Classification of Irrigated Land Using Satellite Imagery, the High Plains Aquifer, Nominal Date 1992

By Sharon L. Qi, Alexandria Konduris, David W. Litke, and Jean Dupree

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ABBREVIATIONS USED IN THIS REPORT

CRP	Conservation Reserve Program
DN	digital number
DTED	Digital Terrain Elevation Data
EROS	Earth Resources Observation Systems
EDC	EROS Data Center
FSA	Farm Service Agency
GIS	Geographic Information System
HPGW	High Plains Regional Ground-Water study
IR	infrared
km	kilometer
km^2	square kilometer
LUDA	Land-Use Data Analysis Program
mi^2	square mile
m	meter
µm	micrometer
MRLC	Multi-Resolution Land Characterization Consortium
MSS	Landsat Multispectral Scanner
NASS	National Agricultural Statistics Service
NAWQA	National Water-Quality Assessment Program
NLCD	National Land-Cover Data
NOAA	National Oceanic and Atmospheric Administration
NWI	National Wetlands Inventory
RASA	Regional Aquifer-System Analysis
TM	Landsat Thematic Mapper
USDA	U.S. Department of Agriculture
USDOC	U.S. Department of Commerce
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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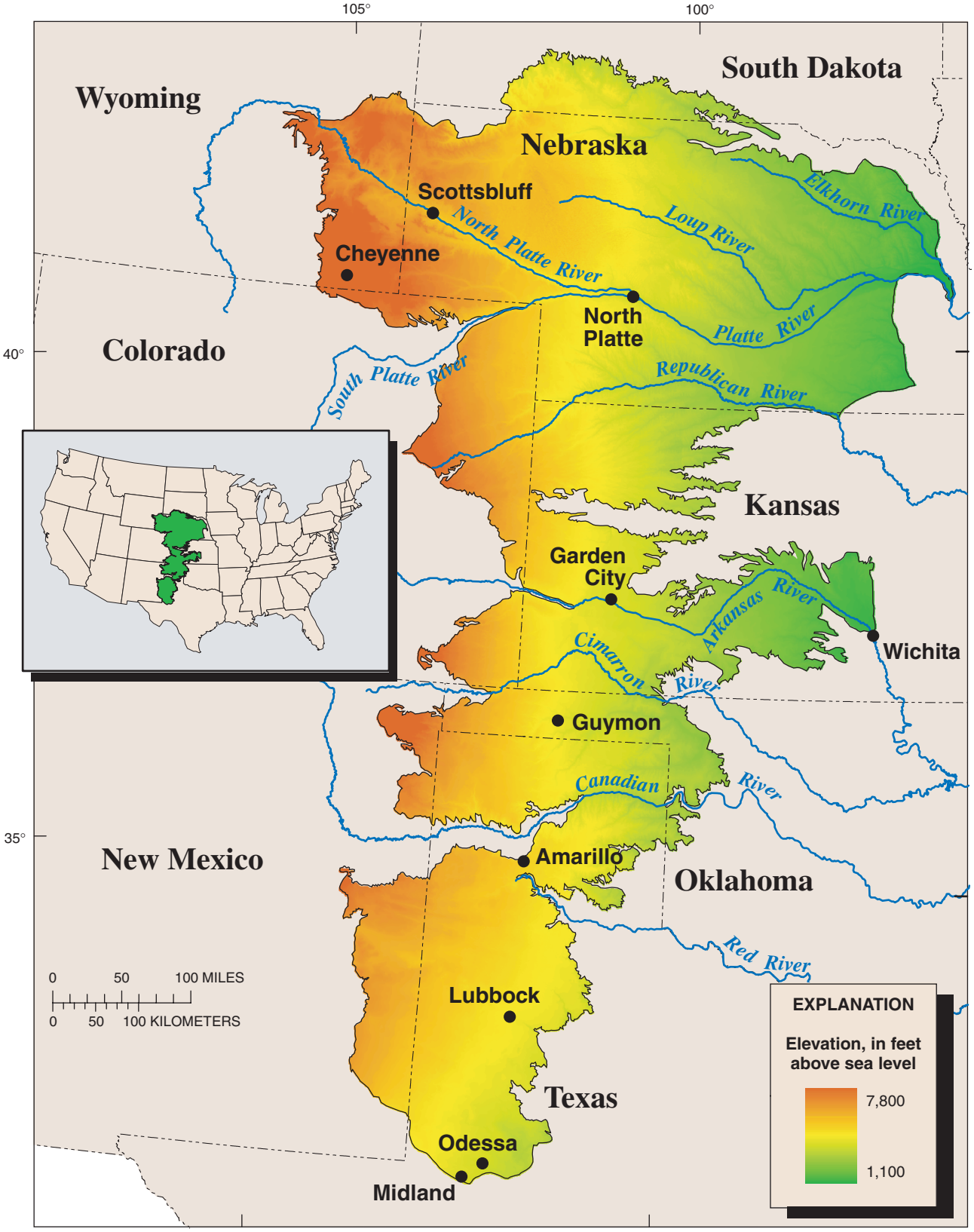
Abstract

Satellite imagery from the Landsat Thematic Mapper (nominal date 1992) was used to classify and map the location of irrigated land across the High Plains aquifer. The High Plains aquifer underlies 174,000 square miles in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. The U.S. Geological Survey is conducting a water-quality study of the High Plains aquifer as part of the National Water-Quality Assessment Program. To help interpret data and select sites for the study, it is helpful to know the location of irrigated land within the study area. To date, the only information available for the entire area is 20 years old. To update the data on irrigated land, 40 summer and 40 spring images (nominal date 1992) were acquired from the National Land Cover Data set and processed using a band-ratio method (Landsat Thematic Mapper band 4 divided by band 3) to enhance the vegetation signatures. The study area was divided into nine subregions with similar environmental characteristics, and a band-ratio threshold was selected from imagery in each subregion that differentiated the cutoff between irrigated and nonirrigated land. The classified images for each subregion were mosaicked to produce an irrigated land map for the study area. The total amount of irrigated land classified from the 1992 imagery was 13.1 million acres, or about 12 percent of the total land in the High Plains. This estimate is approximately 1.5 percent greater than the amount of irrigated land reported in the 1992 Census of Agriculture (12.8 millions acres). This information was also compared to a similar data set based on 1980 imagery. The 1980 data classified 13.7 million acres as irrigated. Although the change in the amount of irrigated land between the two times was not substantial, the location of the irrigated land did shift from areas where there were large ground-water-level declines to other areas where ground-water levels were static or rising.

INTRODUCTION

The High Plains aquifer underlies 174,000 square miles (mi^2) in parts of eight States (fig. 1). The aquifer is an important national resource, providing water for about 27 percent of the irrigated land in the United States and about 30 percent of the ground water used for irrigation in the United States (Dennehy, 2000). Irrigation is the dominant water use in the High Plains, accounting for withdrawals during 1995 of more than 15 billion gallons per day (U.S. Geological Survey National Water Information System database).

Substantial pumping of the High Plains aquifer for irrigation since about the 1940's has resulted in water-level declines in some parts of the aquifer of more than 100 feet (McGuire and Sharpe, 1997). Concern about these declines led the U.S. Congress in 1984 to institute a water-level monitoring program for the aquifer. Water quality of the aquifer is a more recent concern. There have been local studies of water quality, but no large-scale, comprehensive assessment has been made of the entire aquifer system. Knowledge of the quality of water resources is important because of the implications to human and aquatic



Base from U.S. Geological Survey
1:100,000 Digital Line Graphs (DLG).
Elevation data from U.S. Geological Survey
1:250,000 Digital Elevation Models (DEM).

Figure 1. Location of High Plains Regional Ground-Water Study area.

health. In 1991, the U.S. Geological Survey (USGS) began full implementation of the National Water-Quality Assessment (NAWQA) Program. The long-term goals of the NAWQA Program are to describe the status and trends in the quality of the Nation's surface- and ground-water resources and determine the natural and anthropogenic factors affecting the water quality (Gilliom and others, 1995). The High Plains Regional Ground Water (HPGW) study began in October 1998 and represents a modification of the traditional NAWQA design in that the ground-water resource is the primary focus of the investigation.

The HPGW study requires detailed and current information about the location of irrigated land for analyzing water-quality results with respect to land use and the selection of new study sites and for use in ground-water vulnerability modeling. The only existing information on irrigated land for the entire High Plains area is approximately 20 years old (Thelin and Heimes, 1987), and it provides only the percentage of irrigated land in 4-square-kilometer (km^2) grid cells across the High Plains, not the actual locations of irrigated fields.

Purpose and Scope

The purpose of this report is to present the methodology and results of an effort to classify and map irrigated land in the High Plains by using satellite data acquired for a nominal date of 1992. Additionally, a comparison was made between the amount and location of irrigated land determined in the early 1980's (Thelin and Heimes, 1987) with estimates made in this report to determine if the amount of irrigated land has increased, stayed the same, or decreased. This information will help in the analysis of water-quality data, modeling efforts, and future planning and design of the HPGW study.

Acknowledgments

The timely effort of the U.S. Department of Agriculture's Farm Service Agency in providing the historical ground-reference information for approximately 1,000 square miles of the High Plains is gratefully acknowledged. The authors also acknowledge the USGS National Mapping Discipline Earth Resources Observation Systems Data Center for providing the original Landsat Thematic Mapper (TM) imagery.

DESCRIPTION OF STUDY AREA

The High Plains study area occupies the higher elevations of the Great Plains physiographic province. It rises in elevation from 1,100 feet in the east to 7,800 feet in the west and was formed by deposition of sediments of Tertiary age that were eroded from the ancestral Rocky Mountains and carried eastward by streams. The principal geologic unit of the High Plains aquifer is the Ogallala Formation, which consists of a sequence of unconsolidated clays, silts, sands, and gravels of Miocene to Pliocene age. The gently sloping plains and small relief of the High Plains area make it ideal for agriculture. However, the climate is naturally dry with annual precipitation ranging from 16 inches per year in the west to 28 inches per year in the east. The natural vegetation in this area is short-grass prairie, and the natural precipitation can support only drought-resistant crops such as wheat (Dennehy and others, 2002).

Beginning in the 1930's, advances in well technology made deep wells feasible. Development of the High Plains aquifer started in Texas, where depths to water were small, and expanded northward. During 1949–78, irrigated acreage in the High Plains increased from about 2 million acres to 13 million acres, and ground-water pumpage increased from about 4 million acre-feet to 23 million acre-feet (Gutentag and others, 1984). The High Plains aquifer currently (2002) sustains the economy and population of the region by providing water for irrigation, industry, and domestic and public water supplies.

Agricultural practices can increase the rate of recharge to the aquifer; for example, water can more easily percolate downward from fallow fields and from fields where crop growth is at an early stage, as compared to areas covered with natural vegetation (Luckey and Becker, 1999). Estimated recharge to the High Plains aquifer in Oklahoma is almost three times as large as it was prior to development of the aquifer because of dryland cultivation (bare soil), precipitation, and flood irrigation practices for the first 30 years of the aquifer's development (Luckey and Becker, 1999). More detailed descriptions of the study area are in Dennehy and others (2002).

PREVIOUS EFFORTS TO CLASSIFY IRRIGATED LAND

Information about the location of irrigated land is important to the HPGW study, but uniform, detailed, and more current locational information for this large study area is not available. Historical data have been collected by surveys of a statistical sampling of farmers, in which case the results commonly are reported in a tabular format for each county or other administrative unit. Older, georeferenced spatial data may be available in the form of paper maps that report land-use information by parcel on plat maps or on aerial photographs. More recently, land-use estimates have been made using remote sensing techniques and aerial photography or satellite imagery, and results are reported in digital Geographic Information System (GIS) format. This section summarizes selected previous efforts to classify irrigated land conducted at scales ranging from local and State to regional to nationwide.

Local and State Efforts

Information about irrigated land use is needed at the local and State levels for land-use planning, management of irrigation districts, natural resource management, and a multitude of other purposes. Accordingly, localized data-collection efforts are designed to meet specific needs. For administering various farm programs, county Farm Service Agency (FSA) offices maintain hardcopy maps of farm parcels and associated annual farm reports that list field production status. These offices, as well as Cooperative Extension Agency offices, also may produce fact sheets that include tabular data about county agricultural information such as irrigated land. At the multicounty level, irrigation districts (such as the Texas Underground Water District #1 and the Pathfinder Irrigation District in Nebraska), ground-water protection districts (such as the Kansas GW District #3), and various water boards (such as the Texas Water Development Board) commonly maintain paper or digital maps showing irrigated land (or locations of irrigation wells) within their boundaries, which are used for various administrative purposes. Universities and consulting firms also may determine irrigated acreage as part of ground-water quantity or quality studies; for example, land use during 1997 (including crop type and irrigation status) was determined for the Central Platte River Valley of Nebraska as part of the Platte River Cooperative Hydrology Study (Dappen and Tooze, 2001).

State-level agencies also provide land-use and irrigation information. Statewide maps of irrigated land in Nebraska derived from Landsat imagery were published for the years 1972–88. The Kansas Applied Remote Sensing program has produced digital county land-use data sets (Kansas Data Access and Support Center, 1993), although these do not differentiate land within the agricultural land-use class. The Kansas State Water Use Office has also derived maps of irrigated land using well permit and pumpage data (Kenneth Nelson, Data Access and Support Center-Kansas Geological Survey, written commun., 1999).

Due to the differing techniques, objectives, and years of data collection for these local and State efforts, this information cannot be easily synthesized into a single High Plains studywide data set.

Regional Efforts

Two data sets are available that report the location of irrigated land in the High Plains study area. A recent study (Goetz and others, 2000) located fields irrigated by pivots in the High Plains during 1985 and 1996. For this study, irrigated fields were manually digitized using Landsat imagery. This study, however, did not include the entire study area or estimate the location of fields irrigated by methods other than pivots.

A more comprehensive estimate of irrigated acreage in the High Plains during 1980 was conducted by the USGS as part of the Regional Aquifer-System Analysis (RASA) Program (Thelin and Heimes, 1987). Satellite imagery acquired from the Landsat 2 Multispectral Scanner (MSS) was used to map irrigated land in the High Plains. The main objective of this project was to determine the amount of irrigated land in the High Plains in order to estimate water use. The actual location of irrigated fields was less important than obtaining an accurate estimate of the amount of irrigated land. Therefore, the data were aggregated into a percentage of irrigated land in 4-km^2 cells in order to even out misclassified pixels and provide an overall estimate of total irrigated land.

Thelin and Heimes (1987) used crop phenologies (growth patterns) to determine the best dates to

acquire imagery in order to see the crops at their greenest. A band-ratio algorithm (Landsat MSS band 7 divided by band 5) was then used to create a vegetation index for a single-band image made up of pixels of continuous shades from white to black (greyscale). The brighter the pixels the more likely that the pixel represented irrigated land. A threshold, or cut-off, value was then chosen for each scene to distinguish irrigated land from nonirrigated land. Ground-reference information about parcels of land (crops and irrigation status, not farmed, and so forth) was obtained for 13 counties in the study area, and the percentage of correctly mapped, irrigated-land estimates was calculated for each of the 13 counties. Estimates of correctly mapped irrigated land ranged from 22 to 98 percent. Extensive editing was needed in certain areas to correct misclassified pixels where spectral overlap was a problem, such as vegetation areas along streams that were classified as irrigated land. The data were then aggregated into 4-km^2 cells and the percentage of irrigated land was computed for each cell. This study estimated a total of 13.7 million irrigated acres in 1980, or 12.3 percent of the High Plains area.

National Efforts

Classifications of land use in the United States, including the High Plains, have been made for the nominal year of 1980 (Fegeas and others, 1983) and for the nominal year of 1992 (Vogelmann and Wickham, 2000). These classifications, however, do not specify irrigated land but rather categorize agricultural land use by using a modified Anderson classification system (Anderson and others, 1976) in which croplands are not differentiated beyond a cropland and pasture category (1980 data) or beyond pasture/hay, row crops, and small grains categories (1992 data).

Irrigated land is estimated, however, in nationwide county data tabulated by the U.S. Department of Commerce (USDOC) and by the U.S. Department of Agriculture (USDA). The USDOC has collected county-level information on irrigated acreage at approximately 5-year intervals since about 1950 as part of the Census of Agriculture, but digital data are not available for censuses taken before 1978. Census estimates are produced according to exacting statistical methods; as a result, each piece of information has an associated sampling error computed as a percentage of the reported value. For example, county irrigated estimates for 1992 for Nebraska have errors ranging from 0.6 to 7.1 percent (U.S. Bureau of the Census, 1994). This error does not include nonsampling error, however, which consists of errors in data reported on the census forms and associated processing errors.

In addition to the Census of Agriculture (done every 5 years), the USDA also has tabulated irrigation information by county for each year since about 1950 through cooperative agreements between the National Agricultural Statistics Service (NASS) and individual State agricultural statistics services. These estimates are based on smaller sample sizes than the national Census of Agriculture, and the estimates therefore are calibrated and adjusted periodically on the basis of Census of Agriculture data. The NASS estimates of irrigated acreage combined with the Census of Agriculture data are useful to show trends in the amount of irrigated acreage; however, the estimates do not indicate the location of irrigated land. Figure 2 shows that irrigated acreage increased substantially from 1949 to 1978, decreased from 1978 to 1987, and then increased again from 1987 to 1997.

Another deficiency of the national tabular data sets is that the types of data collected by States vary. Not all States report irrigated acreage for all crops; for example, information about the amount of irrigated hay is not available for Nebraska, and irrigated acreage information is not available for sugar beets, soybeans, and sunflower seeds within the study area. NASS data currently (2002) are available in digital format for years after about 1963 (National Agricultural Statistics Service, 2002). Both NASS and Census of Agriculture county data are incomplete due to nonreporting counties or counties where information is withheld due to confidentiality.

NASS county data were compiled for the High Plains study area for years 1972 through 1997. Total irrigated land cannot be estimated from NASS data due to missing information; however, available tabulated data indicate that the principal crops in the study area were corn, wheat, sorghum, cotton, peanuts, dry beans, and alfalfa (table 1). Irrigated corn acreage has steadily increased in the study area from 2.53 million acres in 1972 to 6.95 million acres in 1992. Irrigated wheat has remained steady over this time period at about 2 million acres, while acreage of irrigated cotton has varied from about 1 million acres to about 2 million acres (with the exception of 1972). Sorghum

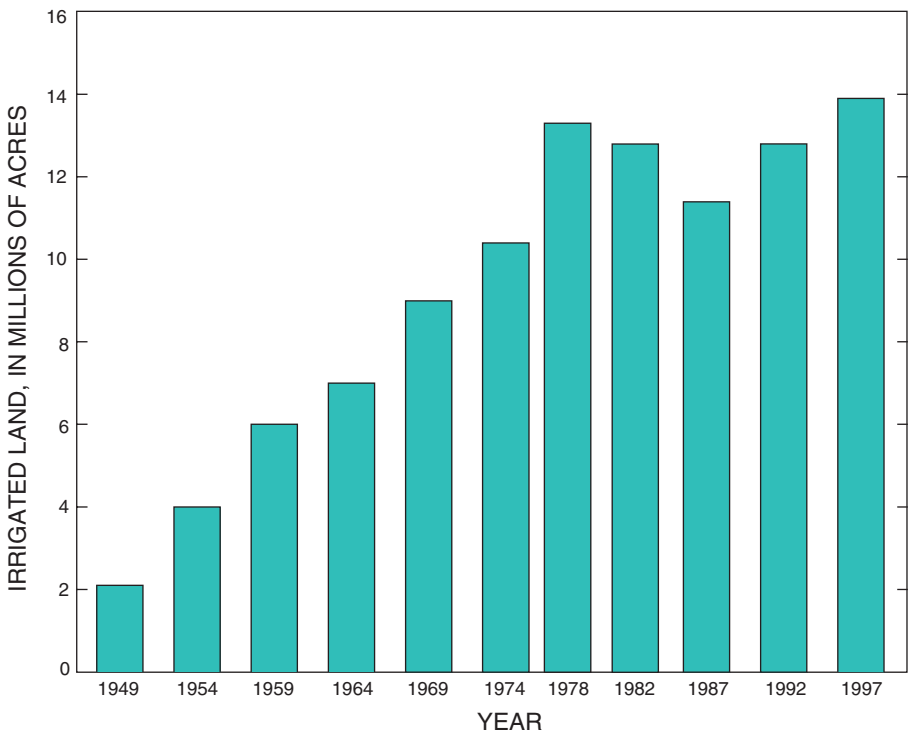


Figure 2. Total irrigated acres in the High Plains study area from 1949 to 1997 (data from Gutentag and others [1984, figure 22] and the Census of Agriculture).

irrigated acreage has decreased from 2.25 million acres in 1972 to 1.54 million acres in 1992. The sum of irrigated acreage for 1992 for available crop data is 12.7 million acres, compared to the Census of Agriculture estimate of 12.8 million acres. The difference can be attributed to nontabulated crops (hay, sugar beets, soybeans, and sunflower seeds) and nonreporting counties.

Although the Census of Agriculture and the NASS data can be used for identifying trends in crop patterns and irrigated acreage, they still are a statistical sampling and provide no information as to the location of irrigated land. Satellite imagery reveals almost every square foot of land surface in the High Plains and provides the opportunity to locate and quantify the total amount of irrigated land.

CLASSIFICATION OF IRRIGATED LAND FOR 1992

Satellite images (scenes) taken by the Landsat TM scanner with a spatial resolution of 30 meters (m) (each pixel in the image is 30 m by 30 m) were mosaicked to provide coverage of the study area. Forty scenes were taken in the summer months (leaf-on) and 40 scenes were taken in the winter months (leaf-off). Because the satellite sensor records spectral signatures that represent differences in soil moisture, plant health, atmospheric conditions, and many other factors, the study area was subdivided into nine subregions based on similar environmental characteristics (fig. 3) such as precipitation, ecoregions, and regional crop patterns and also to limit file size for processing. Therefore, scenes processed for a given subregion should have similar signatures (characteristic reflectance of light from portions of the electromagnetic spectrum). Leaf-on and leaf-off scenes for each subregion were processed separately to classify irrigated fields. The image-processing methodology was similar to that used previously by Thelin and Heimes (1987) so comparisons could be made with the more current (nominal 1992) data.

Description of National Land-Cover Data

The Landsat TM data set used for the HPGW study was nominal 1992, unclassified National Land-Cover Data (NLCD) (fig. 4). The NLCD is produced by the Multi-Resolution Land Characterization Consortium (MRLC), which is a partnership of

Table 1. Total irrigated acreage for selected principal crops in the High Plains study area, 1972–97

[Data from National Agricultural Statistics Service (NASS)]

Crop Year	Corn	Wheat	Sorghum	Cotton	Peanuts	Dry beans	Alfalfa	Total
1972	2,530,000	389,000	2,250,000	1,550,000	2,930	147,000	305,000	7,173,930
1973	2,840,000	1,530,000	2,530,000	1,540,000	3,040	150,000	315,000	8,908,040
1974	3,150,000	1,790,000	2,120,000	1,640,000	2,650	160,000	332,000	9,194,650
1975	3,420,000	1,990,000	2,240,000	1,400,000	3,030	186,000	343,000	9,582,030
1976	3,840,000	1,910,000	1,990,000	1,450,000	3,030	179,000	358,000	9,730,030
1977	4,390,000	1,900,000	1,630,000	1,780,000	3,100	164,000	371,000	10,238,100
1978	4,530,000	1,690,000	1,720,000	1,860,000	3,240	173,000	424,000	10,400,240
1979	4,780,000	1,770,000	1,580,000	2,040,000	3,510	192,000	443,000	10,808,510
1980	4,920,000	2,050,000	1,680,000	2,130,000	2,930	234,000	463,000	11,479,930
1981	4,910,000	2,360,000	1,860,000	2,120,000	3,710	319,000	461,000	12,033,710
1982	4,510,000	2,440,000	1,990,000	1,510,000	11,000	296,000	431,000	11,188,000
1983	3,290,000	2,300,000	1,150,000	1,200,000	16,000	185,000	444,000	8,585,000
1984	4,640,000	2,410,000	1,590,000	1,570,000	33,800	241,000	446,000	10,930,800
1985	4,900,000	2,280,000	1,680,000	1,300,000	45,100	247,000	460,000	10,912,100
1986	5,030,000	2,250,000	1,420,000	1,200,000	25,100	296,000	419,000	10,640,100
1987	4,600,000	2,020,000	1,070,000	1,110,000	17,200	315,000	506,000	9,638,200
1988	4,930,000	1,840,000	958,000	1,320,000	17,700	279,000	507,000	9,851,700
1989	5,410,000	2,090,000	1,280,000	1,300,000	21,100	314,000	519,000	10,934,100
1990	6,290,000	2,130,000	946,000	1,500,000	30,600	373,000	175,000	11,444,600
1991	6,790,000	1,960,000	908,000	1,720,000	50,500	304,000	586,000	12,318,500
1992	6,950,000	2,000,000	1,540,000	1,350,000	44,800	230,000	543,000	12,657,800
1993	6,840,000	1,930,000	675,000	1,580,000	46,200	277,000	515,000	11,863,200
1994	7,280,000	1,830,000	637,000	1,620,000	53,400	299,000	582,000	12,301,400
1995	6,910,000	1,840,000	685,000	1,840,000	44,100	313,000	581,000	12,213,100
1996	7,250,000	1,880,000	875,000	1,810,000	80,200	287,000	594,000	12,776,200
1997	7,260,000	1,830,000	699,000	1,690,000	130,000	250,000	534,000	12,393,000

Federal agencies that produce or use land-cover data. Partners include the USGS, U.S. Environmental Protection Agency (USEPA), the U.S. Forest Service, and the National Oceanic and Atmospheric Administration (NOAA). The base data for NLCD were leaf-off and leaf-on TM imagery for the entire United States and were processed by the USGS Earth Resources Observation Systems (EROS) Data Center (EDC). Other ancillary data layers used by the EROS Data Center to help classify the NLCD included USGS 3-arc second Digital Terrain Elevation Data (DTED) and derived slope, aspect, and shaded relief data, Bureau of the Census population and housing density data, land-use data from the USGS Land-Use Data Analysis (LUDA) program, and National Wetlands Inventory (NWI) data. It is important to note the limitations of the NLCD imagery in terms of its use for this project. Because the NLCD imagery was obtained for a different purpose, the analysts were unable to choose the dates of imagery that may have been more appropriate for the goals of this project. For example, the analysts would want to acquire the most cloud-free imagery possible at a time when the crops were greenest in each region of the study area to classify irrigated land. These may not be the images that the MRLC chose to satisfy the goals of the NLCD.

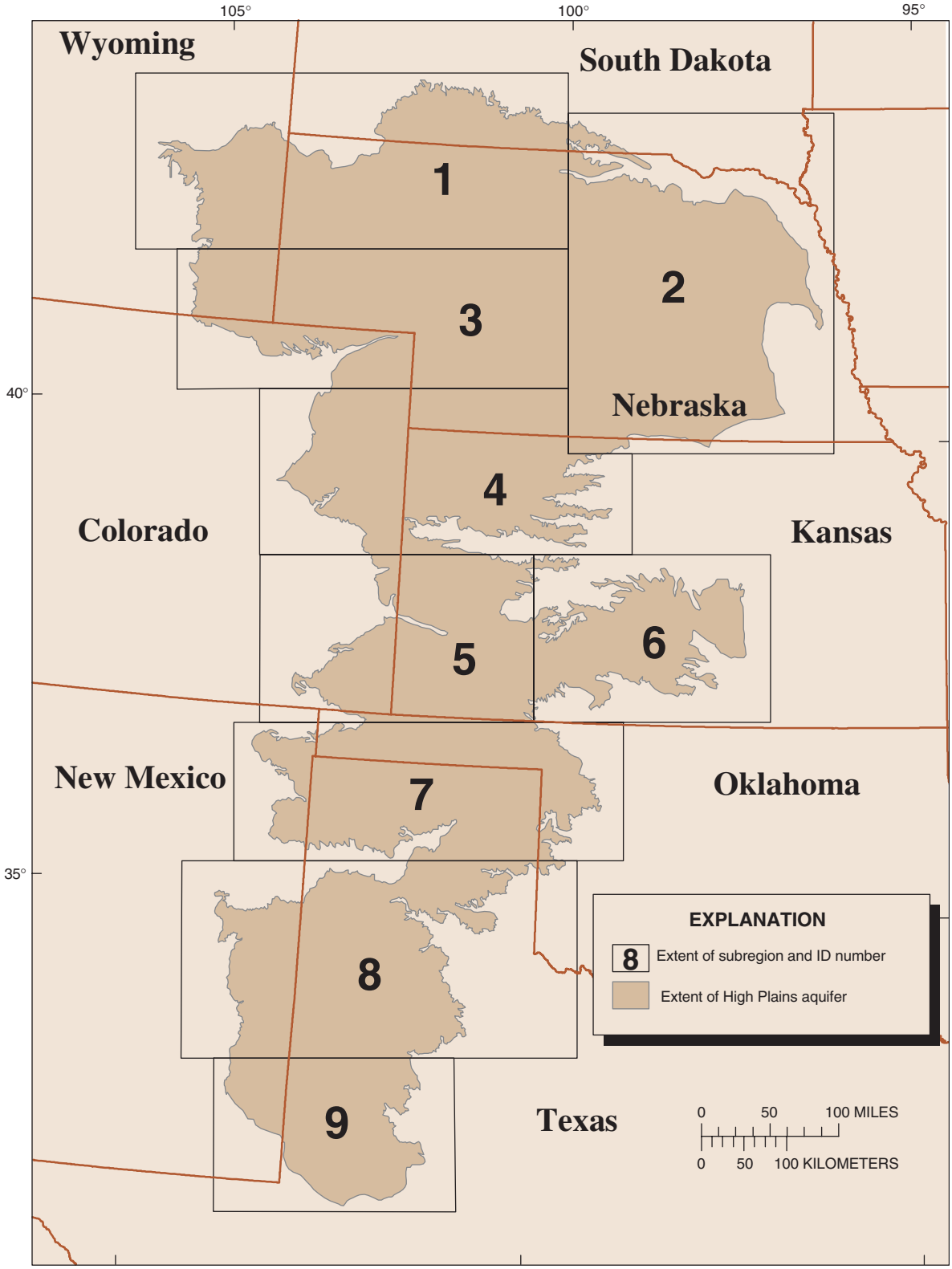


Figure 3. Location and distribution of subregion boundaries.

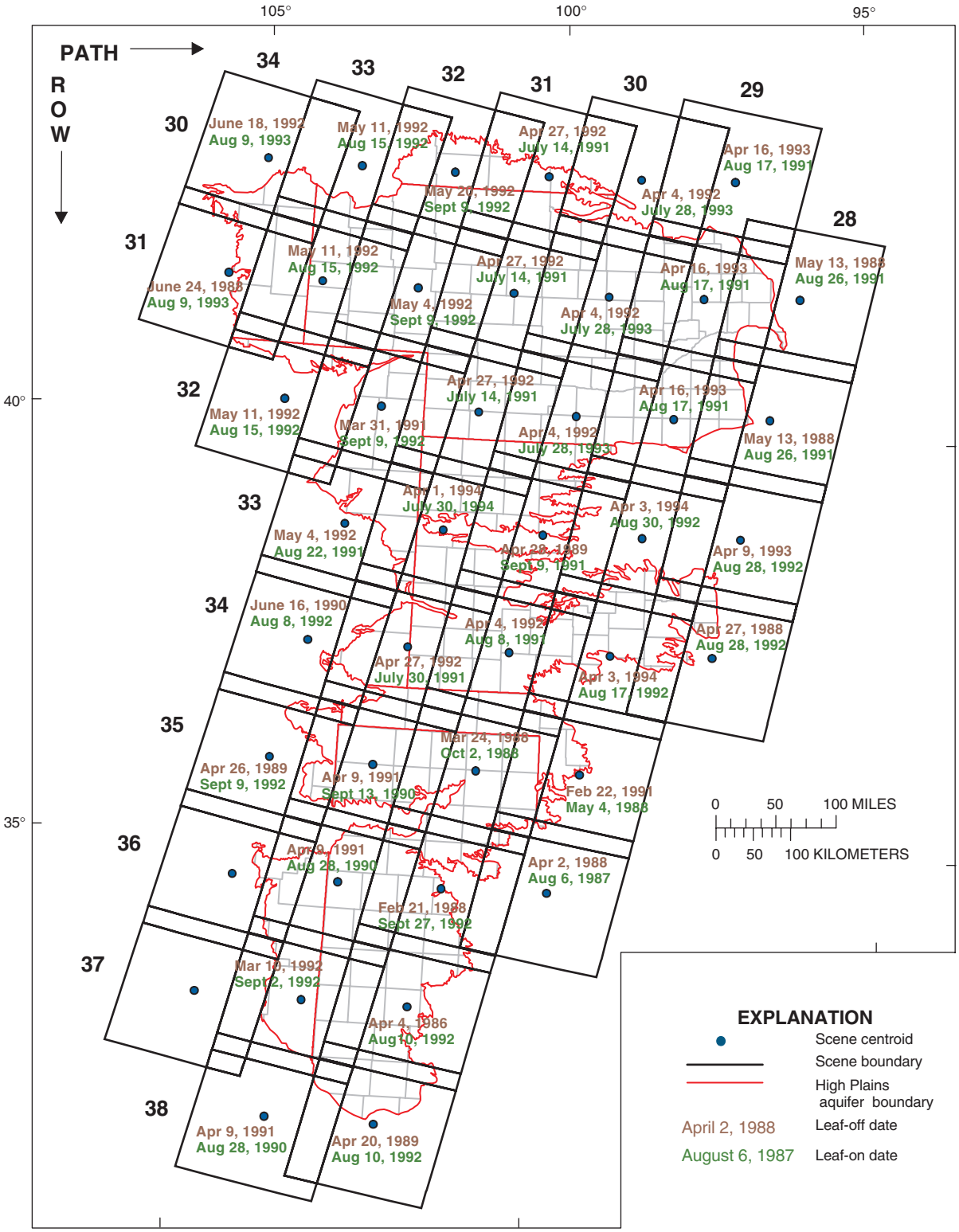


Figure 4. Location of Landsat TM scene boundaries and the dates that they were acquired.

Additionally, the data received from the EDC were adjusted using a histogram matching technique in regions where scene boundaries overlapped.

Because the scene dates were chosen by the MRLC team, an evaluation of the utility of NLCD imagery for this project was made. A comparison of the scene dates was made with phenologies (growth patterns) for crops within the High Plains study area. Based on the planting, maturity, and harvesting dates for each of the major crops (U.S. Department of Agriculture, 1997), ideal dates (in terms of identifying crops and irrigated land) for acquisition of satellite imagery were determined for crops in the study area (Martinko and others, 1981). Scenes farther from these ideal dates are likely to result in greater uncertainty in the identification of irrigated land.

For each State included in the High Plains study area, planting times, growing season, and harvesting times were plotted on a monthly time line for several dominant crops grown in that State (fig. 5). Approximate, ideal TM dates were then plotted for each dominant crop for each State (expressed as early July or mid-July, not as a single day) (Martinko and others, 1981).

The scene dates for leaf-on for all the crops except winter wheat were then plotted on the same time lines to determine how close the scene dates were to the ideal dates (dark green shading). For winter wheat, the leaf-off dates were plotted because winter wheat is planted in the fall, lies dormant over winter, and matures in the spring, not midsummer when other crops mature. The report by Martinko and others (1981) did not report on spring wheat; therefore, no ideal dates are given.

Leaf-on dates generally occurred after the ideal dates but before the harvesting of any of the major crops in each State. A majority of the leaf-off dates occurred before or near the ideal dates for seeing winter wheat and are within the spring growing season. Therefore, the NLCD imagery should have captured the major crops when they were still on the fields in midsummer and also captured the presence of winter wheat in the early spring. The exception is alfalfa, which can have multiple cuttings every growing season, so it may or may not have been captured for the selected dates of imagery.

Data Preprocessing

All of the NLCD data received from the EROS Data Center were already georectified and corrected for atmospheric distortions. The imagery was received in a generic binary format. Each file consisted of four spectral TM bands: band 3 (visible red), band 4 (near infrared), band 5 (mid-infrared; 1.55–1.75 millimeters), and band 7 (mid-infrared; 2.09–2.35 millimeters). The preprocessing steps involved dividing the imagery into nine subregions based on common environmental conditions by visually inspecting overlays of environmental data sets such as crop patterns, precipitation, and ecoregions (fig. 3). Dividing the imagery into subregions also limited file size for processing purposes. This would help ensure that the data being processed in a given subregion would have similar signatures and that the selected threshold to distinguish irrigated from nonirrigated land would be appropriate for that subregion. The next step was to use the NLCD classification of agricultural land to remove nonagricultural areas (masking) that could interfere with the results of the ratio (such as the spectral overlap between riparian pixels and irrigated agriculture pixels). A band ratio (near infrared over visible red) was then calculated similar to Thelin and Heimes (1987) to enhance the vegetation signature. Finally, samples of pixel brightness minimums, maximums, means, and ranges were collected to statistically select a threshold value for classifying land as irrigated or nonirrigated (fig. 6).

Applying the Agricultural Mask

In addition to the unclassified raw TM data, the classified NLCD data for the same scenes were retrieved. Because the MRLC had already spent a great amount of time classifying the TM data into land-cover classes with the use of extensive ancillary data, it was decided that the agricultural classes would be used to mask out pixels that were not considered agricultural land. The agricultural classes included row crops, small grains, pasture/hay, and fallow. The NLCD is still (2002) in the process of being checked for accuracy by the EDC. After the mask was applied, a visual spot comparison over the entire study area was made with the original imagery to determine the accuracy of the NLCD classification. On the basis of this visual inspection, it was determined that the NLCD data were appropriate for this masking procedure.

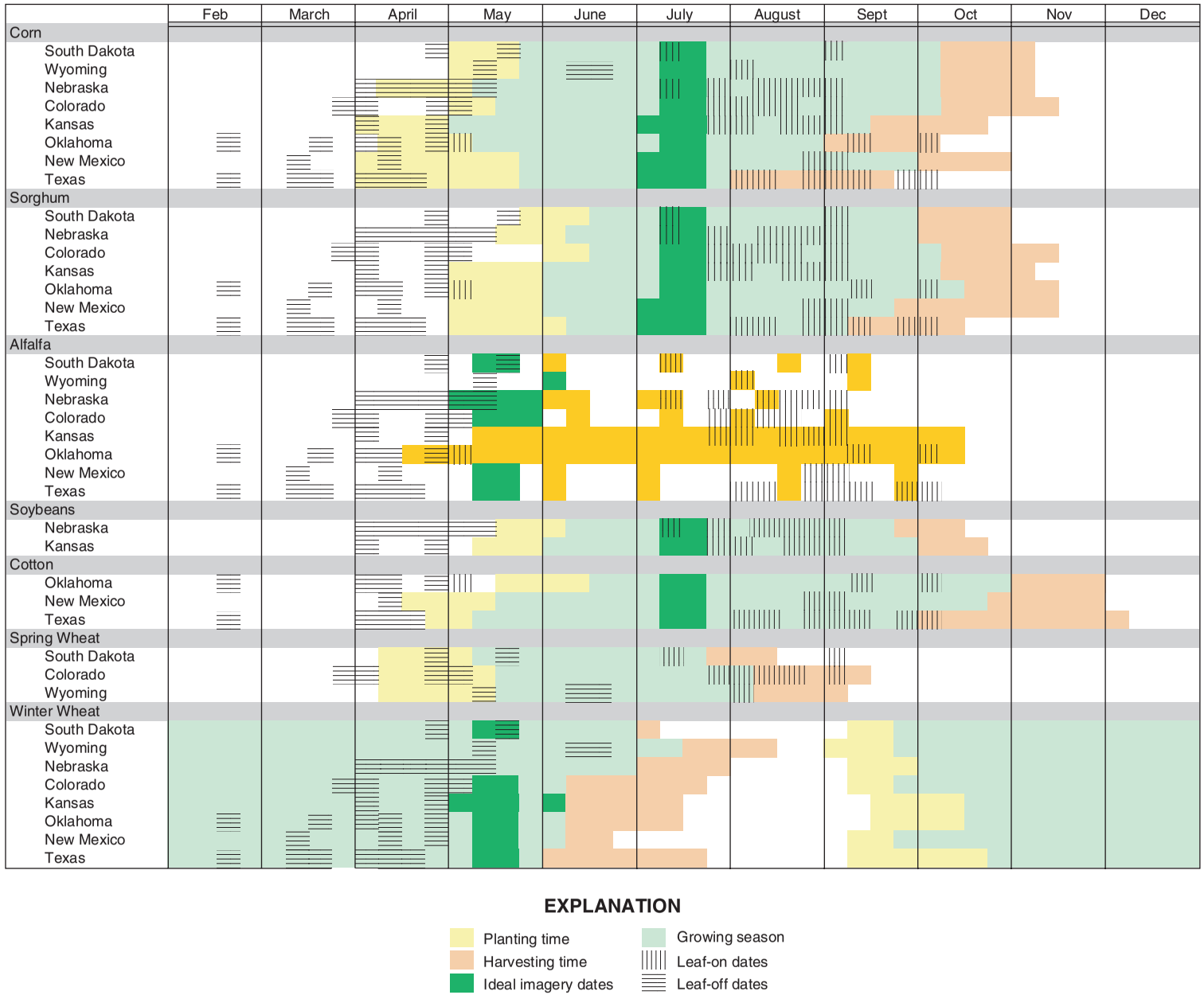


Figure 5. Crop phenology time lines and imagery dates.

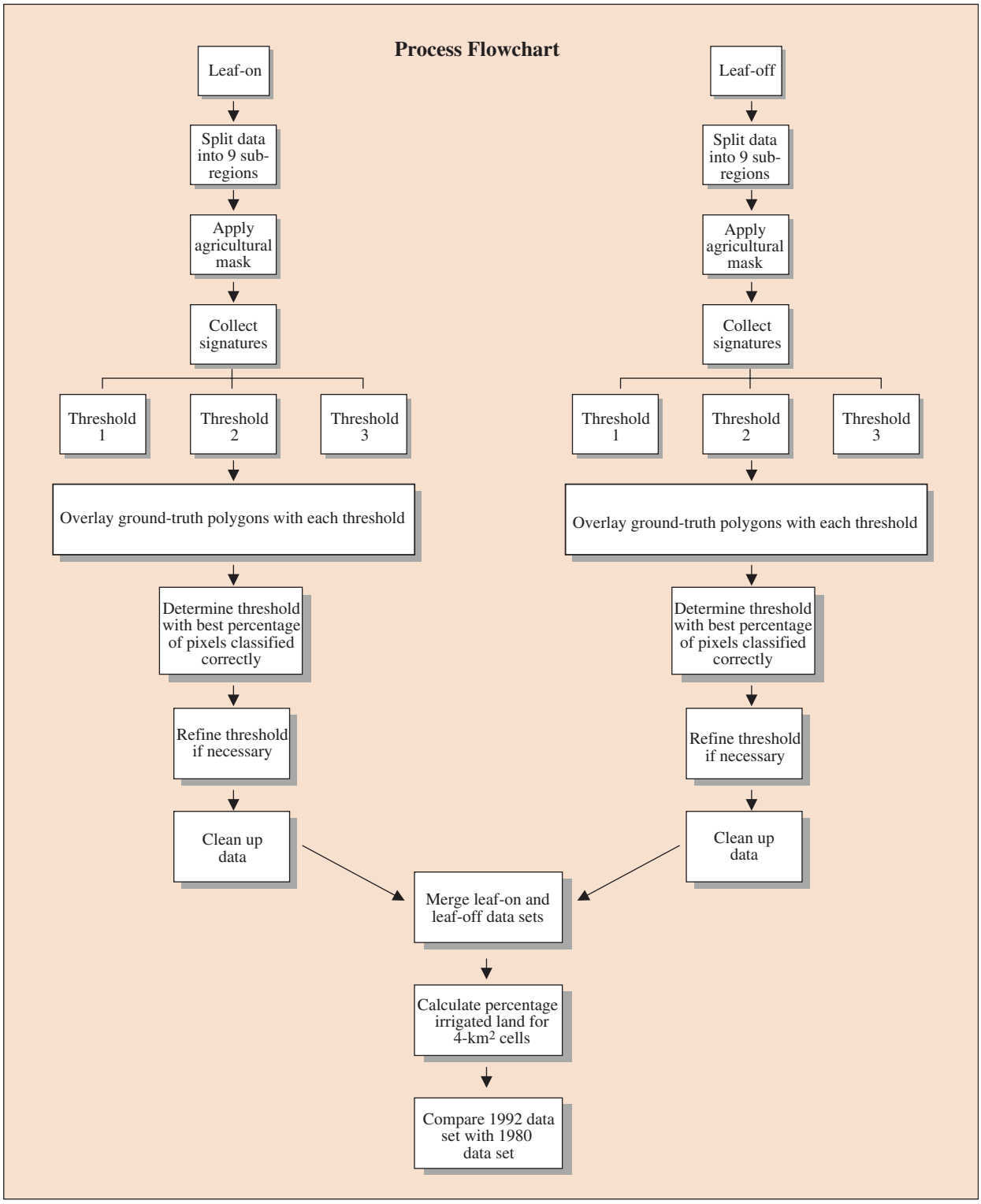


Figure 6. Flowchart used for the analysis and comparison of Landsat Thematic Mapper imagery to determine changes in the amount of irrigated land from 1980 to 1992.

There did not appear to be any extensive omission of agricultural land; however, not all rangeland or riparian pixels were masked out completely due to being misclassified in the NLCD. The masking procedure produced files containing mainly agricultural pixels—the subject of the study (fig. 7).

Calculating the Band Ratio

One of the objectives of this project was to process the imagery using the same techniques used by the 1980 RASA project (Thelin and Heimes, 1987). That project used band-ratio techniques based on the Landsat 2 multispectral-sensor visible-red and near-infrared (IR) bands. This project used the same near-IR/visible-red technique with the more recent Landsat 5 TM sensor data.

A near-IR/visible-red band ratio creates a vegetation index. Multispectral data can be transformed, or enhanced, to generate new sets of image components or bands. The new band or bands represent an alternative description of the original data that may enhance certain features not formerly visible. Image arithmetic, such as a ratio (division) of pixel brightness values (digital numbers [DN]), can reduce effects of topography, create a vegetation index, or enhance differences in the spectral characteristics of rocks and soils (Richards, 1993).

The band ratio used in this study was defined as the TM near-IR band (band 4) divided by the visible-red band (band 3). Each image in the nine subregions was processed using this ratio. The resulting files were a single greyscale band with irrigated agriculture pixels indicated as bright white pixels and all other vegetation a range of gray (fig. 8). Riparian pixels or other wet, green vegetation pixels that were not masked out also were bright white pixels. The next step was to determine the best threshold to apply to the ratio-classified image to determine irrigated land.

Collection of Signatures

The pixel brightness values (DN value) for each of the ratio-classified images generally ranged from 0.031 to 24.793. The higher the number, the brighter/whiter the pixel and the more likely the pixel represented irrigated agriculture. Brightness values for nonirrigated land ranged from an average minimum of 1.426 to an average maximum of 2.873. Brightness values for irrigated land ranged from an average minimum of 2.386 to an average maximum of 7.767. The ideal threshold value would separate the riparian and nonirrigated agriculture pixels from irrigated agriculture pixels.

There are several ways to determine the best threshold. One way is to choose a threshold value arbitrarily and categorize the image by trial and error to get the best result. This approach was considered; however, because several analysts were processing the data, it was determined that a consistent approach was needed. The approach selected was to collect several samples of pixel brightness values (signatures) from areas that the analyst thought to be irrigated (center-pivot irrigation systems) and areas thought to be nonirrigated. The pixels were selected by using a seed tool to click on a pixel in the area of interest, and the tool selects all of the other contiguous pixels that are within a specified geographic distance and(or) a specified spectral distance (similar brightness). The group of pixels selected was considered a sample. The analyst then looked at the minimums, maximums, means, and ranges of the various samples of brightness values to determine the best threshold value that would separate brighter, irrigated pixels from darker, nonirrigated pixels.

The statistics (minimum, maximum, mean, and range of pixel brightness) were gathered solely from the greyscale ratio-classified image. There are certain guidelines to consider when using statistics to threshold or create classes in an image. Generally, 50 samples per class (land-cover type) is a good balance between statistical validity and practicality (Congalton and Green, 1999).

The statistics were used to determine how to group the pixels in the ratio-classified image into their respective land-cover types. The brightness ranges for each sample were plotted on a graph to determine where along the brightness scale the various samples would group for each of the classes (irrigated and nonirrigated) (fig. 9). For example, samples from the brighter pixels, considered irrigated agriculture, have different minimums, maximums, and ranges but generally overlap each other in the graph.

Samples of darker pixels, considered nonirrigated agriculture, also grouped together and have noticeably lower ranges of brightness values but still overlap slightly with the brighter pixel samples. The ideal brightness ranges would not have any overlap, but in this study this never occurred. Any threshold value chosen would always misclassify some nonirrigated pixels as irrigated and some irrigated pixels as nonirrigated.

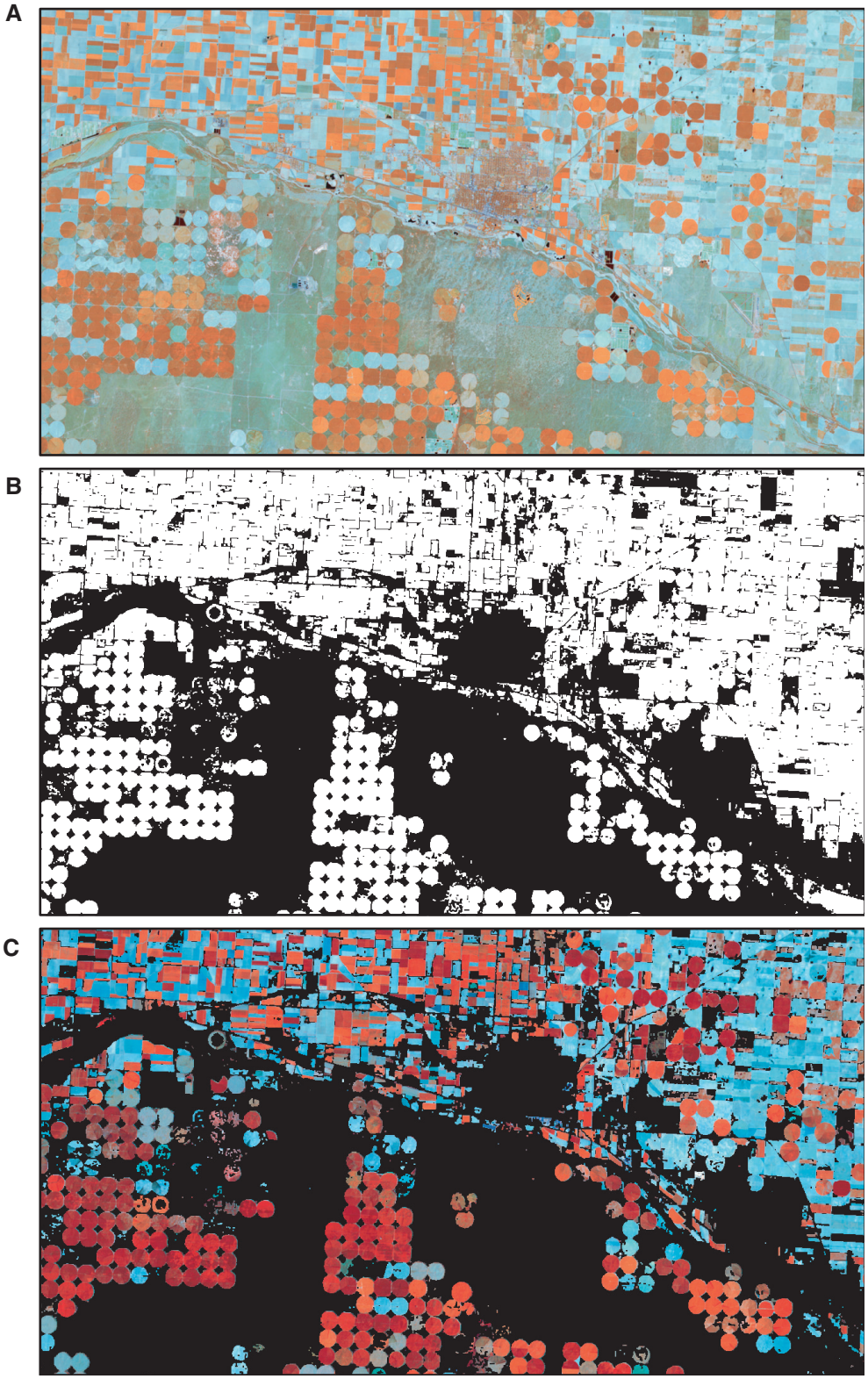
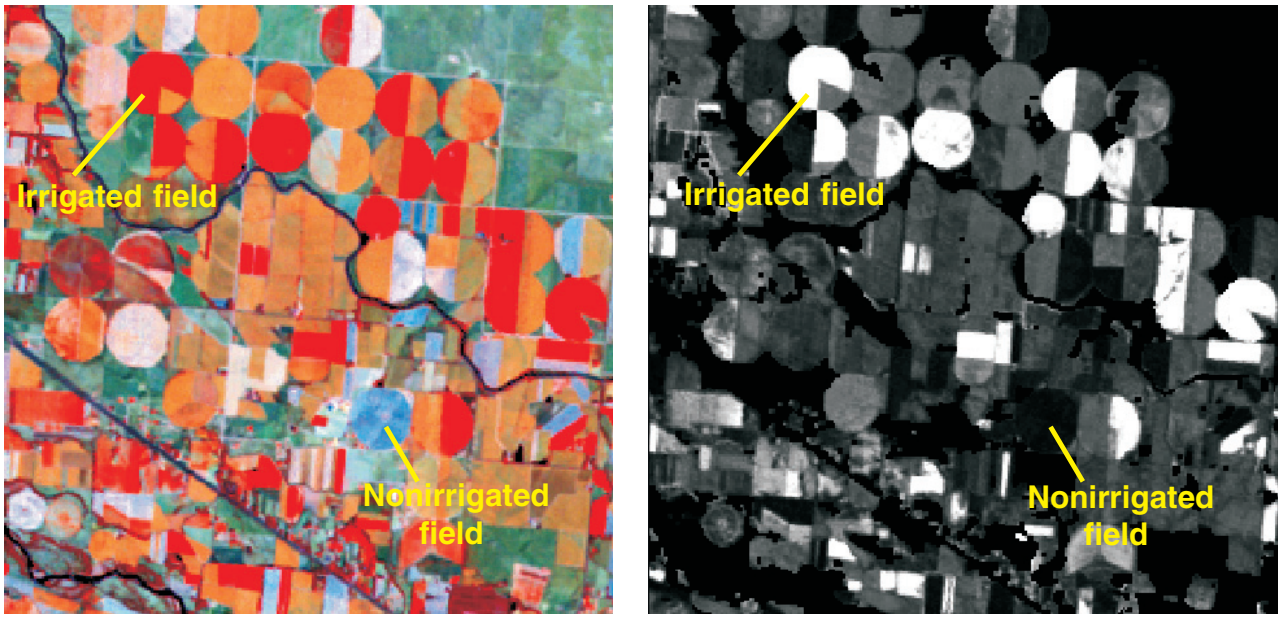


Figure 7. Example of a masked satellite image: (A) The original composite band image, (B) the areas considered as agricultural by the NLCD, and (C) the resulting image to be processed.



Composite image (bands 1, 2, and 4)

Ratio-classified image (band 4/ band 3)

Figure 8. An example of a ratio-classified image. The brightness of pixels represents values for the ratio of band 3 over band 4. The brighter the pixel, the higher the ratio and the healthier and greener the vegetation.

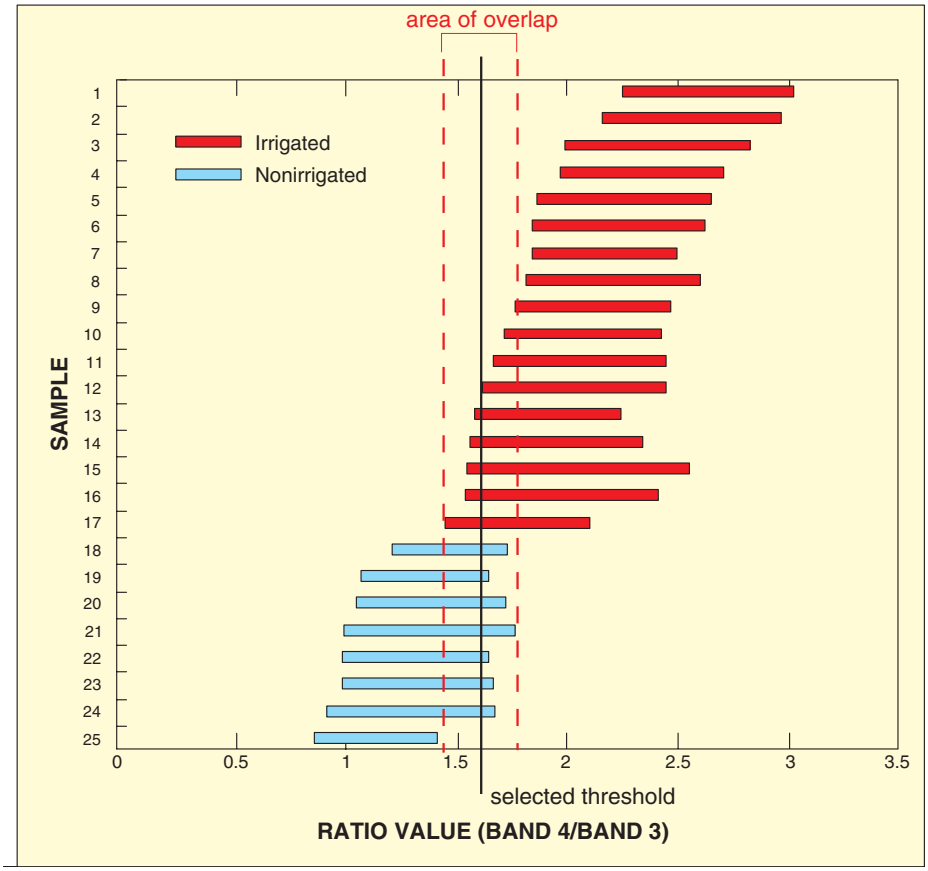


Figure 9. A graph of ratio ranges for each sample of pixels collected. Samples from irrigated land (red) and nonirrigated land (blue) are included.

Selection of Threshold Value

Applying a threshold to an image is another way of categorizing an image. In this case, the reason for choosing a threshold for the image was to create a binary file containing values of 1 to represent irrigated agriculture and 0 to represent nonirrigated agriculture. This file could then be used in a formula to calculate the number of irrigated pixels per unit area.

Thresholds will be different for different image dates. This difference is due to the fact that a pixel's brightness value changes temporally due to changing soil conditions, vegetation health, leaf area, soil moisture, and atmospheric effects. The goal for selecting the best threshold is to work toward achieving 100 percent of the pixels that are irrigated agriculture represented by a single value and 100 percent of nonirrigated pixels represented by a second single value. Achieving this goal is not possible in reality; therefore, a threshold was selected that was in the middle of the overlap area between the minimum of the brighter group of samples (irrigated) and the maximum of the darker group of samples (nonirrigated) (fig. 9). Once a threshold value was selected, a conditional statement was used to classify the image into irrigated and nonirrigated categories. All the brightness values greater than 0 and less than or equal to the selected threshold were set to "0." All of the brightness values greater than the threshold value and less than or equal to the maximum brightness value were set to "1." The resulting image has values that are either 0, representing nonirrigated pixels, or 1, representing irrigated pixels (fig. 10).

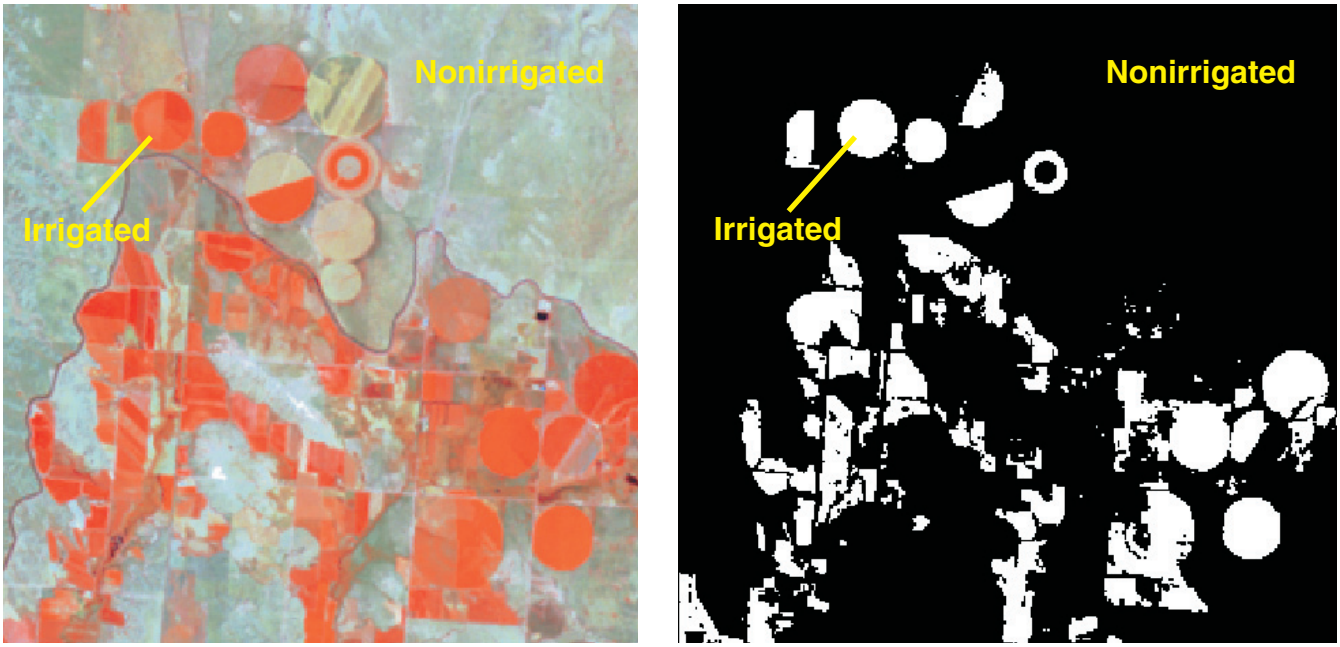
Once the image was classified, the resulting image was visually compared to the original image to determine what errors in classification may have occurred. It was not uncommon for an analyst to reclassify an image several times using different thresholds (mean of all minimums, mean of all maximums, mean of means, and so forth) to try and balance the occurrence of irrigated and nonirrigated errors.

Ground-Reference Information

Ground-reference information is required to calibrate the irrigated-land classification methodology and to assist in the identification of systematic errors such as classifying riparian zones as irrigated agriculture. Ground-reference information for this report was obtained for the same year only as the leaf-on imagery and included crop type and irrigation status (irrigated or nonirrigated) for individual fields in the requested areas. Ground-reference information for leaf-off dates was not acquired because most irrigation takes place in the summer months. Because leaf-on image dates varied across the study area, a date index based on imagery year was created by identifying scene boundaries within the imagery (fig. 11). Where TM scenes overlapped, the more recent date was chosen or the scene that appeared to have more irrigated acreage was chosen. Ground-reference information then was collected for the appropriate date. The ground-reference information was requested from the FSA. The FSA is the arm of the USDA that is responsible for the various farm assistance programs. As part of a farm's participation in these programs they must record, on an aerial photograph of their farm, what crops were grown on the fields, how many acres, and the irrigation status. Because querying all 256 counties in the study area would not be possible due to time constraints, the written and photographic information was requested from only 154 counties that contained more than 50 percent agricultural land based on the NLCD classification. Fifty percent was chosen to ensure that enough irrigated land would be included in the random selection because there is substantially more dryland farming than irrigated farming in the study area. Information for one to 10 one-square-mile sections randomly selected in each county, depending on how much agricultural land was in the county, was requested from the FSA. In total, 90 percent of the data requested from the 154 counties was returned (139 counties). Each request that was returned was digitized using the satellite imagery as a background, and each plot of land was attributed with the crop type and irrigation status (fig. 12). In total, approximately 11,000 polygons equal to 966 mi^2 were digitized for the ground reference (fig. 13), or approximately 1.3 percent of all agricultural land.

Refinement of Irrigated Land Estimates

Once the initial classification was completed, the estimates of irrigated land classified by the leaf-on TM imagery were refined using ground-reference information to adjust threshold values. The ground-reference information on irrigation status was used to determine the initial error estimates for the land-cover



Composite image

Classified image

Figure 10. Example of a composite and resulting classified image. The white areas represent irrigated land and the black areas represent nonirrigated land.

classification. The polygons in the ground reference were classified as being either irrigated or nonirrigated, and this information was overlaid with the classified TM imagery to determine the initial accuracy of the classification for each scene. Both the number of pixels that overestimate irrigated land and the number of pixels that underestimate irrigated land were calculated along with the number of pixels classified correctly (for both irrigated and nonirrigated land) to determine if refinement of the threshold was necessary. To refine the threshold values, the ground-reference data were randomly split in half to produce calibration and verification data sets. The calibration data set was used to refine the thresholds to optimize the amount of irrigated land correctly classified (percent correct) and the amount of irrigated land correctly located. The errors and the percent correct were then verified using the verification data set (table 2).

The percent correct for each subregion was weighted on the basis of the percentage of the total agricultural land in each subregion. The overall weighted percentage of pixels correctly identified by the ratio-threshold process was 77.5 percent. This number increased to 79.8 percent when the effects of subregion 2 were removed. Subregion 2 encompassed eastern Nebraska and included imagery dates from the 1992 and 1993 growing seasons. This concided with the Midwest floods and extremely wet conditions for many Midwestern States. Because of this, most vegetation in the scene was very healthy and wet, and irrigated land was difficult to identify. Additionally, there were large areas where the crops appeared to be flooded and drowned, which also made correct classification difficult. The ground-reference information received from the FSA would report healthy irrigated fields where crops had been destroyed (fig. 14).

Because ground-reference information was obtained for leaf-on imagery only, no error estimate could be made for the leaf-off imagery. Thresholds for leaf-off imagery were refined using brightness statistics only from irrigated center pivots (known to be irrigated). The amount of irrigated land classified from the leaf-off imagery (mostly winter wheat) was added to the classified land from the leaf-on imagery to create the final data set. The amount of leaf-off irrigated land added (496,000 acres) was 5 percent of the leaf-on amount.

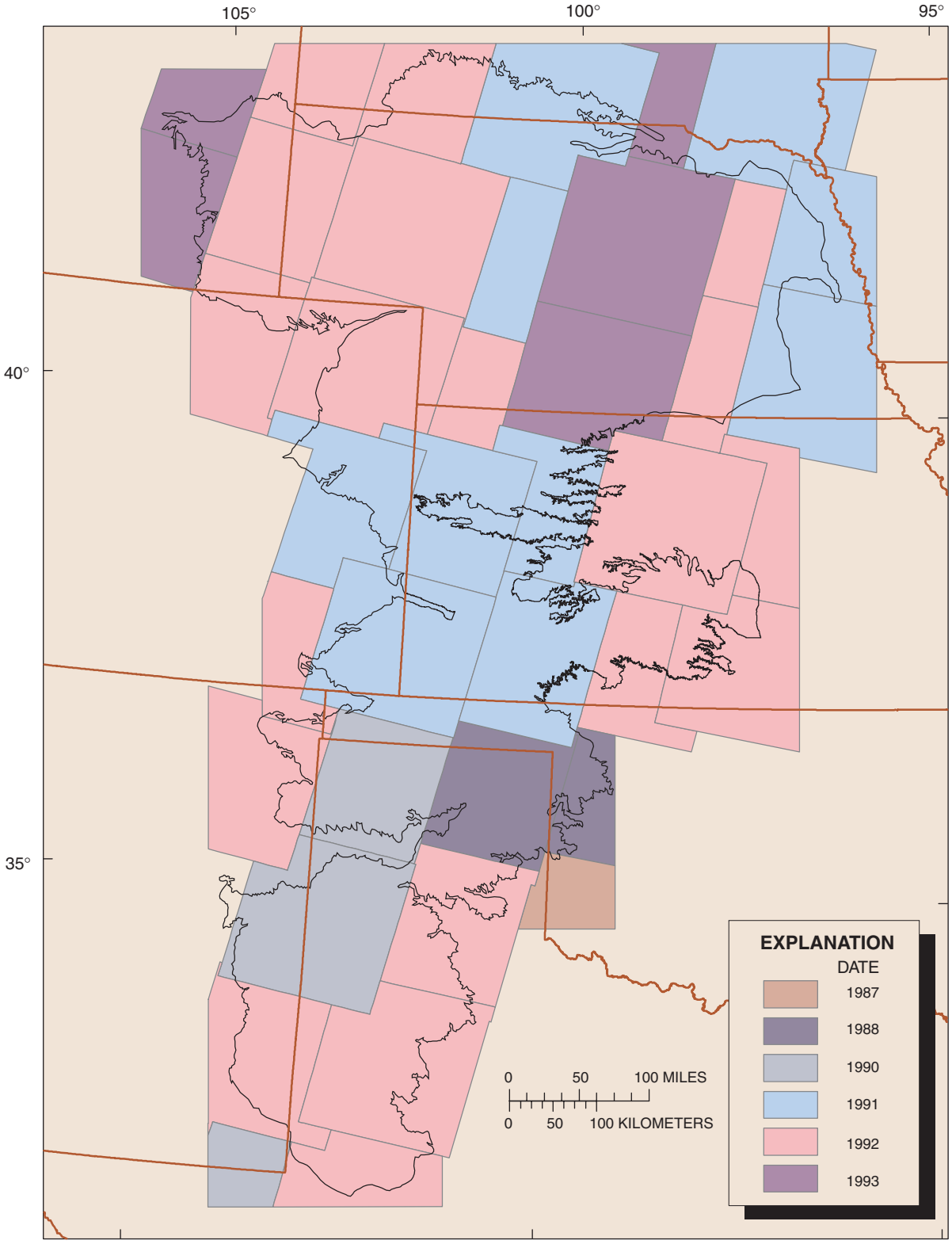
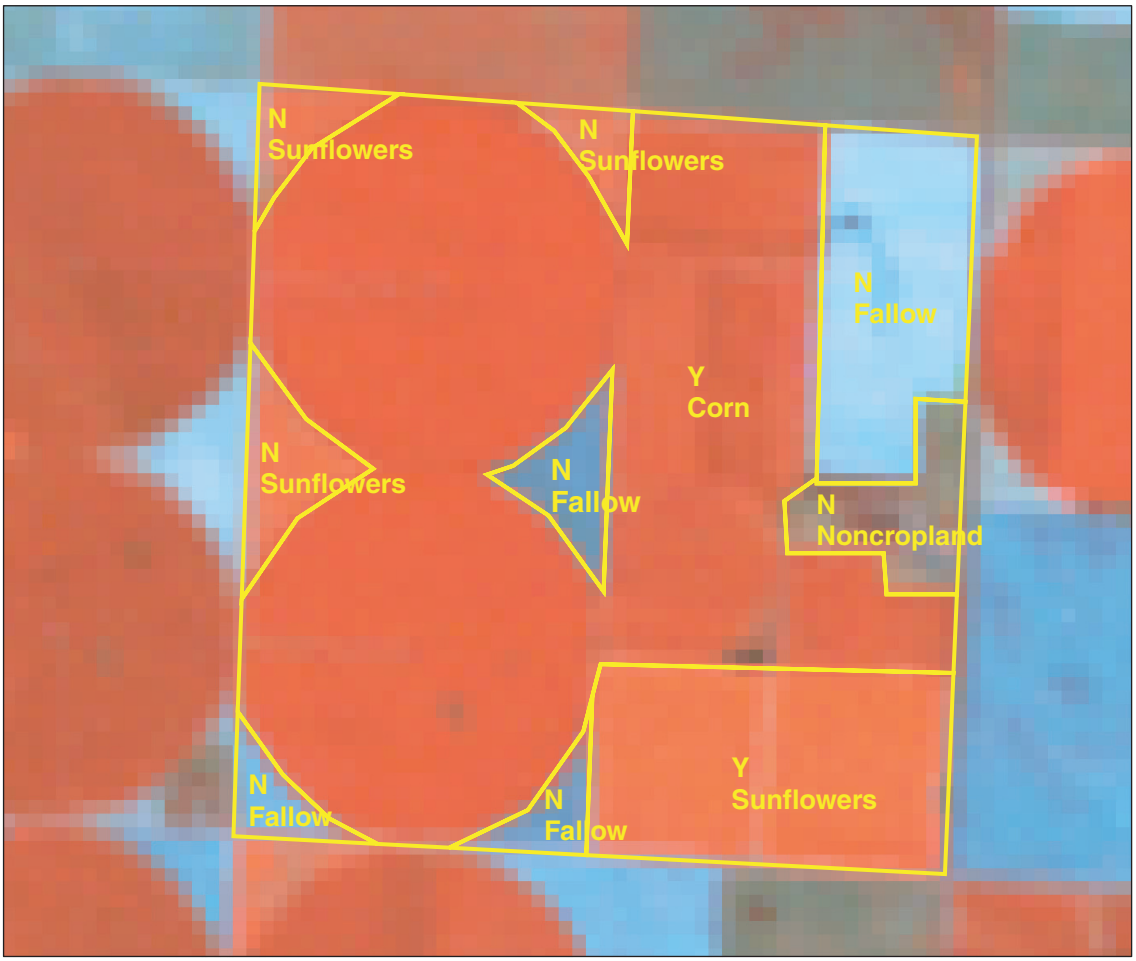


Figure 11. The distribution of image dates across the High Plains.



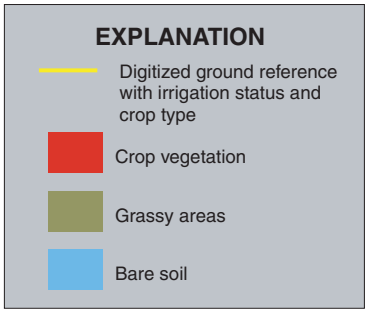


Figure 12. Example of an area of digitized ground-reference information for overlay on the classified imagery. “N” represents nonirrigated land and “Y” represents irrigated land (data from the Farm Service Agency).

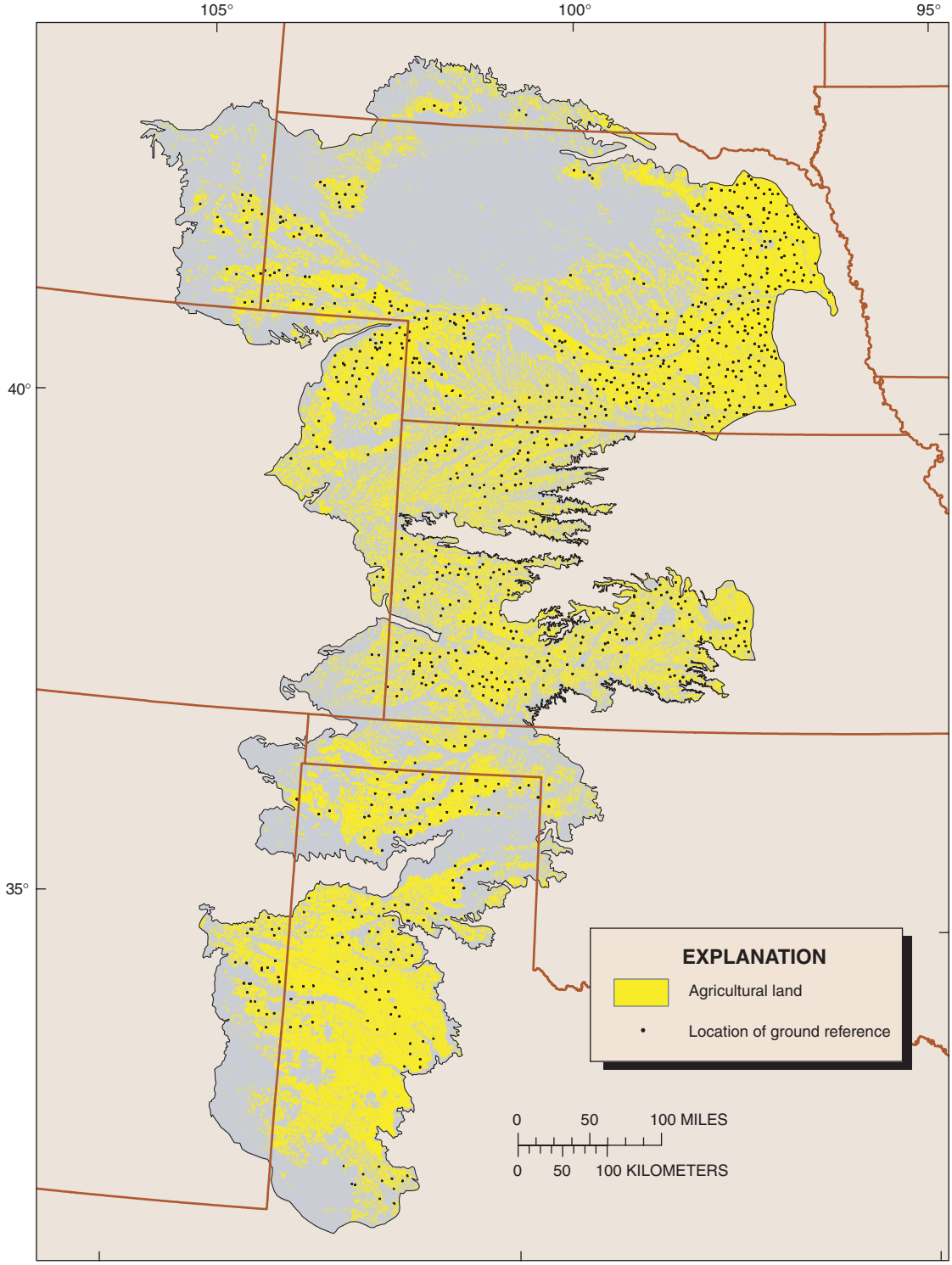


Figure 13. Distribution of ground-reference information in the High Plains (data from the Farm Service Agency).

Table 2. Errors and associated percentage of correctly classified pixels for each subregion after calibration and verification using the ground-reference information

[N/A=no irrigated land in ground-truth data set]

Sub-region	Agricultural land in subregion represented by ground reference (percent)	Agricultural land in subregion (percent)	Irrigated correct (percent)	Non-irrigated correct (percent)	Percent correct (percent)	Irrigated errors (percent)	Non-irrigated errors (percent)	Weighted percent correct (percent)[1]
1	0.6	4.4	25.4	54.6	80.0	13.4	6.6	3.5
2	0.9	23.3	40.5	28.9	69.4	16.6	14.0	16.2
3	0.7	10.2	28.5	52.4	80.8	12.2	7.0	8.2
4	0.4	13.1	20.5	65.9	86.4	4.1	9.5	11.3
5	0.8	9.6	41.7	31.8	73.5	20.3	6.1	7.1
6	0.8	7.3	21.5	56.9	78.4	11.9	9.7	5.7
7	0.3	9.0	34.6	51.8	86.4	3.5	10.2	7.8
8	0.4	17.8	25.5	49.6	75.1	17.9	6.9	13.4
9	0.007[2]	5.4	N/A	79.2	79.2	4.0	16.8	4.3
					Overall weighted percent correct			**77.5**

[1] Weighted percent correct = Percent correct × agricultural land in subregion.
[2] Only one county reported ground-reference information in this subregion.

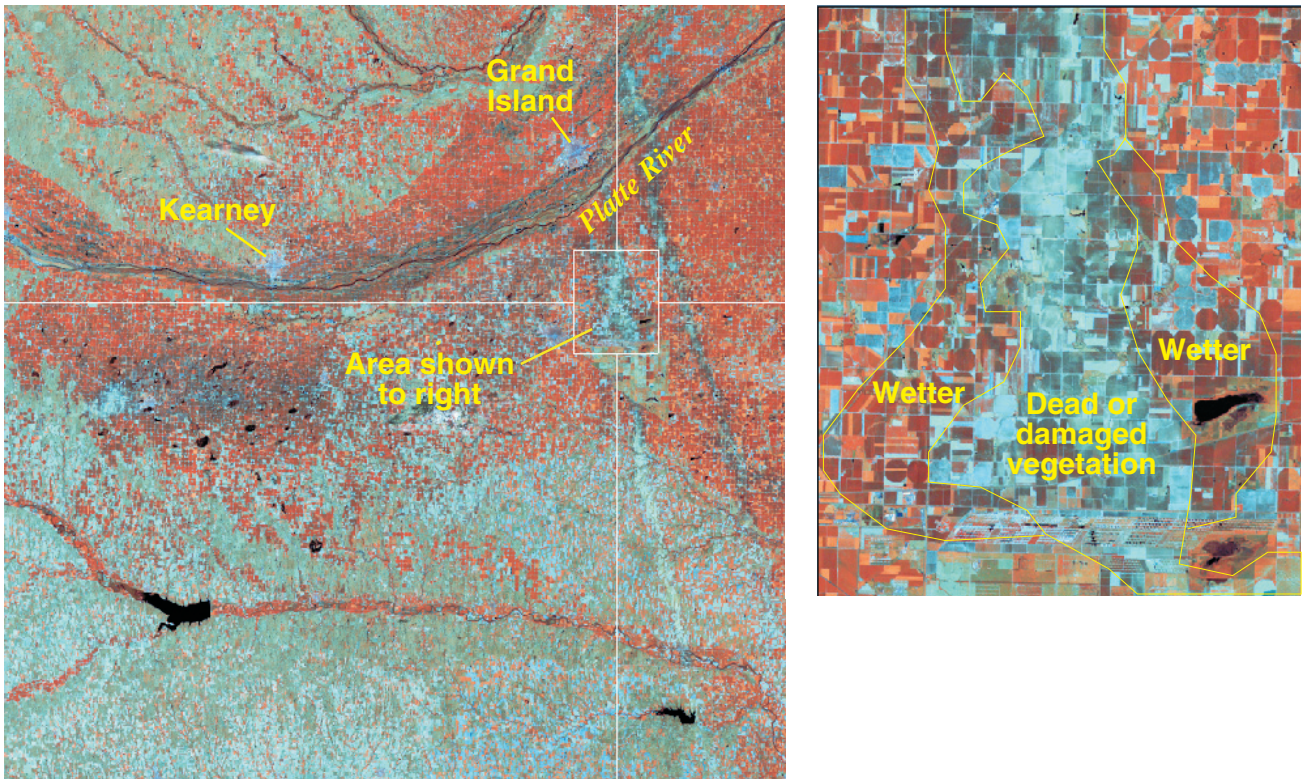


Figure 14. An example of an area in eastern Nebraska where the crops were destroyed.

DESCRIPTION OF IRRIGATED LAND

To compare the present classification to the historical classification of irrigated land, the more recent data were aggregated from the location of individual fields into a more coarse resolution of percentage of land irrigated in an area. By overlaying a grid with 2-km by 2-km cells, a percentage of a cell that was irrigated (irrigation density) was calculated for a nominal date of 1992 (fig. 15). The density ranged from 0 percent irrigated land to 99 percent irrigated land. The total amount of irrigated land classified in the High Plains study area was 13.1 million acres. This was approximately 30 percent of the total agricultural land or approximately 12 percent of the total High Plains area. This grid data set is available on the World Wide Web at URL http://co.water.usgs.gov/nawqa/hpgw/GIS.html/ (Qi and others, 2002)

Location of Irrigated Land

In 1992, the density of irrigated land varied greatly in the High Plains area. The areas of largest concentration of irrigated land were in eastern Nebraska, along the North Platte River in western Nebraska, in southwestern Kansas, and in the Panhandle of Texas (fig. 15). The primary irrigated crops in these areas were corn, soybeans, sorghum, and cotton (Gilliom and Thelin, 1997). It must be noted that the density of irrigated land in the eastern Nebraska part of the study area is problematic. The satellite imagery dates for this region ranged from 1991 to 1993, which was a time of above average rainfall (High Plains Regional Climate Center, 2002) for eastern Nebraska, with 1993 being a time of flooding in the Midwest. Because of the large areas of dead and damaged crops (fig. 14), there was a substantial underestimation (mean of 46 percent) in the density of irrigated land south of the Platte River in the counties of Phelps, Adams, Webster, Hamilton, Clay, Polk, York, Fillmore, and Saline compared to State agricultural statistics (Nebraska Agricultural Statistics Service, 2002). The area in the far northeast of the study area in the counties of Antelope, Boone, Nance, Platte, Madison, Pierce, Wayne, Stanton, Colfax, Cumins, and Dodge shows a substantial overestimation (mean of 33 percent) in the density of irrigated land than may actually have been present (Nebraska Agricultural Statistics Service, 2002) (fig. 16). The area to the south of the Platte River is part of the Rainwater Basin wetlands complex characterized by nearly flat and gently rolling loess plains. Surface drainage is poorly developed, and the soils are more clay rich (Frankforter, 1996; University of Nebraska, 1986). The area to the north of the Platte River is characterized by rolling hills and dissected plains where infiltration is moderate and runoff is high (University of Nebraska, 1986). Therefore, nonirrigated fields to the north of the Platte River would appear very healthy and green (very bright white in the ratio-classified image) to the satellite, whereas areas to the south of the Platte River were substantially wetter with more saturated soils and therefore appeared more damaged or drowned (darker gray or black in the ratio-classified image). Pixel brightness both for irrigated fields (ones that were not damaged or dead) and for many nonirrigated fields were relatively bright and made choosing a threshold very difficult. A lower threshold was required to avoid misclassifying many dark (wet) fields (center pivots) as nonirrigated. Therefore, fields that were healthy and may have been nonirrigated but very green, perhaps due to above-normal rainfall, were also included in the classification.

Comparison of Irrigated Land Estimates from Satellite Imagery and Agricultural Statistics

Statistical information about farms and farmland is gathered every 5 years by the USDA Census of Agriculture. The Census does not publish any location information about irrigated land, but it does publish statistics about the total acres of irrigated land by county and the acres of irrigated land by each crop type. A comparison was made between the 1992 Census of Agriculture and the total acreage of irrigated land that was classified from the imagery. Because the Census of Agriculture data are published by county with no locational information, the amount of irrigated land reported for each county was weighted by how much of that county lay within the High Plains study-area boundary. The weighted total amount of irrigated land within the High Plains according to the Census of Agriculture was 12.8 million acres. The total amount of land classified as irrigated from the imagery was 13.1 million acres—a difference of approximately 1.5 percent. The difference may be because the Census of

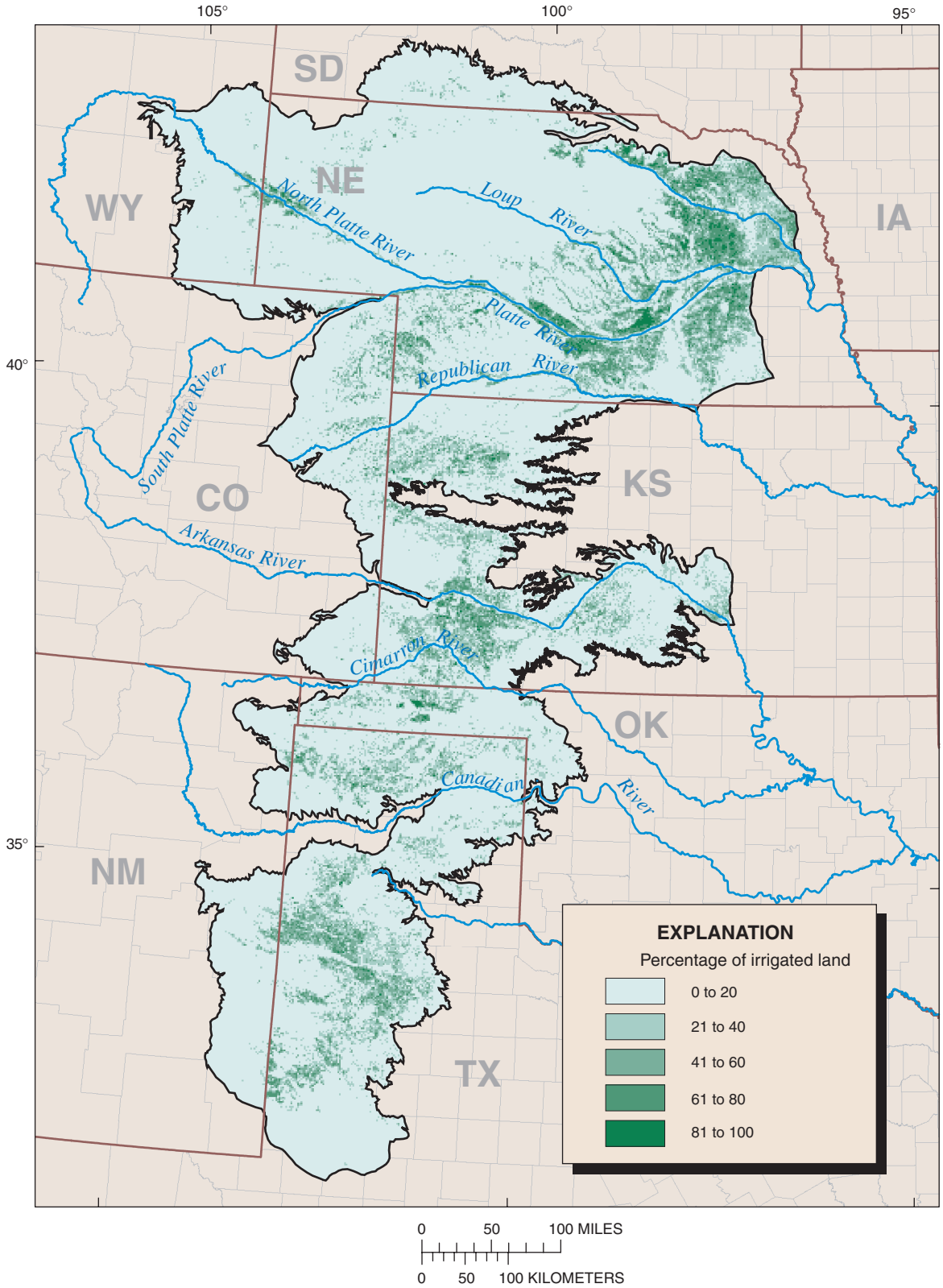


Figure 15. Irrigated land density for the High Plains for a nominal date of 1992.

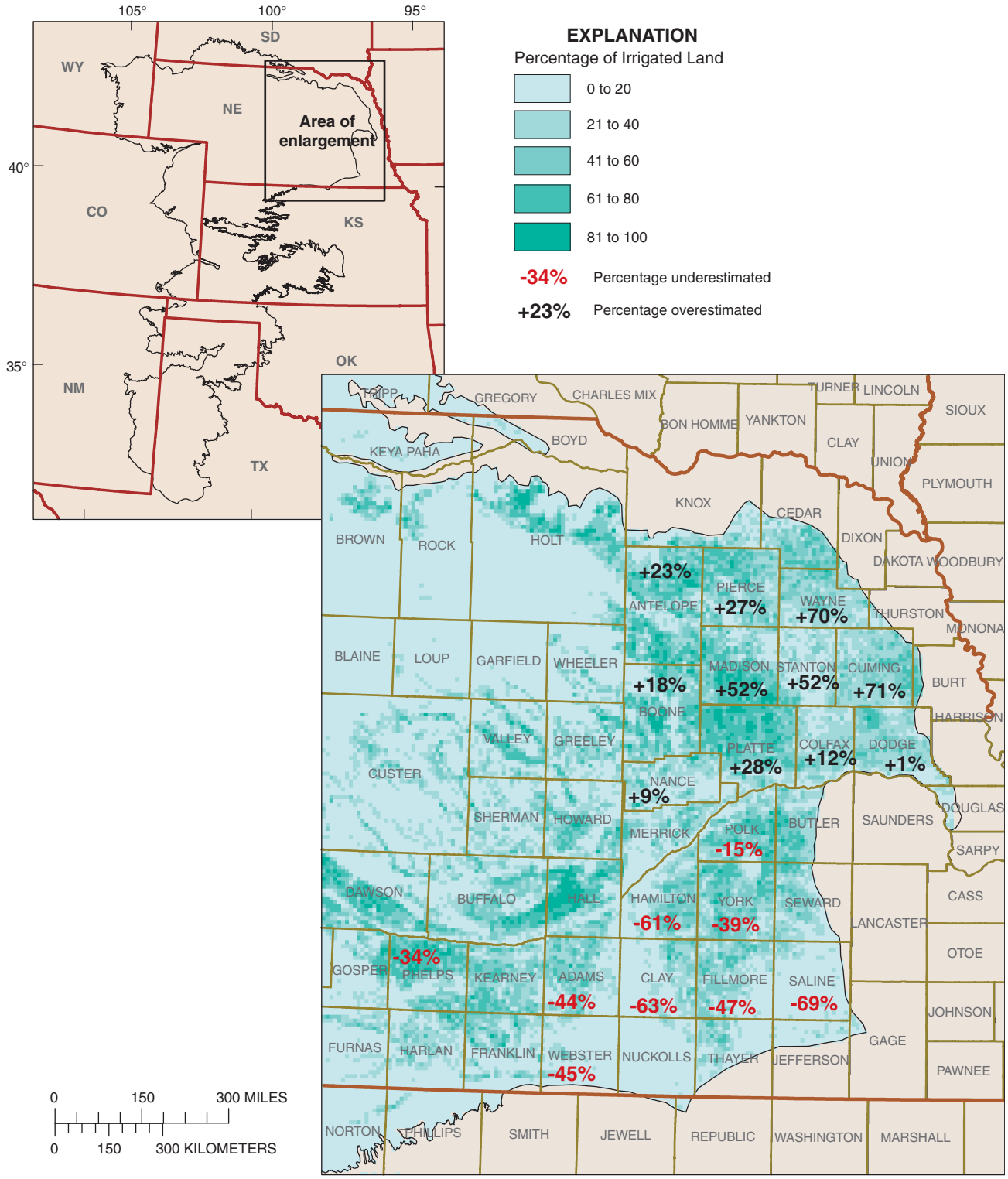


Figure 16. Overestimations and underestimations in the amount of irrigated land north and south of the Platte River in eastern Nebraska (data from Nebraska Agricultural Statistics Service, 2002).

Agriculture is a statistical sampling of farmers whereas the satellite has imaged every field in the High Plains (table 3). Additionally, when choosing the threshold value for each scene, two objectives were required: (1) determine the correct amount of irrigated land and therefore choose the threshold with the greatest percent correct, and (2) determine the most correct locations for the irrigated fields and therefore choose the threshold with the most balanced errors (overestimations and underestimations). To accomplish both objectives it was sometimes necessary to select a threshold that was slightly lower than the analyst would ideally select to represent irrigated land. Therefore, more nonirrigated land in that scene was classified as irrigated, which would increase the total amount of irrigated land calculated from the satellite imagery.

Comparison of 1992 Irrigated Land to 1980 Irrigated Land

The grid of 2-km by 2-km (4 km^2) cells used to represent the density of irrigated land for 1992 was compared to the data set created by RASA for irrigated land in 1980. The total amount of irrigated land calculated from the 1980 RASA data was 13.7 million acres compared to the 13.1 million acres calculated

Table 3. Comparison of band-ratio method of mapping irrigated land to other national efforts

[TM, Landsat Thematic Mapper scanner; NASS, National Agricultural Statistics Service]

Classification	Estimated amount of irrigated land (millions of acres)	Disadvantages	Advantages
1992 TM imagery (band-ratio method)	13.1	• Dates of imagery and cloud cover can be a concern.	• Estimate actual location of irrigated lands. • All of land surface imaged by satellite. • Consistent procedures. • Greater availability of imagery, much faster computing power.
1980 TM imagery (band-ratio method)	13.7	• Dates of imagery and cloud cover can be a concern. • Only aggregated data; no location information preserved. • Imagery not as available; limited computing power.	• All of land surface imaged by satellite. • Consistent procedures.
NASS (1980/1992)	11.5/12.7	• Tabular data by county; no location information available. • Not as large a sampling of farms as in the Census of Agriculture. • Not consistent from year to year/State to State (budget dependent). Reporting varies among States; not all crops/counties are reported. • Reporting error due to unknown accuracy of reported acreages.	• Not affected by clouds, wet years, or date considerations. • Readily available at no cost to user.
Census of Agriculture (1978/1992)	13.6/12.8	• Tabular data by county; no location information available. • A statistical sampling; does not account for every field in the High Plains. • Reporting error due to unknown accuracy of reported acreages. • Done only every 5 years.	• Not affected by clouds, wet years, or date considerations. • Readily available at no cost to user.

from the 1992 imagery, a decrease of approximately 5 percent. However, 5 percent is within the precision of the 1992 estimate considering that the overall weighted percent for correctly classified pixels was 80 percent. Although the amount of irrigated land and the general pattern of the density of irrigated land have not changed significantly, the data indicate areas where the density appears to have been greater in 1980 and to have decreased in 1992, as seen in the lightening of the darker green (greater density) colors (fig. 17) (for example, the Panhandle of Texas). The exception is the area in eastern Nebraska where data anomalies due to flooded fields and very wet conditions have indicated artificial decreases and increases in the amount of irrigated land.

Because the grids for both data sets were exactly the same in terms of location and cell size, a grid representing the change in the percentage of irrigated land from the past to the present was created by subtracting the past values from the present values on a cell-by-cell basis. The areas of greatest decreases in irrigation density are along the North Platte River in western Nebraska, south of the Platte River in south-central Nebraska, in southwestern Kansas, and in the Panhandle of Texas (fig. 18). Although the absolute amount of decrease may be difficult to determine because of classification errors due to differences in imagery from 1980 to 1992 (such as atmospheric conditions), the errors due to differences in imagery probably cannot account for all of the change indicated in these areas. However, the decrease along the North Platte River in western Nebraska can be partially explained by a later scene date (September) in that area for the 1990 imagery than for the 1980 imagery (July). The September scene date might have missed some irrigated crops because they could have been harvested before September.

As discussed previously in the report, the large declines in density in eastern Nebraska south of the Platte River are a result of the large-scale flooding of crops in the area during the time the imagery was acquired. Also, the large increases in irrigation density north of the Platte River in the far northeast of the study area are the result of very wet nonirrigated fields appearing spectrally the same as irrigated fields.

The declines in irrigation density in southwestern Kansas and the Texas Panhandle can be associated with areas of greatest water-level decline in the High Plains aquifer (fig. 19) from 1980 to 1994 (V.L. McGuire, U.S. Geological Survey, written commun., 2002). The decrease in the amount of irrigated land may be a product of a variety of difficulties including inability to deepen existing wells because of cost and lack of saturated thickness, or simply a lack of water along the margins of the aquifer (Nedda Travis, Parmer County, Texas Farm Service Agency, oral commun., 2002; Trish Elliot, Castro County, Texas Farm Service Agency, oral commun., 2002; Sam Vonlintel, Morton County, Kansas Farm Service Agency, oral commun., 2002; Art Boltz, Stanton County, Kansas Farm Service Agency, oral commun., 2002).

Finally, decreases in total irrigated acreage in the Texas Panhandle from 1982 to 1992 were documented using the Census of Agriculture for the eight counties (Bailey, Castro, Deaf Smith, Floyd, Hale, Lamb, Parmer, and Swisher). There was an average decrease of 19 percent in acres irrigated from 1982 to 1992 (U.S. Bureau of the Census, 1994). In contrast, in southwestern Kansas (Hamilton, Stanton, and Morton Counties; fig. 16), an average increase of 10 percent in acres irrigated was observed (U.S. Bureau of the Census, 1994). Examination of irrigated acreage estimates for selected crops (sorghum, wheat, and corn for grain) in this area for 1980 to 1991 (the dates of the imagery in this area) disclosed a substantial increase in the amount of irrigated winter wheat (average 120 percent) and, to a lesser extent, corn for grain (average 36 percent) (National Agricultural Statistics Service, 2002). However, in the same area, sorghum (a summer crop) decreased by an average of 50 percent (National Agricultural Statistics Service, 2002). Because of the net decrease in the amount of irrigated acreage for the summer crops (19 percent), the amount of irrigated land classified from the leaf-on scenes would have shown a decrease in the amount of irrigated land. Some of the large increase in the amount of irrigated winter wheat (a spring crop) may have been missed due to the conservative way irrigated land was classified from the leaf-off imagery (generally February through May).

There were no extensive areas of increase in the amount of irrigated land across the High Plains with the exception of the area north of the Platte River in eastern Nebraska. Again, the explanation for this perceived increase in irrigation density is because of a misclassification related to extremely wet conditions in that area, which made it difficult to distinguish irrigated from nonirrigated land.

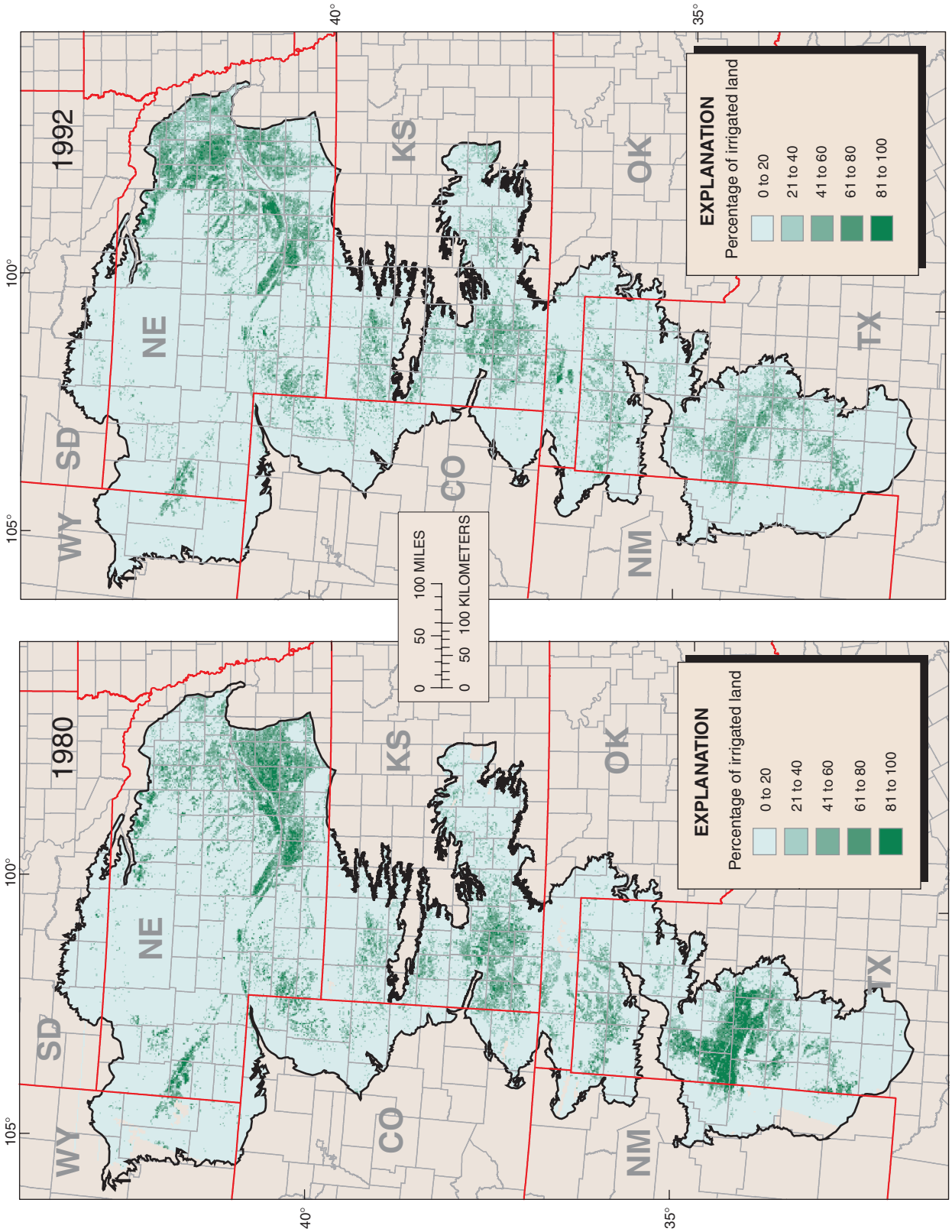


Figure 17. Comparison of irrigation density between 1980 and 1992.

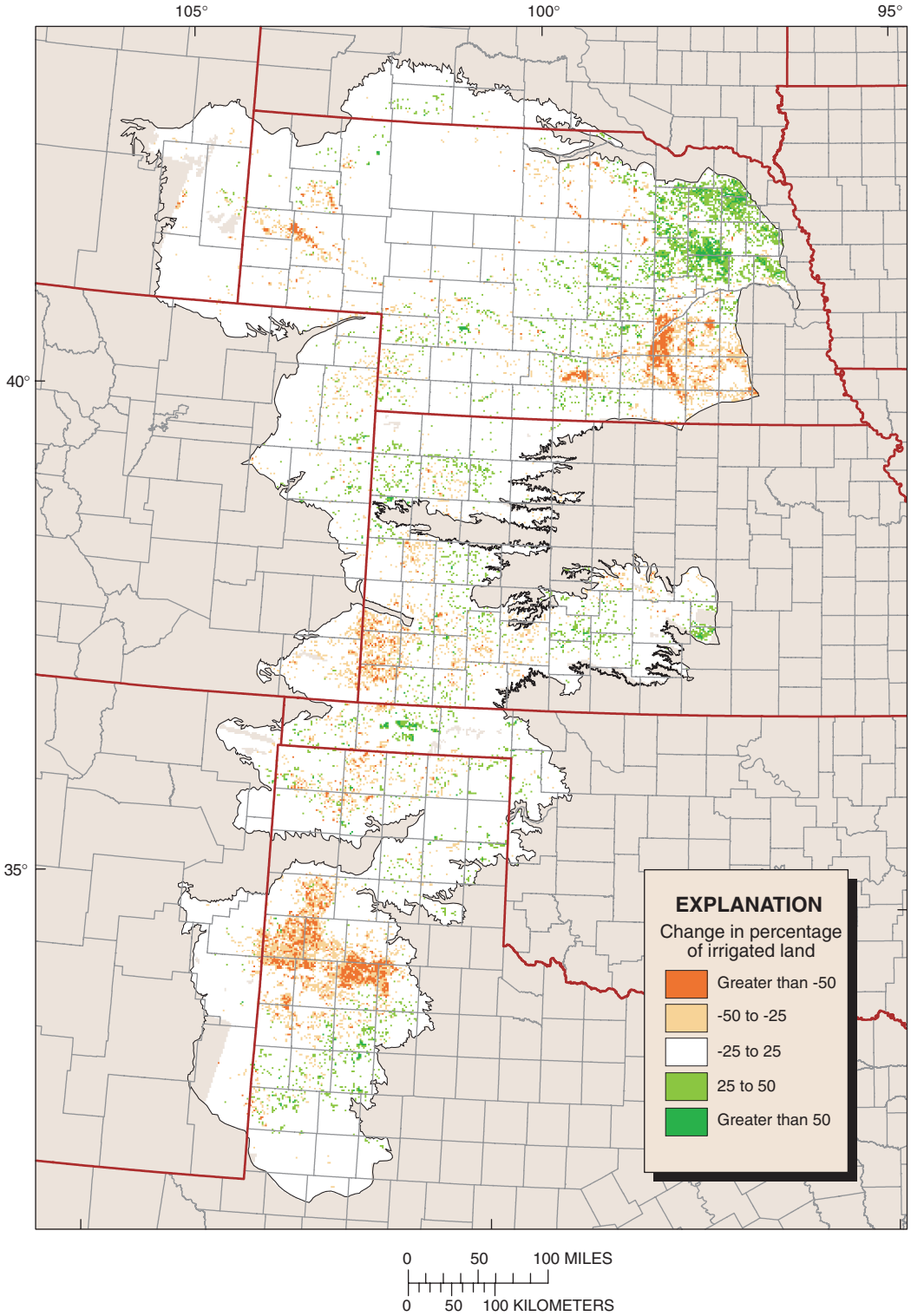


Figure 18. Change in percentage of irrigated land from 1980 to 1992.

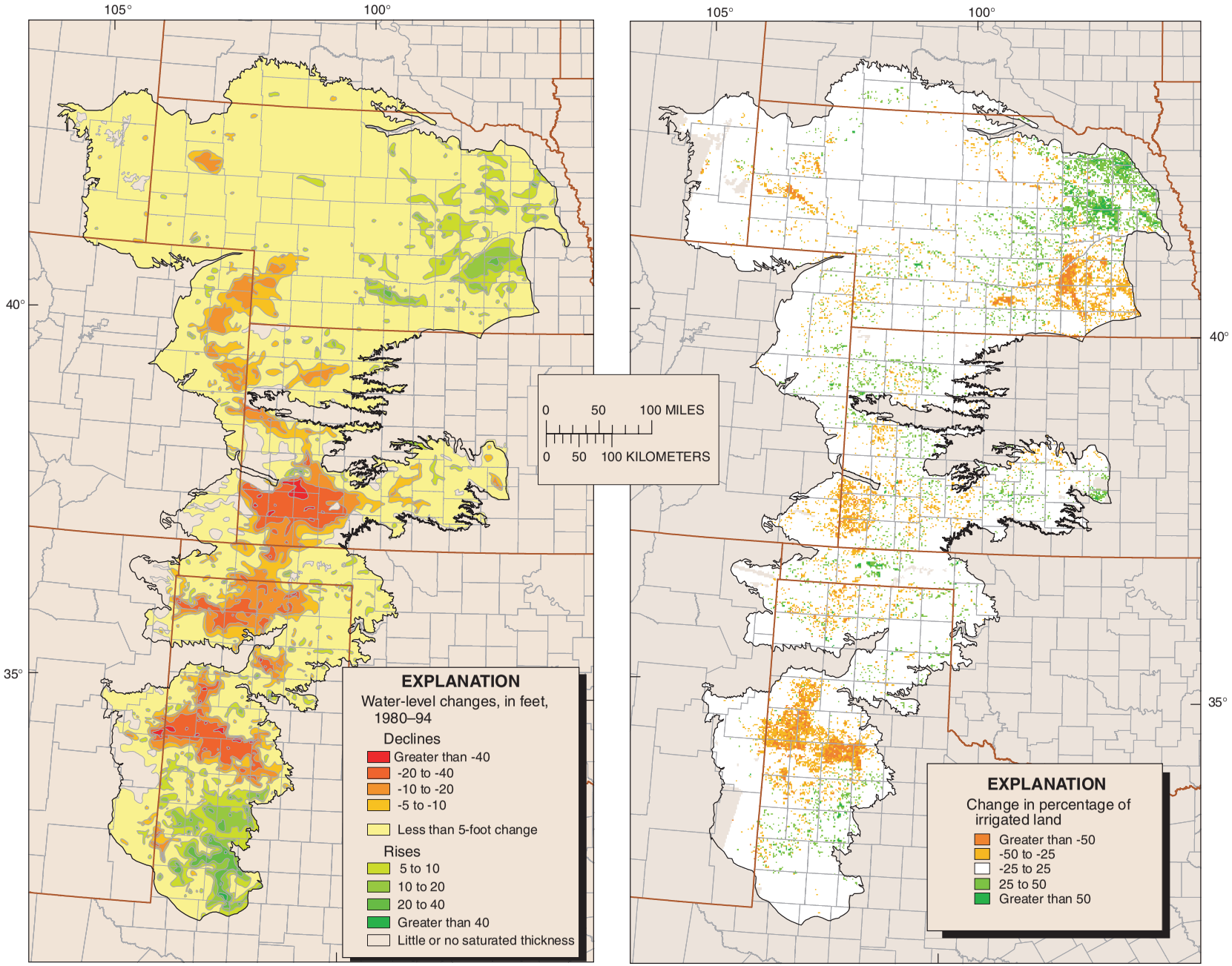


Figure 19. Water-level changes and change in percentage of irrigated land from 1980 to 1994.

SUMMARY

Satellite imagery from the Landsat 5 TM sensor, nominal date 1992, was used to determine the amount and location of irrigated land in the High Plains study area. Forty scenes from the early spring months (leaf-off) and 40 scenes from the summer months (leaf-on) were obtained from the EROS data center. Each set of data was divided into nine subregions based on environmental factors and computer hardware capabilities. The extent of subregions was defined by similar environmental factors such as precipitation, crop patterns, and ecoregions and also to limit file size for easier processing. Similar environmental factors in each subregion would help to ensure that each subregion would have similar signatures. The data were further filtered using a mask of agricultural land defined by the National Land-Cover Data set to select only agricultural land to process. This filtering would help to avoid any problems with spectral overlap such as riparian zones appearing very similar to irrigated fields. A band-ratio method of the near-infrared band (band 4) over the visible-red band (band 3) was used to enhance the signature of vegetation. The band-ratio produced a brightness theme where healthy, green vegetation would be represented by brighter pixels and dryer, less vigorous vegetation and bare soil would be represented by darker pixels. Samples of brightness values for areas thought to be irrigated (center pivots) and areas thought to be nonirrigated (CRP land or fallow fields) were collected to determine a brightness threshold that would be the cutoff value between irrigated land (brighter pixels) and nonirrigated land (darker pixels). Ground-reference information from 139 counties equaling 966 square miles was digitized and overlaid on the classified data to determine an initial error estimate and the percentage of pixels classified correctly. The overall weighted percent correct for the study area was 77.5 to 79.8 percent, depending on inclusion of eastern Nebraska where there were data anomalies due to extremely wet conditions. The 1992 data set was then compared to the 1980 data set to determine the change in irrigated land over time. The amount of irrigated land has not changed substantially from 1980 (13.7 million acres) to 1992 (13.1 million acres). The data, however, indicate a decrease in the amount of irrigated land in areas of large water-level declines and increases where the water levels have remained about the same or have risen.

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