in 1974 (*38*).

## Use for Wheat

Most summer fallowing is practiced in the semiarid dryland areas of Regions 1, 2, and 4, which include primarily the Great Plains and the Northwest States (fig. 2). In 1975, these regions accounted for 82 percent of the harvested acreages of wheat in the United States. Since inadequate precipitation greatly limits wheat production in these semiarid areas, summer fallowing is often used for the primary purpose of storing water in soil before wheat seeding.

Most of the summer fallow in the Western States is used for the production of wheat (*44*). Figure 6 shows the acreage of HRW and

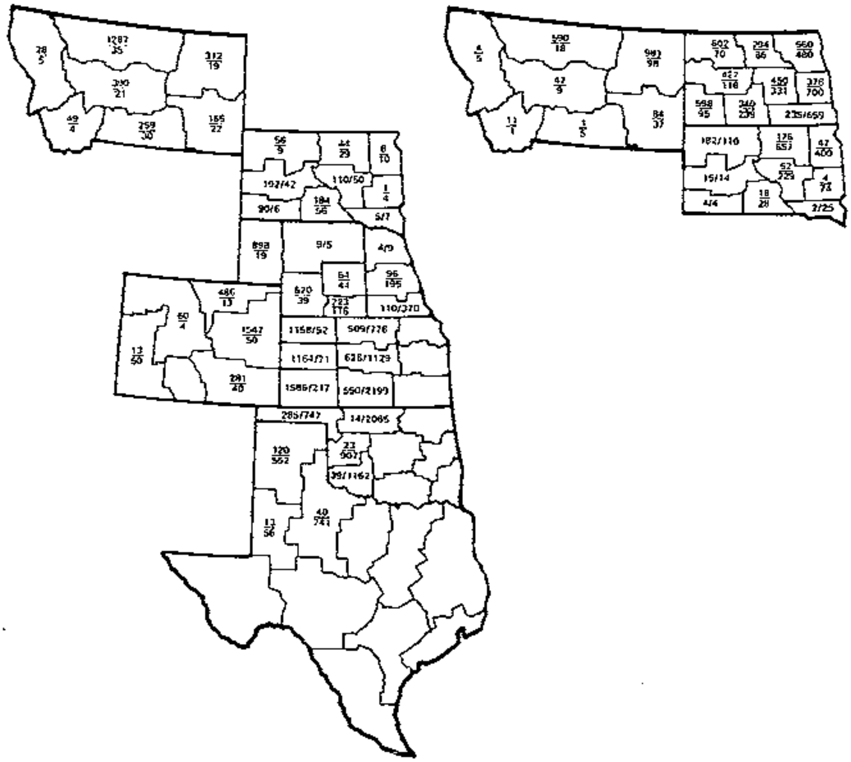

FIGURE 6.—Thousands of harvested acres of dryland Hard Red Winter and Hard Red Spring wheat planted on summer fallow and on continuous cropping in selected Great Plains States, 1974. Top figure is on summer fallow, bottom on continuous. (USDA-ESCS data.)

HRS wheat produced on summer fallow and on continuous cropping in selected Great Plains States in 1974. Data are shown only for those Crop Reporting Districts (CRD's) where both cropping sequences are reported by USDA–ESCS. Summer fallow is also used extensively for wheat production in the Northwest States of Washington, Oregon, and Idaho (*66*).

In 1974 summer fallow was used almost exclusively for wheat growing in Montana and Colorado and was used mostly in the drier western parts of the Great Plains States of North Dakota south to Texas (fig. 6). Summer fallow was used for both HRW and HRS wheats in Montana, North Dakota, and South Dakota.

Wheat yields following summer fallow and continuous cropping for 1974 are shown in figure 7. Although yield data for only 1 year are shown, some general relationships are apparent. In the drier western

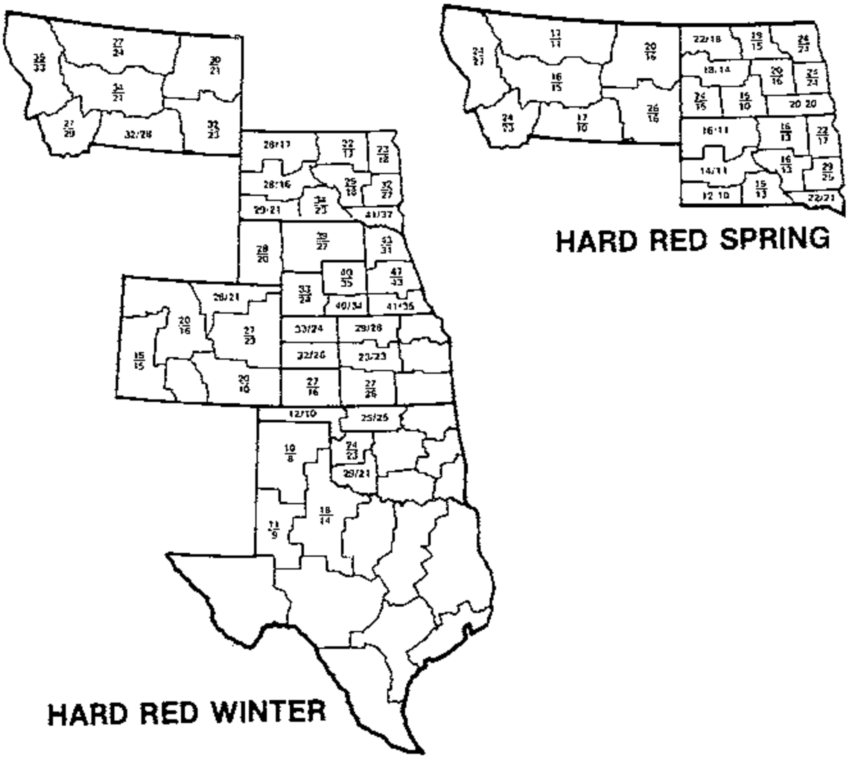

FIGURE 7.—Bushels per harvested acre of dryland Hard Red Winter and Hard Red Spring wheat planted on summer fallow and on continuous cropping in selected Great Plains States, 1974. Top figure is on summer fallow, bottom on continuous. (USDA–ESCS data.)

areas, yields after fallow are much greater than on continuous cropping. In the eastern parts of these States, however, yields are not increased as much by summer fallow as they are farther west. In some instances, yields on summer fallow are no greater than on continuous cropping. Where HRW and HRS wheats are extensively grown, as in Montana and South Dakota, HRW wheat yields, both on summer fallow and continuous cropping, are significantly greater than those of HRS.

Durum (a spring wheat) yields were similar to those of the HRS wheat, grown on corresponding summer fallow or continuous cropping conditions, in North Dakota, South Dakota, and Montana (not shown). The yield increase for summer fallowing over continuous cropping decreases from north to south. For example, only a 2- to 4-bushel-per-acre increase was measured in Texas in the southern Great Plains; whereas 5- to 10-bushel-per-acre increases were not uncommon in the northern Great Plains. The smaller yield increase on summer fallow in the southern Great Plains is due largely to fallow efficiencies (percentage of precipitation stored in the soil) that decline from north to south as higher average temperatures increase evaporation *(71)*.

Figures 6 and 7 should be considered simultaneously when yields on summer fallow and continuous cropping are compared. In those CRD's where almost all of the wheat is produced either on summer fallow or continuous cropping, the yields are not entirely comparable. For example, in Montana and Colorado where more than 90 percent of the wheat is produced on summer fallow, farmers tend to utilize the more productive soils for continuous cropping *(46)*.

From its 1949 peak, wheat acreage declined to a low in 1970; reversing the 1970's, it reached a level slightly below the 1949 peak (fig. 1). Summer fallow acreage during this period was negatively correlated with wheat acreage but generally preceded the wheat acreage trend by a year. Summer fallow acreages peaked in 1969 at 41 million acres *(38)*. Much of the increased acreage of wheat since 1970 was brought about by the decreased use of summer fallow. Changes that occurred within individual CRD's in the Great Plains States are depicted in figure 8. In most of the CRD's in the Great Plains, the percentage of wheat produced on summer fallow decreased between 1970 and 1974. However, in the drier western Great Plains summer fallow areas, such as in Montana and most of Colorado, the decrease was not great. The greatest decreases occurred in the more humid eastern parts of North Dakota, South Dakota, and Nebraska.

Except for the drier western CRD's, the use of summer fallow for wheat almost ceased in the southern Great Plains States of Oklahoma and Texas. Because HRW wheat yields responded more to summer

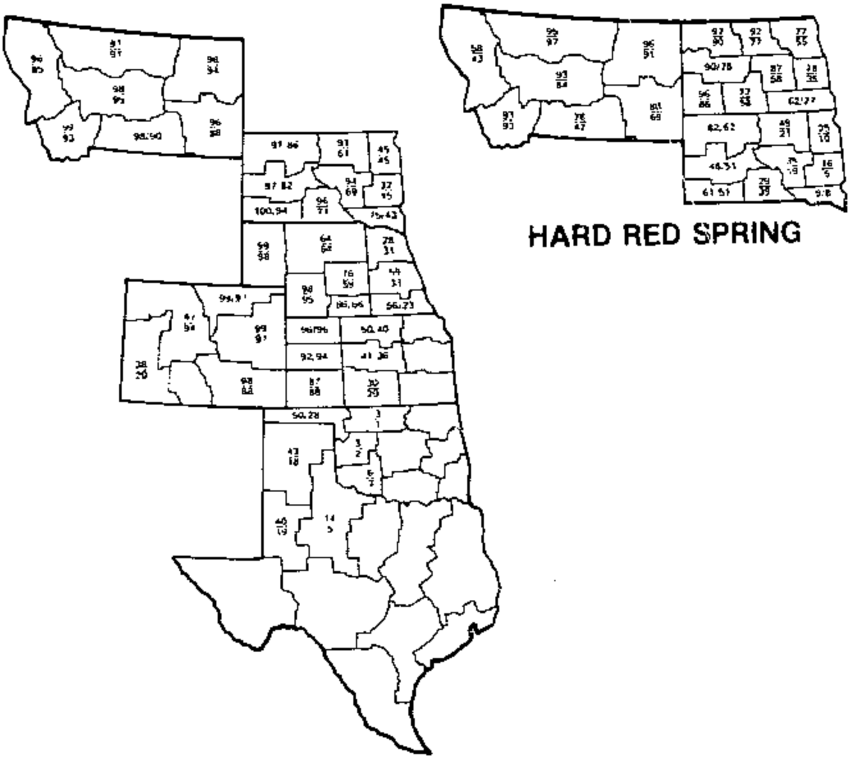

FIGURE 8.—Percent of harvested dryland Hard Red Winter and Hard Red Spring wheat planted on summer fallow in selected Great Plains States for the 1970 and 1974 crops. Top figure is for 1970; bottom for 1974. For Oklahoma, 1968 data are shown instead of 1970. (USDA-ESCS data.)

fallow than did the HRS wheat yields (fig. 7), in both 1970 and 1974 a greater percentage of HRW wheat than HRS wheat was planted (for example in Montana and South Dakota) on summer fallow (fig. 8). However, between 1970 and 1974 the use of summer fallow declined for both HRW and HRS wheats.

The more frequent occurrence of saline seeps was also a significant factor in decreasing the use of summer fallow between 1970 and 1974 in western North Dakota and in much of Montana (fig. 8). Saline seeps develop where the deep percolation of water moves below the root zone and subsequently moves horizontally when a permeable layer is underlaid by a less permeable layer (*45*). The excess water, together with the dissolved salts accumulated as the water moves through the underlying strata, eventually reaches the soil surface at a lower position on the landscape and forms a "saline seep." These largely unproductive saline seeps are associated with summer fallow and occur much less frequently with continuous cropping.

Long-term records are available on the use of summer fallow for wheat in the Great Plains States of Kansas, Nebraska, and North Dakota (fig. 9). Generally, the proportion of wheat grown on summer fallow increased from 1949 to the early 1970's in all three States. Because yields after summer fallow are higher than after continuous cropping, increased use of summer fallow caused a significant part of the upward trend in yields since 1949. However, the percentage on summer fallow has decreased particularly since 1973, and this decrease tended to lower average wheat yields.

Average wheat yields from 1949 to 1975 with continuous wheat and after summer fallow for Kansas, Nebraska, and North Dakota are given in table 3. More meaningful yield comparisons can be made between cropping sequences than with only the 1974 data (fig. 7). The yield advantages for summer fallow are greater for CRD's in the drier western one-third of each State than those for CRD's farther east in the central and eastern parts.

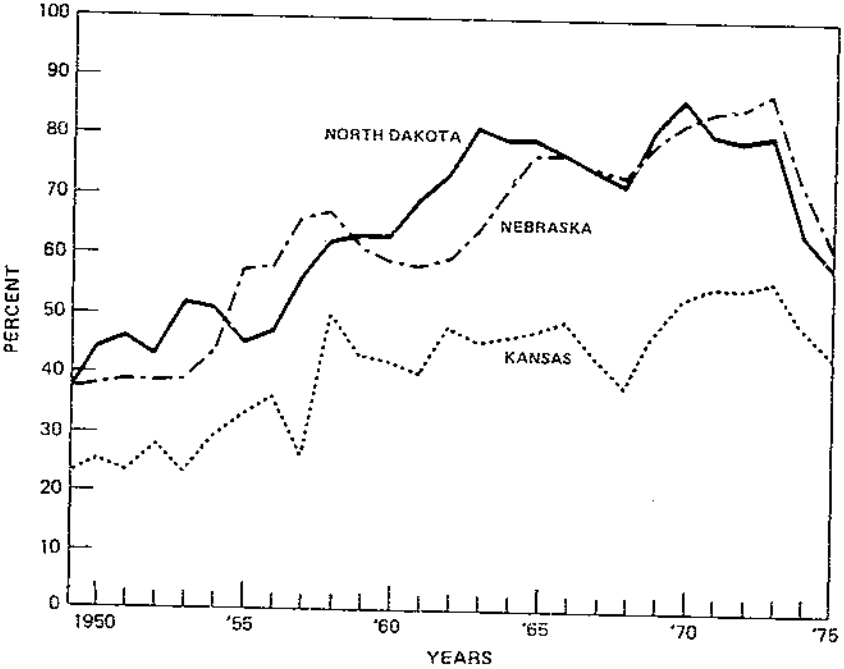

FIGURE 9.—Harvested acres of dryland wheat produced on summer fallow as a percentage of total harvested acres of all wheat for three Great Plains States, 1949-75. (USDA-ESCS data.)

USDA–ESCS yield data show that wheat yields after summer fallow are about 7 or 8 bushels (near 50 percent) more than continuous cropping in the western one-third of the HRW wheat States of Kansas and Nebraska. There is a disproportionate acreage of wheat after summer fallow in these CRD's (fig. 8). Generally, in CRD's west of the 100th meridian, continuous cropping represents wheat grown on the better soils—and on lowland sites. If comparable acreages were used for both summer fallow and continuous cropping, yields after summer fallow would show a greater difference. For example, long-term experimental plot data in northwestern Kansas (*62*), as well as more recent research in northwestern Kansas (*47*), and southwestern Kansas (*17*), showed that wheat yields after summer fallow more than doubled the yields on continuous cropping.

In the central one-third of the HRW wheat States of Kansas and Nebraska (table 3), where there are significant acreages of both continuous wheat and wheat after summer fallow (fig. 6), wheat yields after summer fallow are about 3 to 6 bushels greater (14 to 27 percent increase for Kansas and Nebraska, respectively) than on continuous cropping. Experimental plot data in these regions indicate yield increases after summer fallow (compared with continuous cropping), ranging from 57 percent (*69*) to over 300 percent (*102*). This is the "fallow transition" zone where an estimated 45 percent of the area is on a fallow-wheat-sorghum sequence (*42*). A partial cause for the smaller increases in wheat yields after summer fallow in the central region is that the approximately 10-month-fallow period between sorghum and wheat as contrasted to the longer 14-month period between alternating wheat crops further west (*42*) reduces preseasonal soil water storage.

Wheat yields are lower on both continuous cropping and after summer fallow in the predominantly HRS and D wheat State of North Dakota than in the HRW wheat States of Kansas and Nebraska (table 3). Although North Dakota wheat yields after summer fallow were greater than those after continuous cropping, the response difference was generally less than in Kansas and Nebraska. The yield increase with summer fallow was also greater in North Dakota's western and central CRD's than in the eastern one-third. However, yields for both continuous cropping and wheat after summer fallow were comparable in the western and central one-third of the State. The lack of a pronounced differential response to summer fallow from west to east in North Dakota (as compared to Kansas and Nebraska) is partly because the gradient in rainfall from west to east in North Dakota is less than in Nebraska and Kansas (*114*).

For the central one-third of North Dakota, long-term (1915–48)

TABLE 3.—*Average wheat yield per harvested acre (1949–75), standard deviation, and coefficient of variation of all dryland wheat grown on continuous cropping and after summer fallow in the western, central, and eastern one-third of 3 Great Plains States*

| State | Continuous Cropping | | | After fallow | | | |
|---|---|---|---|---|---|---|---|
| | Yield | Standard deviation | Coefficient of variation | Yield | Standard deviation | Coefficient of variation | Yield difference |
| | *Bushels per acre* | *Bushels per acre* | *Percent* | *Bushels per acre* | *Bushels per acre* | *Percent* | *Bushels per acre* |
| WESTERN ONE-THIRD (CRD 1, 4, 7) [1] | | | | | | | |
| Kansas | 15. 4 | 6. 6 | 43 | 23. 0 | 8. 3 | 36 | 7. 6 |
| Nebraska | 18. 8 | 7. 1 | 38 | 26. 8 | 6. 4 | 24 | 8. 0 |
| North Dakota | 15. 1 | 5. 7 | 38 | 20. 3 | 6. 7 | 33 | 5. 2 |
| CENTRAL ONE-THIRD (CRD 2, 5, 8) | | | | | | | |
| Kansas | 22. 1 | 7. 5 | 34 | 25. 3 | 9. 6 | 38 | 3. 2 |
| Nebraska | 21. 9 | 7. 9 | 36 | 27. 9 | 8. 1 | 29 | 6. 0 |
| North Dakota | 14. 8 | 5. 8 | 30 | 21. 5 | 7. 1 | 33 | 6. 7 |
| EASTERN ONE-THIRD [2] (CRD 3, 6, 9) | | | | | | | |
| Nebraska | 26. 9 | 8. 1 | 30 | 32. 6 | 7. 8 | 24 | 5. 7 |
| North Dakota | 20. 0 | 6. 6 | 33 | 24. 7 | 6. 7 | 27 | 4. 7 |

[1] Crop Reporting Districts 1 and 7 only for Nebraska.

[2] Continuous cropping and after fallow not reported separately in Kansas.

Source: USDA–ESCS data.

experimental plot yields at Mandan were 14.9 and 20.9 bushels per acre for continuous wheat and wheat after summer fallow, respectively (*45*). These experimental plot data compare favorably with the USDA–ESCS data for the area. In the western part of North Dakota at Dickinson, long-term (1908–51) experimental wheat yields were 11.6 and 20.9 bushels per acre for continuous cropping and wheat after fallow, respectively. (*26*). This is a 9.3-bushel increase for summer fallow.

## Yield Stability

Standard deviations for yields on continuous cropping and after summer fallow for different portions of Kansas, Nebraska, and North Dakota are given in table 3. Even though yields are increased by the use of summer fallow in all instances as compared with continuous cropping, there is no apparent change in the standard deviation. This would indicate that yields vary similarly on both cropping sequences across the range of climatic conditions covered by the period of years involved. On the other hand, when yields are increased by summer fallow, there is generally a decrease in the relative variation in yields as indicated by the coefficient of variation.

One point should be kept in mind when evaluating the impact of cropping sequence on the wheat yields discussed herein, that is all other production inputs involved with dryland wheat are included over time. In the subsequent sections, several of these other inputs will be evaluated separately.

## Soil Productivity Base

One factor involved in wheat yield trends is the productivity of different tracts of land used for growing wheat. In the more important wheat-growing regions as wheat acreage increases, soils of lower productivity are brought into production. Conversely, when wheat acreage is controlled, as with government programs, soils of higher productivity are used for wheat. In areas where the most important crops, such as wheat, barley, oats, flax, and rye, are "close-grown" as in Region 2, wheat usually is grown on the most productive land because of its generally higher income per acre.

Using North Dakota as an example, in 1949 there were slightly more than 11 million acres of all wheat seeded in the State (fig. 10). The acreage declined little until the initiation of acreage restrictions in the early fifties. By 1957, there were only 6.5 million acres planted to wheat in North Dakota. Government acreage allotment and other programs caused planted wheat to remain near this level for the following decade—the average acreage planted to wheat during the period of 1957 through 1966 was 6.5 million acres. Changes in government programs allowed the wheat acreage to increase somewhat after 1966 to almost 9 million acres by 1973. USDA–ESCS data for 1976 indicate 11.9 million planted acres of all wheat—greater than the previous high of 1949.

The increase in wheat acreage in North Dakota from 1967 to 1976 came from three primary sources: (1) Decreases in the acreage of other crops, (2) less use of summer fallow preceding wheat (fig. 9), and (3) the conversion of formerly diverted acres to wheat growing. From 1970 to 1974, the combined seeded acreage of oats, flax, and rye in North Dakota decreased by about 2 million acres and acreage of summer fallow decreased by 1.9 million acres (USDA–ESCS data). Since summer fallow is used primarily for subsequent wheat crops to increase

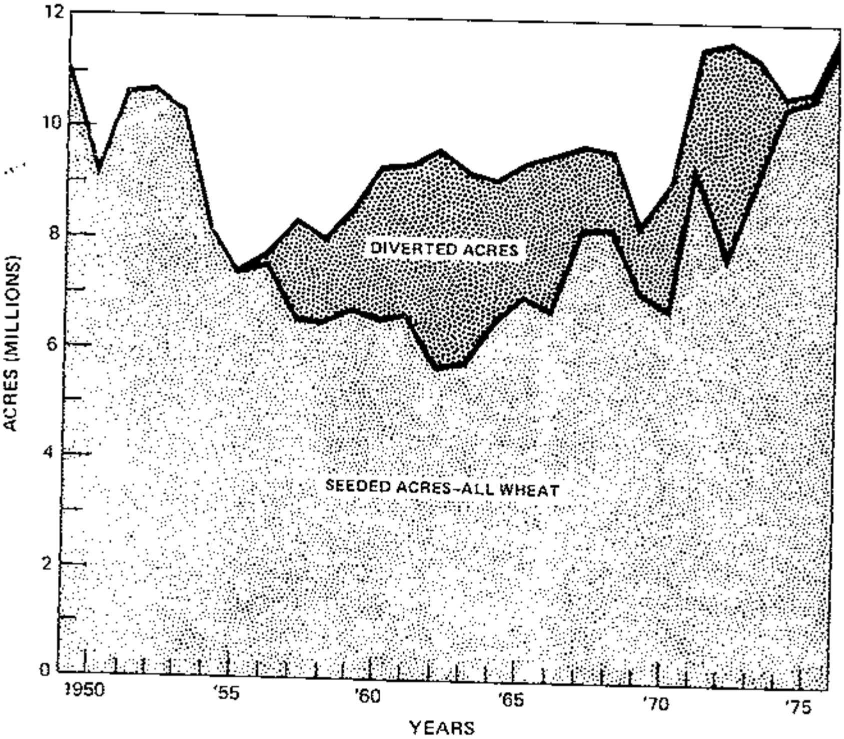

FIGURE 10.—Seeded acres of all wheat and diverted acres under Government farm programs in North Dakota, 1949–76. (USDA–ESCS and USDA–ASCS data.)

soil-water storage before seeding, to release available plant nutrients, and to control weeds, there is little reason to believe that summer fallow acreages are less productive than the wheat acreages. However, both diverted acreages and other crop acreages converted to wheat production will likely have a lower average productivity capability than those acreages in wheat during the decade from 1957 through 1966 (fig. 10).

From 1956 through 1973, various government diversion programs occupied a significant acreage in North Dakota (fig. 10). These government programs included the Conservation Reserve Program, Acreage Reserve Program, Wheat Program, Cropland Conversion Program, and Crop Adjustment Program (USDA Agricultural Stabilization and Conservation Service data). Of the several programs, the acreage in the Conservation Reserve Program (Soil Bank) is less likely to have a productivity greatly different from nondiverted acreage because in some instances entire farms were placed in the Conservation Reserve Program. However, in those instances where entire farms were placed in the Conservation Reserve Program, such farms more likely were located in the drier and less productive western part of North Dakota.

A detailed study of the productivity of the diverted acreage in 1966 concluded that, "After considering all sources of variation, the production of the diverted acreage as a percentage of the acreage in production was estimated at 90 percent for wheat . . ." (*120*, p. 14). If the assumption were made that of the approximately 5 million additional acres of wheat in North Dakota between 1966 and 1976, about 3 million acres came from diverted acreages and acreage of other crops (with potential productivity of 90 percent as compared with wheat acreages), then calculations can be made on the impact of these acreages on wheat yield trend.

Considering wheat yield trends in North Dakota, in 1966 wheat yields were about 25 bushels per acre. If diverted acreages and acreages in other crops were about 10 percent less productive, then these acreages would potentially produce about 2.5 bushels per acre less than those wheat acreages in 1966. Since the 3 million acres involved are about 25 percent of the 1976 wheat acreage of near 12 million acres, then (based on 1966 wheat yield trends) 1976 wheat yields in North Dakota should be reduced by 0.6 bushel per acre. Since 1966, wheat yield trends in North Dakota have continued to move upward because of greater varietal productivity and increased use of fertilizer. These trends, however, are offset by the decreased use of summer fallow (fig. 9). The 0.6-bushel-per-acre value may, therefore, be somewhat conservative.

The example for North Dakota points out that changes in the soil productivity base within a given area can have an impact on potential wheat yield. Although the calculated overall decrease in productivity is not large for North Dakota, an increase in wheat acreage in other wheat-growing regions of the United States could have an even greater impact on potential wheat productivity and should be considered in evaluating wheat yield trends.

## Irrigation

### Use for Wheat

Irrigation is an important component of the wheat acreage and production in many areas of the Western United States. In Northwest Region 4, nearly 500,000 acres are irrigated (*91*). Irrigation makes the biggest contribution to wheat grown in Region 5, where most of the wheat grown in Arizona and Nevada and about one-fourth of California's wheat is irrigated (*91*).

However, the largest irrigated acreage is in the Great Plains Regions. In 1974, there were 1.74 million harvested acres of irrigated wheat grown in the eight Great Plains States (fig. 11). The greatest acreage of irrigated wheat occurs in three States of Region 1. Texas, Kansas, and Oklahoma. In fact, almost one-half of all the irrigated wheat acreage in the Great Plains is located in CRD 1–N of the Texas Panhandle. In 1974, 56 percent of the harvested wheat acreage in CRD 1–N was irrigated. Irrigated wheat is also of major importance in Texas CRD 1–S, in Kansas west central CRD 1 and southwestern CRD 7, in the Oklahoma Panhandle's CRD 1 and New Mexico CRD 3 (fig. 11).

In the Great Plains, it was after World War II before wheat was irrigated on a major scale. For example, less than 10 percent of the wheat acreage in Texas CRD1–N was irrigated in 1949 (fig. 12). The proportion of irrigated wheat acreage increased greatly during the fifties and peaked in 1963 at about 66 percent of the harvested wheat acreage. Since 1963, the proportion of wheat acreage irrigated has been gradually declining. In 1974, however, farmers, responding to high wheat prices, increased the proportion of irrigated wheat acreage to 56 percent of harvested wheat acreage from 36 percent in 1972.

Irrigated wheat yields have also increased over time (fig. 13). In 1949, 1950, and 1951, irrigated wheat yields in Texas CRD 1–N were not much greater than those grown on dryland. However, irrigated wheat yields increased greatly during the fifties and except for yield variations due in part to weather have been fairly constant for the past decade. Wheat yields grown on irrigated land are significantly greater, however, than those grown under dryland conditions. For example, in Texas CRD 1–N wheat yields from 1968 through 1975 averaged 30.6 and 15.6 bushels per harvested acre, respectively, for irrigated and dryland conditions.

Most of the upward trend in wheat yields since 1949 in those CRD's where irrigation is important (fig. 11) is, therefore, due to two factors: (1) The increase in the proportion of wheat grown under irrigation (fig. 12) and (2) an increase in irrigated wheat yields over time (fig. 13). In those CRD's where irrigation is an important factor in wheat production, the potential for wheat yield increases under dryland conditions is often limited by the amount of available water.

The increases in irrigated wheat yields over time were largely due to improved irrigation water management, improved varieties, and the increasing use of fertilizers *(60, 74, 82, 84)*. In 1976, irrigation of wheat in Texas, Oklahoma, and Kansas was still the more "extensive" type, that is, supplemental to rainfall with weather retaining an important role, as contrasted to intensive irrigation of many other crops

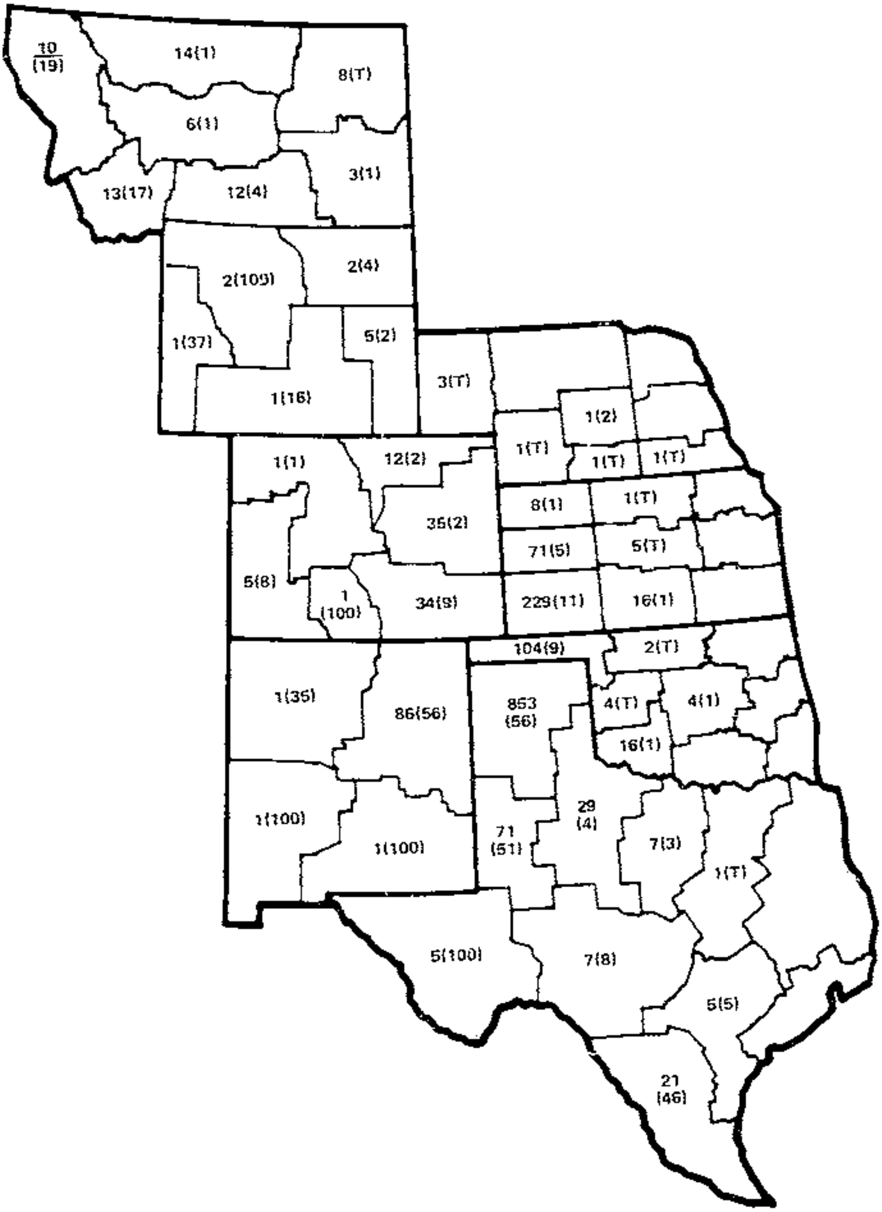

FIGURE 11.—Thousands of harvested wheat acres and percentage of harvested wheat acres irrigated (in parentheses) for the 1974 crops in selected Great Plains States. (T=less than 1 percent) (USDA–ESCS data.)

where plant-water stress is largely eliminated. As a consequence, irrigated wheat yields are still subject to significant yearly variations.

### Yield Stability

Comparative data for analyzing the effect of irrigation on wheat yield stability were available for CRD 1-N in Texas and for CRD 4 and 7 in Kansas (table 4). The standard deviation of wheat yields for both dryland cropping sequences and for irrigated wheat is similar in these two States. However, corresponding with much lower dryland yields, in Texas the standard deviation was slightly lower for dryland wheat than for irrigated wheat. In Kansas the standard deviation of irrigated wheat yields was lower than the standard deviation of wheat yields after summer fallow or after continuous cropping. Nevertheless, these results show that although irrigated wheat remains subject to annual variations in yield caused largely by annual climatic variations, irrigation reduces relative yield variability as shown by coefficient of variations.

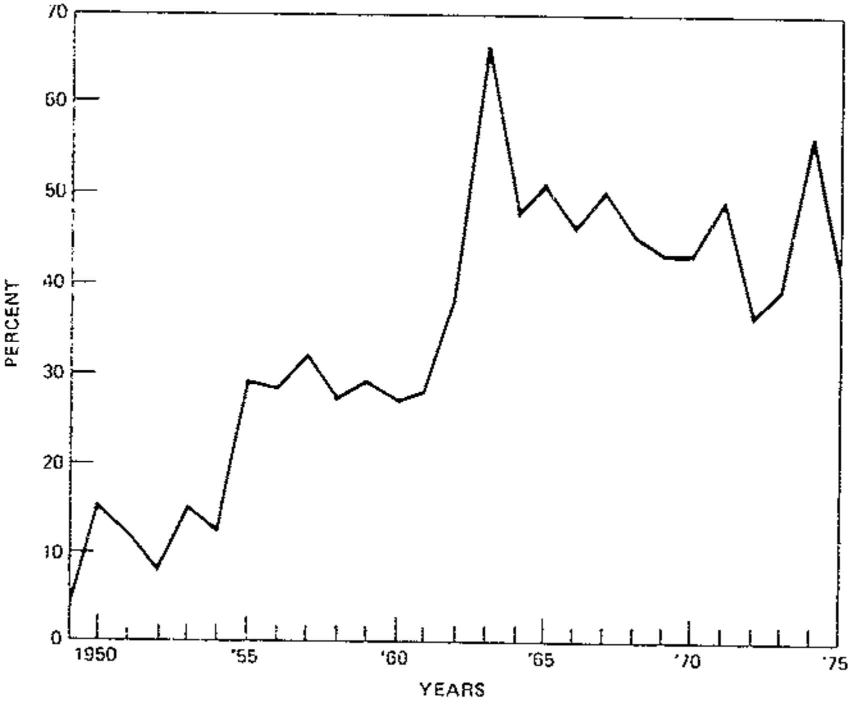

FIGURE 12.—Percentage of harvested wheat acreage irrigated in Crop Reporting District 1-N of Texas, 1949–75. (USDA-ESCS data.)

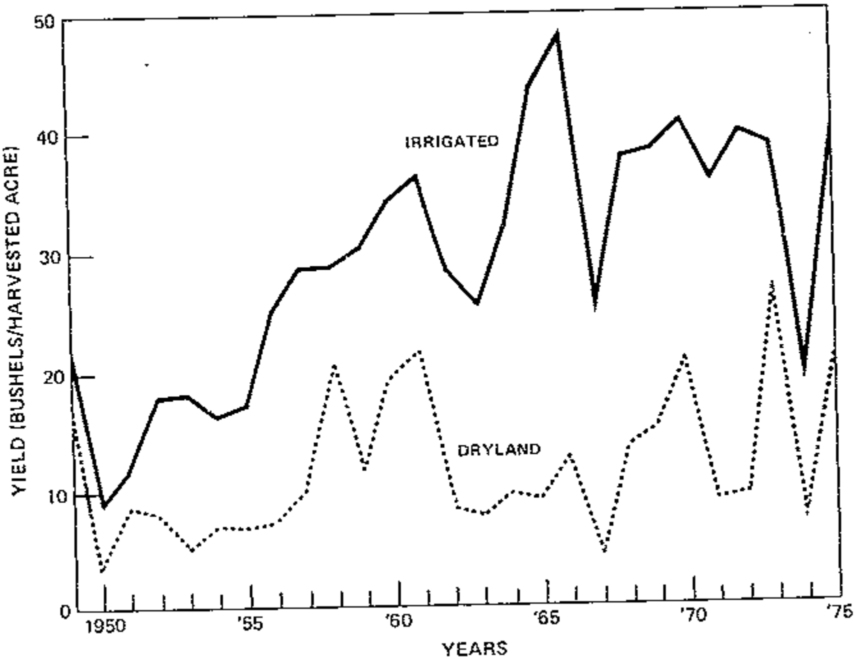

FIGURE 13.—Yield of irrigated wheat and dryland wheat in Crop Reporting District 1–N of Texas, 1949–75. (Yields are average for Briscoe, Castro, Deaf Smith, Floyd, Hale, Parmer, and Swisher Counties.) (USDA–ESCS data.)

## Wheat Varietal Productivity

### Variety Improvement

Variety improvement has played a significant role in the increasing wheat yields that have occurred (fig. 5) in all wheat-growing regions. To quantify the role of variety improvement, individual field plot variety trials were used for seven locations in North Dakota [5] and three in Missouri [6] as examples of a major HRS–D wheat State and a predominately SRW wheat State, respectively.

The approach developed by Auer [7] was used to develop varietal pro-

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[5] North Dakota variety performance data were provided by L. A. Jensen and J. F. Carter, Agronomy Department, North Dakota State University, Fargo.

[6] Missouri variety performance data were provided by J. M. Poehlman and D. Sechler, Agronomy Department, University of Missouri, Columbia.

[7] AUER, L. IMPACT OF CROP-YIELD TECHNOLOGY ON U.S. CROP PRODUCTION. Unpublished Ph. D. thesis. Iowa State University of Science and Technology, Ames. 1963.

TABLE 4.—*Average yield per harvested acre, standard deviation, and coefficient of variation of irrigated and dryland wheat grown in selected Crop Reporting Districts of the southern Great Plains*

| State | Crop reporting district | Years | Irrigated |  |  | Dryland—after fallow |  |  | Dryland—continuous |  |  | Dryland—combined[1] |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | Yield | Standard deviation | Coefficient of variation | Yield | Standard deviation | Coefficient of variation | Yield | Standard deviation | Coefficient of variation | Yield | Standard deviation | Coefficient of variation |
|  |  |  | *Bushels per acre* | *Bushels per acre* | *Percent* | *Bushels per acre* | *Bushels per acre* | *Percent* | *Bushels per acre* | *Bushels per acre* | *Percent* | *Bushels per acre* | *Bushels per acre* | *Percent* |
| Texas | 1–N[2] | 1949–75 | 29. 0 | 7. 5 | 26 | --- | --- | --- | --- | --- | --- |  |  |  |
| Do | 1–S[3] | 1949–75 | 27. 3 | 7. 6 | 28 | --- | --- | --- | --- | --- | --- | 11. 9 | 6. 0 | 50 |
| Kansas | 4 | 1957–75 | 38. 0 | 6. 5 | 17 | 24. 8 | 8. 4 | 34 | 18. 3 | 7. 0 | 38 | 13. 1 | 5. 8 | 44 |
| Do | 7 | 1957–75 | 36. 7 | 6. 2 | 17 | 23. 2 | 8. 6 | 37 | 16. 9 | 6. 9 | 41 | --- | --- | --- |

[1] Wheat yields on summer fallow and continuous cropping not reported separately for all years in Texas.

[2] Yields for the period are an average for Briscoe, Castro, Deaf Smith, Floyd, Hale, Parmer, and Swisher Counties.

[3] Yields for the period are an average for Bailey, Crosby, Lamb, and Lubbock Counties.

Source: USDA–ESCS data.

ductivity indexes with time. With this approach, an initial check variety was selected and for each year the check variety was taken as 100 percent. The performance of other varieties was calculated each year as a percentage of the check variety. Since the check variety first selected was not grown in variety trials for all test years, the use of other check varieties was necessary after 1970 in North Dakota and after 1966 in Missouri. To do this, an overlap period of years was used (3 to 12 years for North Dakota and 5 to 10 years for Missouri) to convert the performance of the second check variety into a percentage of the first check variety and so on for the entire test period. For North Dakota, Thatcher was the first check variety and Chris, the second.[8] For Missouri, Clarkan, Monon, and Arthur were the first, second, and third check varieties, respectively. All varietal performances were ultimately calculated as a percentage of the first or original check variety.

Varietal productivity indexes for North Dakota and Missouri were calculated for the census year—1949, 1954, 1959, 1964, 1969 and 1974. For each census year, an index of varietal performance was calculated by averaging 5 years of experimental plot performance data (when data were available), and using the census year as the midpoint. After calculating a relative performance index for each variety, individual census year-variety-survey data were used to estimate the varieties' share of wheat acreage in the State. Where unidentified varieties usually less than 10 percent) were shown in the census survey, the share of each identified variety was adjusted upward proportionately so that the identified varieties totaled 100 percent for the State. For each census year, the performance index for each variety was multiplied by its share of the wheat acreage in the State. Summing these calculations provided a varietal productivity index for the year.

The productivity of North Dakota in relation to the Thatcher variety (HRS) and of Missouri wheat to the Clarkan variety (SRW) is shown in figure 14. For North Dakota, relative varietal productivity increased about 10 percent since 1949; for Missouri it increased about 40 percent since 1959. The productivity of Missouri wheat below 100 percent in 1949 and 1954 was primarily due to growing some HRW wheats that yielded less than the SRW Clarkan check variety in these years.

Although data were unavailable for analysis of the whole region, the varietal productivity values for North Dakota may be indicative of varietal improvement in the drier HRS wheat area of Region 2; and the varietal productivity values for Missouri may be indicative of the more humid conditions of SRW wheat Region 3. Much of the increased varietal productivity in the SRW wheat States is due to the

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[8] For Mandan, Waldron was used as the second check variety.

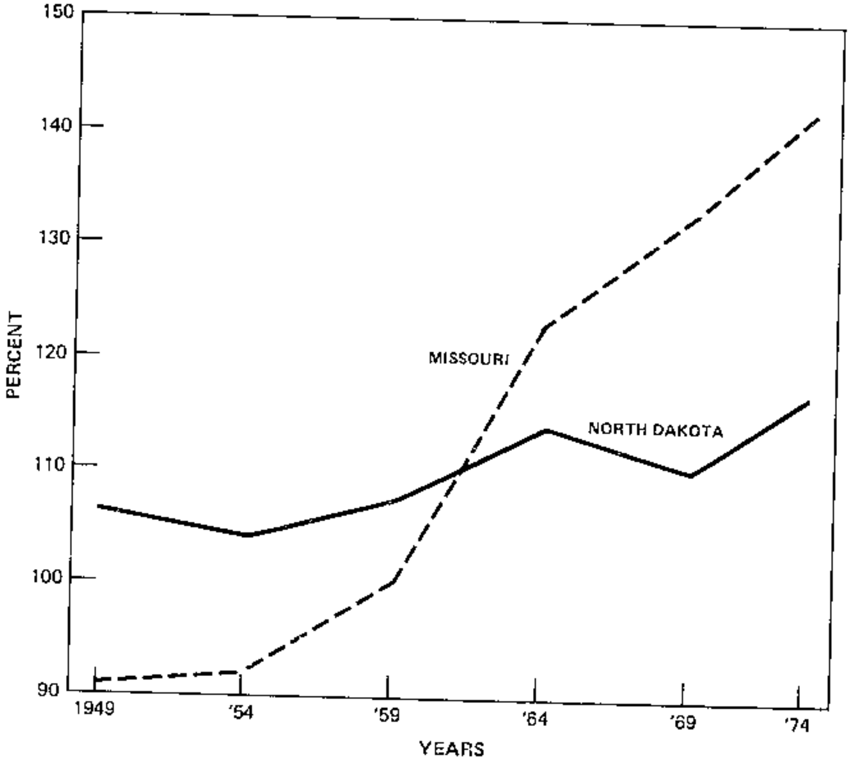

FIGURE 14.—Productivity of North Dakota wheat in relation to the Thatcher variety and of Missouri wheat in relation to the Clarkan variety, census years 1949–74. (See text.)

highly productive Arthur (*80*) and Arthur 71 varieties. They accounted for about two-thirds of all the wheats grown in 1974 in the States of Ohio, Illinois, Missouri, and Indiana (USDA–ESES data). Although Arthur and Arthur 71 are not classified as semidwarf wheats, they do have strong straw and good disease resistance and respond well to applied fertilizer (*54*).

Much has been written (*103*) about the "Green Revolution" and the impact of the high-yielding wheat varieties (HYV) that occupied over 40 million acres in Asia and North Africa in 1973 (*27*). As previously emphasized (*94*), Norin 10 and other Japanese strains were first used in the United States in the State of Washington by Vogel and associates (*118*) and outside the United States by Borlaug and associates in Mexico (*16*). Both of these wheat-breeding programs have had a significant impact in the United States on the development of high-yielding semidwarf wheats, for example Gaines, which are resistant to lodging and responsive to production inputs such as water (from either rainfall or irrigation) and applied fertilizer, particularly nitrogen (*97*).

Table 5 shows the use of semidwarf varieties in U.S. wheat in 1974 and 1975 in the leading wheat State in each of the five wheat-growing regions (fig. 2). For the State of Washington in 1974 and 1975, Gaines (*116*) and Nugaines (*119*) occupied almost one-half of the wheat acreage, and in 1975, Paha occupied almost one-seventh of the acreage. These semidwarf white wheats are adapted to the more humid parts of Northwest Region 4 and are quite responsive to applied nitrogen (*117*). Obviously, these highly productive semidwarf varieties have had a great impact on the upward trend in Northwest Region 4 (fig. 5).

The most dramatic impact of the high-yielding semidwarf wheats (for the States shown in table 5) has been in the State of California where virtually all of the wheat grown in 1974 and 1975 were Mexican varieties[9] and, for 1975, wheat yields per harvested acre exceeded 60 bushels per acre (table 2).

In the generally dry Great Plains wheat States of Kansas and North Dakota, semidwarf wheats have not yet had a major impact (table 5). In Kansas, the semidwarfs Satanta and Chanute occupy a minor percentage of the total acreage. In North Dakota, the HRS wheat semidwarf varieties Era, Lark, and Bounty 208 still occupy a small proportion of the acreage; whereas the variety Olaf occupied 11.1 percent of the acreage in 1975.

In somewhat wetter Minnesota, semidwarfs are very important where, for example, in 1974 Era occupied 62 percent of the total wheat area (USDA-ESCS data). Under Minnesota conditions, Era yields were 62 percent greater than the older variety Thatcher over a 4-year test period (*49*).

Although semidwarf wheats have not yet had a major impact on yields under the dryland conditions of the Great Plains, semidwarf wheats have contributed to higher irrigated wheat yield levels in the southern Great Plains. In the early years of irrigated wheat production in the southern Great Plains, the application of adequate water and large amounts of nitrogen fertilizer often caused severe lodging and associated yield reductions (*60, 74, 83*). The wheat varieties available at the time were developed primarily for dryland conditions. However, high-yielding short-stature (semidwarf) varieties resistant to lodging under intensive irrigation and high applied nitrogen levels

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[9] Varieties released by the Cooperative Program of the Instituto Nacional de Investigaciones Agricolas (INIA) and the International Maize and Wheat Improvement Center (CIMMYT) in Mexico.

TABLE 5.—*Wheat variety surveys for the 1974 and 1975 crops in the leading wheat States of each wheat-growing region.*[1]

| Region, State, and variety | Market class | Percentage of acreage in | |
|---|---|---|---|
| | | 1974 | 1975 |
| Region 1, Kansas: | | | |
| Scout | Hard Red Winter | 36. 5 | 33. 2 |
| Eagle | do | 17. 8 | 22. 6 |
| Centurk | do | 9. 5 | 9. 8 |
| Triumph | do | 8. 3 | 8. 2 |
| Parker | do | 7. 6 | 6. 4 |
| Satanta [2] | do | 4. 7 | 2. 7 |
| Chanute [2] | do | 2. 7 | 2. 0 |
| Gage | do | 2. 4 | 2. 2 |
| Region 2, North Dakota: | | | |
| Waldron | Hard Red Spring | 33. 9 | 29. 9 |
| Rolette | Durum | 12. 8 | 10. 0 |
| Leeds | do | 9. 7 | 4. 8 |
| Wells | do | 6. 5 | 3. 6 |
| Lark [2] | Hard Red Spring | 5. 6 | . 7 |
| Ward | Durum | 4. 7 | 18. 2 |
| Era [2] | Hard Red Spring | 4. 5 | 4. 8 |
| Bounty 208 [2] | do | 3. 9 | 1. 4 |
| Chris | do | 2. 7 | 1. 6 |
| Olaf [2] | do | 2. 7 | 11. 1 |
| World Seeds 1809 [2] | do | 2. 6 | 1. 2 |
| Region 3, Ohio: | | | |
| Arthur | Soft Red Winter | 42. 2 | (3) |
| Arthur 71 | do | 19. 3 | (3) |
| Logan | do | 13. 0 | (3) |
| Monon | do | 9. 1 | (3) |
| Reed | do | 5. 1 | (3) |
| Region 4, Washington: | | | |
| Gaines and Nugaines [2] | White [4] | 47. 7 | 45. 1 |
| Wanser | Hard Red Winter | 13. 8 | 16. 1 |
| Paha [2] | White | 13. 5 | 14. 8 |
| Moro | do | 11. 8 | 10. 7 |
| Omar | do | 4. 4 | 2. 3 |
| McCall | Hard Red Winter | 3. 4 | 1. 9 |
| Hyslop [2] | White | 1. 6 | 3. 8 |

See footnotes at end of table.

TABLE 5.—*Wheat variety surveys for the 1974 and 1975 crops in the leading wheat States of each wheat-growing region*[1]—Continued

| Region, State, and variety | Market class | Percentage of acreage in | |
|---|---|---|---|
| | | 1974 | 1975 |
| Region 5, California: | | | |
| Inia 66 and 66R[2] | Hard Red Spring | 22. 7 | 30. 6 |
| Anza[2] | do | 21. 1 | 40. 7 |
| Pitic 62[2] | do | 16. 8 | -------- |
| Cajeme[2] | do | 13. 3 | 13. 5 |
| Siete Cerros 66[2] | White | 7. 8 | -------- |
| Blue Bird 2[2] | Hard Red Spring | 4. 1 | 1. 3 |
| Ramona 50 | White | 2. 2 | 1. 9 |

[1] Only those varieties are shown that occupy greater than 2 percent of the total State wheat acreage in either year.

[2] Semidwarf plant height (*91*).

[3] No survey for 1975.

[4] For Washington, White wheat includes Club wheat.

Source: USDA-ESCS data.

have been developed and used by farmers. For example, the Sturdy variety was the first short-stature Hard Red Winter wheat recommended for Texas. It was released in 1966 (*4*) and by 1974 was the leading variety in that State, grown on 15.9 percent of the total acreage (USDA-ESCS data). TAM W-101, released in 1971 (*83*) is also highly productive under intensive irrigation and fertility management. Thus, the potential exists for even higher future irrigated wheat yield levels in the southern Great Plains.

The discussion on semidwarf wheats does not infer that significant improvements have been confined to these varieties. Certainly increased varietal productivity has been partly responsible for the upward yield trend in all wheat-growing regions (fig. 5). Most of the wheats grown in the United States are located in the semiarid Great Plains; hence, weather plays a major role in holding down yields regardless of potential productivity.

Much of the effort in wheat breeding in the Great Plains is directed toward resistance to pests, such as plant diseases and insects. For example, varietal resistance to leaf rust in wheat is highly transitory, and a continuing breeding effort is required to maintain varieties with resistance to new physiologic forms of this disease (*100*). Most wheat-breeding programs strive to reduce plant height and obtain greater straw strength to increase lodging resistance. Even with conventional varieties, developing moderately short wheats with good lodging resistance for semiarid dryland conditions has been possible (*100*).

### Yield Stability

Wheat variety performance data for North Dakota were used to assess the impact of higher yielding varieties on yield stability (table 6). For Hard Red Spring wheats the newer Selkirk variety increased average yields by 2.6 bushels per acre over the older Thatcher variety for the 89 location years analyzed. For Durum wheats, the newer Wells variety increased average yields by 8.2 bushels per acre over the older Mindum variety for 96 location years. In both cases the standard deviation of yields tended to increase with the new higher yielding varieties, but the coefficient of variation declined indicating greater yield stability. However, additional analyses for other varieties under farm conditions are needed before concluding that the higher yielding varieties have reduced relative yield variability over time.

## Wheat Class Productivity

Closely associated with wheat varietal productivity is the subject of wheat class productivity. However, whereas wheat varieties reflect genetic factors, wheat class reflects market factors such as protein content, gluten content, baking time, and other factors affecting milling and baking use. Different wheat classes contain varieties with varying yield potentials. However, changes in market conditions or the development of a new variety with different yield potential can alter farmers' preferences for a wheat class.

The growing of Hard Red Winter wheat has been moving northward in the Great Plains for many years primarily due to the development of more highly productive and winter-hardy HRW varieties. Spring wheats were widely grown in Kansas up to 1880, and spring wheat predominated in Nebraska until after 1900 (*99*). A good illustration of the northward movement of HRW wheat into South Dakota and Montana is shown in figure 15. Since 1950 harvested acreages of HRW wheat have increased from about 10 to 30 percent of the total harvested acreage in South Dakota and from about one-fourth to nearly one-half of Montana. Since HRW wheat has a higher average yield per acre than HRS wheat, the impact on production over time has been even greater. During the 5-year period 1970-74, HRW wheat contributed about one-third and two-thirds of the production in South Dakota and Montana, respectively.

TABLE 6.—*Yield, standard deviation, and coefficient of variation of 2 Hard Red Spring and 2 Durum varieties released at different times and tested in North Dakota*

| Station | Years | Hard Red Spring | | | | | |
|---|---|---|---|---|---|---|---|
| | | Thatcher [1] | | | Selkirk [2] | | |
| | | Yield | Standard deviation | Coefficient of variation | Yield | Standard deviation | Coefficient of variation |
| | | *Bushels per acre* | *Bushels per acre* | *Percent* | *Bushels per acre* | *Bushels per acre* | *Percent* |
| Langdon | 1954–68 | 37. 0 | 12. 0 | 32 | 44. 0 | 10. 0 | 22 |
| Minot | 1953–67 | 31. 0 | 13. 0 | 42 | 33. 4 | 9. 4 | 28 |
| Carrington | 1962–69 | 27. 0 | 8. 0 | 29 | 31. 1 | 7. 4 | 24 |
| Mandan | 1953–68 | 27. 2 | 12. 0 | 43 | 31. 0 | 11. 3 | 36 |
| Dickinson | 1953–69 | 22. 4 | 10. 2 | 46 | 22. 8 | 9. 8 | 43 |
| Williston | 1953–70 | 22. 4 | 7. 1 | 32 | 23. 0 | 9. 0 | 38 |
| Combined location-years | 89 | 27. 6 | 11. 5 | 42 | 30. 2 | 11. 8 | 39 |

| | | Durum | | | | | |
|---|---|---|---|---|---|---|---|
| | | Mindum [3] | | | Wells [4] | | |
| | | Yield | Standard deviation | Coefficient of variation | Yield | Standard deviation | Coefficient of variation |
| | | *Bushels per acre* | *Bushels per acre* | *Percent* | *Bushels per acre* | *Bushels per acre* | *Percent* |
| Fargo | 1957–73 | 29. 0 | 12. 3 | 42 | 47. 0 | 9. 3 | 20 |
| Langdon | 1957–71 | 43. 0 | 12. 8 | 30 | 53. 2 | 13. 5 | 25 |
| Minot | 1958–70 | 35. 3 | 12. 3 | 35 | 40. 8 | 12. 5 | 31 |
| Carrington | 1962–70 | 24. 0 | 12. 1 | 51 | 37. 0 | 11. 0 | 30 |
| Mandan | 1958–69 | 26. 2 | 13. 0 | 49 | 32. 0 | 15. 5 | 49 |
| Dickinson | 1958–69 | 24. 6 | 9. 6 | 39 | 27. 2 | 10. 4 | 38 |
| Williston | 1958–75 | 22. 0 | 7. 3 | 33 | 23. 6 | 9. 1 | 39 |
| Combined location-years | 96 | 29. 4 | 13. 1 | 45 | 37. 6 | 15. 3 | 41 |

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[1] Thatcher was released in 1934 and, for census years, reached a peak in 1939 as 41.6 percent of the total North Dakota wheat acreage (*25*).

[2] Selkirk was released in 1955 and, for census years, reached a peak in 1959 as 57.1 percent of the total North Dakota wheat acreage (*93*).

[3] Mindum was released in 1917 and, for census years, reached a peak in 1954 as 12.9 percent of the total North Dakota wheat acreage (*92*).

[4] Wells was released in 1960 and, for census years, reached a peak in 1964 as 26.3 percent of the total North Dakota wheat acreage (*93*).

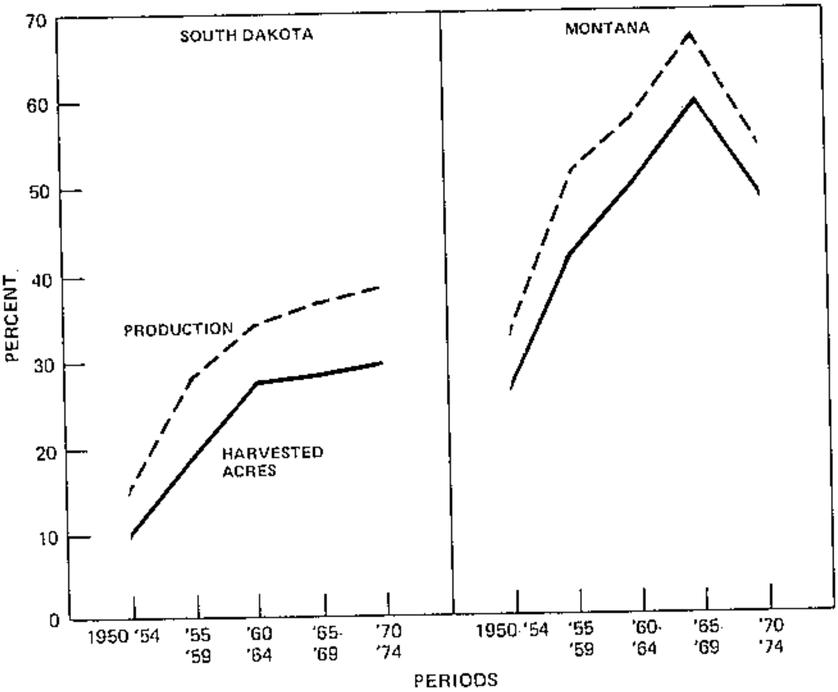

FIGURE 15.—Hard Red Winter wheat harvested acres and production as a percentage of all wheat harvested acreage and production averages by 5-year intervals, South Dakota and Montana, 1950–74. (USDA-ESCS data.)

The trend from HRS to HRW wheat also has an impact on cropping sequences. The short time interval between harvest and wheat seeding (for soil water storage) in these northern Great Plains States of South Dakota and Montana necessitates that summer fallow precede HRW wheat. As a consequence, in those Crop Reporting Districts of South Dakota where large acreages of HRW wheat are grown, that is, the six western CRD's (fig. 6), more than three-fourths of the HRW wheat was grown on fallow as late as 1974 (fig. 8) after acreage restrictions were largely eliminated. In contrast, significant shifts occurred between 1970 and 1974 in the percentage of HRS wheat planted on summer fallow and continuous cropping (fig. 8). In eastern and central South Dakota, usually less than one-fourth of the HRW wheat was grown on summer fallow by 1974. Farther west in Montana where rainfall is less than in South Dakota, both HRW and HRS were grown primarily on summer fallow in 1974 (fig. 8). These changes in wheat class productivity and cropping sequences and their effects on yields would indicate that monitoring with time is necessary if accurate wheat production estimates from a given geographical region are to be made.

Even when two wheat classes have the same growing season, such as Hard Red Spring and Durum wheats, which are spring-seeded, there may be significant shifts depending, among other factors, on the price and market demand for each wheat class. A good example of the change occurring between two spring classes is shown in figure 16. During the latter fifties and early sixties, the proportions of Durum wheat in North Dakota increased from about 10 to 35 percent; afterward the proportion in Durum remained relatively high to 1975. During the sixties, Durum wheat accounted for a greater percentage of the production than of the harvested acreages (fig. 16). This difference was due to the release of superior Durum varieties (primarily the Wells variety), which yielded more than HRS wheat varieties (*1*). By the early seventies harvested acreage and production of Durum wheat were again nearly equal as more productive HRS varieties were adopted.

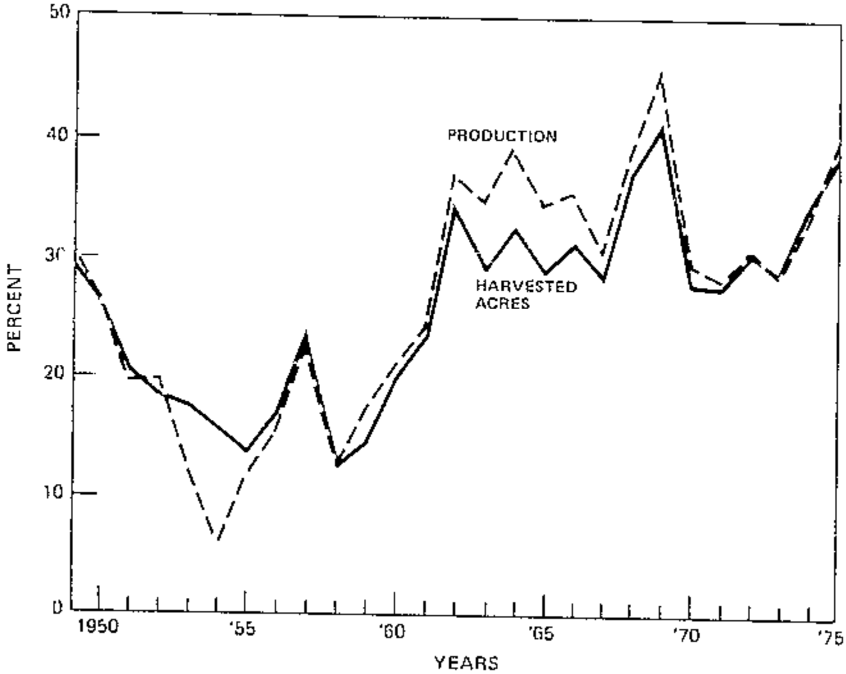

FIGURE 16.—Durum wheat harvested acres and production as a percentage of all wheat harvested acres and production in North Dakota, 1949-75. (USDA-ESCS data.)

Another example of shifts between wheat classes occurred in the SRW wheat States of Illinois and Missouri. In the midsixties, SRW wheat occupied about 40 percent of acreage in these States: by 1974, SRW wheat occupied about 80 percent (USDA-ESCS data). In addition to the strong export demand for SRW wheat, a significant factor causing this shift was undoubtedly the development of higher yielding SRW wheat varieties, such as Arthur and Arthur 71, which by 1974 occupied over 60 percent of the acreages in Illinois and Missouri (USDA-ESCS data).

## Fertilizer

### Use on Wheat

Figure 17 shows the proportion of wheat acreage receiving nitrogen (N) and phosphorus (P) fertilizer since 1959 for the 1975 leading wheat States—Kansas, North Dakota, Ohio, Washington—in four of the five wheat-growing regions. Figure 18 shows the rate of applied N and P per acre receiving fertilizer for these same States. A data series showing fertilizer usage on wheat was not available for the Southwest Region. To construct a trend with time, with one excep-

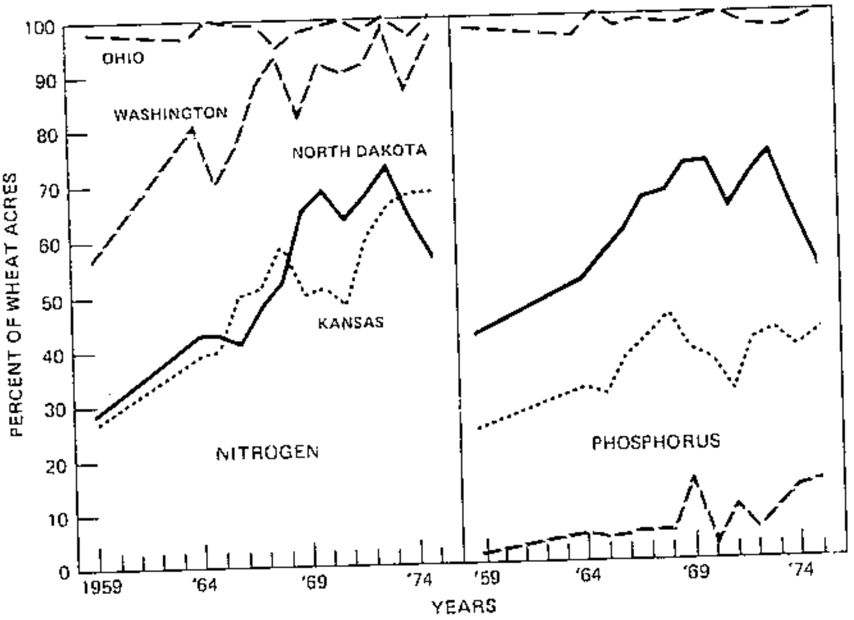

FIGURE 17.—Percentage of wheat acres receiving nitrogen (N) and phosphorus (P) fertilizer in Kansas, North Dakota, Ohio, and Washington, 1959-75. (USDA-ESCS data.)

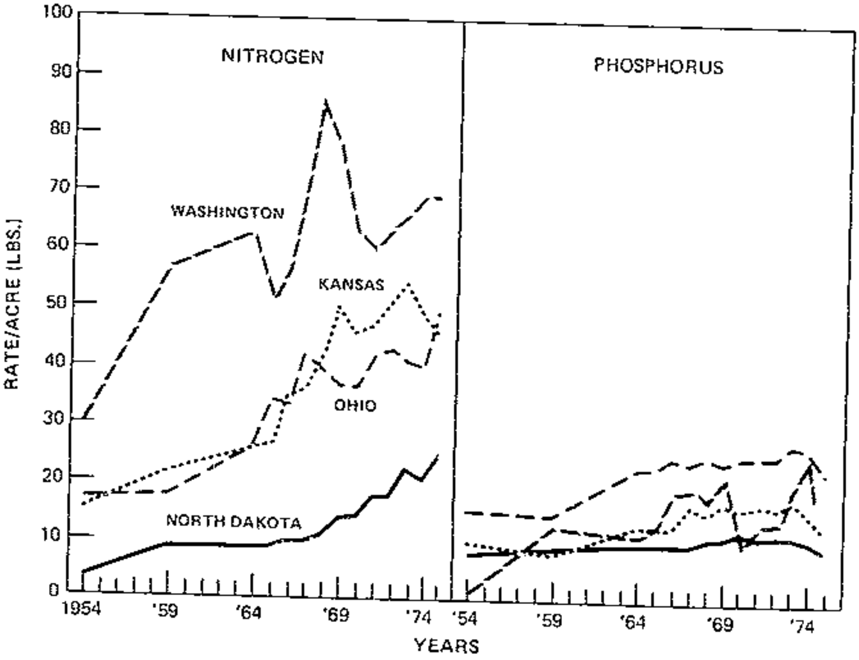

FIGURE 18.—Rate of applied nitrogen (N) and of applied phosphorus (P) per acre of wheat receiving fertilizer in Kansas, North Dakota, Ohio, and Washington, 1954–75. (USDA–ESCS data.)

tion, census data were used for 1954 (*109*) and 1959 (*57*) and annual USDA–ESCS survey data were used for 1964–75 (*106*, *107*, *108*, *112*). The exception was in 1964, where wheat receiving the N and P rate per acre for the State of Washington was obtained from the census data (*55*) rather than the annual survey data (*107*). Since the percentage of wheat acreages receiving N and P were not reported separately in 1954 (*109*), the time series for these data begins with 1959 (fig. 17).

Virtually all of the SRW wheat grown in Ohio received both N and P each year since 1959 (fig. 17). In addition, almost all wheat in the other important SRW wheat States of Illinois, Indiana, and Missouri (table 1) received N and P each year. N use on wheat in Washington State increased from about one-half of the wheat receiving N fertilizer in 1959 to nearly 90 percent for the past 9 years (fig. 17). Conversely, very little of the wheat grown in Washington receives P. N and P use on wheat in Oregon is similar to that in Washington.

The proportion of wheat receiving N in Kansas and North Dakota is comparable and, since 1959, has increased from about one-third to two-thirds of the acreage (fig. 17). P use, however, is much greater in North Dakota than in Kansas. In North Dakota, wheat acreage fertilized usually received both N and P, whereas in Kansas, about 25 percent more of the wheat acreage received N than received P. Other important wheat States also recorded significant increases in the proportion of wheat acreage receiving fertilizer. For example, only 6 percent of the wheat acreage in both South Dakota and Montana received N as recently as 1964. Since 1971, about one-third received N. HRS wheat in more humid Minnesota is fertilized more frequently than in adjacent North and South Dakota. In Minnesota about 85 to 90 percent of the wheat acreage received both N and P each year since 1969.

The rate of N and P per acre for those acreages receiving fertilizer has increased with time in those States shown in figure 18. The N rate per acre was greatest in Washington. Comparable N rates were also used for wheat in Oregon. N rates per acre fertilized were comparable in Kansas and Ohio, increasing from about 20 pounds N per acre in the fifties up to almost 50 pounds in 1975. For those States shown in figure 18, rates per acre fertilized were lowest in North Dakota with less than 25 pounds N per acre applied in 1975. Comparable N rates were used in South Dakota: whereas in Minnesota where precipitation is normally higher, N rates fertilizer exceeded 50 pounds per acre from 1972 through 1975. Some of the highest N rates on wheat were recorded in Texas: more than 100 pounds of N per acre fertilizer were reported in 1971 and 1973. In Texas, N fertilizer is applied to wheat to increase vegetative production for grazing, particularly under irrigation (*5*) and to increase grain production.

The rate of applied P per acre in Kansas, Ohio, North Dakota, and Washington is similar and has changed little during the past 15 years (fig. 18). However, P rate in the SRW wheat State of Ohio was somewhat greater than for the other three States.

Potassium (K) fertilizer is applied to wheat primarily in the SRW wheat States of Region 3. About 85 percent of the wheat acreages in these States received K at an average rate of 45 pounds K per acre in 1974 (*108*) and in 1975 (*112*). In the Great Plains and Northwest wheat States, K is normally applied to less than 10 percent of the wheat acreages.

There are many factors involved in the response of wheat to applied fertilizer. Because of complicated interrelationships of these factors, the response of wheat to applied fertilizer will be discussed by wheat-growing regions. Within a given wheat-growing region, some of the more important factors are climate (including irrigation), soils, cropping sequences, and varieties. In discussing the use of fertilizer in the several wheat-growing regions, several basic principles applicable to all regions can be enumerated.

First, any time the available water supply for wheat is sufficiently great (either from rainfall or irrigation) for a high potential yield level, the likelihood of obtaining a fertilizer response is greater.

Second, wheat is best adapted to medium- to fine-textured soils (*70*). Wheat, however, is often successfully grown on coarse-textured soils. When grown on coarse-textured soils, the likelihood of a nutrient deficiency is greater than on medium- or fine-textured soils.

Third, cropping sequence plays a major role in response of wheat to fertilizer. Where summer fallow precedes wheat, organic nitrogen is mineralized to plant available nitrate nitrogen. As a consequence, for a given soil, wheat following summer fallow is much less likely to respond to applied N than after continuous cropping. When wheat follows a crop that produces a large quantity of carbonaceous top and root growth (such as sorghum), wheat is much more likely to respond to applied N.

Fourth, applied N and P behave differently when applied to soils. If sufficient water is available for adequate growth, moderate rates of applied N normally are used by the plant during the year of application. Only a small portion of the applied P, on the other hand, is available for plant growth each year and, after application, may be utilized over a period of several years. Quantitatively, the phosphorus requirements for wheat are not great in relation to other crops such as legumes. As a consequence, P is often conceptually regarded as being either adequate or inadequate in contrast to applied N where rates of application of N are often important. There is often an interaction between applied N and P. For example, when either N or P is applied alone, the yield response may be small; when applied together, the response may be great. At lower yield levels (as with no applied N or with small amounts of applied N), there may be no response to applied P. Only after yield levels are increased by higher rates of applied N, will wheat respond to applied P.

In addition to the aforementioned factors, which are not necessarily time related, at least two major time-related factors can be enumerated that control the response of wheat to applied fertilizer. First, there is a tendency for soil fertility to decrease with time as a result of the normal decrease in organic matter associated with the breaking of perennial grassland sod and the initiation of cultivated agriculture as well as nutrient losses associated with water and wind erosion. Second, wheat yield potential increases with time due to such things as higher yielding varieties, better weed control, and increased water conservation. Consequently, as soil fertility decreases and wheat yield potential increases with time, the need for and response to applied fertilizer are greater.

*Region 1, the Central and Southern Great Plains States.*—In Region 1, spatial and annual variations in climate, particularly rainfall, but also temperature, complicate the prediction of wheat response to fertilizer. Under dryland conditions in the western part of Region 1, where wheat is most often grown after summer fallow (fig. 8) on medium- to fine-textured soils, wheat very seldom responds to applied fertilizer. For example, at Bushland, Tex., (CRD 1–N) dryland wheat did not respond to applied N nor to P after summer fallow or on continuous wheat on a silty clay loam soil (*30*). At Colby in northwestern Kansas, applied N had no effect on wheat yields either on wheat after summer fallow or on continuous wheat on a silt loam soil (*47*). In eastern Colorado on a loam soil, yields of wheat were increased somewhat by applied N on continuous wheat but were decreased by the application of N after summer fallow (*18*).

Of 77 Nebraska field trials conducted in the fifties, where N was applied to wheat after summer fallow, the average increase with 20 to 40 pounds of applied N per acre was about 2 bushels (*77*). However, either no response or a negative response was obtained in 48 of the 77 trials. Fertilizer trials conducted in the generally wetter sixties showed 40 pounds of applied N per acre increased yields 5 to 7 bushels in west south central and western Nebraska (*29*). Very often, wheat response to applied N in the predominately summer fallow area of the western part of Region 1 is confined to those fields where wheat is grown on coarse-textured soils. At Alliance in northwestern Nebraska, 20 to 40 pounds of N per acre after summer fallow on a very fine sandy loam soil increased wheat yields 2 to 4 bushels per acre (*34*). Very few instances are citable where wheat responds significantly to applied P in the western parts of Region 1.

However, wheat grown under irrigation in the western part of Region 1 has an entirely different response to fertilizer. With the wheat varieties used in the fifties and early sixties, irrigated wheat on a clay loam soil receiving 30 to 60 pounds of N per acre at Garden City, Kans., yielded only 6 bushels per acre more than soil without applied N (*74*). At Bushland, Tex., (CRD 1-N) on a silty clay loam soil, irrigated wheat yields in the fifties were increased an average of 17 bushels per acre with 80 to 120 pounds of applied N (*60*). In Texas (CRD 1–N) during the period from 1957 through 1961, 45 fertilizer trials on irrigated wheat produced average wheat yields on clay loam soils of about 34 bushels per acre without applied N and 47 bushels with 80 pounds of applied N (*82*). On fine sandy loam soils, both applied N and P were required: as compared with no applied N or P, 40 pounds N per acre and 35 pounds of applied P per acre combined increased average yields by 23 bushels per acre (*82*).

In the fifties and early sixties, irrigated wheat almost always lodged when high rates of N were applied (*60, 74*). Maximum irrigated wheat yields usually ranged from 40 to 80 bushels per acre. Since the sixties, however, short-stature wheats resistant to lodging when subjected to high levels of applied N (often in combination with applied P) and irrigation water have been developed. Consequently, irrigated wheat yields ranging from 80 to 90 bushels per acre were reported in 1973 in the western part of Region 1 (*84*).

In the central and eastern parts of Region 1 where irrigated wheat is not important (fig. 11), the likelihood of a response to applied fertilizer under the generally wetter dryland conditions becomes greater. However, weather is still a major factor in determining fertilizer response. For example, in the 53 western Oklahoma experiments where P was applied, wheat yields on soils low in available P were increased by 3 to 4 bushels per acre (*31*). However, combining measurements of soil moisture at seeding, date of seeding, and soil P test from 44 of the experiments failed to produce a satisfactory regression equation to predict yield response (*31*).

An analysis of N response in western Oklahoma from 104 field fertilizer experiments showed 40 pounds of applied N per acre increased wheat yields about 4 bushels (*32*). However, little success was obtained in relating N response to measured soil moisture or weather variables (*32*). In Kansas (*115*), applied N was significantly related to yield; but applied N contributed less to predictive equations than did measurements of soil moisture at seeding, precipitation, variety, and seeding rate. Even though it is difficult to statistically relate weather to fertilizer response, weather still plays an important role. For example, during the drought years of 1950–57, at Woodward, Okla., applied N did not affect wheat yields (*68*). During the wet years of 1958–63, however, 40 pounds of applied N each year increased wheat yields by about 5 bushels (*68*).

In the central and eastern parts of Region 1, wheat more likely responds to both applied N and P on coarse-textured soils than on fine-textured soils. At Chillicothe, Tex., in CRD 2, 3-year average wheat yields on a fine sandy loam soil were increased by 8 bushels per acre with the combination of 30 pounds of applied N per acre and 13 pounds of applied P per acre (*73*). In the more humid part of Texas, wheat responds to fertilizer also on fine-textured soils. For example, on a clay soil at Denton, Tex., in CRD 4, yields of continuous wheat were increased from 25 bushels without fertilizer to 36 bushels with 40 pounds of N per acre and 17 pounds of P per acre combined (*95*). Without fertilizer, wheat yields after grain sorghum were only 16 bushels per acre whereas with 40 pounds N and 17 pounds P wheat yields after grain sorghum were 30 bushels per acre (*95*).

In Region 1, where precipitation increases from west to east, more wheat is grown on continuous cropping than after summer fallow in eastern sections of the States (fig. 8). There is, therefore, a greater likelihood of response to applied N. In the east, because more rainfall increases potential wheat yields and in some instances inherent soil fertility may be lower than farther west, there is more likelihood of a response to applied P, particularly if adequate nitrogen is available either originally in the soil or as applied N.

Over the past quarter century, research workers in Nebraska have conducted some of the more extensive field trials with fertilizer on wheat in Region 1 (*20, 77, 78*). A 1969 publication (*20*) summarizes fertilizer trials with applied N and P conducted in central and eastern Nebraska on wheat during the sixties. The results are as follows:

| *Area* | *Number of trials* | *Cropping sequence* | *Check yield* | *Yield increase* | |
|---|---|---|---|---|---|
| | | | | *40N* | *40N+10P* |
| | | | *Bushels per acre* | | |
| Central | 11 | After summer fallow. | 30 | 2 | 1 |
| East South Central | 20 | Continuous | 22 | 4 | 7 |
| Southeast | 13 | do. | 32 | 7 | 10 |

In east south central and southeastern Nebraska, a good response was obtained on continuous cropping with applied N and P combined. In the central part of the State, factors other than soil fertility appeared to be limiting yields (*20*). In this area (largely CRD 5 of Nebraska), response to applied N is closely correlated with the amount of soil water at seeding (*89*) and long-term studies have shown that wheat responds significantly to applied N on continuous cropping but not after summer fallow (*102*). Even with applied N, continuous wheat yields were only about one-third as great as after summer fallow (*102*).

*Region 2, the Northern Great Plains States.*—In this Hard Red Spring, Durum, and Hard Red Winter wheat-growing region, wheat usually responds to applied P regardless of cropping sequences or soils and from the drier western part to the wetter eastern part of Region 2. In some instances, however, wheat may not respond to applied P under very dry conditions as at Huntley, Mont., in CRD 8 where an 8-year study with HRS wheat and a 3-year study with HRW wheat showed little or no response to applied N, P, or N-P combined (*21*). In other instances, as at Brookings, S. Dak., in CRD 6, application of both N and P was necessary to obtain a wheat yield response (*87*).

In Montana, which is the generally drier western part of Region 2 and where most of the HRW and HRS wheats are grown after summer fallow (fig. 8), both HRS and HRW wheats usually respond to applied P. In the fifties, northeastern Montana (CRD 3) HRS wheat over a period of 4 years at a total of 13 experimental sites yielded an average of 2 bushels more with the application of 7 pounds of P per acre than without applied P (*86*). The response to applied P was influenced by available soil P, the amount of soil moisture at seeding, and seasonal precipitation (*86*). In northeastern Montana in the good wheat year of 1968, HRS wheat yields increased from 30 bushels per acre with no applied P to 38 bushels with 20 pounds of applied P per acre (*12*). The beneficial effects of applied fertilizer were expressed through adventitious roots per plant, tillers per plant, and head-producing tillers (*12*).

Since HRW wheat in Montana (fig. 7) usually yields more, has a better root system, and has a longer growing period than HRS (*19*), HRW wheat appears more responsive to applied fertilizer than the HRS wheat. The soil organic matter content in Montana has decreased to the point that responses to applied N are now being obtained after summer fallow (*19*). Under the more favorable climatic conditions near Bozeman, Mont., 60 pounds of applied N (blanket application of 15 pounds of applied P per acre) increased HRW wheat yields from 24 bushels per acre with no applied N to 46 bushels with 60 pounds of applied N (*20*)—an increase of 22 bushels per acre. However, HRW wheat yield increases with applied fertilizer are not quite so great, over a range of climatic conditions and sites. For example, experiments in 1970 and 1971 at a total of 18 sites throughout Montana showed that 60 pounds of applied N and 40 pounds of applied P per acre increased average HRW wheat yields by 4 bushels per acre as compared with no applied fertilizer (*101*) In northeastern Montana (CRD3) where HRS wheat is more widely grown than is HRW wheat (fig. 6), HRS wheat after summer fallow responds to applied N in addition to applied P (*12*).

Further east in North Dakota and South Dakota where HRS wheat predominates, both continuous wheat and wheat after summer fallow are important (fig. 8). In these States, wheat responds to applied P, both on continuous cropping and after summer fallow (*8, 10, 23*). Results from 115 trials in North Dakota on HRS wheat after summer fallow showed that 15 to 18 pounds of applied P per acre increased wheat yields almost 5 bushels per acre (*8*). After summer fallow applied N increased HRS wheat yields by more than 1 bushel per acre in only 29 of 115 trials (*8*). When yields were increased, 10 pounds of applied N per acre were usually adequate. (*8*).

On the other hand, applied N is needed for maximum wheat yields on continuous cropping in North Dakota (*10*). In fact where water is adequate, applied N on continuous wheat can largely eliminate the yield advantage of summer fallow (*43*). With continuous wheat, however, the magnitude of the response to applied N is closely correlated with the total water supply (both soil water at seeding and seasonal precipitation). Data from 64 HRS wheat continuous cropping sites in North Dakota over a 3-year period show that growing season precipitation and stored soil water at seeding accounted for 40.3 percent of the yield response to applied N (*10*).

Continuous HRS wheat may exhibit differences with respect to the responses to applied N between years, depending upon the amount and distribution of the water supply during the growing season. In an experiment with continuous HRS wheat in central North Dakota (*15*) over 4 consecutive years on the same site, 0, 30, 60, and 120 pounds of applied N per acre (uniform application of 20 pounds of applied P per acre) produced yield changes as follows: First year, slight yield response to N at lower application rates, none with 120 pounds; second year, slight positive linear yield response with all N rates; third year, decrease in yield with all N rates proportional to the rate of applied N; and fourth year, marked positive yield response to all N rates proportional to the rate of applied N.

When properly fertilized, HRS wheat grown continuously and after summer fallow responded from the drier western part to the wetter eastern part of North Dakota as follows (*6*):

| *Area* | *Yield, bushels per acre* | | | |
|---|---|---|---|---|
| | *Continuous wheat* | | *After summer fallow* | |
| | *Check* | *Fertilized* | *Check* | *Fertilized* |
| West | 16 | 19 | 24 | 30 |
| West-central | 18 | 22 | 26 | 33 |
| East-central | 22 | 29 | 28 | 38 |
| Red River Valley | 28 | 38 | 29 | 41 |

Fertilized continuous wheat yields were increased from 3 to 10 bushels per acre from west to east across the State. Fertilized wheat on summer fallow comparably increased from 6 to 12 bushels per acre across the State. In the Red River Valley, yields on continuous cropping were almost as great as those after summer fallow. The lack of a large yield response to summer fallow in eastern North Dakota is largely responsible for the marked decrease in the use of summer fallow between 1970 and 1974 (fig. 8).

Semidwarf HRS wheats subjected to high rates of applied N and irrigation have not been superior to the so-called standard wheat varieties under North Dakota conditions. Under irrigated conditions at Carrington, N. Dak., rates of up to 200 pounds of N per acre applied to four semidwarf varieties and Waldron (standard variety) showed that the semidwarfs did not outperform the standard variety (*7*). Near maximum yields on both irrigation and dryland were obtained with only 50 pounds of applied N per acre (*7*).

Under Minnesota dryland conditions, the semidwarf variety Era responded well to applied N. During the period from 1971 through 1975, 40 to 50 pounds of applied N per acre for 3 years at Crookston, 1 year at Staples, and 4 years at Waseca resulted in average Era wheat yields 12 bushels per acre greater than without applied N.[10] In some instances Era responded well to even higher rates of applied N.

*Region 3, the Midwest and Eastern States.*—Almost all of the Soft Red Winter and White wheats grown in Region 3 receives applied N, P, and K fertilizer (*112*). Because Region 3 receives more rainfall than other wheat areas further west in the United States, there is likelihood of a greater wheat yield response. Rainfall is also less variable from year to year than in the drier areas further west (*51*). The response of wheat to fertilizer is also complicated by crop rotations, that is, wheat often utilizes the residual fertilizer applied to other crops in the rotation (*99*).

Of the wheat varieties grown in the fifties and early sixties, wheat yield responses commonly ranged from 5 to 20 bushels per acre with 40 to 80 pounds of applied N per acre (*121*). The Arthur and Arthur 71 varieties, now widely grown in Region 3 (table 5) with stiffer straw than the earlier popular varieties, are less likely to lodge with high fertility levels. With high rates of applied N (*63*), however, varieties with even stiffer straw are needed to decrease lodging. Apparently, applied fertilizer in Region 3 has contributed significantly to the upward trend in yields with time (fig. 5).

*Region 4, the Northwest States.*—Wheat yields in this White (includes White Club) and Hard Red Winter wheat-growing region are the highest of any region in the United States (fig. 5), except for Southwestern States where irrigation exerts a major influence on yields. In eastern Washington of Region 4, where average annual precipitation ranges from 18 to 23 inches per year, wheat yields of 100 bushels per acre on dryland are not uncommon (*79*). In this area, research has shown that 2.7 pounds of N are required for each bushel of wheat when maximum yields are attained (100 bushels=270 pounds). Since the

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[10] Minnesota data were provided by W. E. Fenster, Agricultural Extension Service, University of Minnesota, St. Paul, and were obtained by Branch Station personnel of the Minnesota Agricultural Experiment Station.

soil provides 120 to 140 pounds of N per acre for a crop in a 2-year fallow cycle, 130 to 150 pounds of N per acre must be added as fertilizer (*79*). Consequently, the rate of fertilizer N applied per acre in the State of Washington is among the highest of any wheat State in the United States (fig. 18).

The unusually high wheat yields in the wetter eastern part of Washington are due largely to the widespread use of the semidwarf white winter wheats Gaines and Nugaines, which have a high yield potential and do not lodge with high fertility levels (*117*). Precipitation in much of the Northwest occurs primarily during the winter months and is efficiently stored in the soil during a period of low evaporation (*66*). Consequently, the Northwest is among the more efficient wheat areas in the United States in terms of bushels of wheat per inch of precipitation.

In western Oregon with 37 inches of average annual precipitation, 125 pounds of applied N per acre on Nugaines wheat yielded more than 100 bushels per acre (*64*). Under the appropriate climatic conditions, using Gaines and Nugaines varieties, yield increases due to applied N of more than 30 bushels per acre are common (*96*).

Not all of the Northwest is fortunate enough to receive 20 inches or more of annual precipitation primarily during the winter months (as in eastern Washington and northwestern Idaho) and to produce 100 bushels of wheat with appropriate varieties and fertilization. Further west, the Columbia Plateau receives from 9 to 18 inches of annual precipitation primarily during the winter months. Research in the Columbia Plateau has shown that wheat yields may be limited by moisture supply or nutrients supply, or both (*65*). Cropping sequences are also closely related to the precipitation received. Generally, wheat after summer fallow is used with less than 13 inches of annual precipitation; with 13 to 16 inches, the area is transitional; and with over 16 inches, annual cropping of wheat or wheat after peas predominates (*66*). In the drier parts of the Columbia Plateau, HRW wheat is grown more often (*93*) than the W wheat. Even under these drier conditions, however, wheat responds to applied N, with the recommended rate of applied N increasing from west to east as precipitation increases (*67*).

Even with the high wheat yields that are often obtained in the Northwest Wheat Region 4, applied P is usually not needed. Often responses to applied P are obtained only on eroded hilltops and ridges (*79*). On the other hand, sulfur fertilizer is sometimes needed for maximum wheat yields. A wheat yield response to applied sulfur is more likely to occur with spring wheat than with winter wheat and more likely with continuous cropping than with wheat after summer fallow (*66*). Once applied, residual sulfur may be used by several consecutive wheat crops (*88*).

*Region 5, Southwest States.*—The wheat-growing changes that have occurred in this Hard Red Spring, White, and Durum wheat region are so recent that a large volume of fertilizer research data are not yet available. In Region 5, irrigated wheat is quite important, semidwarf wheats predominate (table 5), and yield levels are the highest of all wheat-growing regions in the United States (fig. 5). High rates of applied N are necessary for maximum yields of irrigated wheat in the region. In Arizona, the application of 100 pounds of applied N per acre to semidwarf HRS wheat increased yields from 17 to 31 bushels per acre (compared with no applied N) in three different experiments and produced an average yield of 100 bushels per acre (*41*).

### Yield Stability

To assess the impact of applied fertilizer on the stability of wheat yields, several multiple-site experiments were used to compute standard deviations and coefficient of variation (table 7). Even though within a given year, data for several sites were often averaged and not reported separately, enough data were available in most instances for sample size (*n*) to be greater than 10. In all instances paired data were used to compute the standard deviation and coefficient of variation. Hence, even though climate varied between sites and years, all compared treatments were subjected to the same conditions.

For a given report, the application of either applied N, P, and N-P combined usually had relatively little impact on the standard deviation (table 7). In Oregon, where the largest yield increases of about 20 to 30 bushels per acre were obtained, there was a tendency for the standard deviation to increase with increasing rates of applied N. Similarly, in the greater than 15-inch rainfall area of eastern Washington on continuous cropping, there was an increase in the standard deviation with a yield increase of 18.5 bushels per acre. For instances other than Oregon and Washington, the standard deviations were quite similar over a wide array of conditions and most were fairly close to 10 bushels. However, in those instances where the standard deviations were near 10 bushels, yield increases with applied fertilizer generally ranged from 2 to 6 bushels per acre.

These results indicate that the small yield increases often obtained with the application of fertilizer to wheat have no measurable impact on the absolute yield variations using the standard deviation as a measure. On the other hand, when large yield increases with applied fertilizer of 15 bushels or more are obtained, then there is a tendency for yields to vary more than with the small yield increases. Whether or not wheat yields were increased by N, P, or N–P combined, apparently had no impact on the standard deviation. The relative variation of

TABLE 7.—*Yield, standard deviation, and coefficient of variation of wheat as influenced by different fertilizer treatments in selected multiple site experiments of the Western United States* [1]

| State and cropping conditions | Number of years | Year(s) | Type of data | Fertilizer treatment | | Average yield | Standard deviation | Coefficient of variation | Source |
|---|---|---|---|---|---|---|---|---|---|
| | | | | N | P | | | | |
| | | | | *Pounds per acre* | *Pounds per acre* | *Bushels per acre* | *Bushels per acre* | *Percent* | |
| North Dakota: | | | | | | | | | |
| Dryland, continuous | 1 | 1958 | 24 sites ($n=24$) | 0 | 15 | 26.3 | 11.0 | 42 | (*9*, table 1). |
| | | | | 20 | 15 | 30.4 | 11.6 | 38 | |
| | | | | 40 | 15 | 31.8 | 11.8 | 37 | |
| Dryland, after fallow | 6 | 1955–60 | 129 sites ($n=129$) | 0 | 0 | 26.9 | 10.8 | 40 | (*8*, 2A through 2F) |
| | | | | 0 | [2] 7–9 | 30.6 | 11.0 | 36 | |
| | | | | 0 | 15–18 | 32.0 | 11.8 | 37 | |
| Nebraska: | | | | | | | | | |
| Dryland, as found | 5–7 | 1946–52 | 93 sites ($n=27$) | 0 | 0 | 21.7 | 10.2 | 47 | (*78*, table 4). |
| | | | | 40 | 0 | 26.3 | 11.8 | 45 | |
| | | | | 40 | 13 | 28.0 | 12.0 | 43 | |
| Dryland, continuous (Southeast and East South Central). | 8 | 1961–68 | 33 sites ($n=16$) | 0 | 0 | 27.3 | 9.6 | 35 | (*29*, tables 9, 12, 16, 18, and 25). |
| | | | | 40 | 0 | 32.9 | 10.9 | 33 | |
| | | | | 40 | 10 | 35.8 | 10.7 | 30 | |
| Dryland, after fallow (Central, West South Central, and Western). | 8 | 1960–68 | 58 sites ($n=24$) | 0 | 0 | 29.1 | 9.0 | 31 | Do. |
| | | | | 40 | 0 | 33.5 | 9.4 | 28 | |
| Montana: | | | | | | | | | |
| Dryland, as found (usually after fallow). | 2 | 1970–71 | 18 sites ($n=30$) | 0 | 0 | 34.4 | 10.0 | 29 | (*101*, table 1). |
| | | | | 60 | 40 | 38.4 | 9.2 | 24 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Dryland, after fallow | 3 | 1955–57 | 13 sites ($n=13$) | (3) | 0 | 22. 0 | 10. 3 | 47 | (*86*, table 3.) |
| | | | | (3) | 7 | 24. 0 | 10. 3 | 43 | |
| Washington: | | | | | | | | | |
| Dryland, after fallow (less than 10-inch rainfall area). | 5 | 1953–57 | 24 sites ($n=24$) | 0 | (3) | 21. 1 | 7. 6 | 36 | (*67*, tables 2, 4, 6, 10.) |
| | | | | 20 | (3) | 25. 3 | 6. 3 | 25 | |
| Dryland, after fallow (10 to 15-inch rainfall area). | 5 | 1953–57 | 28 sites ($n=28$) | 0 | (3) | 31. 4 | 9. 4 | 30 | Do. |
| | | | | 20–30 | (3) | 37. 5 | 9. 8 | 26 | |
| Dryland, after fallow (more than 15-inch rainfall area). | 5 | 1953–57 | 14 sites ($n=14$) | 0 | (3) | 40. 0 | 10. 8 | 27 | Do. |
| | | | | 30–60 | (3) | 50. 9 | 10. 7 | 21 | |
| Dryland, continuous (more than 15-inch rainfall area). | 4 | 1953–56 | 29 sites ($n=29$) | 0 | (3) | 26. 2 | 11. 3 | 43 | Do. |
| | | | | 40–80 | (3) | 44. 7 | 14. 3 | 32 | |
| Oregon: | | | | | | | | | |
| Dryland, as found | 3 | 1967–69 | Gaines and Nugaines varieties 19 sites ($n=19$). | 0 | (3) | 42. 4 | 17. 4 | 41 | (*96*, table 8.) |
| | | | | 75–100 | (3) | 74. 3 | 18. 6 | 25 | |
| | | | | 125–150 | (3) | 76. 1 | 18. 3 | 24 | |
| | | | Druchamp variety 11 sites ($n=11$) | 0 | (3) | 43. 5 | 19. 1 | 44 | |
| | | | | 75–100 | (3) | 66. 1 | 25. 1 | 38 | |
| | | | | 125–150 | (3) | 70. 9 | 26. 3 | 37 | |

TABLE 7.—*Yield, standard deviation, and coefficient of variation of wheat as influenced by different fertilizer treatments in selected multiple site experiments of the Western United States* [1]—Continued

| State and cropping conditions | Number of years | Year(s) | Type of data | Fertilizer treatment |  | Average yield | Standard deviation | Coefficient of variation | Source |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | N | P |  |  |  |  |
|  |  |  |  | *Pounds per acre* | *Pounds per acre* | *Bushels per acre* | *Bushels per acre* | *Percent* |  |
| Texas: |  |  |  |  |  |  |  |  |  |
| Irrigated | 4-5 | 1957-61 | 45 trials ($n=9$) | 0 | (3) | 34.6 | 10.0 | 29 | (*82*, tables 1 and 2.) |
|  |  |  |  | 40 | (3) | 50.2 | 12.0 | 24 |  |
|  |  |  |  | 80 | (3) | 55.0 | 12.1 | 22 |  |

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[1] Some publications included fertilizer rates higher than shown or treatments that resulted in a small yield response. In this table only those treatments were used that (for the first increment) gave an average positive response of at least 2 bushels over the check treatment and (for additional increments) at least 1 bushel over the previous increment of fertilizer.

[2] Range of fertilizer application rates.

[3] Fertilizer applied but held constant across the variable application of the other fertilizer element.

wheat yields, using the coefficient of variation as a measure, decreased in all instances when fertilizer increased yields (table 7).

### Fertilizer Data Limitations

Because of the many factors affecting the response of wheat to applied fertilizer, use of State-level fertilizer data for predicting wheat yields is limited. Approaches have been developed for estimating average crop yield response to fertilizer over large geographical areas (*56*). Where soils and climate vary widely, regressing a straight average of fertilizer applied per acre against average State wheat yields is likely to give biased regression coefficients. Within a given State, more detailed data are needed. For example, within North Dakota a 1971 survey showed that the rate of N applied by farmers was about twice as great on continuous cropping as after summer fallow (*50*). The rate of applied N increased from west to east as precipitation increased, and in the eastern part of the State application rates were at least three times as great as in the west (*50*).

In Texas, where high rates of applied N are used on wheat, most of the fertilizer is used either in the eastern subhumid part or in the semiarid western part under irrigation. Most of the wheat grown under semiarid dryland conditions in the State does not respond greatly to applied N.

Information now available on fertilizer applied to wheat in each State has some value. However, survey data by subregions within a State and for irrigation or dryland, and continuous wheat or after summer fallow would increase the yield predictive usefulness of the data by severalfold.

## Pesticides

### Use on Wheat

Of the pesticides, only herbicides and insecticides are used to any great extent in wheat growing (table 8). Fungicides, nematocides, and other pesticides are used on more intensively cultivated crops than wheat (*2*). In 1971, 41 percent of the wheat acreages in the United States were treated with herbicides. Herbicides were used on about two-thirds of the wheat acreages in the Mountain Region, the Lake States, and the Pacific States; about one-half in the Northern Plains; and almost none in the Southern Plains and Corn Belt (table 8). Insecticides were used on 7 percent of the wheat acreages in the United States with most being used in the Southern Plains (table 8).

Herbicides are the most extensively used for continuous cropping. In 1971 (*2*), only 2 percent of the summer fallow acreages preparatory to wheat seeding were treated with herbicides. The necessity for herbi-

TABLE 8.—*Use of herbicides and insecticides on wheat in selected farm production regions and the United States in 1971*

| Region and State | Wheat acres | Wheat acres receiving— | |
|---|---|---|---|
| | | Herbicides | Insecticides |
| | *Thousands* | *Percent* | *Percent* |
| Southern Plains: Oklahoma, Texas | 8, 502 | 3 | 35 |
| Northern Plains: North Dakota, South Dakota, Nebraska, Kansas | 23, 846 | 48 | 1 |
| Mountain: Montana, Idaho, Wyoming, Nevada, Utah, Colorado, Arizona, New Mexico | 8, 954 | 68 | 1 |
| Corn Belt: Ohio, Illinois, Indiana, Missouri, Iowa | 3, 688 | (1) | ---------- |
| Lake States: Minnesota, Wisconsin, Michigan | 2, 146 | 71 | ---------- |
| Pacific: Washington, Oregon, California | 3, 835 | 67 | 7 |
| United States | 53, 810 | 41 | 7 |

[1] Less than 0.5 percent.

Source: *Farmers' Use of Pesticides in 1971—Extent of Crop Use (2).*

cide treatment within the growing wheat crop may also be influenced by winter or spring wheat growth habit.

In the Central and Southern Great Plains HRW wheat (Region 1), often weeds can be controlled mechanically by tillage before seeding. In addition, the once well-established HRW wheat is a good competitor with weeds.

On the other hand, in the Northern Great Plains States, particularly where HRS and Durum wheats are grown in continuous cropping rotations, there are limited possibilities for mechanical weed control because the soil is either too dry or cold for significant weed growth during the noncropped period. Undisturbed standing stubble is left from harvest to freezeup. In the spring, wheat is seeded at or immediately after seedbed preparation. Because of their shorter growing season and less extensive root system, the HRS and Durum wheat generally are not as competitive with weeds as the HRW wheat. In the Northern Plains of the United States and in Canada, the competitive efficiency of spring wheat with weeds was less than that for barley or rye but greater than for oats or flax (*81*). Consequently, some of the most extensive use of herbicides on wheat within the United States has been recorded in Region 2. County surveys conducted in the mid-sixties primarily in the eastern two-thirds of North Dakota, northern South Dakota, and in the Red River Valley of Minnesota showed that 75 percent and 86 percent of the wheat acreages were treated with herbicides in 1964 and 1966, respectively (*28*).

The use of herbicides for weed control in growing wheat is mainly for the control of broadleaf annuals. Noxious weeds, usually localized, reduce wheat yields as they would any other crop. Grassy weeds also reduce wheat yields in certain areas; for example, downy brome (*Bromus tectorum*) in western Nebraska (*23*) and Washington, Oregon, and Idaho (*98*) and wild oat (*Avena fatua*) in the Dakotas (*11*). Totally successful herbicides for grassy weed control are still under development.

In 1971, 11 to 17 percent of the farmers in the eastern third of North Dakota used herbicides for wild oat control (*50*). The broadleaf annuals in growing wheat are controlled on an extensive scale primarily by use of 2,4-D and MCPA (*76*). Of the two, 2,4-D is by far the most widely used on wheat (*28*). MCPA is used more on oats and flax and to a lesser extent on wheat (*28*).

Since the discovery of 2,4-D in 1944, its use has increased rapidly for the control of broadleaf weeds in the growing wheat fields, such as in Region 2 where broadleafs in spring wheat may be a serious problem both from the standpoint of reducing wheat yield and lowering grain quality (*76*). North Dakota data indicate how the use of 2,4-D on Hard Red Spring and Durum wheat has changed with time (fig. 19).

The original data [11] for figure 19 were in terms of all acreages treated with herbicides in North Dakota for the various years indicated. Certain assumptions were, therefore, made in calculating the data for figure 19, which, although not entirely correct, do provide an idea on the use of 2,4-D on wheat with time. First, since 68, 72, and 64 percent of all herbicide-treated acreages in 1969, 1972, and 1974, respectively, were treated with 2,4-D, an average of 68 percent was used to calculate acreage treated with 2,4-D. Second, since 93, 93, and 95 percent of all 2,4-D treated acres was for small grain (wheat, oats, and barley) in 1969, 1972, and 1974, respectively, an average of 94 percent was used to calculate the acreages of wheat treated with 2,4-D.

The use of 2,4-D on wheat in North Dakota (fig. 19) increased rapidly during the fifties. For the past 10 years, at least one-half of all

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[11] MITICH, L. W. SUMMARY OF THE CHEMICAL WEED CONTROL SURVEY. Summaries for the 1969, 1972, and 1974 surveys. Mimeo. in 1970, 1973, and 1975, respectively. North Dakota Agricultural Extension Service, Fargo. (Figure 19 is adapted from these data.)

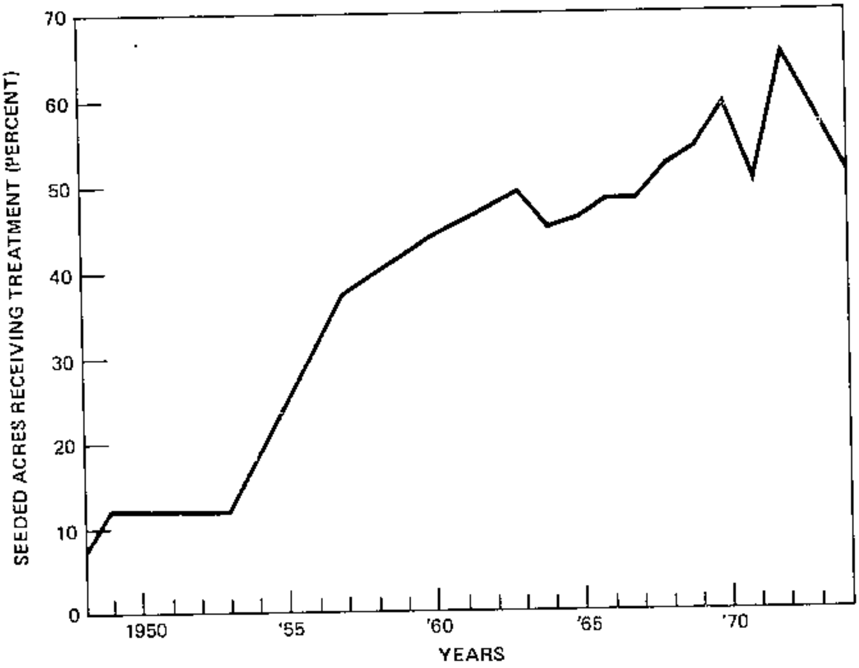

FIGURE 19.—Calculated use of 2,4-D for broadleaf weed control on wheat in North Dakota, 1948–74. (See footnote 11.)

the wheat acreages in that State received 2,4-D for broadleaf weed control in the growing crops. The data in figure 19 are conservative because a greater percentage of wheat than barley or oats receives 2,4-D (*28*). Most of the wheat acreages in North Dakota in need of 2,4-D for broadleaf weed control were treated at least for the past decade. Annual variations in treatment occurred because of the character of the growing season. For example, during a late season, weeds may be effectively controlled by tillage before seeding or good growing conditions may establish a wheat crop that will effectively compete with the weeds. In addition to 2,4-D, several other herbicides were used to control weeds in wheat in North Dakota.[12]

To obtain an idea of the impact of weeds on wheat yields (using Hard Red Spring wheat as an example), one can compare wheat yields from plots with natural, uncontrolled weed populations to wheat yields from plots where weeds are completely eliminated (as with hand

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[12] See footnote 11.

weeding). Availability of data is limited from HRS wheat Region 2 of the United States, but some excellent data are available from adjacent Manitoba, Canada. In Manitoba, with a total of 69 field trials on wheat over a 3-year period (1956–58), spring wheat yields were reduced from 13 to 19 percent (average of 15.6 percent) with natural weed populations as compared with hand-weeded plots (*39*). Compared with hand-weeded plots, naturally weedy wheat plots yielded an average of 4.3 bushels less (*39*).

All weeds are not usually controlled with herbicides. Even though the use of 2,4-D may effectively control broadleaf annual weeds, 2,4-D will not control grassy annuals. Consequently, long-term use of 2,4-D as in the HRS wheat-growing area will bring about a change in the weed population whereby grassy annuals, such as green foxtail (*Setaria viridis*), will increase and become a major competitor of HRS wheat. Consequently, herbicides must also be used to control green foxtail (*24*).

To quantify the overall impact of a herbicide program, such as 2,4-D in North Dakota, on wheat yields is very difficult. However, simultaneously considering the Manitoba results (*39*) where weed-free wheat yielded about 17 percent more than weedy wheat, and the long-term tendency for grassy weeds to increase with the use of 2,4-D, suggests that the intensive herbicide program of the past decade may have increased HRS wheat yields in North Dakota about 10 percent. Within the State, of course, the effectiveness of herbicides in increasing wheat yields would be related to such things as cropping sequences (more weeds on continuous wheat than after summer fallow), climate (more weeds in the wetter eastern part of the State), and other production inputs such as fertilizer and varieties. Applied fertilizer usually reduces the wheat yield loss associated with weeds (*11, 75*).

## Yield Stability

To obtain a concept of the influence of weed control on the stability of wheat yields, selected data are summarized in table 9 where weedy and weed-free wheat yields are compared. By using the standard deviation as a measure of absolute variations, the data suggest that, except where weed control brings about a rather large yield increase (as in the Washington data where yields were increased over 20 bushels by weed control), weed control has a minor impact on absolute yield variations. Relative variations in yields, using the coefficient of variation as a measure, were decreased in all instances with the higher yielding weed-free treatments as compared with those of the weedy treatments.

TABLE 9.—*Yield, standard deviation, and coefficient of variation of wheat as influenced by weed control at selected locations in the United States and Canada*

| Location | Number of years | Plots and treatments | Average yield | Standard deviation | Coefficient variation | Source |
|---|---|---|---|---|---|---|
| | | | *Bushels per acre* | *Bushels per acre* | *Percent* | |
| North Dakota | 3 (1964–66) | 2 locations (n=10) [1]: | | | | |
| | | Weedy [2] | 20.6 | 9.5 | 46 | (*11*), table 1. |
| | | Weed free | 27.6 | 11.6 | 42 | |
| Washington | 3 (1963–65) | 6 locations (n=12): | | | | |
| | | Weedy [3] | 21.8 | 14.2 | 65 | (*95*), table 2. |
| | | Weed-free [4] | 44.3 | 24.4 | 55 | |
| Manitoba, Canada | 2 (1957–58) | 33 locations (n=33): | | | | |
| | | Weedy [5] | 25.1 | 9.8 | 39 | (*40*), tables 1 and 2. |
| | | Weed-free [4] | 28.4 | 9.7 | 34 | |
| Do | 1 (1955) | 6 locations (n=12) [1]: | | | | |
| | | Weedy [5] | 32.9 | 9.9 | 30 | (*75*), table 2. |
| | | Weed-free [4] | 38.5 | 8.5 | 22 | |
| Do | 2 (1969–70) | 6 varieties (n=11): | | | | |
| | | Weedy [5] | 29.9 | 6.9 | 23 | (*24*), table 2. |
| | | Weed-free [4] | 30.8 | 6.8 | 22 | |

[1] Using both fertilized and nonfertilized plot data.

[2] Using treatment of 70 wild oat plants per square yard (except 80 per square yard for the one location tested in 1964).

[3] Plots contained from 65 to 900 downy bromo plants per square yard for different locations and years.

[4] Hand weeded.

[5] Natural weed populations as found.

## Cultural Practices

Cultural practices for wheat may be categorized in terms of: (1) Field operations performed between crops (tillage for weed control and seedbed preparation), and (2) field operations which relate to seeding (method and date of seeding). Little quantitative data are available in either category with respect to cultural practices with time as they relate to wheat yield increases. However, selected examples of data obtained in the Central and Southern Great Plains Region 1 and the Northern Great Plains Region 2 will be discussed.

Between wheat crops tillage is performed to control weeds (thus storing soil water, decomposing plant residues, and mineralizing nutrients to the plant available form) and to prepare a seedbed. The time period for tillage between crops is, of course, dictated by the cropping sequence. With the HRW wheat in Region 1, depending on latitude, the time period between harvest and seeding of continuous wheat is about 2 to 4 months; between a summer-growing crop, such as sorghum or corn and wheat, about 1 year: and between alternate wheat and summer fallow, about 14 to 16 months. With HRS and Durum wheats, in Region 2, the time period between continuous spring wheat crops is about 9 months and with alternating summer fallow, about 21 months. The efficiency of soil water storage between crops (the percentage of the precipitation accounted for as stored soil water) is inversely related to the length of the noncropped period *(71)*. However, because of the longer period for storage, the quantity of water stored after summer fallow is almost always greater than after continuous cropping *(71)*.

Some experimental data in the predominately summer fallow HRW wheat area of the Central Great Plains (Region 1) suggest that the efficiency of storing soil water on summer fallow has increased with time *(42)*. For the last quarter century, results from Akron, Colo., suggest about a 2-inch increase in stored water in summer fallow and for North Platte, Nebr., about 4 inches. The increase in soil water storage with time was attributed to the development of better tillage equipment (rodweeders and sweep machines) and fall weed control between wheat harvest and freezeup *(42)*. Assuming a 3-inch average increase in soil water storage on summer fallow over the last quarter century and a conservative estimate of 3 bushels of wheat per inch of soil water at seeding *(61, 102)*, the increase in soil water storage would increase wheat yields 9 bushels per acre.

In the central and eastern parts of Region 1, improvements in tillage over the last quarter century probably have not contributed greatly to increased wheat yields due to the short time interval between continuous HRW wheat crops. With continuous HRW wheat, farmers are very aware of the need to begin tillage soon after harvest to prepare for the following crop. Improved and more timely use of tillage equipment has probably been a significant factor in better weed control and increased soil water storage.

The method of seeding wheat may be an important factor in wheat yields. Single- and double-disk drills have been used for seeding in the more humid parts of Regions 1 and 2 over the last quarter century. However, the development of hoe drills, which can move aside several inches of dry soil and reach moist soil for timely establishment of HRW wheat, was a significant factor in improved seeding in the drier parts of Regions 1 and 2 *(52, 85)*.

Even though early research work indicated that HRW wheat could be seeded over a period of 1 month without a significant change in yields *(99)*, more recent research has resulted in refinement in the recommended seeding dates for HRW wheat. The date of seeding is often critical in those dry areas where establishing good wheat stands is the most difficult. If wheat is sown too early, excess vegetative growth may extract too much stored soil water before winter weather slows growth. Early planted wheat is subject to Hessian fly injury (*52*) and, when planted very early for grazing as in Region 1, is more susceptible to infestation by wheat curl mite which is the vector for wheat streak virus.[13] If sown too late, the wheat may not develop an adequate root system and often is winterkilled. To minimize root and crown rot on HRW wheat in western Nebraska, from a 4,000-foot base elevation, each 100-foot difference in elevation means a 1 day difference in the recommended seeding date (*37*). As elevation decreases, later planting is advised.

The date of seeding the spring-sown HRS and Durum wheats in Region 2 is also very important. For highest yields, spring wheats should (after a certain earliest date that is often considered to be near April 1) be seeded as early as field conditions permit (*99*). In Montana, seeding later than May 10 decreased yields by 15 to 58 percent as compared with early seeding (*85*). At Minot, N. Dak., spring wheat seeded on June 1 yielded 40 percent less than early seeded wheat and at Williston, N. Dak., when seeded 3 to 4 weeks past the early seeding date, yields were reduced 13 percent (*59*).

Over the period of 1950-75, farmers in North Dakota did not decrease the time required to seed the spring sown wheats (fig. 20). Except for one year (1953), about one to two weeks were required to seed the middle 50 percent of the crop (fig. 20). There has been a tendency over time for spring wheat in North Dakota to be seeded progressively later (fig. 21). The date when 50 percent seeded is highly erratic mainly because of spring weather conditions. In addition, farmers have delayed seeding over the past decade or so in order to perform tillage for wild oat control prior to seeding. However, since the spring wheat is usually 50 percent seeded by day–135 (mid-April), early enough to maintain yields, the apparent trend toward later seeding probably has had no measurable impact on yields.

## ECONOMIC FORCES AFFECTING U.S. WHEAT PRODUCTION

The structure and organization of agriculture at a given time is largely a function of the values of farmers and the general public, the stage of economic development, the natural resource base, and technology. These forces underlying the structure are highly interrelated, making it impossible to analyze one apart from another. For example,

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[13] Porter, K. B. Texas Agricultural Experiment Station, Southwestern Great Plains Research Center, Bushland, Tex. Personal correspondence.

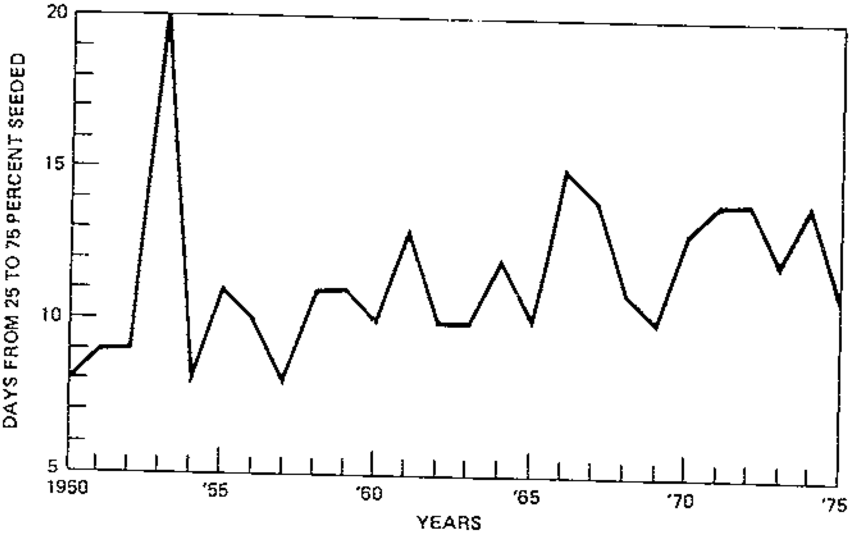

FIGURE 20.—Number of days between 25 and 75 percent seeded for spring wheat in North Dakota, 1950–75. (USDA-ESCS data.)

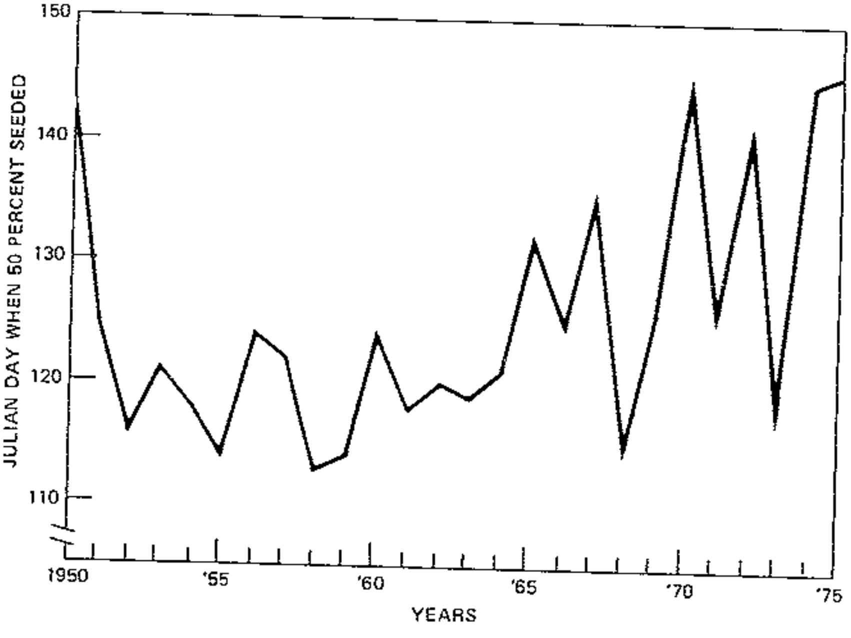

FIGURE 21.—Day of the year when 50 percent of the spring wheat in North Dakota was seeded, 1950–75. (USDA-ESCS data.)

the technology of agriculture at a given time is a reflection of past resource (or input) demand and supply conditions. Resource demand and the consequent organization of agriculture are specified largely by the relative prices of resources, technological coefficients, and goals and values. Changes in any of these areas often induce changes in the structure and organization of farming.

This report has examined national and regional changes in wheat production, acreage, and yields during 1949-76 and the technological factors contributing to these changes. The following sections examine further the forces leading farmers to substitute inputs for land and to change land use practices. Since 1949 the development process in the wheat sector has been toward increasing industrialization of the farm sector. As wheat farmers have increased their use of nonland inputs, they have become increasingly dependent on the agribusiness sector that supplies these inputs.

## Wheat Disappearance

Farmers grow wheat primarily for monetary gain. Monetary gain depends directly on the number of bushels harvested and sold times the average prices received (including government payments) per bushel minus production costs. Differences between prices received and production costs play a major role in farmer decisions on wheat plantings and production input combinations. Prior to examining the relationships between wheat and input use rates, it is helpful to overview the forces affecting wheat prices received by farmers.[11]

In a free market, wheat prices are determined by supply demand relationships. Ultimately, wheat has value in terms of its utility for gratification of human desires. Consumption, in economic terms, means the destruction of utility. Wheat consumption creates additional demands, whereas production creates additional supplies. Without consumption there would soon be little demand for additional production, wheat prices would plummet, and a major incentive encouraging farmers to produce wheat would be eliminated. Thus, the forces affecting U.S. wheat demand play a major role in directing U.S. production trends.

Wheat grain is generally not consumed directly by humans but is processed into bread, cake, cookies, cereals, and other products. It is also used as animal feed and as seed to grow next year's crop. Much of U.S. wheat production is exported. Because wheat grain and many of the processed products are relatively nonperishable, final consumption

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[11] For a good reference on the economics of agricultural production and resource use see (78).

often lags production by months or even years, making consumption rates difficult or impossible to estimate. Instead, USDA estimates disappearance of wheat grain during a marketing year. For domestic use wheat is considered to disappear when it arrives at a place (miller, processor) where it changes form, that is, where it is to be processed into flour or other products, is fed, or is used for seed. In the case of exports, wheat disappears when it leaves the United States.

### Domestic Use

*Food.*—Most domestic use of wheat is for food (table 10). Seed and feed use are the other components of domestic disappearance. During the 1949–76 period domestic food use has been the most stable component of disappearance. Food use declined from 492 million bushels in the 1949/50 marketing year to a low of 481 million bushels in 1955/56 and 1956/57. From these lows, domestic food use gradually increased to 559 million bushels in 1975/76 (table 10). However, food use as a share of total disappearance has declined from over one-half of total disappearance in 1949/50 to less than one-third in 1976/77.

*Seed.*—Wheat acreage planted for the next crop year largely determines seed use in the current year. Consequently, seed use declined with planted acreage in the fifties and sixties and increased during the seventies. Seed use ranged from 56 million bushels in 1961/62 and 1969/70 to 99 million bushels in 1975/76 (table 10). Seed use in the United States usually averages 1.1 to 1.2 bushels per planted acre; but the amount used varies regionally from about ⅓ bushel to 2 bushels per acre depending on expected yield, local climate, seedbed conditions, irrigation practices, and other factors (*91*).

*Feed.*—Although normally accounting for a small share of total disappearance, feed use showed large variability during the period. Feed use ranged from 19 million bushels in 1962/63 to 266 million bushels in 1971/72. Feed use is mostly confined to the Southern Plains and Western States where it competes primarily with grain sorghum in feeder cattle rations (*113*, 1973). Feed demand depends on the price differential between wheat and grain sorghum as well as the number of cattle on feed. With the downward adjustment in the national wheat loan rate (table 11) wheat became more competitive during the 1964/65–72/73 period and feed use increased from the low levels of the 1954/55–63/64 period, declining again when large export demands pushed wheat prices up after 1972/73 (tables 10 and 11).

### Exports

During the period, exports were one of the more important and, also, the most variable component in the disappearance of U.S. wheat. Ex-

### TABLE 10.—*Wheat: Production and disappearance, United States, 1949–77*

| Year beginning July 1 | Production | Share of production exported | Disappearance: Domestic Use: Food[1] | Disappearance: Domestic Use: Feed | Disappearance: Domestic Use: Seed | Disappearance: Domestic Use: Total | Disappearance: Exports of wheat, flour, and products[2]: Under government programs | Disappearance: Exports of wheat, flour, and products[2]: Total | Total disappearance | Exports: Share of total disappearance[3] |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Million bushels* | *Percent* | *Million bushels* | *Million bushels* | *Million bushels* | *Million bushels* | *Percent* | *Million bushels* | *Million bushels* | *Percent* |
| 1949 | 1, 098 | 28 | 492 | 107 | 81 | 680 | 75 | 303 | 983 | 31 |
| 1950 | 1, 019 | 36 | 493 | 103 | 88 | 690 | 85 | 366 | 1, 056 | 35 |
| 1951 | 988 | 48 | 497 | 103 | 88 | 689 | 47 | 475 | 1, 164 | 41 |
| 1952 | 1, 306 | 24 | 488 | 84 | 89 | 661 | 33 | 318 | 978 | 33 |
| 1953 | 1, 173 | 18 | 488 | 77 | 69 | 634 | 9 | 217 | 851 | 25 |
| 1954 | 984 | 28 | 486 | 60 | 65 | 611 | 46 | 274 | 886 | 31 |
| 1955 | 937 | 37 | 481 | 54 | 68 | 604 | 58 | 346 | 950 | 36 |
| 1956 | 1. 005 | 55 | 481 | 49 | 58 | 589 | 70 | 549 | 1, 138 | 48 |
| 1957 | 956 | 42 | 487 | 42 | 63 | 592 | 68 | 402 | 994 | 40 |
| 1958 | 1, 457 | 30 | 498 | 47 | 64 | 609 | 61 | 443 | 1, 051 | 42 |
| 1959 | 1, 118 | 46 | 497 | 37 | 63 | 597 | 68 | 510 | 1, 107 | 46 |
| 1960 | 1, 355 | 49 | 497 | 42 | 64 | 603 | 74 | 662 | 1, 265 | 52 |
| 1961 | 1, 232 | 58 | 502 | 50 | 56 | 608 | 69 | 719 | 1, 327 | 54 |
| 1962 | 1, 092 | 59 | 500 | 19 | 61 | 580 | 68 | 644 | 1, 224 | 53 |
| 1963 | 1, 147 | 75 | 503 | 20 | 65 | 588 | 76 | 856 | 1, 444 | 59 |
| 1964 | 1, 283 | 57 | 509 | 69 | 66 | 644 | 59 | 725 | 1, 369 | 53 |
| 1965 | 1, 316 | 66 | 515 | 154 | 61 | 732 | 78 | 867 | 1, 599 | 54 |
| 1966 | 1, 305 | 57 | 502 | 94 | 77 | 674 | 50 | 744 | 1, 417 | 53 |

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| 1967 | 1, 508 | 50 | 519 | 43 | 71 | 633 | 63 | 761 | 1, 394 | 55 |
| 1968 | 1, 557 | 35 | 520 | 155 | 61 | 735 | 56 | 544 | 1, 280 | 42 |
| 1969 | 1, 443 | 42 | 521 | 195 | 56 | 772 | 54 | 606 | 1, 378 | 44 |
| 1970 | 1, 352 | 55 | 520 | 187 | 62 | 768 | 46 | 738 | 1, 506 | 49 |
| 1971 | 1, 618 | 39 | 526 | 266 | 63 | 855 | 50 | 632 | 1, 487 | 43 |
| 1972 | 1, 545 | 77 | 528 | 190 | 67 | 785 | 16 | 1, 186 | 1, 971 | 60 |
| 1973 | 1, 711 | 64 | 530 | 139 | 84 | 754 | 6 | 1, 217 | 1, 970 | 62 |
| 1974 | 1, 782 | 57 | 521 | 59 | 92 | 672 | 12 | 1, 018 | 1, 690 | 60 |
| 1975 | 2, 122 | 55 | 559 | 63 | 99 | 721 | 11 | 1, 173 | 1, 895 | 62 |
| 1976 | 2, 142 | 44 | 552 | 103 | 92 | 748 | (4) | 950 | 1, 698 | 56 |

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[1] Includes shipments to U.S. territories and wheat for military food use at home and abroad.

[2] Includes exports of flour and semolina and macaroni products in terms of wheat. Include bulgur and rolled wheat in terms of wheat.

[3] Adjusted for transshipments of U.S. wheat through Canada.

[4] Not available.

Source: *Agricultural Statistics* (105).

## TABLE 11.—*Wheat: Price-support operations, United States, 1948–77*

| Year beginning July | Season average price per bushel [1] | Support price | | Put under support [4] | | Acquired by CCC under support program [5] | U.S. Stocks | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Per bushel [2] | Percent-parity [3] | Quantity | Percentage of production | | Controlled by CCC | | Total (CCC plus private) | Proportion owned by CCC |
| | | | | | | | Owned | Under loan or reseal [6] | | |
| | *Dollars* | *Dollars* | *Percent* | *Million bushels* | *Percent* | *Million bushels* | *Million bushels* | *Million bushels* | *Million bushels* | *Percent* |
| 1949 | 1.88 | 1.95 | 90 | 380 | 35 | 248 | 227 | 16 | 307 | 79 |
| 1950 | 2.00 | 1.99 | 90 | 197 | 19 | 42 | 328 | 34 | 425 | 85 |
| 1951 | 2.11 | 2.18 | 90 | 213 | 22 | 91 | 196 | 11 | 400 | 52 |
| 1952 | 2.09 | 2.20 | 90 | 460 | 35 | 398 | 143 | 12 | 256 | 60 |
| 1953 | 2.04 | 2.21 | 91 | 553 | 47 | 486 | 470 | 23 | 606 | 81 |
| 1954 | 2.12 | 2.24 | 90 | 430 | 44 | 392 | 775 | 75 | 934 | 91 |
| 1955 | 1.98 | 2.08 | 82 | 318 | 34 | 277 | 976 | 14 | 1,036 | 96 |
| 1956 | 1.97 | 2.00 | 83 | 252 | 25 | 148 | 951 | 29 | 1,034 | 95 |
| 1957 | 1.93 | 2.00 | 80 | 256 | 27 | 194 | 824 | 13 | 909 | 92 |
| 1958 | 1.75 | 1.82 | 75 | 609 | 42 | 511 | 835 | 18 | 881 | 97 |
| 1959 | 1.76 | 1.81 | 77 | 317 | 28 | 182 | 1,147 | 96 | 1,295 | 96 |
| 1960 | 1.74 | 1.78 | 75 | 424 | 31 | 261 | 1,195 | 92 | 1,313 | 98 |
| 1961 | 1.83 | 1.79 | 76 | 271 | 22 | 120 | 1,243 | 125 | 1,411 | 97 |
| 1962 | 2.04 | 2.00 | 83 | 300 | 27 | 245 | 1,097 | 95 | 1,322 | 90 |
| 1963 | 1.85 | 2.03 | 81 | 172 | 15 | 74 | 1,083 | 97 | 1,195 | 99 |
| 1964 | 1.37 | 1.78 | 71 | 206 | 16 | 85 | 829 | 63 | 901 | 99 |
| 1965 | 1.35 | 1.72 | 67 | 173 | 13 | 87 | 608 | 75 | 817 | 83 |
| 1966 | 1.63 | 1.90 | 74 | 133 | 10 | 11 | 262 | 78 | 535 | 64 |
| 1967 | 1.39 | 1.85 | 71 | 282 | 19 | 12 | 124 | 78 | 424 | 48 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1968 | 1.24 | 1.83 | 69 | 453 | 29 | 83 | 102 | 227 | 539 | 61 |
| 1969 | 1.25 | 1.94 | 70 | 408 | 28 | 178 | 163 | 459 | 817 | 76 |
| 1970 | 1.33 | 2.00 | 71 | 254 | 18 | 97 | 301 | 436 | 885 | 83 |
| 1971 | 1.34 | 1.79 | 61 | 438 | 27 | 11 | 370 | 200 | 732 | 78 |
| 1972 | 1.76 | 1.72 | 57 | 143 | 9 | 13 | 367 | 347 | 863 | 83 |
| 1973 | 3.95 | 1.46 | 43 | 60 | 4 | ---- | 144 | 67 | 438 | 48 |
| 1974 | 4.09 | 2.05 | 53 | 36 | 2 | ---- | 19 | (7) | 247 | 8 |
| 1975 | 3.56 | 2.05 | 45 | 48 | 2 | ---- | 1 | 1 | 340 | 1 |
| 1976 | 2.73 | 2.25 | ---- | 468 | ---- | ---- | ---- | ---- | 435 | ---- |

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[1] Obtained by weighting State prices by quantity sold. Includes allowance for unredeemed loans and purchases by the Government valued at the average loan and purchase rate, by States.

[2] A loan level of $1.82 in 1963, $1.30 in 1964, and $1.25 from 1965 to 1973, plus the average marketing certificate payment per bushel paid to program participants. Loan level protection for 1974 and 1975 is $1.37, and for 1976 is $1.50 on entire production. For 1974 to 1976, the target level is a price guarantee on allotment production at levels indicated under support price.

[3] Percentage of parity price at beginning of marketing year.

[4] Represents loans made, purchases, and purchase agreements entered into.

[5] Acquisitions through loan cancellations and purchases (under agreement and direct) only from crop harvested in the year indicated.

[6] Under loan on July 1 from year earlier crop and under reseal from previous crops.

[7] Less than 0.5 million bushels.

Source: *Agricultural Statistics (105)*.

ports of wheat, flour, and products ranged from 217 million bushels equivalent in 1953/54 to a record of 1,217 million bushels in 1973/74 (table 10). Increases in wheat exports have been the major factor contributing to the upward trend in wheat disappearance during the period. The relative importance of exports in total wheat disappearance has increased with time, accounting for a low of 25 percent of total disappearance in the 1953/54 marketing year to a high of 62 percent in the 1975/76 marketing year (table 10). Except for four years, 1968/69–71/72, wheat exports have exceeded domestic use since 1960–61.

Thus, export levels play a major role in determining U.S. wheat prices. U.S. wheat trade is directly influenced by the level of world production. The export market for U.S. wheat is also affected by the economic conditions and policy considerations of trading countries, such as trade barriers, internal allocation policies, and bilateral trade agreements. U.S. wheat prices under free market conditions are extremely vulnerable to changes in conditions over which U.S. farmers have little control.

## Government Programs

Since 1949, except for a period of high export demand during 1973–76, government programs have played a major role in the production and marketing of wheat. Because of "over production" and resulting low farm prices for wheat and other grains during most of this period, farm organizations have actively sought government help to improve farm prices and farm income.

### Agricultural Adjustment

Under legislation passed by Congress and modified to meet changing economic conditions, the U.S. Department of Agriculture initiated many programs intended to support the price of farm products and encourage farmers to adjust production to demand (*53*). Most U.S. Government programs involving wheat production since World War II centered on supply adjustment and producer income protection. These programs attempted to adjust farm production to domestic and export needs. The provisions of the wheat programs varied from year to year.

Income maintenance was largely accomplished through government support of wheat prices received by farmers. Prices were supported by government loans on wheat at varying rates during the period (table 11). In the early years of the period, support prices were maintained at a relatively high level but were gradually reduced with time. The Commodity Credit Corporation (CCC) was an important tool in government price support activities. When prices fell below the support price, the farmer could turn the grain over to the CCC in payment of the loan. During the fifties and sixties the CCC acquired large amounts of wheat through these programs (table 11).

Farmers, of course, desire a high support price. High support prices, however, encourage production, discourage consumption, and increase government costs. To keep government costs within "acceptable" levels, effective support prices were gradually lowered during the period, and ways were sought to keep production within expected domestic and export needs. Income maintenance programs gradually became less dependent on direct price support activities (through loan rates) and more dependent on direct income payments to farmers. Most programs provided various incentives to reduce acreage planted to a national allotment level expected to produce enough wheat to meet domestic and export needs. Producers were required to stay within individual acreage allotments to be eligible for wheat loan rates and other program payments.

During 1950–63, wheat marketing quotas based on producers' historical acreage allotments and projected yields were approved by annual referenda. During the Korean War (1951–53), allotments and quotas were suspended and loan rates were maintained at relatively high levels to assure sufficient food and fiber to meet any eventuality. After the Korean War the CCC accumulated sizable carryover stocks (table 11), and acreage allotments were instituted. Participating farmers had to divert wheat acreage from their historic base allotments and stay within their allotted acreage to qualify for price support loans and avoid penalties. Some wheat could be grown in response to market price expectations; nonparticipating producers generally could plant up to 15 acres of wheat and not be subject to penalties. Nevertheless, government programs played a major role in determining the amount of wheat acreage planted during this period.

The period from 1963–72 saw additional changes in wheat and feed grain programs. In the fall of 1963, with the failure of the marketing quota referendum, the wheat program reverted to earlier legislation that specified sharply reduced loan rates ($1.25 per bushel) with no penalties or quotas. Producers who did not participate in the loan program were free to plant unrestricted acreages. However, a policy decision was made to maintain gross income for "participating wheat producers through direct payments via a voluntary acreage-controlling program" (*53*, p. 33). Allotments were low, being based on estimated domestic needs. Direct payments for diverting acreage from wheat production were based on the allotted acreage. During the following years, on allotted acreage the effective support level, including program payments, was set at 65 to 90 percent of parity. In 1964 and 1965 participating farmers also received marketing certificates. During much of the period, provisions allowing substitution of feed grain and wheat for producers participating in both the feed grain and wheat programs after mandatory diversions were met resulted in additional wheat acreage (*53*).

These programs continued without major change until 1973. However, the Agricultural Act of 1970 discontinued the use of acreage allotments and marketing quotas for wheat, upland cotton, and feed grains. To qualify for price supports the farmer was required to "set aside" to conserving practices a specific percentage of his cropland. These farmers became eligible for their share of domestic marketing certificates. The value of the certificates was to be the difference between the wheat parity price and the average price received by farmers during the first 5 months of the marketing year.

The Agricultural and Consumer Protection Act of 1973 simplified the provisions of previous programs and allowed farmers greater decisionmaking flexibility (*53*). Under the act, a target price was set and if the average weighted U.S. price received by farmers fell below the target price during the first 5 months of the marketing year, direct payments were made to make up the difference on individual allotments. The Food and Agriculture Act of 1977 extended the target price and loan rate system of providing price and income support protection to participating farmers.

The various programs have supported wheat and other basic commodity prices during most of the period after 1949. The acreage allotments and either mandatory or voluntary acreage diversion and the set-aside features of the programs have played a major role in farmers' decisions on how much wheat acreage to plant. However, the acreage reductions were partially self-defeating. Where possible, farmers diverted or set aside their lowest quality land, increasing the average productivity of the remaining land. Acreage restrictions provisions also encouraged summer fallow. The yield benefits of summer fallowing have already been noted.

In addition, farm programs encouraged the adoption of yield increasing practices during the fifties and sixties. Acreage reductions and price supports for production on allotted acreage provided farmers with incentives to find land substitutes capable of increasing the yield on allotted acreage. In a sense, acreage restrictions created an artificial shortage of wheat land; and price supports increased the value of any cultural practices and production inputs that could contribute to higher productivity on allotted acreage. Of course, farmers will be encouraged to increase production by adding fertilizer, pesticides, and other inputs if the expected return, discounted for risk, from these inputs is greater than the expected cost of the last unit of the input. Price supports help to reduce farmers' risk by reducing the possibility of unexpected downward price adjustments for the supported commodity.

### Export Programs

In addition to influencing wheat production, government actions have been an important factor in U.S. wheat export levels. Except for 1951/52 through 1954/55, 1966/67, 1970/71, and the 4 years from 1972/73 to 1976/77 over half of the wheat and products that were exported during the marketing year received government assistance primarily under Public Law 480 authorization (table 10). Types of assistance included sales for foreign currency, long-term dollar and convertible foreign currency credit sales, government to government donations for disaster relief and economic development, donations through voluntary relief agencies, and barter for strategic materials (the latter ending in 1966).

Government assistance programs directly or indirectly helped to dispose of CCC acquired grain stocks, reducing storage costs. Between 1949 and 1973 the CCC controlled a major share of U.S. old crop wheat stocks, ranging from not less than 48 percent (July 1, 1967) to not more than 99.0 percent (July 1, 1963 and 1964) of old crop stocks (table 11). After 1973, high export demand and a change in U.S. agricultural policy allowed CCC to dispose of all but a small fraction of its stocks by July 1, 1975. Nevertheless, during most of this period the CCC played a significant role in marketing U.S. wheat. In addition, the USDA has promoted market development efforts in many importing countries.

## Changes in Input Economics

During 1949–76, U.S. agriculture became increasingly industrialized and dependent on the nonfarm sector of the economy for many of its production inputs. Increases in farmer usage of fertilizer, more responsive wheat varieties, pesticides, energy, and irrigation contributed to increasing wheat yield trend. These inputs are largely developed and supplied by the nonfarm (private and public) sector. Consequently, nonfarm technical developments affecting the availability and cost of these inputs to farmers have had an important role in wheat yield changes.

Many farmers, when making decisions on which inputs and how much of an input to use, analyze the expected contribution of that input to net farm income. Input costs, availability, expected yield/input response rates, and crop prices are important elements in a decision. Changes in input cost or availability will induce many farmers to alter the amount used. Changes in the amount used will in turn change wheat yields. However, because variation in climate and other natural conditions can also change wheat yields, the contribution of an input to increased production in any year is uncertain. Wheat prices can also change between the time a crop is planted and harvested (or marketed). An unexpected drop in wheat price or an unexpected drought, which reduces the yield response of wheat to a production input such as fertilizer, may cause the actual returns from a production input to fall below the expected returns. If the reduction in wheat price or yield response is large enough so that returns do not cover input costs, the earlier decision to apply the input will appear unwise by the time the wheat is harvested or sold.

Because the process of decisionmaking under uncertainty involves individual psychology as well as economics, new production practices are adopted by different farmers at different rates. The role of uncertainty in production decisions has long been recognized (*48*). Not all potential yield-increasing practices are readily adopted by farmers. In fact, increases in yields per acre are primarily a secondary goal of most farmers who adopt only those practices expected to increase net farm earnings. Different farmers will discount expected earning increases at different rates. Many production input decisions can be altered from one year to the next as expected conditions change. This fact partly explains why many inputs show a gradual change in use over time.

## Technical Complements

Many production techniques require a "complement" of resources to be economically fully effective in increasing yields per acre. Because high-yielding varieties, fertilizer, and irrigation factors are *technical complements* over some range of the crop response function, they are also *economic complements*. Factors are technical complements when the marginal productivity of each is increased when used in combination with the other factor or factors (*48*). For example, many of the high-yielding varieties are little if any more productive than traditional varieties at low levels of soil fertility and soil moisture. However, in areas where precipitation is relatively high or under irrigation, these varieties are more responsive to fertilizer. Thus, the optimum rate of fertilizer application is increased by irrigation and by more responsive varieties. The highest yields per acre often result from combining several production inputs, and the use of one production input often encourages the use of another.

## Fertilizer

Nitrogen fertilizer, the major nutrient applied on wheat, has been known for decades to increase wheat yields in nitrogen-deficient soils. Nevertheless, the widespread use of nitrogen fertilizer on wheat required a reduction in its cost. The technology to cheaply produce nitrogen fertilizer was discovered in the 1930's; and the need for nitrogen in explosives during World War II led to the construction of fertilizer production facilities using this new nitrogen-producing technique. After the end of World War II, a surplus of manufacturing capacity eventually led to cheaper nitrogen fertilizer. High wheat prices and restrictive acreage allotments after the war increased farmers' incentives to use more fertilizer on wheat.

As a result of the more efficient fertilizer production technology developed in the 1930's and continued investment in plant capacity after World War II, fertilizer prices increased less than 10 percent from 1950 to 1972 (table 12) much less than the prices of many other inputs. For example, farmland increased 330 percent during the same period (table 12). The relative price stability of fertilizer during the fifties and sixties encouraged commercial fertilizer sales with nitrogen ingredients alone rising from 1 million tons in 1950 to over 9 million tons in 1970 (*111*). The amount of phosphorus and potassium increased at a similar rate. However, fertilizer prices more than doubled from 1972 to 1975 (table 12). Increased world wide fertilizer demand as farmers increased crop acreages in many countries and higher energy costs contributed to price rises during these years.

However, it is not so much the absolute fertilizer price that determines the use of fertilizer but the response of wheat to the applied fertilizer and the relationship of fertilizer prices to other input costs and to wheat prices. A Kansas example for 1964–76 shows that the wheat/fertilizer price ratio reached a peak in 1973 and has since leveled off (table 13).

A regression analysis of Kansas data for 1964 to 1976 (table 13) shows a positive but weak relationship between the wheat/fertilizer price ratio and pounds of nitrogen fertilizer applied per acre. The results of the regression analysis are:

$$\begin{aligned}
&(1)\quad Y_{rt} = 29.20 + 0.26X_t + 1.79T_t \text{ and}\\
&\qquad\qquad\qquad\quad + (1.14) \qquad (4.96)\\
&(2)\quad Y_{bt} = 10.49 + 0.24X_t = 1.910T_t\\
&\qquad\qquad\qquad\quad + (1.75) \qquad (8.91)
\end{aligned}$$

Where:

$Y_{rt}$=the pounds of nitrogen per acre receiving in (1),
$Y_{ht}$=the pounds of nitrogen per acre harvested in (2),
$X_t$=the wheat/fertilizer price ratio from table 13, and
$T_t$=a surrogate time variable, $T_{1964}=1$, $T_{1965}=2$ and etc.

TABLE 12.—*Index numbers of fertilizer and farm real estate prices, 1950–76*

| Year | Index | | | |
|---|---|---|---|---|
| | Fertilizer[1] | | Farm real estate | |
| | (1950=100) | (1967=100)[2] | (1950=100) | (1967=100)[3] |
| 1950 | 100 | | 100 | 40 |
| 1951 | 106 | | 115 | 46 |
| 1952 | 108 | | 128 | 51 |
| 1953 | 109 | | 130 | 52 |
| 1954 | 110 | | 128 | 51 |
| 1955 | 108 | | 132 | 53 |
| 1956 | 106 | | 138 | 55 |
| 1957 | 106 | | 145 | 58 |
| 1958 | 106 | | 152 | 61 |
| 1959 | 106 | | 165 | 66 |
| 1960 | 106 | | 170 | 68 |
| 1961 | 107 | | 172 | 69 |
| 1962 | 106 | | 182 | 73 |
| 1963 | 106 | | 192 | 77 |
| 1964 | 105 | | 205 | 82 |
| 1965 | 106 | 103 | 215 | 86 |
| 1966 | 106 | 102 | 232 | 93 |
| 1967 | 105 | 100 | 250 | 100 |
| 1968 | 103 | 94 | 268 | 107 |
| 1969 | 99 | 87 | 282 | 113 |
| 1970 | 103 | 88 | 292 | 117 |
| 1971 | 108 | 91 | 305 | 122 |
| 1972 | 110 | 94 | 330 | 132 |
| 1973 | 122 | 102 | 375 | 150 |
| 1974 | | 167 | 467 | 187 |
| 1975 | | 217 | 535 | 214 |
| 1976 | | [4] 181 | 610 | [4] 244 |

[1] A consistent price index for the 1950–75 period is not available for fertilizer.

[2] Index values for 1965–75 were revised using 1971–73 weights.

[3] Calculated from the 1950 base index.

[4] Preliminary.

Source: For 1950 index source is *Wheat Situation, (118,* 1974). 1974. For 1967 index source is *Handbook of Agricultural Charts* (*111,* 1977, p. 457).

The Student "*t*" values for each equation coefficient are shown in parentheses. The coefficients for $X_t$ are not different from zero at the 0.05 level of significance, although the $T_t$ coefficients are nonzero at the 0.01 level. For equation (1), $R^2=.78$ and for equation (2), $R^2=0.92$.

However, the wheat/fertilizer price ratio does not appear to be the major cause of annual changes in fertilizer use. Other factors besides the wheat/fertilizer price ratio affect fertilizer use. Farmers have been increasing fertilizer use with time. Generally, farmers slowly adopt practices requiring large sums of money or having highly variable or uncertain returns. In areas such as Kansas where variable rainfall (*51*) causes wheat yields to vary over a wide range from year to year, farmers may have difficulty determining whether yield responses are from fertilizer application or from climate. In much of the Great Plains potential yield increases are small under normal dryland conditions. Yield responses to fertilizer are related to soil moisture supply. Because

TABLE 13.—*Index of wheat prices received, index of fertilizer prices paid, percentage of wheat acreage receiving nitrogen fertilizer, nitrogen applied per acre receiving, and nitrogen per harvested acre by Kansas farmers, 1964–76*

| Year | 1967=100 | | Wheat/fertilizer price ratio | Nitrogen fertilizer | | |
|---|---|---|---|---|---|---|
| | Index of wheat prices [1] | Index of fertilizer prices [2] | | Percentage of acres receiving | Pounds per acre receiving | Pounds per acre harvested |
| 1964 | 101 | 109 | 93 | 39 | 26.1 | 10.2 |
| 1965 | 102 | 107 | 95 | 40 | 26.9 | 10.8 |
| 1966 | 132 | 104 | 127 | 50 | 34.6 | 17.3 |
| 1967 | 100 | 100 | 100 | 51 | 36.0 | 18.4 |
| 1968 | 88 | 90 | 98 | 59 | 42.1 | 24.8 |
| 1969 | 86 | 82 | 105 | 50 | 49.9 | 25.0 |
| 1970 | 94 | 80 | 118 | 51 | 46.2 | 23.6 |
| 1971 | 95 | 85 | 112 | 48 | 46.8 | 22.5 |
| 1972 | 127 | 86 | 148 | 60 | 51.1 | 30.7 |
| 1973 | 328 | 101 | 325 | 66 | 53.6 | 35.4 |
| 1974 | 293 | 207 | 142 | 68 | 48.9 | 33.7 |
| 1975 | 281 | 236 | 119 | 68 | 46.8 | 31.8 |
| 1976 | 208 | 182 | 114 | 73 | 51.8 | 37.9 |

[1] Wheat price index is calculated from the average of August and September prices received by Kansas farmers.

[2] Fertilizer price is for ammonium nitrate.

Sources: (*104*, *108*).

of the large annual climate variations farmers' experiences with yield/fertilizer response relationships are highly uncertain. Under these conditions, farmers may require considerable time to acquire evidence of favorable returns to fertilizer and are likely to only slowly increase fertilizer use. Farmers would be expected to apply fertilizer only as they become convinced of the direct benefits and the opportunities for more profitable investments declined.

### Pesticides

A different production response relationship for pesticides makes the economics behind the increased use of pesticides on wheat somewhat different from fertilizer economics. Effective weed or insect control requires a certain minimum amount of the pesticide. Once a threshold amount is applied, additional amounts have little benefit. The cost of the chemical itself is often less than its cost of application.

Hence, the farmer's major economic decision is concerned with how many acres or what proportion of the acreage to treat with pesticides. Once this decision is reached, the rate of application per acre is mostly a technical one. A comparison of estimated total treatment (pesticide plus application) costs per acre with the estimated value of the increased production per acre provides a useful decision rule for determining the number of acres treated. For a given level of effectiveness (increased yields) as pesticide costs decline or wheat prices increase, farmer's demand and usage of pesticides on wheat will rise. The extent of weed, insect, or other pest problems in a particular year is often a major factor determining the number of acres treated.

Long-term annual statistical series on costs and pesticide use on wheat are scarce. However, the trend in both use and per acre pesticide costs appears to be upward. Based on special farm surveys (*13*, *14*) the proportion of acres treated rose in the United States from 30 percent in 1966 to 47 percent in 1971 (table 14). Approximately one half of the acreage was custom treated (*35*). The average cost increased from $0.56 per acre in 1964 to $0.79 per acre treated in 1971 (table 14). The prices paid by farmers rose rapidly after 1972, increasing by 4 to 35 percent from 1973 to 1974 depending on the pesticide product, by an average of 25 percent from 1974 to 1975, and by an average of 3 percent from 1975 to 1976 (*3*). The demand for pesticides on wheat was estimated to have increased by 3 percent from 1975 to 1976, primarily as a result of increased wheat acreage.

Herbicides are by far the most important of the pesticides used on wheat (table 14). Herbicides are most often used on the growing wheat crop where mechanical cultivation is not possible. Wheat producers began to use phenoxy herbicides in the 1940's with the

TABLE 14.—*Acres treated and costs per acre for selected pesticides used on wheat in the United States, selected years*

| Year | All pesticides [1] | | Herbicides | | Insecticides | |
|---|---|---|---|---|---|---|
| | Acres treated | Cost per acre | Acres treated | Cost per acre | Acres treated | Cost per acre |
| | *Percent* | *Dollar* | *Percent* | *Dollar* | *Percent* | *Dollar* |
| 1964 | 28 | 0.56 | (2) | (2) | (2) | (2) |
| 1966 | 30 | .61 | 28 | 0.59 | 2 | 0.78 |
| 1971 | 47 | .79 | 41 | .69 | 7 | 1.17 |

[1] Of all pesticides, mostly herbicides and insecticides are used on wheat.
[2] Not available.

Source: Selected tables from *Farmers' Use of Pesticides in 1971 (13)* and *Farmers' Pesticide Expenditures in 1966 (14)*.

discovery of 2,4-D. Because the phenoxy herbicides were shown to provide selective control of broadleaf weeds and to be cost effective, by 1966 wheat growers were treating 28 percent of the total wheat acreage, and by 1971, 41 percent (table 14). In 1971, about one-half of all the wheat acres treated with herbicides were in the Northern Plains and over 90 percent in the combined Northern Plains, Mountain and Pacific Regions (table 8).[15]

Environmental issues are often associated with use of pesticides. The USDA studied the economic consequences of removing phenoxy herbicides, primarily 2,4-D and 2,4,5-T, from the market because of its concern about the potentially adverse effects of eliminating the use of these chemicals on crop production (*37*). For 1966 conditions and prices, it was estimated that U.S. farmers' total direct production costs would increase about $290 million. The net reduction in farm income from wheat was estimated at $51 million. This estimate considered the potential weed control of known substitute herbicides at that time.

For 1966, the researchers estimated that on about one-half of the wheat acreage there would be a loss of 30 percent in yield if these herbicides were withdrawn (*37*). If substitute herbicides were withdrawn, losses would be greater. Besides controlling weeds by additional cultivations, maintaining production would require the planting

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[15] Regional data in literature citations (*2*), (*13*), and (*14*) are reported by Farm Production Regions (table 8) and do not correspond with the regional boundaries used in this report.

of 3.3 million acres more wheat. Additional costs from adding acreages would increase variable costs by $40 million and machinery investment and depreciation by $5 million (1966-dollars). Additional labor would be required, and additional fallowing to control certain weeds would increase costs.

## Irrigation

Under conditions where wheat is suffering from plant water stress, applying additional water by irrigation can greatly increase yields. In most major wheat-producing areas, stress caused by a lack of available soil water limits yields. Irrigation also increases yield response to other inputs such as applied fertilizer and higher yielding varieties.

For all its potential to increase land productivity, however, there are several obstacles that the farmer must overcome when adopting irrigation. The best utilization of irrigation equipment and water often requires changes in farm enterprise combinations, input combinations, and cropping practices all requiring increased technical knowledge and managerial skills on the part of the farmer. Moreover, irrigation development generally requires substantial capital investments. An efficient irrigation system may be designed to irrigate in 160-acre or larger units making capital requirements quite large even when a water source is readily available. Many farmers are unable to obtain the large amounts of capital required. Given the added managerial requirements, others are unwilling to commit the capital.

The lack of a ready supply of water often prohibits the farmer from adopting irrigation. Sufficient ground water supplies may not be available or may be uneconomical. When ground water is available, capital requirements for developing new wells are often substantial. Irrigation using stored surface water generally requires an investment in storage facilities and in water transportation facilities to move the water from the stream or source of runoff to the farmer's field. Because of the considerable cost of facilities for storage and transportation, economical development of many surface water sources for irrigation has often required large-scale delivery systems and, consequently, public funding.

The economics of allocating irrigation water are similar to the economics of allocating other resources in the production process.[16] Farmers will desire to allocate their water to crops that will give them the highest expected return. Historically, budgets calculating expected

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[16] Such a statement partially avoids the legal-institutional concerns about water "rights" and "needs" which play a very important role in many Western States in determining the allocation of water to irrigation and other uses and also determines who can acquire water-use "rights".

returns from such crops as hay, pasture, and small grains often indicate a questionable ability to repay investments in irrigation facilities. In the past, profitable irrigation development in many areas often depended on the economic feasibility of high-value crops, such as fruits and vegetables *(122)*. A high rate of return per acre was required to repay the high capital costs.

Nevertheless, once irrigation facilities are in place many factors determine which combination of crops is grown. An important component of system costs is the water delivery capacity of the system. The peak water needs of a crop are one of the factors determining how many acres can be irrigated by a system. These peak needs often arise during the summer months with warm season crops. The fact that wheat requires water primarily in the spring when needs of other crops are minimal is important in explaining irrigated winter wheat production in some areas of the United States. This production is mainly exclusively in the southern Great Plains and in the Western States. In most of these areas irrigated wheat is normally not the most profitable crop, but it can be a profitable one. Irrigated wheat is thus often a companion crop fitting into many rotations and not competing for water needed by more responsive and higher value crops. However, wheat prices are a factor in determining the role of wheat in irrigated crop rotations. High wheat prices encouraged farmers to increase irrigated wheat acreage for the 1974 crop (fig. 12).

Projected irrigation budgets for the Texas Panhandle (CRD 1–N) for 1975 indicated that with average yields of 37 bushels per acre and a wheat price of $3.25 per bushel estimated net returns are a minus $31 *(84)*. However, when fixed costs were excluded, the estimated income above variable costs would be $42 per acre; and since fixed costs are incurred anyway, irrigated wheat is economically justified.

In the southern Great Plains, the use of irrigated winter wheat for both grazing and grain production is also a common practice. The extent of this practice varies with the relative prices of cattle and wheat *(84)*. Grazing beyond a certain date in the spring reduces the yield of grain. However, with low wheat prices and high beef prices farmers sometimes find that grazing their irrigated wheat is more profitable than harvesting it.

The availability of water for irrigation is an important factor in determining use on wheat. Declining ground water tables are becoming a problem in some areas, for example in the southern Great Plains area underlain by the Ogallala aquifer. As ground water levels decline, increased energy requirements to pump water from greater depths and energy-price rises may make irrigation in much of the area noneconomical sometime in the future. Once the variable costs of pumping water become greater than the additional returns from irrigation, farmers will idle or sell their equipment.

How long irrigated wheat will retain an important position in wheat production in the southern Great Plains will depend on many factors among which are the relative price of wheat and other crops that can be irrigated, the use of irrigated wheat for livestock pasture, and the price of wheat relative to irrigation costs that are increasing as energy costs rise and underground water levels for tubewell irrigation decline.

The increasing competition for nonagricultural uses of water, such as energy development, may reduce irrigation or limit its further development in many Western States.

## Wheat Classes

Besides having different yield potentials, wheat varieties differ in their protein and other baking qualities. Wheat composition and quality are the results of the interaction of variety characteristics with environment and soil.

The processing and multiplicity of products produced from wheat create demands for specific quality characteristics. The milling and baking industry separate wheat into different classes or products based on characteristics that make each class uniquely or better suited for use in different bakery items. Although substitution occurs, each wheat class partly enters different markets. The price received for each class reflects world demands and world supplies of each class. Individual farmers can have little, if any, effect on these prices, but their combined actions will influence the prices they receive.

Because prices and yield potentials often differ by wheat class, farmers consider each wheat class or variety as a crop alternative. They respond to price changes for various wheat classes. The importance of relative prices is illustrated by analyzing recent changes in the market prices received by North Dakota wheat farmers for Durum and Hard Red Spring wheats and the responses of farmers to these changes.

For North Dakota, where Durum wheat varieties are readily adaptable, yield differences between HRS wheat and Durum wheats are small. ESCS crop budgets for 1970 (*72*) and 1975 (*113*) indicate Durum costs slightly more to produce, largely because of higher seed costs. The ratio of Durum prices received by North Dakota farmers to other spring wheat (HRS) prices received in the months before planting (March and April) gradually increased from 0.95 in 1971 to 1.44 in 1975 but declined in 1976 (table 15). Although Durum plantings were subject to uncertainties about the continuance of the favorable price, increased managerial difficulties, and possible lower yields outside the area most adaptable to Durum, the increase in the price of Durum relative to HRS caused farmers to increase the ratio of Durum to other spring wheat acreage planted from 0.38 in 1971 to 0.67 in 1975 (table 15). By 1976 relative prices had become more favorable to the production of HRS wheat, and the proportion of acreage planted to Durum declined in 1976.

## Cropping Sequences

Changes in economic conditions also affect the cropping sequences of an area. For example, a combination of higher wheat prices and less restrictive government programs caused farmers to reduce the proportion of wheat planted on summer fallow in certain areas during the early 1970's. In the driest wheat-producing areas, where yield differences are the largest, however, little change occurred. The economics of the situation is illustrated by analyzing costs and returns of two alternative cropping sequences (rotations) for a complete production cycle.

A wheat-fallow rotation requires a 2-year production cycle. For analytic simplicity, the total 2-year costs and returns of wheat after summer fallow are compared with 2-year costs and returns of a wheat-wheat rotation. The economic principles do not change with other rotations (cropping sequences). The total or 2-year costs of producing continuous wheat are greater than the 2-year cost of a wheat-fallow rotation. In 1970, estimated costs were $4.06 ($2.03 annually) per planted acre more to produce wheat-wheat than wheat-fallow in the central North Dakota Durum wheat region (*72*). Fertilizer, labor, pesticides, and harvesting costs were greater for the two wheat crops than for wheat-fallow.

The following tabular example shows the minimum (breakeven) yield increase needed during a 2-year rotation period to economically justify switching from a wheat-fallow to a wheat-wheat rotation under four price and cost difference assumptions. If during the 2-year rotation period the average farm price received[17] is as given in column (1) and the additional costs of continuous cropping are either $4.06 or $8.12, to break even 2-year yields on continuous cropping must be larger than on wheat-fallow by the amount shown in columns (2) and (3) respectively.

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[17] The prices shown are for illustrative purposes only. If income (prices received times yield) per acre is not expected to exceed variable costs per acre, farmers are unlikely to plant any wheat.

| Farm price received<br>(1) | Costs are— | |
|---|---|---|
| | $4.06 greater<br>(2) | $8.12 greater<br>(3) |
| *Per bushel* | *Bushels per acre* | |
| $1.00 | 4.06 | 8.12 |
| 2.00 | 2.03 | 4.06 |
| 3.00 | 1.35 | 2.71 |
| 4.00 | 1.02 | 2.03 |

At a given price level, when expected yield differences for continuous wheat are larger than those shown, economic considerations indicate that the farmer should switch from a summer fallow rotation to a continuous crop rotation. As the price level increases, the 2-year yield difference needed on continuous cropping declines. That is, higher wheat prices encourage farmers to switch from a wheat-fallow rotation to a continuous cropping rotation while higher production costs reverse the incentive. Absolute yield levels do not directly affect the rotation decision and are not shown. However, in dry areas where the probability of a crop failure under continuous cropping is large compared with wheat after summer fallow, farmers may discount the expected average yield from a continuous cropping rotation. In addition, a certain minimum yield is required before a farmer recovers his production costs regardless of cropping sequence.

Regardless of the prices being paid for wheat, before a farmer will switch from wheat-fallow to wheat-wheat, the 2-year production from wheat-wheat must be greater than the 2-year production from wheat-fallow. The reason for this is that the 2-year production costs of a wheat-wheat rotation are greater than that of a wheat-fallow rotation. In much of the central and eastern areas of the Great Plains States, from North Dakota south to Texas, in parts of Montana, and in parts of the Northwest, such a situation exists. Thus, changes in cropping sequences are likely to occur as prices and costs change. As illustrated, increases in production costs, such as higher prices for fertilizer and seed, will have the reverse effect of higher wheat prices on cropping sequence. Wheat yield levels which are so low that they do not cover a farmer's variable costs at existing wheat prices will cause him to idle the land or switch to more profitable crops.

Thus, an analysis of the economic conditions of production indicates that the greatest shifts in cropping sequences should occur in areas where the annual yield increases from summer fallow are the smallest. In areas of little or no annual yield increase, summer fallow is unlikely to be used unless government acreage control (allotment) programs

TABLE 15.—*Prices received annually and in March and April by North Dakota farmers and acreage planted of all wheat, other spring wheat, and Durum, 1971–76*

| Year | All wheat | Other spring [1] | Durum | Ratio of Durum to other spring |
|---|---|---|---|---|
| | | PRICES RECEIVED | | |
| 1971 | $1. 38 | $1. 38 | $1. 33 | 0. 96 |
| March | 1. 45 | 1. 47 | 1. 40 | . 95 |
| April | 1. 44 | 1. 46 | 1. 40 | . 96 |
| 1972 | 1. 53 | 1. 53 | 1. 55 | 1. 01 |
| March | 1. 35 | 1. 33 | 1. 39 | 1. 04 |
| April | 1. 35 | 1. 33 | 1. 39 | 1. 04 |
| 1973 | 3. 27 | 2. 98 | 3. 93 | 1. 32 |
| March | 1. 98 | 1. 93 | 2. 11 | 1. 09 |
| April | 2. 06 | 2. 01 | 2. 17 | 1. 08 |
| 1974 | 5. 19 | 4. 68 | 6. 33 | 1. 35 |
| March | 5. 56 | 4. 95 | 6. 99 | 1. 41 |
| April | 4. 50 | 4. 03 | 5. 61 | 1. 39 |
| 1975 | 4. 44 | 4. 05 | 5. 18 | 1. 28 |
| March | 4. 38 | 3. 97 | 5. 24 | 1. 32 |
| April | 4. 61 | 4. 03 | 5. 81 | 1. 44 |
| 1976 | 2. 60 | 2. 67 | 2. 47 | . 93 |
| March | 4. 00 | 3. 94 | 4. 10 | 1. 04 |
| April | 3. 81 | 3. 78 | 3. 87 | 1. 02 |
| | | ACREAGE PLANTED<br>*(Thousands)* | | |
| 1971 | 9, 426 | 6, 762 | 2, 592 | . 38 |
| 1972 | 7, 627 | 5, 221 | 2, 333 | . 45 |
| 1973 | 8, 940 | 6, 270 | 2, 590 | . 41 |
| 1974 | 10, 500 | 6, 770 | 3, 600 | . 53 |
| 1975 | 10, 627 | 6, 130 | 4, 080 | . 67 |
| 1976 | 11, 930 | 8, 080 | 3, 710 | . 46 |

[1] Hard Red Spring (HRS) wheat.

Source: (*106, 110, 111*).

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are involved. As expected, the large shifts to continuous cropping occurred in the eastern parts of the Northern Plains States and eastern parts of Kansas, Oklahoma, and Texas (fig. 8) as wheat prices increased from 1972 to 1974. Without acreage allotments or set-aside incentives, much of this area is likely to remain in a continuous cropping sequence unless wheat prices decline substantially.

Farther west, however, where the rainfall declines and the annual yield increase for wheat after summer fallow is larger, the proportion of wheat grown on fallow becomes increasingly dependent on farmers' expected wheat prices. In the central areas of these States, that is, the fallow transitional areas, the proportion of wheat acreage switched from one rotation to another is expected to be sensitive to changes in wheat prices, particularly in areas where annual wheat yields after fallow are several bushels greater than those for continuous cropping. However, in areas where wheat yields after fallow are almost twice the yields for continuous cropping, only extremely high wheat prices will affect cropping sequence. Thus, in important wheat-fallow areas the decline in yields will be large for acreages switching cropping sequences; but, as annual yield differences increase, the proportion of the acreage being switched by farmers will decline.

The example presented above is a great oversimplification of reality in many of the wheat-producing areas. For example, in many areas, the wheat-sorghum-fallow zone in the central one-third of Kansas and Nebraska, conditions are favorable for cropping sequences that include other crops in a rotation. In these cases, the economic analysis becomes more complicated but the principles of analysis remain the same. Yields, crop prices, and production costs for each of the alternative rotations are analyzed, and the one expected to give the highest returns above costs for the relevant rotation period selected.

Prices of alternative crops can be an important factor determining the acreage of wheat grown in an area. Relative prices change from years to year (table 16) in response to changes in supply and demand conditions. In 1973, wheat prices increased substantially more than prices for other major grains (crop/wheat price ratios declined). In 1974, farmers reacted to the higher 1973 prices and planted relatively more acreages of wheat thereby increasing wheat supply. Prices of these other grains then tended to "catch up," bringing about a more "normal" relation among crop prices. Often, farmers can readily adjust between crops like wheat and barley where machinery and management requirements are similar.

TABLE 16.—*Ratio of season average price per bushel received by U.S. farmers for selected grains, 1959–76* [1]

| Marketing year [2] | Barley / Wheat | Oats / Wheat | Sorghum / Wheat | Corn / Wheat |
|---|---|---|---|---|
| 1959–60 | 0.49 | 0.37 | 0.49 | 0.60 |
| 1960–61 | .48 | .34 | .48 | .57 |
| 1961–62 | .53 | .35 | .55 | .60 |
| 1962–63 | .45 | .30 | .50 | .55 |
| 1963–64 | .49 | .34 | .53 | .60 |
| 1964–65 | .69 | .46 | .77 | .85 |
| 1965–66 | .76 | .46 | .73 | .86 |
| 1966–67 | .65 | .41 | 63 | .76 |
| 1967–68 | .73 | .47 | .71 | .74 |
| 1968–69 | .74 | .48 | .77 | .87 |
| 1969–70 | .70 | .46 | .86 | .93 |
| 1970–71 | .73 | .47 | .86 | 1.00 |
| 1971–72 | .74 | .45 | .78 | .77 |
| 1972–73 | .69 | .41 | .78 | .89 |
| 1973–74 | .54 | .30 | .54 | .65 |
| 1974–75 | .67 | .38 | .69 | .73 |
| 1975–76 | .68 | .41 | .67 | .71 |
| 1976–77 [3] | .79 | .44 | .71 | .77 |

[1] Excludes government payments.

[2] The marketing year for wheat and barley is from July 1 through June 30. Beginning in 1973/74 the marketing year was revised to June 1 through May 31. The marketing year for corn and sorghum runs from October 1 through September 30.

[3] Preliminary.

Source: Calculated from prices in (*104*).

## CONCLUSIONS AND IMPLICATIONS

Since 1949, the acreage, yield, and production of U.S. wheat have shown considerable annual variability. In 1949 an alltime high 83.9 million acres of wheat were planted in the United States. During the fifties and sixties wheat acreage, controlled by a series of government farm programs, declined to reach a low of 48.7 million acres in 1970. After the large wheat export sales of 1972, planted acreage greatly increased, reaching 80.2 million acres in 1976—almost as high as the 1949 level. All wheat-growing regions of the United States have shared in the wheat acreage increases that have occurred since 1972.

The large increase in U.S. wheat production since 1949 is accounted for by a doubling of harvested yields per acre, from about 15 bushels in 1949 to 30 bushels in 1976. During the 1949–76 period, U.S. wheat yields trended upward from 1949, peaking in 1971. Since 1972 the yield trend has been level or declining. Explanation of yield trends and yield variability during the 1949–76 period requires analysis of technical, economic, and climatic developments.

Since 1949, the agribusiness and public sectors have made substantial investments directed at discovery, reduction in costs, and speeding the adoption of innovations. This study has focused on those innovations and production input changes that have increased wheat yields per acre. U.S. wheat farming became more industrialized and consequently more dependent on the rest of the economy during the 1949–76 period. Although farmers made the decisions to adjust production input combinations, they were strongly influenced by changing technical and economic conditions occurring outside of agriculture. During this period, the increasing availability of fertilizer, pesticides, improved wheat varieties, and irrigation facilities at prices that were increasing less rapidly than land prices encouraged the substitution of these inputs for land. Farm programs encouraged the substitution of nonfarm inputs for land and the adoption of land use practices that contributed to an increasing trend in yields.

Much of the change in trend in U.S. wheat yields is explained by farmer adjustments in production input combinations. Input adjustments contributing to wheat yield changes have included changes in (1) summer fallow, (2) soil productivity base, (3) irrigation, (4) wheat varieties, (5) wheat market classes, (6) fertilizer, (7) pesticides, and (8) cultural practices. A decline in the rate of wheat yield increases in the seventies compared to the rate of the fifties and sixties is partially a result of changes in land use practices. The large wheat export sales in 1972 caused an increase in land planted to wheat with less wheat grown on summer follow acreage and more on lower productivity soils.

The amount of irrigated wheat has somewhat stabilized in recent years. Continued irrigation on wheat will depend on economic factors and, in some areas, on how long underground water supplies for irrigation last.

Variety improvement (both within and between wheat classes) have contributed to increased wheat yields during the past quarter century. However, new physiological forms of plant diseases could within a short period of time influence the yield advantage of newer varieties.

Increased use of fertilizer, in combination with wheat varieties more resistant to lodging and responsive to fertilizer, has contributed to increased wheat yields. However, the high response rates to fertilizer obtained in the generally favorable climatic conditions of the sixties may be greatly influenced with the return of drought, especially for wheat grown in semiarid regions. Because wheat is not one of the field crops more responsive to applied fertilizer, continued use of fertilizer is dependent upon the relationship between fertilizer costs and wheat prices.

Pesticides, particularly herbicides, are important inputs to wheat yields. However, environmental concerns and associated regulations on use of pesticides could have a significant impact on future pesticide use.

As wheat yields have been greatly increased since 1949 by increased use of, or improvements in, these inputs or production practices, maintaining and increasing wheat yields in the future depend on continued use of presently known production inputs and the acquiring of new knowledge through research. The potential yield loss associated with the removal of one or several inputs increases as yields are increased. Consequently, the continuous monitoring of production inputs is a necessary prerequisite to wheat yield prediction.

Continued high yield levels that require high rates of input use by farmers will also depend on favorable input/wheat price ratios. Future shortages of energy or other resources that supply the raw materials for fertilizer, pesticides, irrigation, and mechanical tillage could adversely alter the economic conditions conducive to high yield levels.

Many of the large year-to-year changes in U.S. wheat yields were caused by year-to-year variations in climate. For example, unfavorable climatic conditions in the United States contributed to lower yields after 1972, particularly in 1974. Climatic effects and technology effects are often confounded, however, making it extremely difficult to precisely measure the relative importance of climatic variations and of changes in production input combinations in a particular year. Lack of precise information on changes in production inputs contributes to this measurement problem. Many wheat experiments are not specifically designed to analyze the impact of annual climate variability of wheat/input response relationships. In many cases where experimental data could provide information on crop responses to production inputs over a range of climatic conditions, the original data needed to estimate standard deviations and coefficients of variation were not published and often are no longer available.

However, some data were available to calculate the mean yield, standard deviation of yield, and the coefficient of variation (mean yield divided by the standard deviation) for both an "improved" production input or practice and for a controlled situation where both were subjected to the same local climate variations. The results show that when a production input increased, the mean yield absolute yield variability (standard deviation) usually increased but occasionally declined. Where yields were increased over the controlled situation, the relative yield variability (coefficient of variation) associated with annual climate variations declined.

These results imply that as farmers adopted production practices that increase wheat yields, those yields became *relatively* less dependent on year-to-year variations in climate. However, this conclusion is limited to the 1949–76 period of study. More conclusive evidence requires additional data for a wider range of climate, soil, and production input combinations. Wheat yields appear only *relatively* less responsive to climate variations; the large standard deviations and coefficients of variation ranging from 20 to 50 percent for "improved" production practices show yields remained quite responsive to annual climate changes. Nor does the application of the technology which has raised U.S. yield levels guarantee crop failure will not be caused by changes in climate or other natural conditions.

Nevertheless, it appears that since 1949 U.S. wheat production has become relatively less dependent on "normal" climatic variations and more dependent on changes in the U.S. and world economic conditions, particularly changes in product demand and input supply relationships. The doubling of U.S. wheat production since 1949 has been achieved by doubling land productivity. Increased yields resulted from the adoption of certain production practices and increased usage of inputs supplied by industry. U.S. wheat farming has become more industrialized and consequently more dependent on the rest of the economy but less dependent on domestic variations in climate.

As a result of the increased industrialization of agriculture, U.S. wheat yield levels have become more dependent on the capability of the industrial sectors of the U.S. economy to respond to changing natural, economic, and social conditions. At the same time, the increased dependency of the U.S. wheat market on export demands has made U.S. wheat prices more vulnerable to variations in the climatic, economic, and political conditions of foreign countries. An implication of this increased export dependency is a greater need for information on foreign production to make rational wheat production and marketing decisions. Future U.S. yield increases or even maintenance of current yield levels will depend on a continuation of efforts to discover, reduce the costs, and speed the adoption of innovations. The agricultural research system must be ready to meet new challenges.

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