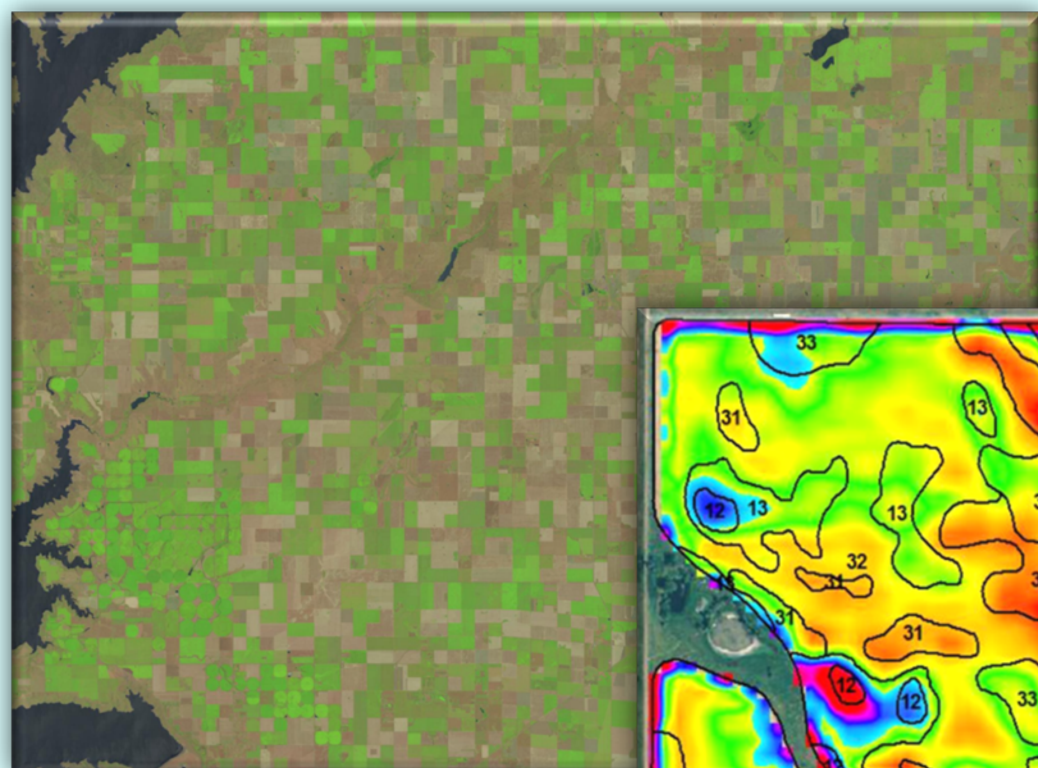
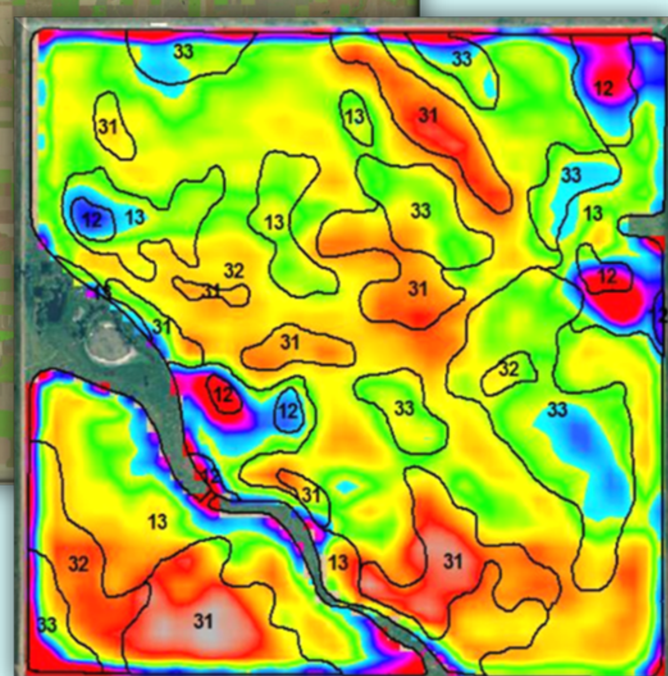
Landsat and Agriculture—Case Studies on the Uses and Benefits of Landsat Imagery in Agricultural Monitoring and Production

By Colin R. Leslie, Larisa O. Serbina, and Holly M. Miller





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Cover: 2015 Landsat image of South Dakota farm fields (back left). Photo credit: USGS Landsat Look Viewer. A zone map of a corn field in 2013 (front right). Photo credit: Jason Miller, Independent Crop Consultant, South Dakota.

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Abbreviations

ADMS	Ag Data Mapping Solutions
AgRISTARS	Agriculture and Resource Inventory Surveys through Aerospace Remote Sensing
AWiFS	Advanced Wide Field Sensor
CDL	Cropland Data Layer
DMC	Disaster Monitoring Constellation
ETM+	Enhanced Thematic Mapper Plus
FAS	Foreign Agricultural Service
MODIS	Moderate Resolution Imaging Spectrometer
NAIP	National Agriculture Imagery Program
NASS	National Agricultural Statistics Service
NDVI	Normalized Difference Vegetation Index
NIR	near infrared
SIA	Satellite Imagery Archive
SWIR	short-wave infrared
TM	Thematic Mapper
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VR	variable rate
WASDE	World Agricultural Supply and Demand Estimates

Landsat and Agriculture—Case Studies on the Uses and Benefits of Landsat Imagery in Agricultural Monitoring and Production

By Colin R. Leslie,[1] Larisa O. Serbina,[2] and Holly M. Miller[2]

Executive Summary

The use of Landsat satellite imagery for global agricultural monitoring began almost immediately after the launch of Landsat 1 in 1972, making agricultural monitoring one of the longest-standing operational applications for the Landsat program. More recently, Landsat imagery has been used in domestic agricultural applications as an input for field-level production management. The enactment of the U.S. Geological Survey's free and open data policy in 2008 and the launch of Landsat 8 in 2013 have both influenced agricultural applications. This report presents two primary sets of case studies on the applications and benefits of Landsat imagery use in agriculture. The first set examines several operational applications within the U.S. Department of Agriculture (USDA) and the second focuses on private sector applications for agronomic management.

Information on the USDA applications is provided in the U.S. Department of Agriculture Uses of Landsat Imagery for Global and Domestic Agricultural Monitoring section of the report in the following subsections:

- *Estimating Crop Production*.—Provides an overview of how Landsat satellite imagery is used to estimate crop production, including the spectral bands most frequently utilized in this application.
- *Monitoring Consumptive Water Use*.—Highlights the role of Landsat imagery in monitoring consumptive water use for agricultural production. Globally, a significant amount of agricultural production relies on irrigation, so monitoring water resources is a critical component of agricultural monitoring.
- *National Agricultural Statistics Service—Cropland Data Layer*.—Highlights the use of Landsat imagery in developing the annual Cropland Data Layer, a crop-specific land cover classification product that provides information on more than 100 crop categories grown in the United States.
- *Foreign Agricultural Service—Global Agricultural Monitoring*.—Highlights Landsat's role in monitoring global agricultural production. The USDA has been using Landsat imagery to monitor global agricultural production since the launch of Landsat 1 in 1972. Landsat imagery provides objective, global input for a number of USDA agricultural programs and plays an important role in economic and food security forecasting.

[1]Contractor: Fort Collins, Colorado. Work done under contract to U.S. Geological Survey.
[2]U.S. Geological Survey

- *U.S. Department of Agriculture—Satellite Imagery Archive.*—Highlights a number of the experiences of the USDA in acquiring, sharing, and managing moderate resolution imagery to support the diversity of USDA operational programs.

Private sector applications using Landsat imagery for agricultural management are discussed in the Landsat Imagery Use and Benefits in Field-Level Agricultural Production Management section of the report in the following subsections:

- *Field-Level Management*.—Provides an introduction to what field-level production management is and how it can be applied to agricultural management. This section explores the concept of zone mapping and how Landsat imagery can be used to identify different conditions within a field. The section also provides a case study of zone-mapping software, developed by GK Technology, Inc., that is used by numerous agricultural consultants.
- *Putting Zone Maps to Work*.—Highlights several case studies of private agricultural consultants who have been using Landsat imagery to develop zone maps for farmers. Landsat imagery is helping consultants and farmers optimize agricultural inputs, including fertilizer and seed, which leads to higher yield and economic return for the farmer.
- *Increasing Yield*.—Highlights the primary benefit of zone mapping using Landsat imagery. Using 5-year market average prices for a number of commodities, this section provides examples of how yield increases translate into higher returns for farmers.

Introduction

Landsat satellites have been operating continuously since 1972 when the first Landsat satellite, Earth Resources Technology Satellite 1, was launched. In February 2013, the National Aeronautics and Space Administration successfully launched the most recent Landsat satellite, Landsat 8, and in May 2013, operational control was given to the U.S. Geological Survey (USGS). Currently, two Landsat satellites are operational: Landsat 7 and 8. Landsat 7 has a technical issue that results in missing data in each scene, which at times limits data uses. Landsat 8 is currently collecting hundreds of complete, high-quality scenes every day.

The ongoing collection of Landsat imagery for more than 40 years has resulted in the longest continuous archive of satellite imagery currently available. At the end of 2008, the entire archive of Landsat imagery became available online at no cost to all users. USGS's free and open data policy has had a significant effect on users, resulting in a tenfold increase in the number of users registered with the USGS, as well as a more than hundredfold increase in the number of scenes distributed annually.

Landsat imagery has a vast number of users and uses. The benefits of the information that Landsat data provide range from conserving water and protecting public health and safety to informing decisionmakers in fields like natural resource management and planning and development. Although some studies have been conducted, the total benefit provided by open access to Landsat imagery is difficult to estimate due to numerable downstream and value-added uses. There are various approaches for estimating the value of information using quantitative economic models and qualitative descriptors. In 2009 and 2012, Landsat users registered with the USGS Earth Resources Observation and Science Center were surveyed, in part to estimate the value of Landsat data (Miller and others, 2011, 2013). These surveys used the contingent valuation method to quantify the economic benefits direct users received from Landsat imagery.

As a complementary effort to the quantifiable surveys conducted by Miller and others (2011, 2013), the USGS has been conducting an ongoing series of case studies. These case studies take a more qualitative approach, exploring each particular use of the imagery and its benefits and challenges as perceived by the users. The case studies provide a story of users and uses by providing specific examples of the applications of the imagery and the benefits and challenges that are associated with such applications. The case studies enrich our understanding by providing context for the economic-benefit modeling and demonstrating the value of Landsat imagery.

The case studies in this report focus on the use of Landsat data in the area of agriculture, including U.S. and international uses and benefits in the government and private sectors. As the Earth's population continues to increase, monitoring agricultural production and food security has become a major application area for satellite imagery. Advances in agricultural practices such as irrigation, crop rotation, hybridization, fertilization, precision agriculture, and other technologies have greatly increased global agricultural productivity, particularly during the past 50 years (Wik and others, 2008). Whether at the scale of monitoring global agricultural production or maximizing yield for an individual field, Landsat imagery has played an important role in informing management decisions. The following case studies explore a number of agricultural applications and uses for Landsat imagery and offer insights into both the benefits and challenges in applying this technology.

U.S. Department of Agriculture Uses of Landsat Imagery for Global and Domestic Agricultural Monitoring

Monitoring Agriculture from Space

In 2016, global production and trade of agricultural commodities are more complex in economic and geographic scale than at any point in history. Countries, including the United States, have realized many benefits from increased trade including accessibility to more varieties of food and greater seasonal availability. However, the complexity of agricultural markets has led to certain challenges, particularly from a policy standpoint. Developing sound agricultural policy, including timely, objective, and accurate collection and dissemination of data is essential in facilitating the efficient functioning of agricultural markets (Han and others, 2012). Collecting data at the temporal and geographic scales necessary to capture agricultural activities is a significant endeavor. Remote sensing technology, such as satellite imagery collected by Landsat, offers one of the most effective and efficient means of collecting timely and objective data on agricultural activities (Johnson and Mueller, 2010).

As specified in the Agricultural Trade Act of 1978 (P.L. 95-501), a key objective of U.S. agricultural policy is ensuring the collection of sound data to improve the competitiveness of U.S agricultural commodities in the world market. Within the United States, the U.S. Department of Agriculture (USDA) is the chief agency in charge of public agricultural data collection and dissemination. In order to meet policy objectives, the USDA administers a number of programs (fig. 1), including the acquisition and analysis of satellite imagery, to monitor agricultural activity in both foreign and domestic markets (Vogel and Bange, 1999).

The information collected by these programs is compiled by the World Agricultural Outlook Board, which operates as a primary source for economic intelligence and commodity outlook information for U.S. and world agriculture (U.S. Department of Agriculture [USDA], 2014a). A chief product of the World Agricultural Outlook Board is the World Agricultural Supply and Demand Estimates (WASDE) report, which provides a monthly forecast of supply and demand for major crops in both U.S. and global markets (USDA, 2014b). Although the primary objective of the USDA is to support U.S. agricultural interests, global market response to WASDE and other USDA reports, including response in futures markets prices, has been well documented (Vogel and Bange, 1999; Lusk, 2013).

Given the influence of USDA public information products in both domestic and global agricultural markets, the continuing availability of reliable data inputs, such as Landsat imagery, is important for developing accurate, objective, and timely products. To contextualize the importance of Landsat imagery in the USDA case studies presented in this report, it is helpful to know how satellite imagery is used to monitor agricultural activities. The following sections provide a brief overview of two of the most important applications of satellite imagery in agriculture: estimating crop production and monitoring consumptive water use.

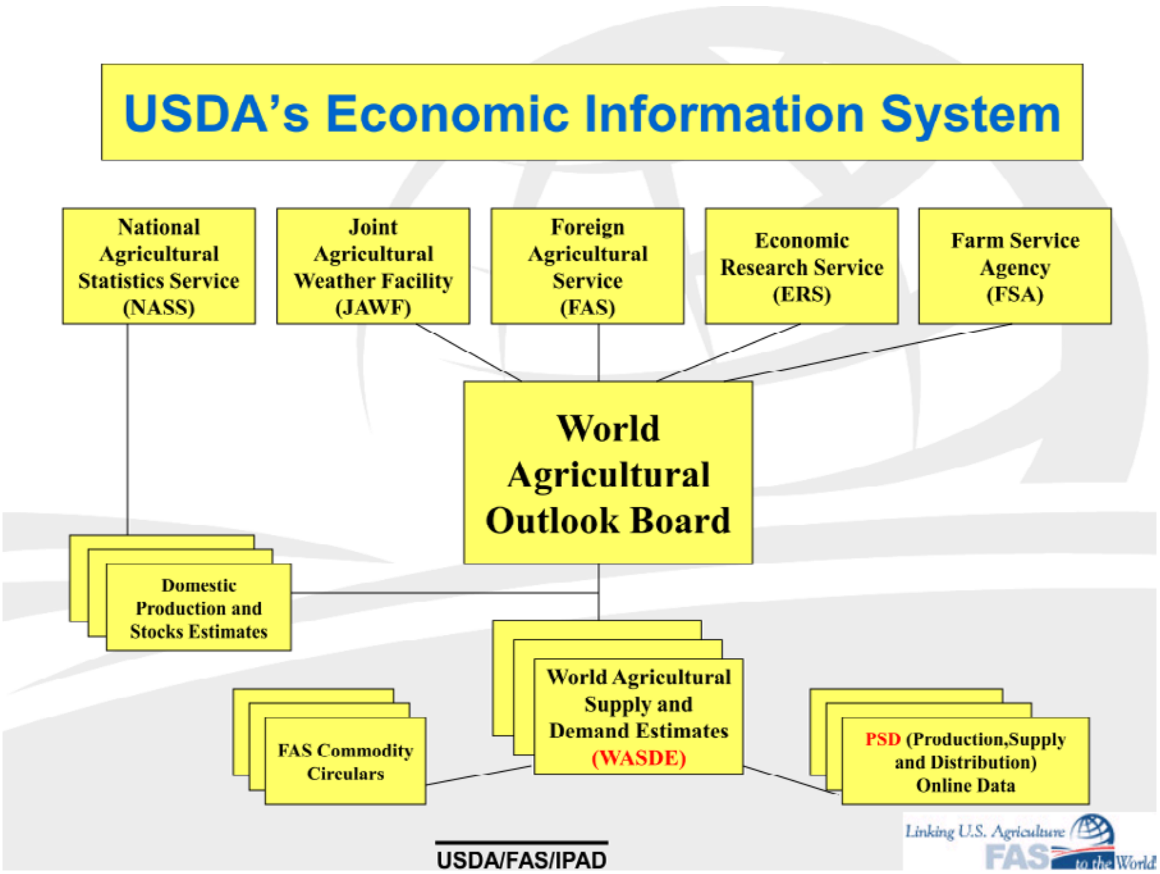


Figure 1. Overview of the programs that compose the U.S. Department of Agriculture's (USDA's) Economic Information System. The National Agricultural Statistics Service and the Foreign Agricultural Service are the primary agencies for developing domestic and global crop production estimates, respectively. (From Curt Reynolds, U.S. Department of Agriculture, Foreign Agricultural Service. [IPAD, International Production Assessment Division])

Estimating Crop Production

Perhaps one of the most important applications of satellite imagery is developing crop production estimates. In particular, satellite imagery plays an important role in enhancing the accuracy and reliability of global crop production estimates (Vogel and Bange, 1999). Domestically, satellite imagery provides supplemental data to ground-based annual agricultural surveys. Notably, the ability of satellite imagery to provide near-real-time production estimates of major crops is increasing, with significant strides occurring in the last decade. Estimating crop production is the responsibility of the National Agricultural Statistics Service (NASS) for U.S. domestic production and the Foreign Agricultural Service (FAS) for all global production (excluding the United States).

Developing crop production estimates requires accurate assessment of two primary inputs: crop acreage and yield. Crop acreage is a measure of the land area in production and yield is an estimation of the productivity of that area. Currently, both the NASS and FAS rely on Landsat and Disaster Monitoring Constellation (DMC) satellite imagery as primary sources for developing crop acreage estimates. Using a combination of red, near infrared (NIR), and short-wave infrared (SWIR) (only on Landsat) bands, acreage is determined using classification algorithms which are able to differentiate between specific crops. With two Landsat satellites currently in operation (7 and 8), a new moderate resolution (30-meter) scene can be acquired as often as every 8 days. This interval, however, represents ideal conditions because occlusion of the land surface by clouds means, realistically, that most locations have an effective acquisition rate of only a few cloud-free scenes each growing season.

Yield estimates, when developed using satellite imagery, rely primarily on vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), that monitor crop phenology (Prasad and others, 2006). Broadly speaking, crop phenology can be divided into emergence, vegetative growth, flowering, fruit/seed development, and maturity. Crop coefficients, which are unique for each type of crop and based on the relationship between historic crop phenology and yield data, are then applied in order to estimate potential yield for the current crop. Figure 2 illustrates how current season cropland NDVI can be compared to a historical average in order to monitor crop condition.

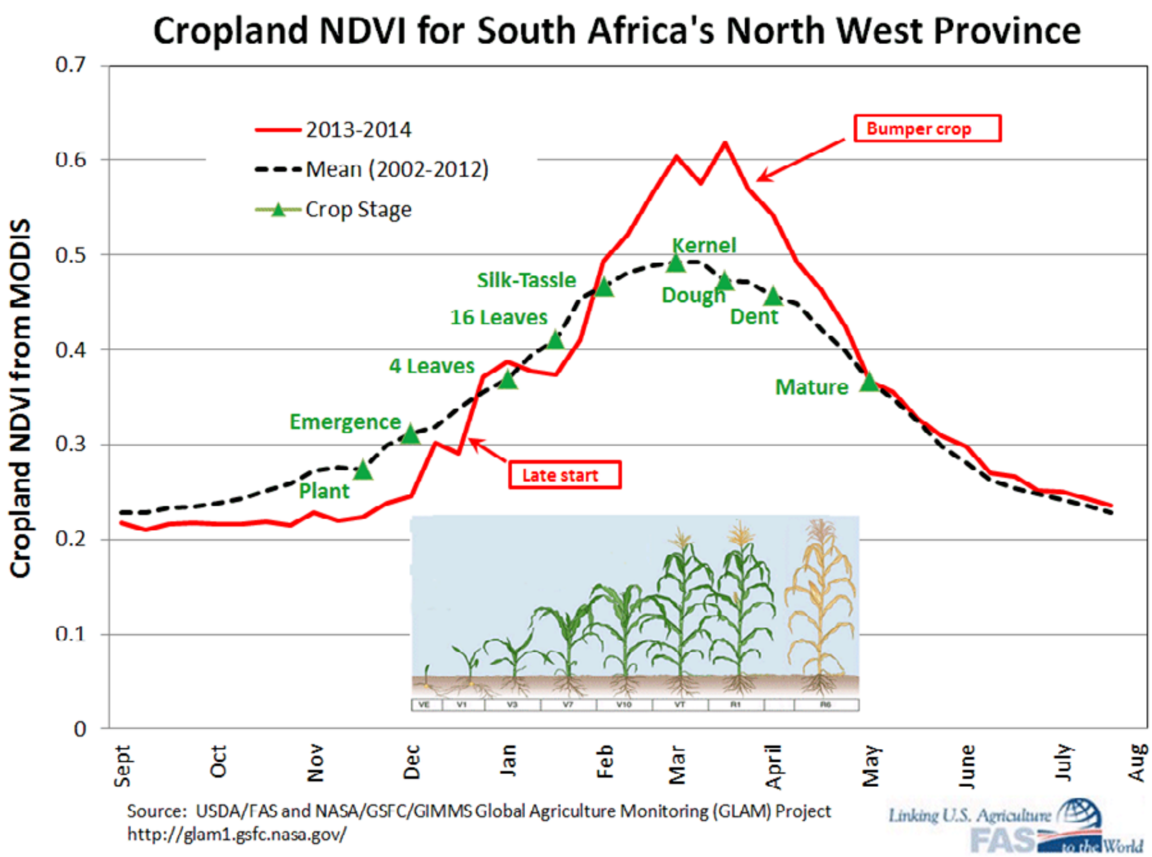


Figure 2. Cropland Normalized Difference Vegetation Index (NDVI) used to monitor crop phenology and potential crop yield. (From Curt Reynolds, U.S. Department of Agriculture, Foreign Agricultural Service. [MODIS, Moderate Resolution Imaging Spectrometer; USDA, U.S. Department of Agriculture; FAS, Foreign Agricultural Service; NASA, National Aeronautics and Space Administration; GSFC, Goddard Space Flight Center; GIMMS, Global Monitoring and Modeling Systems])

Both NASS and FAS derive NDVI primarily from imagery collected by the Moderate Resolution Imaging Spectrometer (MODIS) sensors onboard the Aqua and Terra satellites. MODIS has significantly lower spatial resolution at 250 meters compared to Landsat at 30 meters. However, because crop phenology is dynamic throughout the growing season, the higher revisit frequency of 1–3 days provided by the Aqua and Terra satellites is preferable to higher resolution from Landsat. MODIS imagery can also be used as a gap filler when there is limited moderate-resolution imagery coverage to derive crop acreage estimates; however, finer spatial resolution (such as Landsat at 30 meters) significantly improves both the appearance and accuracy of crop classification (Johnson and Mueller, 2010). Currently, the Cropland Data Layer (CDL) that categorizes different crops is used as an input mask to isolate pixels containing corn and soybeans, and the NASS remote-sensing yield estimation program uses MODIS NDVI and other ancillary datasets throughout the growing season to derive yield estimates (Johnson, 2014). MODIS is appropriate for crop condition and yield assessments, but Landsat does not have the temporal frequency needed at the field level to provide such global crop assessments.

Monitoring Consumptive Water Use

In addition to monitoring crop acreage and yield, monitoring consumptive water use at both global and field scales is another component of global agricultural monitoring (Curt Reynolds, USDA FAS, written commun. and oral commun., 2014). Much of global agricultural production relies, at least in part, on irrigation (fig. 3). In the United States, agriculture accounts for around 80 percent of consumptive water use on average, reaching upwards of 90 percent in many western states (USDA Economic Research Service [ERS], 2014).

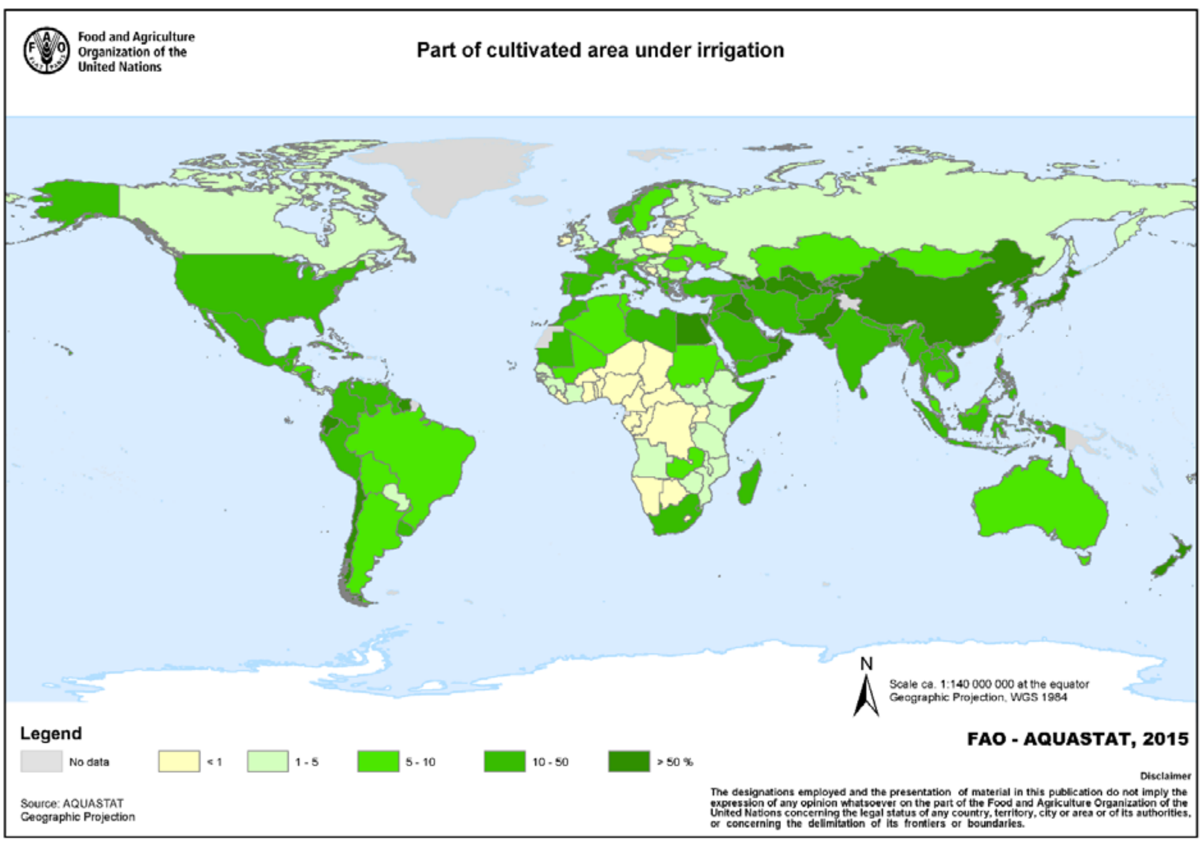


Figure 3. Percentage of cultivated area under irrigation by country. (From Food and Agriculture Organization of the United Nations, 2017)

An assessment of consumptive water use (that is, the amount of water that does not return to surface or groundwater sources) is one primary need for water and water rights management. Using thermal satellite imagery to measure evapotranspiration, the combination of evaporation and transpiration, is an effective and objective way to monitor consumptive water use across a broad geographic area (Anderson and others, 2012). Both Landsat and MODIS satellites have thermal imaging capabilities. Landsat has significantly higher resolution thermal imaging capabilities at 100 meters compared to MODIS at 1 kilometer. MODIS thermal imagery is best suited for monitoring global consumptive water use because of its higher revisit frequency of 1–3 days. However, Landsat thermal imagery is capable of measuring evapotranspiration at the field level (fig. 4), which is particularly important in the United States where water and water rights are increasingly valuable commodities (Allen and Morse, 2012). Monitoring evapotranspiration can also provide early indications of water stress, such as drought, which can significantly harm crop yield and potentially wipe out an entire season of crop production (Jackson and others, 2004).

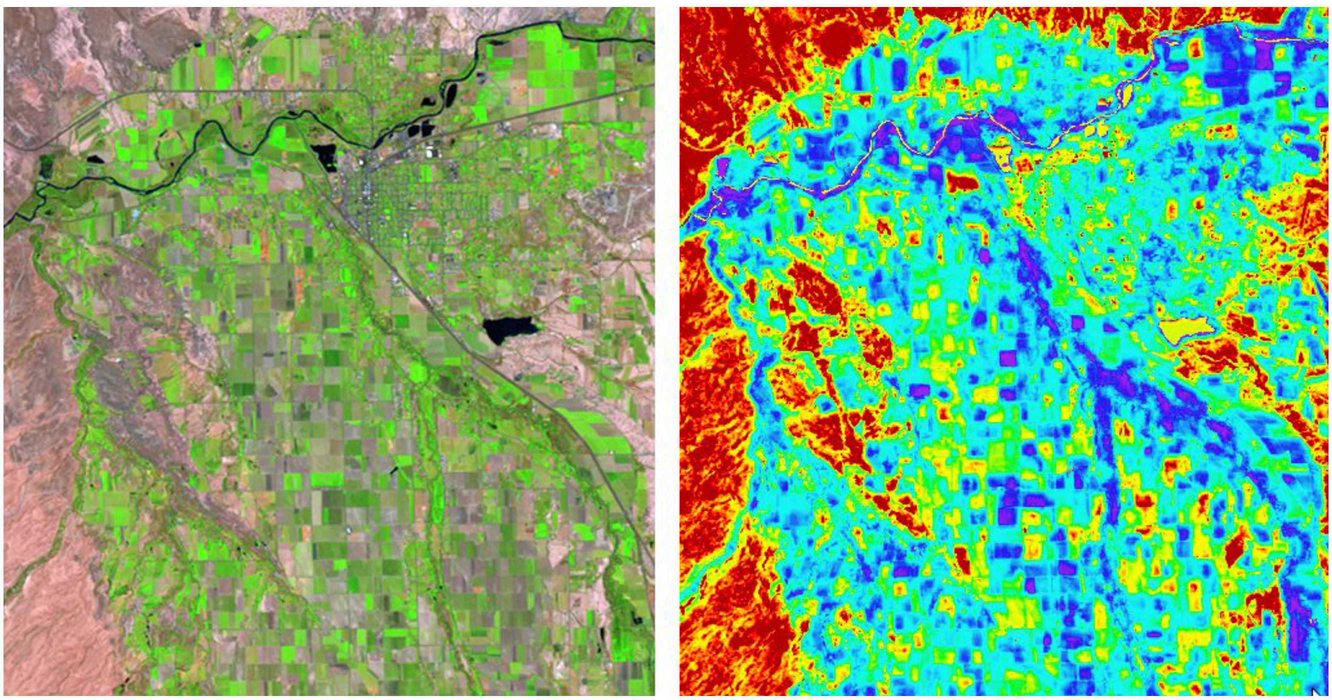


Figure 4. Landsat 5 Thematic Mapper images taken June 2006 of portions of the Uncompahgre River valley and lower Gunnison River valley in the upper Colorado River Basin. The image on the left is a composite color image and the right image shows 24-hour evapotranspiration developed using an energy balance model. (From Eckhardt, 2017 [red: low evapotranspiration rates to purple: high evapotranspiration rates])

U.S. Department of Agriculture Programs and Products

Both the NASS and FAS utilize Landsat imagery in a similar manner; however, the two programs remain independent and provide unique data products and services (table 1). The following sections provide a brief discussion of the individual products and services produced and the specific role of Landsat imagery in the development of those products.

Table 1. Overview of the products developed by the National Agricultural Statistics Service and Foreign Agricultural Service and the major associated reports derived from those products.
[DMC, Disaster Monitoring Constellation; MODIS, Moderate Resolution Imaging Spectrometer; USDA, U.S. Department of Agriculture; WASDE, World Agricultural Supply and Demand Estimates]

	National Agricultural Statistics Service	Foreign Agricultural Service
Spatial products	Cropland Data Layer	Global Agricultural Monitoring System
Inputs	Landsat, DMC, MODIS	Landsat, DMC, MODIS
Landsat use	Crop area, crop phenology (some crops)	Crop area
Users	USDA, research, crop consulting	USDA, research
Product reports	WASDE, Crop Production Reports	WASDE, Commodity Intelligence Reports
Function	Provide annual data layer of crop coverage grown during the previous year within the United States. Provide real-time yield estimates for select states/crops during the growing season.	Provide monthly estimates of global crop coverage and yield. Real-time monitoring of major regional crop impacts (for example, natural disaster).

National Agricultural Statistics Service—Cropland Data Layer

The CDL is a product of the NASS, whose mission is "to provide timely, accurate and useful statistics in service to U.S. agriculture" (Johnson and Mueller, 2010, p. 1204). The CDL is a crop-specific land cover classification product that provides information on more than 100 crop categories grown in the United States. CDLs are derived using a supervised land cover classification of satellite imagery collected throughout the growing season. Supervised classification requires manually identifying pixels within certain images, often called training sites, which represent the same crop or land cover type. Using these training sites, a spectral signature is developed for each crop type that is then used by the analysis software to identify all other pixels in the satellite image representing the same crop. Using this method, a new CDL is derived monthly throughout the growing season for purposes of acreage estimation in support of monthly production reports. The CDL is then released to the public a few months after the end of the growing season through the online CropScape data portal (fig. 5), which can be accessed at http://nassgeodata.gmu.edu/CropScape/.

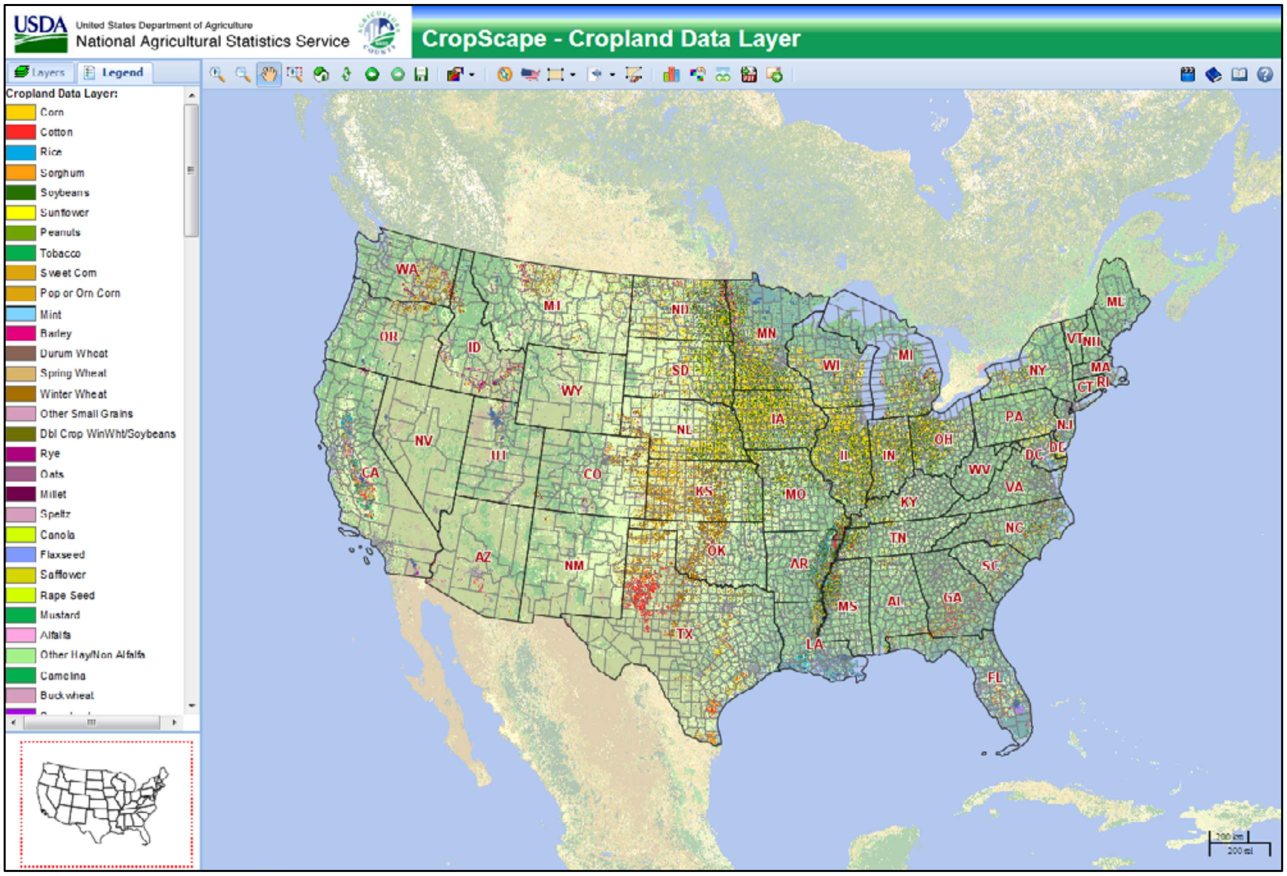


Figure 5. The CropScape data portal, which allows for the display of the Cropland Data Layer by year from 1997 to the present; derived products such as the Cultivated and Crop Frequency Layers; and supporting layers like boundaries, water, and roads. (USDA National Agricultural Statistics Service, 2017)

The first CDL, which was produced in 1997 using data from Landsat 5, covered three states: Arkansas, North Dakota, and South Dakota. Since then, the program has expanded to include more states as well as additional satellite data. By 2008, the annual CDL provided coverage for the entire continental United States and was being released at 56-meter resolution. Additionally, several real-time CDL acreage estimates were being produced during the growing season for winter wheat, corn, and soybeans. During its lifetime, the CDL has utilized a number of different earth observation satellites, including Landsats 4, 5, and 7; IRS-P6 Resourcesat-1 Advanced Wide Field Sensor (AWiFS) MODIS Aqua and Terra; DMC Deimos-1 and UK-2; and, starting in 2013, Landsat 8.

Until 2006, CDLs relied primarily on Landsat 5 and 7 data. An aging Landsat 5, a scan line corrector failure on Landsat 7, and uncertainty regarding the future launch of Landsat 8, forced NASS to begin exploring alternative satellites to fill the potential data gap. The Indian Space Research Organization satellite Resourcesat-1, which was launched in 2003 carrying AWiFS, was selected as the most viable alternative and the USDA began sensor testing in 2004. The AWiFS bands 2–5 are very similar in spectral range to those of the Landsat Enhanced Thematic Mapper Plus (ETM+). Although AWiFS had a slightly lower resolution (56 meter) than Landsat Thematic Mapper (TM) and ETM+ (both 30 meter), its increased revisit time of 5 days was beneficial given the dynamic nature of crops. Between 2006 and 2009, AWiFS provided the majority of imagery for CDLs. The 56-meter AWiFS resolution, though adequate for mapping homogeneous crops such as soybeans and corn, had a lower accuracy for smaller, less homogenous crops, but its better temporal resolution provided a tradeoff for its lower spatial resolution. Beginning in 2010, because of the failure of Resourcesat-1 AWiFS, CDLs were released at 30-meter resolution using a combination of Landsat TM/ETM+ and DMC. Additionally, because of the decommissioning of Landsat 5, the 2012 30-meter resolution CDL was constructed entirely from DMC data. The most recent CDL for 2015 was released February 2016 and relies primarily on Landsat 8 and DMC imagery.

The expansion of the CDL coverage from regional to national was made possible largely through the growing availability of low cost and free mid-resolution Landsat-like imagery (Johnson and Mueller, 2010). The future of the CDL program is closely tied to the continuing availability of multi-spectral, mid-resolution imagery that is collected at a sufficient temporal frequency for crop forecasting. It is not a coincidence that the CDL program expanded to national coverage after the implementation of the free and open Landsat data policy in 2008. NASS utilizes CDLs as principal components of crop yield modeling research (Johnson, 2014) and for developing real-time crop acreage estimates during the growing season. Reports of area estimates are produced once a month for June and August, and twice each month for September, October, and December using Landsat imagery and DMC data (Rick Mueller, USDA NASS, oral commun. and written commun., 2014). Although the final CDL is not released until January the following year, monthly in-season estimates serve as a source for domestic production figures in the WASDE report. Outside of NASS, CDLs are being increasingly used in research and management applications including crop rotation, land use change, yield estimates, water use, and effects of natural disaster (Boryan and Yang, 2013; Mueller and Harris, 2013).

Foreign Agricultural Service—Global Agricultural Monitoring

The FAS is responsible for USDA international activities, including the monitoring and estimation of crop supply and demand across global markets. Estimates of foreign production, supply, and demand are developed primarily through agricultural attachés. Attachés are based in foreign embassies, primarily in countries representing potential markets for U.S. crops. Currently, FAS has 93 offices in 72 countries that serve an additional 98 countries (USDA Foreign Agricultural Service, 2016). The FAS attachés are further assisted by the International Production Assessment Division, which collects and analyzes global crop condition and production. International Production Assessment Division crop production analysts and FAS Global Agricultural Information Network reports both provide crucial inputs for the monthly WASDE report.

Enabled by the launch of Landsat 1 in 1972, FAS began monitoring global agricultural production using satellite imagery that year. Interest and the need for satellite monitoring of crop production was in part driven by the 1972 grain crop failure in the former Union of Soviet Socialist Republics (U.S.S.R.). Although the crop failure was widespread throughout the U.S.S.R., information and detection of the failure remained unknown until later that year. The lack of timely global production estimates allowed the U.S.S.R. to purchase U.S. wheat at lower prices than the true market value (Curt Reynolds, USDA FAS, written commun. and oral commun., 2014).

Global supply and demand estimates developed by FAS and the World Agricultural Outlook Board are important inputs for a variety of derivative products, including monthly WASDE reports and FAS Commodity Intelligence reports. Although the WASDE is an important market intelligence source for agricultural commodities, Commodity Intelligence reports from FAS provide on-demand assessments of specific regions. The ability to rapidly assess changes in a region's agricultural status, whether due to natural disaster, drought, or political unrest, is crucial for anticipating market impact, food shortages, and humanitarian needs (Curt Reynolds, USDA FAS, written commun. and oral commun., 2014).

Currently, FAS utilizes a combination of Landsat, DMC, and MODIS imagery for monitoring crop production. Known generally as the Global Agricultural Monitoring Project, the Global Agricultural Monitoring System was developed in order to provide global coverage with near-real-time estimates of crop production (Becker-Reshef and others, 2010) (fig. 6). Data from Landsat and DMC, which provide 30- and 22-meter resolution, respectively, are used primarily for developing crop acreage estimates. MODIS, which has a lower resolution at 250 meters but a higher revisit rate of 1–3 days, is used for monitoring crop phenology (fig. 6).

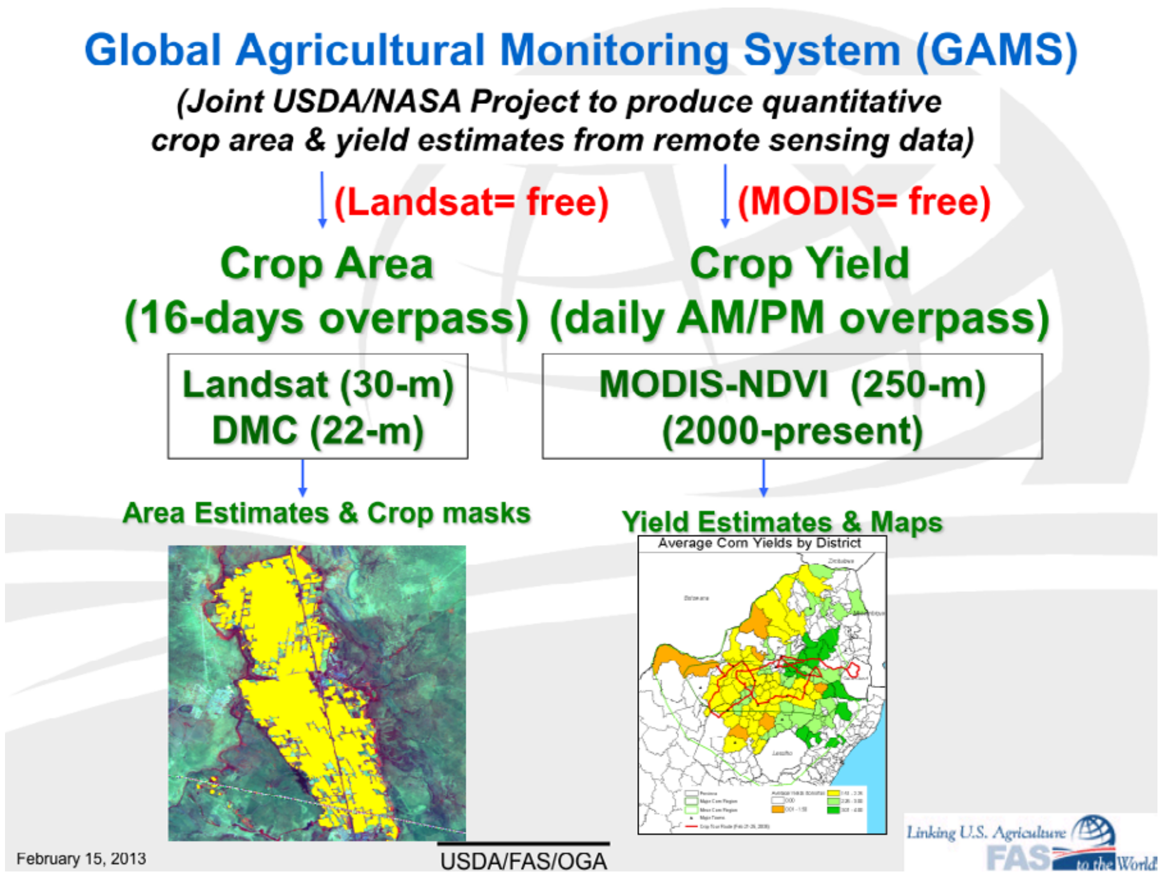


Figure 6. The Global Agricultural Monitoring System, a joint project between the U.S. Department of Agriculture (USDA) and the National Aeronautics and Space Administration (NASA) to monitor crop area and yield using remote sensing data. (From Curt Reynolds, U.S. Department of Agriculture, Foreign Agricultural Service. [MODIS, Moderate Resolution Imaging Spectrometer; NDVI, Normalized Difference Vegetation Index; DMC, Disaster Monitoring Constellation; FAS, Foreign Agricultural Service; OGA, Office of Global Analysis])

The first large-scale USDA program for monitoring global crop production (using Landsat imagery) was the Agriculture and Resource Inventory Surveys through Aerospace Remote Sensing (AgRISTARS) satellite that launched in 1979 (Caudill and McArdle, 1979). A number of objectives were outlined for AgRISTARS, but the primary focus was on early warning/crop condition assessment and foreign commodity production forecasting. In the late 1980s, AgRISTARS was officially moved to Washington, D.C., to be administered by the FAS. Although AgRISTARS has since been superseded by a number of newer analysis platforms at FAS, the objectives remain largely the same and early warning/crop condition assessment covering seven countries has now expanded to coverage of most of the agricultural production areas of the globe (Curt Reynolds, USDA FAS, written commun. and oral commun., 2014).

U.S. Department of Agriculture—Satellite Imagery Archive

As one of the single largest users of satellite imagery in the United States, the USDA set up the Satellite Imagery Archive (SIA) in 2000 to streamline acquisition and reduce the overall agency cost of acquiring imagery. Before the creation of the SIA, and for the first several years after its creation, Landsat served as the primary source for moderate-resolution imagery. By 2003, because of the advanced age of Landsat 5 and the scan line corrector-off problem with Landsat 7, insufficient coverage was being provided, and SIA searched for the most cost-effective way to address the 2003–2013 Landsat data gap (Curt Reynolds, USDA FAS, written commun. and oral commun., 2014) (fig. 7).

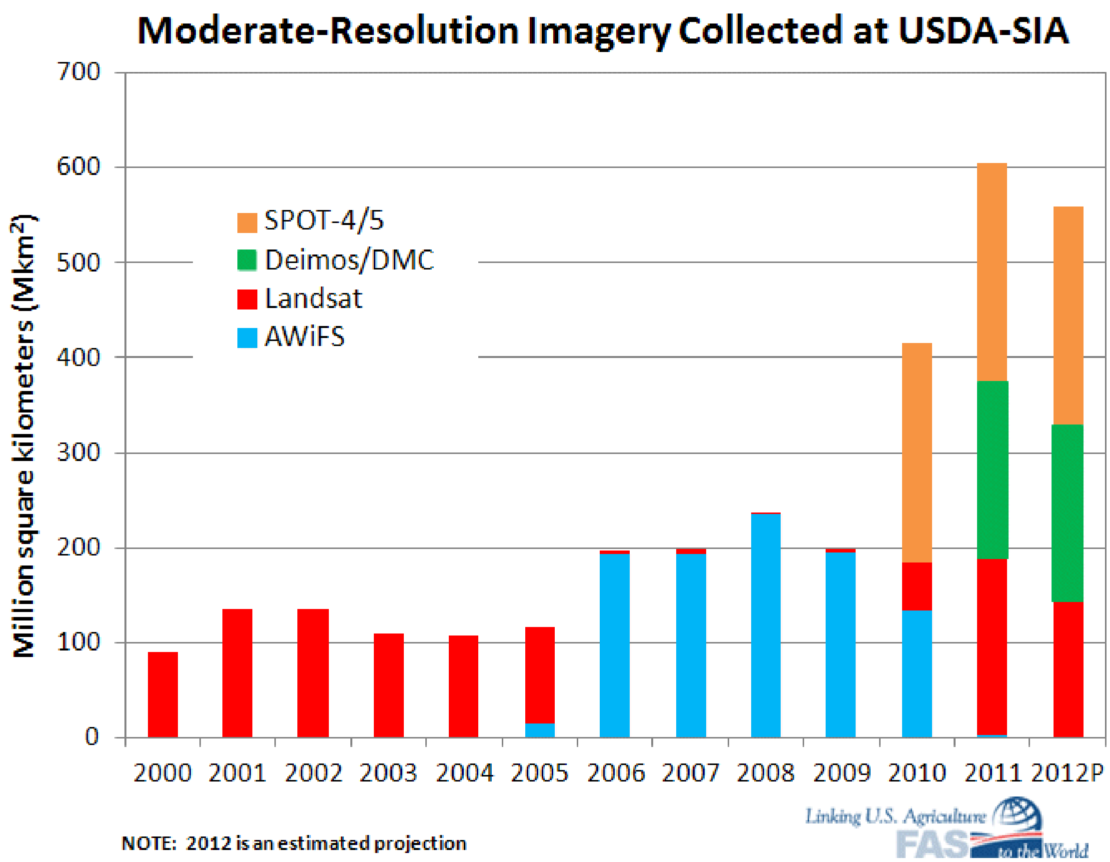


Figure 7. Number of square kilometers of remotely sensed imagery collected by the U.S. Department of Agriculture (USDA) Satellite Imagery Archive (SIA). Although the chart does not show Landsat 8, which began collecting imagery in 2013, both the National Agricultural Statistics Service and Foreign Agricultural Service utilized Landsat 8 imagery extensively in 2013. (From Curt Reynolds, U.S. Department of Agriculture, Foreign Agricultural Service. [DMC, Disaster Monitoring Constellation; AWiFS, Advanced Wide Field Sensor; FAS, Foreign Agricultural Service])

In 2005, the USDA contracted for IRS Resource-1 AWiFS satellite imagery as a Landsat data-gap replacement. AWiFS served as the primary imagery source of moderate resolution imagery from 2006 until the AWiFS sensor suffered a major malfunction in 2010. Beginning in 2010, USDA contracted DMC and Deimos moderate-resolution imagery through the SIA to monitor the U.S. growing seasons and to serve other USDA remote sensing programs within the NASS, U.S. Forest Service, Risk Management Agency, Agricultural Research Service, Natural Resources Conservation Service, and Animal and Plant Health Inspection Service. DMC and Deimos satellites are capable of providing large volumes of imagery, with 3–5 day, full-repeat coverage. Budget constraints limited the USDA to purchasing near-cloud-free images from April 1, 2010 to September 30, 2010, for the lower 48 states. The increase in the number of cloud-free images collected during the growing season (five to six for DMC compared to one to two for Landsat) improved crop classification accuracy despite the lack of a SWIR band on the DMC and Deimos satellites. FAS continued to use Landsat 7 imagery after it became free in October 2008 in accordance with Landsat's open data policy. Although this meant no additional acquisition cost for FAS, 22 percent of each Landsat 7 scan line corrector-off image was not usable due to pixel loss (Curt Reynolds, USDA FAS, written commun. and oral commun., 2014).

In anticipation of the potential loss of Landsat 5 prior to the launch of Landsat 8, USDA entered into individual contracts with private and foreign satellite operators, and a collaborative effort was undertaken by the National Aeronautics and Space Administration, USGS, and the USDA in 2010. The North American Data Buy allowed for the establishment of a ground-receiving unit for the SPOT 4, and later SPOT 5, French satellites at the Earth Resources Observation and Science Center in South Dakota. The USGS North American Data Buy for SPOT 4 and SPOT 5 imagery was for 3 years, and after 18 months, the USGS also began orthorectifying the SPOT 4 and SPOT 5 imagery. All of the orthorectified SPOT 4 and SPOT 5 imagery from the North American Data Buy contracts is available for free to U.S. federal civil agencies, state and local government users, and U.S. tribal governments from the USGS Earth Resources Observation and Science Earth Explorer Web site (http://earthexplorer.usgs.gov).

Landsat Benefits and Challenges for Agricultural Monitoring

The benefits of satellite-based agricultural monitoring were recognized early and satellite-based monitoring has become a cornerstone of domestic and foreign agricultural monitoring. The USDA has been using Landsat imagery to monitor crop production since the launch of Landsat 1 in 1972, making the agency the first and longest-running operational land-imaging satellite user in the United States. The technical benefits of using Landsat imagery for crop monitoring are largely similar for the FAS and NASS because the imagery provides an objective and unbiased assessment of farm-level crop production.

Landsat imagery provides many technical benefits for crop production monitoring and the Landsat program as a whole further provides several additional benefits to programs such as the FAS and NASS. The known stability of spectral and spatial resolution across Landsat satellites, as well as the high level of image orthorectification and radiometric correction, have helped establish Landsat as a gold standard among earth observation satellites. The pixel resolution of the multi-spectral data collected by Landsat since 1982 has become a standard for land cover classification, enabling a high level of classification accuracy at the same time as balancing the processing realities of classifying imagery at a global scale (Johnson and Mueller, 2010). In practical terms, the availability of consistently collected (across multiple satellites and years), accurately corrected, and as of 2008, freely available Landsat data is an important benefit for agencies such as the FAS and NASS. These agencies, which remain primarily operational in nature, have limited time and budget for purchasing satellite imagery from commercial sources (Curt Reynolds, USDA FAS, written commun. and oral commun., 2014).

Finally, monitoring field-level consumptive water use is becoming increasingly important for agricultural and water managers (Allen and Morse, 2012; Serbina and Miller, 2014). Currently, Landsat provides the only continuously collected, publicly available thermal imagery of sufficient resolution to monitor consumptive water use at the field level. Although Landsat's ability to provide data for development of individual products such as NDVI or evapotranspiration is important, the ability to collect data for multiple products concurrently is also important. By collecting a single, multi-spectral image, derivative products representing a range of environmental variables allow for temporally relevant comparisons among those products.

Landsat Imagery Use and Benefits in Field-Level Agricultural Production Management

Field-Level Management

In the United States, as in many parts of the world, farmers face many challenges that must be addressed in today's modern agricultural economy. Increasing food production to feed a growing global population; higher input costs for fertilizer, seed, and water; and growing concerns about the effects of agricultural activities on the environment require constant innovation in technology and methods for modern agronomic management (Stafford, 2000; Seelan and others, 2003). One such innovation that has developed during the last few decades is field-level production management, which is both a precursor to, and a component of, modern day precision agriculture. Aided by advances in ground-based and remote sensing technologies, field-level production management is allowing farmers to observe, measure, and respond to varying conditions throughout a field in order to more efficiently manage crop production (Zhang and others, 2010). A major advancement in the use of remote sensing for agronomic management was the introduction of moderate-resolution, multi-spectral satellite sensors, such as those found aboard the Landsat series of satellites.

Using a combination of sensors to collect imagery at a maximum of up to 30-meter spatial resolution, Landsat satellites can provide farmers with valuable information on the status of their fields. Understanding how crop-limiting factors such as soil composition, nutrient availability, topography, and water availability fluctuate throughout a field allows farmers to more efficiently and effectively produce crops and at the same time help limit negative environmental effects from nutrient and chemical leaching and runoff. Although farmers have a growing array of tools and technologies at their disposal for field-level production management, Landsat imagery continues to play a critical role in both pre- and post-planting crop management. To better understand Landsat's vital role, a number of case studies focusing on users of Landsat imagery were conducted. The following case studies, which are primarily centered on the USDA's Northern Great Plains and Heartland Farm Resource Regions (fig. 8), exemplify some of the products, services, benefits, and challenges of Landsat imagery in agricultural management.

Since the advent of agriculture, environmental factors including water, soil, nutrients, and climate have been key in determining both the type of crops that can be grown in a region and the yield that farmers can expect from those crops. Regional variability in the particular combination of these factors has helped shape the current agricultural landscape of the United States (fig. 8). The Heartland Farm Resource Region, which is characterized by fertile soils, moderate average rainfall, and cold winters, has become a major producer of corn and soybeans. By contrast, the Fruitful Rim Farm Resource Region, which offers generally fertile soils and more moderate year-round temperatures, has become a major producer of fruits and vegetables. Although production differences between regions are largely the result of broad-scale geographic variability in environmental factors, small-scale variability at the county, and even field-level, is becoming an increasingly important determinant of overall crop production (Stafford, 2000).

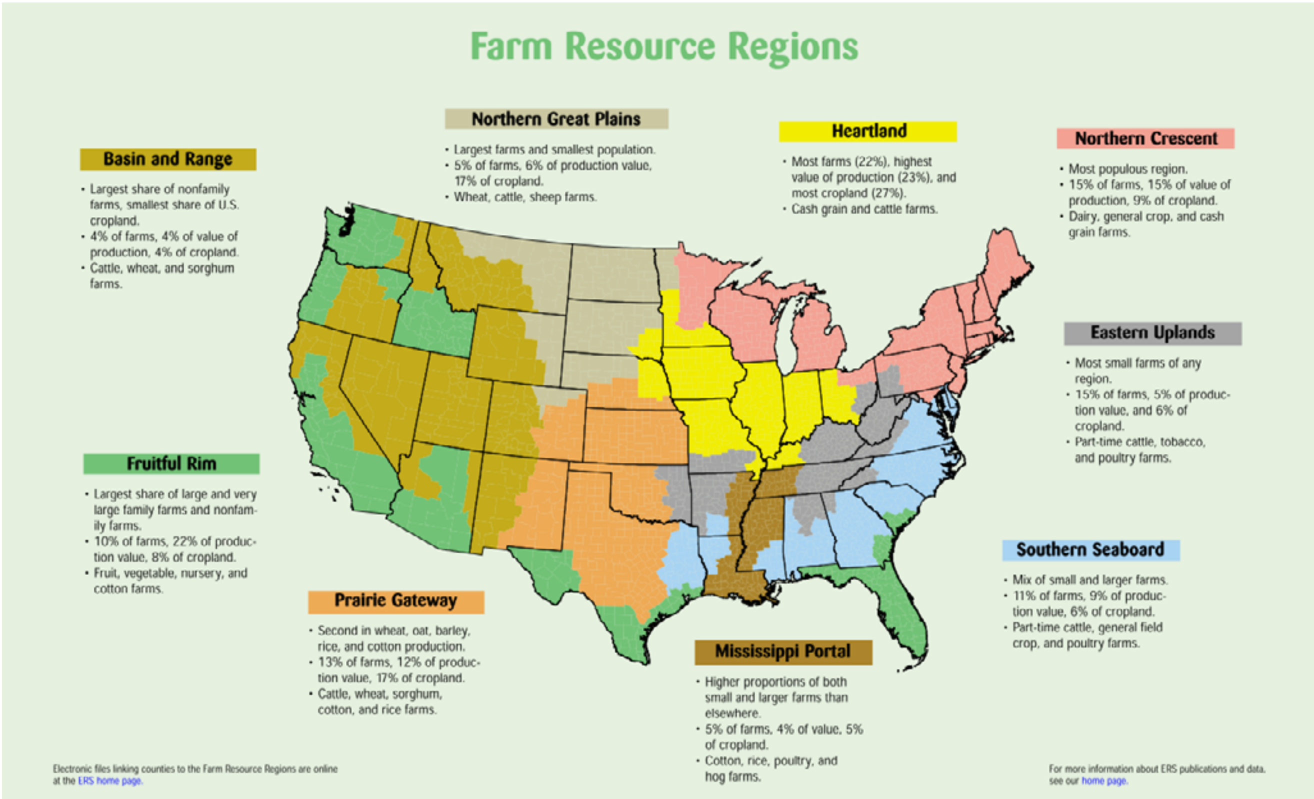


Figure 8. Farm Resource Regions developed by the U.S. Department of Agriculture's Economic Research Service (ERS) based on geographic specialization in production of farm commodities. (USDA ERS, 2000)

Zone Mapping

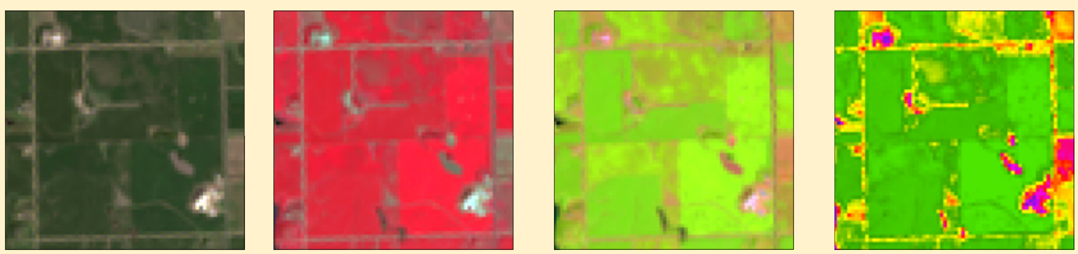
Farmers have long known that not all areas in a field produce the same yield, yet the ability to measure and map this variability is a fairly recent innovation in agronomic management. The practice of measuring and mapping yield-limiting variables throughout a field is generally referred to as "zone mapping" (Zhang and others, 2010). Zone maps are used to identify areas within a field that are similar in one or more characteristics, including soil properties (for example, structure, organic content, depth, drainage), nutrient levels, topography (for example, flat land, rolling hills), and historic crop growth and yield. A prerequisite to mapping these factors is the ability to accurately and consistently measure them at a high enough spatial resolution to rectify differences at the sub-field level. Multi-spectral sensors such as the Operational Land Imager (OLI) aboard Landsat 8 and the previous-generation ETM+ aboard Landsat 7 have been shown to be exceptionally capable in this regard. Additionally, both the OLI and ETM+ sensors collect imagery at 30-meter resolution for multi-spectral bands, which is sufficient for mapping variability at the field level. By utilizing different combinations of bands, it is possible to measure different environmental factors, particularly soil properties and vegetation status (see box titled Measuring Crop Characteristics Using Remote Sensing).

Measuring Crop Characteristics Using Remote Sensing

In agricultural applications, remote sensors measure the amount of light that is reflected and (or) emitted from a field in order to measure vegetation, soil, or moisture characteristics. Multi-spectral sensors such as those aboard Landsat satellites are capable of sensing visible (red, green, blue) as well as nonvisible (NIR, SWIR, long-wave infrared) portions of the electromagnetic spectrum. The Operational Land Imager and the Thermal Infrared Sensor aboard Landsat 8 measure reflected and emitted energy in 11 bands, ranging from very deep blue and violet (band 1) to long-wave infrared (band 11).

By using different combinations of bands, it is possible to detect differences in vegetation and soil characteristics within a field, even when those differences may not be visible to the human eye (fig. 9). For example, green leaves that are high in chlorophyll content absorb red and blue light that drives photosynthesis and reflect light in the green and NIR wavelengths. High levels of chlorophyll, which is a key indicator of plant health, reflect strongly in the NIR wavelengths. Subtle changes to the level of light reflected in NIR can help producers detect plant stress, even if the visible greenness of the leaf appears similar or unchanged.

Although some conditions can be measured using individual bands, remotely sensed data for vegetation are often analyzed using vegetation indices, which calculate the difference, or ratio, between two spectral bands. One of the most common vegetation indices is the NDVI. As previously noted, plant leaves tend to reflect light in NIR wavelengths and absorb in the red wavelength. By calculating the ratio between the NIR and red wavelengths, NDVI can differentiate high biomass (dense, healthy vegetation) and low biomass (sparse or stressed vegetation). Numerous other vegetation indices have been developed during the last several decades that can be used to measure and monitor a wide range of crop characteristics, including nitrogen levels, water stress, crop disease, and soil composition.



Application:	True Color Image	Color Infrared	Agriculture	NDVI
Bands:	Red, Green, Blue	NIR, Red, Green	SWIR 1, NIR, Blue	Red & NIR
Description:	Uses the visible red, green, and blue bands to create a true color image	Healthy vegetation is bright red and stressed vegetation is dark red	Vigorous vegetation is bright green, stressed vegetation is dark green, and barren ground is brown	High biomass is bright green, low biomass is dark green to yellow, and barren ground is magenta to blue

Figure 9. False color Landsat 8 images, such as the color infrared and agriculture images above, use nonvisible bands to reveal different vegetation characteristics that may or may not be visible using a true color image, such as the one on the far left. Images were created using ArcGIS Landsat 8 Views service. (NDVI, Normalized Difference Vegetation Index; NIR, near infrared; SWIR, short-wave infrared)

Zone-Mapping Software

Used independently, data on field conditions such as soil properties, vegetation status, historic yield, and crop condition are of limited value (Doraiswamy and others, 2004). To fully realize the value of these data, they must be combined using specialized software. One example of this type of software is Ag Data Mapping Solutions (ADMS), produced by GK Technology. ADMS is designed to manage and manipulate a range of geographic data, including the creation of zone maps from satellite imagery. Using a combination of bare soil and vegetation maps derived from Landsat imagery along with National Agriculture Imagery Program (NAIP) imagery and past yield data, zone maps can be created for a field (Kelly Sharp, GK Technology, oral commun. and written commun., 2014) (fig. 10). The goal is to define management areas in a field by defining an optimal amount of inputs to reach a target output. Zone maps can be created for any input or combination of inputs such as water, fertilizer, seed, pesticides, or herbicides. For corn and soybeans that are primary crops in the rainfall-dependent Heartland Farm Resource Region, zone maps are most often developed for variable rate (VR) application of fertilizer and seed.

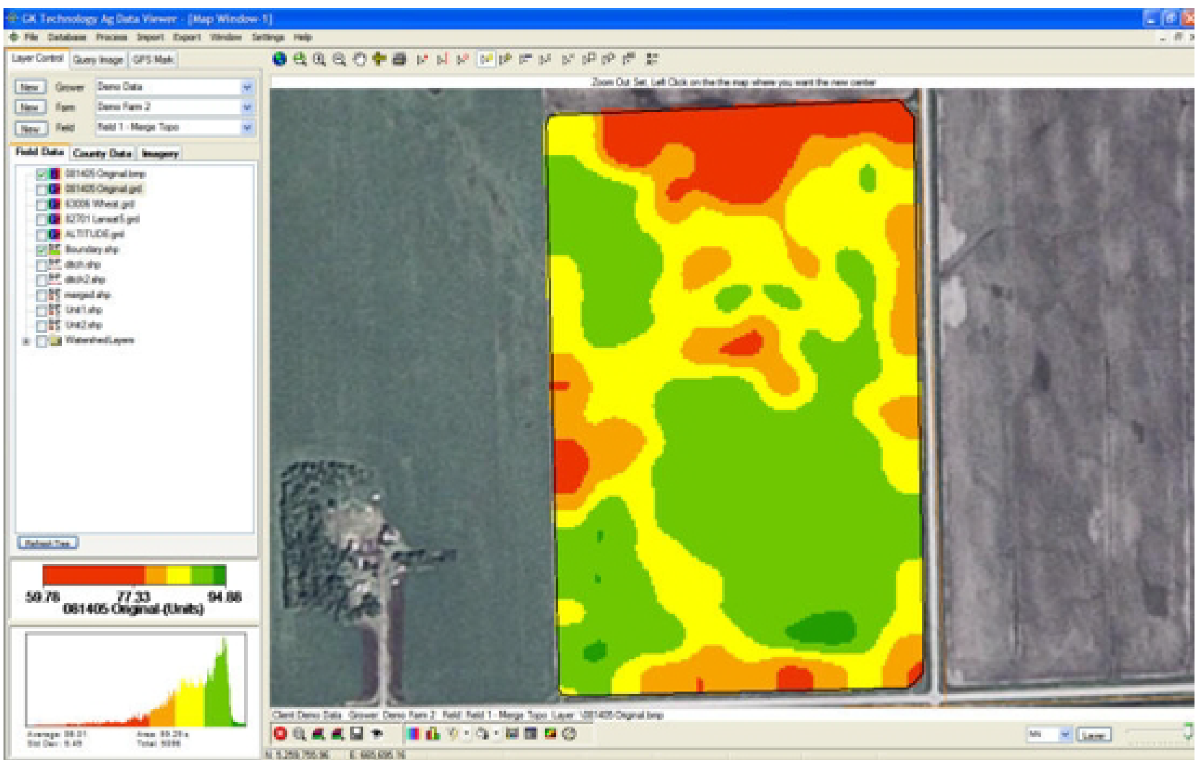


Figure 10. The Ag Data Mapping Solutions software provided by GK Technology provides an interface that allows users to manipulate various geographic information system and global positioning system data, including the creation of zone maps from satellite imagery such as Landsat. (From GK Technology)

Although some agricultural cooperatives and consulting firms employ proprietary in-house software solutions, the ADMS software is available for use by both independent crop consultants and producers. Currently, more than 1,000 customers are using the software to improve agricultural production through VR zoning, with the majority of customers in Minnesota, South Dakota, North Dakota, the Pacific Northwest, and Canada (Kelly Sharp, GK Technology, oral commun. and written commun., 2014).

Putting Zone Maps to Work

The availability of software like ADMS is allowing independent crop consultants such as Mark Foster and Jason Miller to supply agricultural consulting services to farmers throughout South Dakota. Both Foster and Miller utilize Landsat imagery along with other crop data inputs to develop VR maps for their clients.

Mark Foster currently develops VR maps for more than 30,000 acres of corn. Using Landsat and NAIP imagery along with soils and historic yield data, he is able to develop prescription zone maps for VR fertilizer application (fig. 11). By using VR mapping, Foster is able to optimize fertilizer application on the basis of productive variability throughout the field, which may decrease costs or prevent losses. The amount of cost savings is highly dependent on the level of straight-rate fertilization that occurred prior to adoption of VR application. If straight-rate fertilizer application was, on average, above optimal levels for field productivity, then users are likely to see at least some savings by switching to VR application. If straight-rate application was at or near average optimal levels, however, the redistribution of fertilizer between high and low productivity areas using VR application may result in minimal or no overall cost savings (Mark Foster, SD Consulting, oral commun. and written commun., 2014).

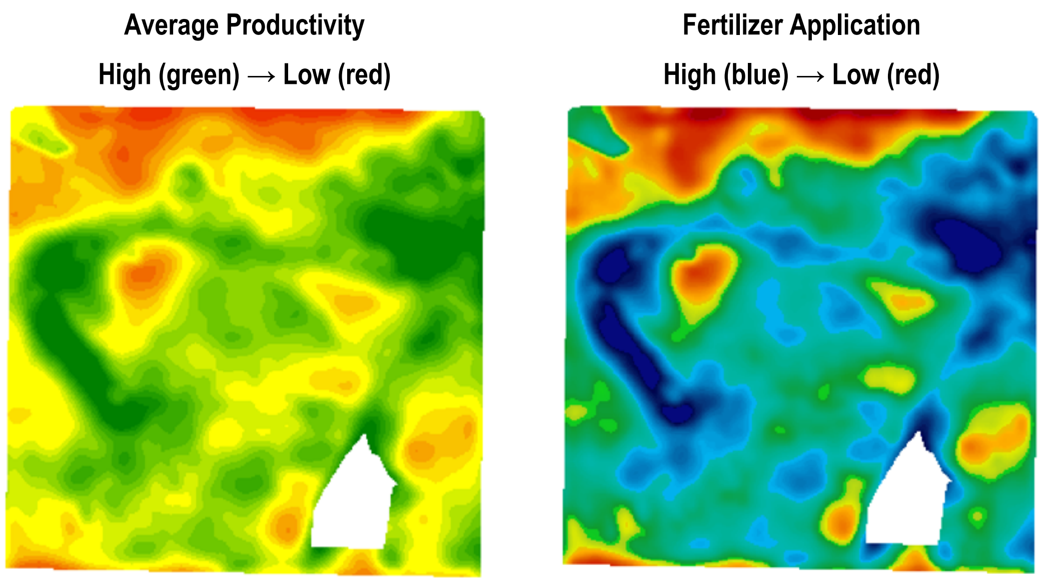


Figure 11. The images show the relationship between average productivity and the prescription for fertilizer application. In this case, high productivity areas (green in left image) receive a higher level of fertilizer application (blue in right image). (From Mark Foster, SD Consulting)

Ultimately, the goals of optimizing fertilizer application rates are to obtain high yields and minimize losses through the appropriate application of fertilizer and seed to poor soils and the avoidance of runoff or leaching due to over-application of fertilizer. To this end, Foster notes that in some cases, VR application may lead to an increase in fertilizer use as more aggressive yield quotas are set for high productivity areas. Although this means that some clients are not necessarily seeing savings on overall fertilizer costs, they are benefiting from not applying too much fertilizer and seed to low productivity areas. However, the greater benefit of VR application for Foster's clients is an increase in yield per acre, generally on the order of 10 percent, which equates to an increase in revenue. According to Foster, "[Providing] this kind of critical [Landsat] data for variable rate application is very important work that the government is doing. Landsat imagery is critical for agriculture" (Mark Foster, SD Consulting, oral commun. and written commun., 2014).

Jason Miller is another independent crop consultant who has been using Landsat imagery to develop VR maps for clients since 2009, shortly after the imagery and historical archive became free. Currently, he manages around 50,000 acres and uses Landsat imagery along with on-the-ground soil testing to develop soil management plans for producers and managers. Based on soil characteristics, Miller develops management zones within fields (fig. 12) that are then used to develop VR zones for fertilizer and seed application. According to Miller, his clients see a mix of both cost savings and increases in revenue after implementing VR fertilizer and seed application. For example, corn and sunflowers respond extremely well to VR application of fertilizer and seed, with yield increases from 10–25 percent. Wheat also responds well, although at a slightly lower yield increase of 5–10 percent (Jason Miller, oral commun. and written commun., 2014).

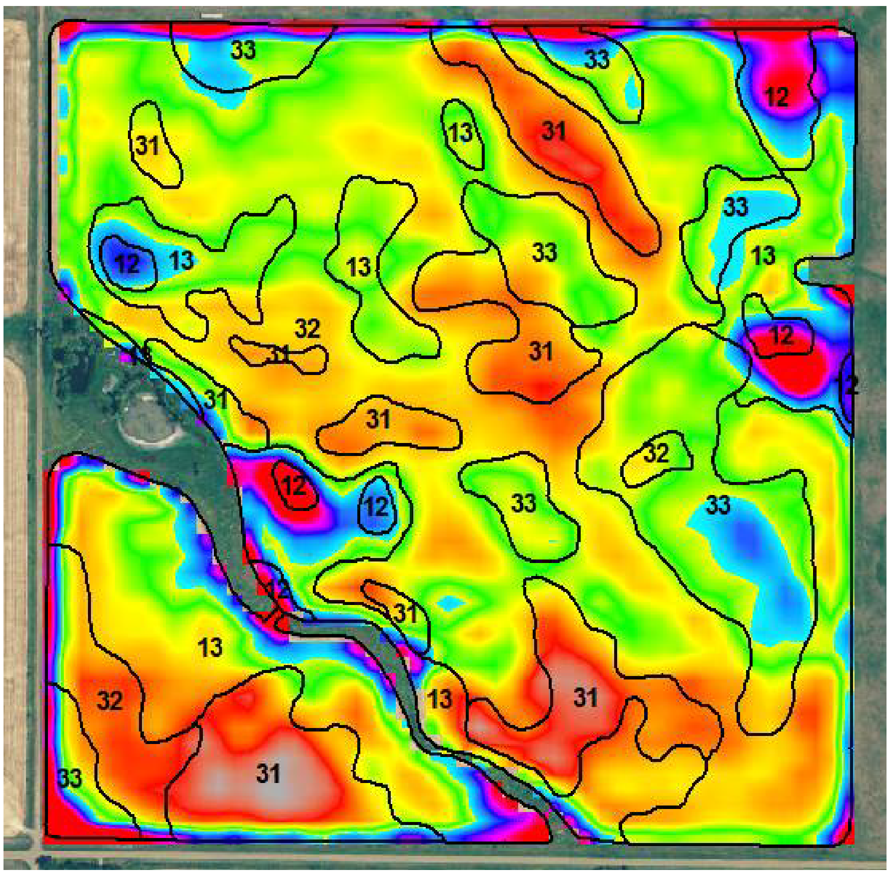


Figure 12. The image shows a corn field in 2013, overlaid with a zone map created by Jason Miller. For corn productivity, zone 31 has the best soil followed by zone 32 then zones 33, 13, and 12. (From Jason Miller)

In addition to its use by independent consultants, Landsat imagery is utilized extensively for the development of VR products by small consulting firms and farmer cooperatives. Hofer Seeds, a crop consulting firm in South Dakota, has been using Landsat imagery followed by soil testing for the last six years and has developed zone maps for more than 80,000 acres. Jon Hofer, owner of Hofer Seeds, says that producers see benefits from increased yield after switching to VR application. For corn, producers see an average increase of 6–12 bushels per acre. Wheat, which is slightly less responsive to VR application than corn, generally increases by 3–6 bushels per acre. However, wheat producers are also seeing improvements in quality due to higher protein content, which both protects farmers against protein deficiency issues, and at times, depending on market demand, increases the price paid for higher quality wheat (Jon Hofer, Hofer Seeds, oral commun. and written commun., 2014).

Cooperatives, such as North Central Farmers Elevator in South Dakota, are reporting similar success with VR application. George Sperry, a Precision Ag Consultant with North Central Farmers Elevator says that zone maps are created using Landsat imagery, verified through soil testing, and then used to calculate an optimal level of fertilizer. By implementing VR application, producers are seeing yield increases of 5–40 bushels per acre for corn and approximately 5 bushels per acre for wheat. Similar to customers of Hofer Seeds, North Central Farmers Elevator customers are also seeing increases in wheat quality (George Sperry, North Central Farmers Elevator, oral commun. and written commun., 2014).

Although the use of Landsat imagery to develop VR zone maps is most often performed by crop consultants, Landsat imagery is increasingly being utilized directly by farm managers, including Dan Forgey of Cronin Farms in South Dakota. Cronin Farms currently manages 22,000 acres; 10,000 acres are farmed for wheat and corn and the remaining 12,000 are used for livestock pasture. Forgey has used Landsat imagery to develop zone maps for VR application of fertilizer and has seen an increase in corn yield of about 120–155 bushels per acre (a 29 percent increase). Additionally, he is exploring the potential for using Landsat imagery to help guide livestock rotation on the remaining 12,000 acres. Rotational grazing provides a number of benefits, including lower production costs compared to confinement feed systems, improvements to soil quality, reduction of soil erosion, improvement of wildlife habitat, improved animal quality of life, and reduction of disease. Forgey anticipates that Landsat data will allow him to know exactly where to send cattle during rotation time, helping optimize their feed availability and allowing the pasture to regrow (Dan Forgey, Cronin Farms, oral commun. and written commun., 2014).

For corn, wheat, and soybeans, increasing yield through higher overall biomass per acre is the primary method for increasing revenue. However, for some crops, such as sugar beets, value is not determined based on biomass but rather on the content (sugar in the case of sugar beets) of the crop itself. For sugar beets, as for many crops, nitrogen is an important nutrient for growth. Over-application of nitrogen, however, will cause excessive growth and low sugar content, which may result in an inferior grade beet with lower market value (Davis and Westfall, 2009). To address this issue, Gary Wagner of AWG Farms in Minnesota has been using Landsat imagery since 1997 to monitor nitrogen content in beet leaves (fig. 13). During sugar beet harvest, the stalks are left in the field and deposit nitrogen back into the soil during tillage. Landsat imagery allows Wagner to monitor nitrogen levels during the growing season, as well as estimate the amount of nitrogen going back into the soil after harvest. Using global positioning system-enabled applicators, Wagner can automate the application of any additional fertilizer. According to Wagner, this method of application saves AWG Farms 60–70 pounds of nitrogen per acre and reduces effects on the environment from nutrient runoff and leaching caused by the over-application of fertilizer (Gary Wagner, AWG Farms, oral commun. and written commun., 2014).

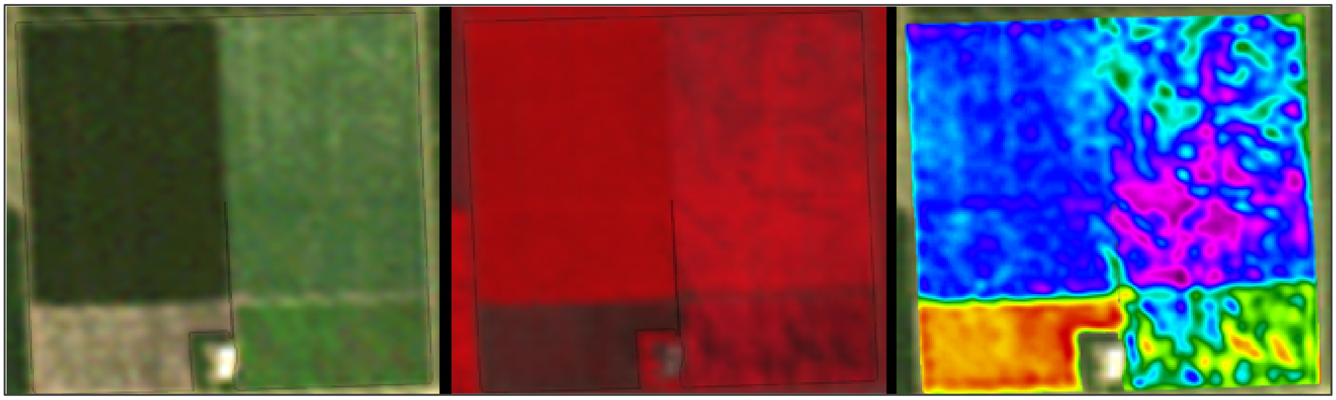


Figure 13. Images derived from Landsat 5 imagery collected July 13, 2005, showing a true color composite (left), color infrared (center), and just the near-infrared band (right) processed to show vegetation status related to nitrogen. Several fields are visible in the images, with the upper right field planted in sugar beets. In the processed near-infrared image (right), magenta indicates vigorous growth and high nitrogen and lighter green indicates low nitrogen and plants under stress. In the case of sugar beets, slight levels of stress are desired because stress maximizes development of sugar content. (From Gary Wagner, AWG Farms)

Increasing Yield

For producers in the Heartland and Northern Great Plains Farm Resource Regions, as in many parts of the United States, new or fallow land for cultivation is virtually nonexistent and revenue is now primarily determined through yield per acre and price. Tracking market prices and timing the sale of crops are challenging, leaving crop yield, and in some cases, crop quality as the primary mechanisms for increasing revenue. Achieving optimal yield by adjusting fertilizer and seed through VR application currently offers the most viable solution to producers.

All users profiled in this study reported increases in yield and (or) quality after moving from straight-rate to VR application of fertilizer and seed. For corn, yield increases ranged from 5 bushels to as high as 40 bushels per acre. Given the U.S. marketing-year average price from 2009–2013 of $5.18 per bushel of corn (University of Illinois, 2017), estimated revenue gains would range from roughly $25 to $200 per acre. Wheat producers reported yield increases of 3–6 bushels per acre. Using U.S. marketing-year average price from 2009–2013 of $6.40 per bushel of wheat (University of Illinois, 2017), estimated revenue gains would range from $19 to $38 per acre on average. Five-year U.S. yield averages are around 147 bushels per acre for corn and 41 bushels per acre for wheat (table 2). Regional combined yield averages for the Heartland and Northern Great Plains Farm Resource Regions are slightly lower than the U.S. average for corn (140 bushels per acre) and slightly higher for wheat (50 bushels per acre).

Table 2. Yield average (bushels per acre) for corn and wheat from 2009 to 2013. (From USDA ERS, 2017)

	Heartland Farm Resource Region	Northern Great Plains Farm Resource Region	Combined average of Heartland and Northern Great Plains Farm Resource Regions	U.S. average (all regions)
Corn	155	126	140	147
Wheat	59	42	50	41

Improving the management of inputs, particularly fertilizer and seed, is becoming increasingly important because these inputs represent a growing portion of operating costs of production, particularly for corn (fig. 14). Although no case studies were able to provide exact figures on savings or avoided losses for inputs, almost all mentioned optimizing the use of fertilizer and seed to increase yield as important in considering the adoption of VR application.

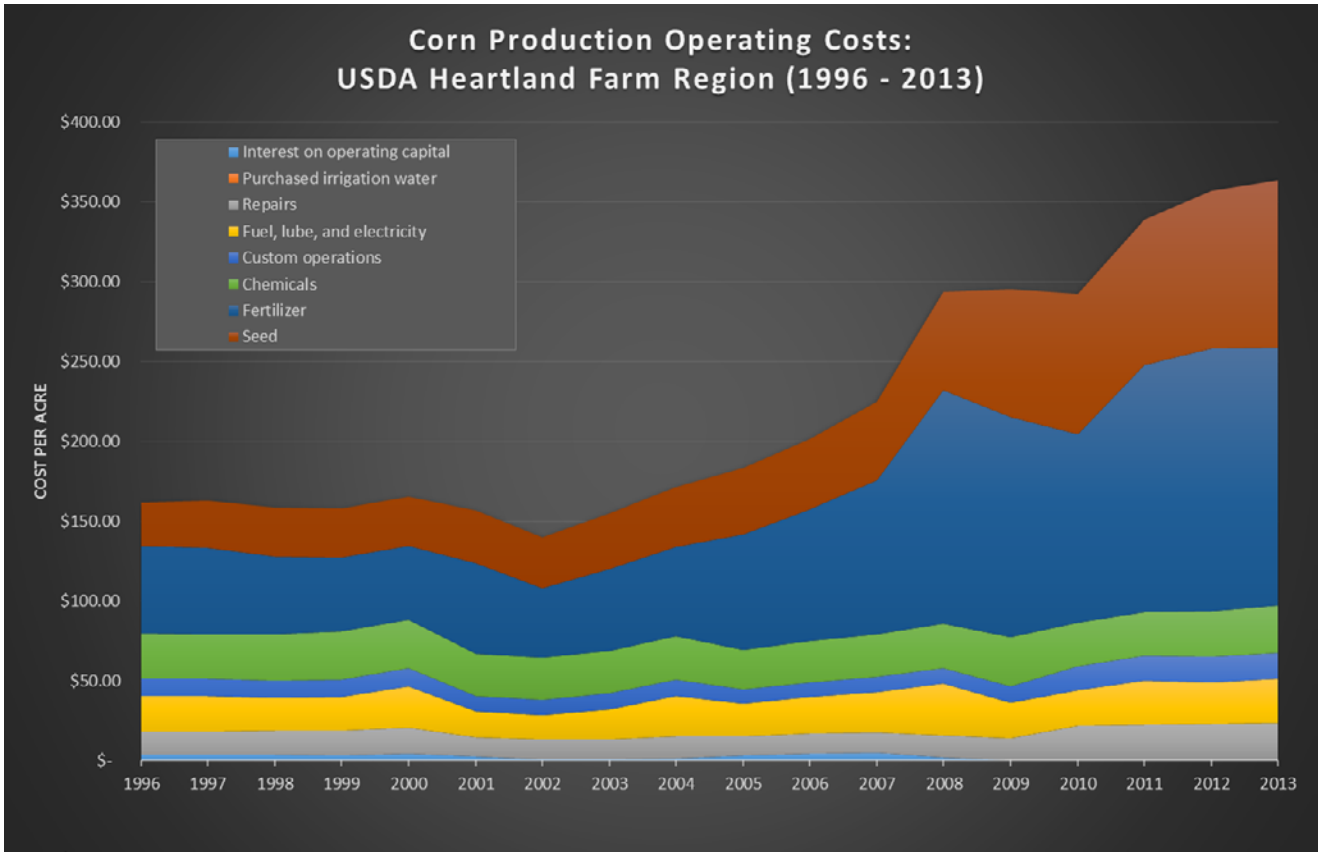


Figure 14. Recent operating costs per acre for corn production in the Heartland Farm Resource Region. Fertilizer and seed have seen the most substantial growth in operating costs, beginning around 2005. (USDA ERS, 2017)

Benefits and Challenges of Using Landsat Imagery for Production Management

The case studies detailed in this report focus on developing zone maps for VR application of seed and fertilizer. For crops that tend to be grown in large homogenous acreages, such as corn, soybeans, and wheat, Landsat imagery provides a level of efficiency, accuracy, and resolution that is difficult to achieve by traditional on-the-ground sampling methods. In particular, the NIR and SWIR bands are extremely useful for measuring soil and vegetation characteristics (Boettinger and others, 2008). Developing zone maps for VR application allows for optimization of inputs, and in many instances, increases yield per acre, which translates into greater revenue for producers. For many producers, increased revenue is the bottom line driving adoption of new agricultural methods and technology, such as VR application (Schimmelpfennig and Ebel, 2011). For crop consultants such as Mark Foster in South Dakota, this type of bottom line means Landsat imagery represents both a huge benefit and a challenge for his operation. On one hand, the free and open data policy for Landsat imagery means he can pass on savings to his clients, helping them realize greater return on their initial investments in switching to VR application. On the other hand, though 30-meter resolution is sufficient for mapping field characteristics of large acreages, private satellites continue to offer increasingly higher resolution imagery. Foster would like to explore using higher resolution imagery but the current cost is a significant factor that would have to be passed on to his clients (Mark Foster, SD Consulting, oral commun. and written commun., 2014). The same challenge holds true for small consulting firms such as Hofer Seeds. According to Jon Hofer, if Landsat imagery were not available, he would face two options. The first is to purchase private satellite imagery which would require passing on costs to his clients, reducing their return on investment. Or second, he would need to rely more heavily on yield maps derived from combine-mounted sensors, which he notes are often poor quality data for developing VR products (Jon Hofer, Hofer Seeds, oral commun. and written commun., 2014).

Another major benefit of Landsat imagery is the ability to monitor crop conditions during the growing season. Important conditions to monitor for include vegetation stress from nutrient and (or) water deficiency and fungal or pest outbreaks. AWG Farms has been using Landsat imagery during the growing season to monitor vegetation condition to refine the application of fungicide to their dry bean fields. The primary challenge in applications such as this is obtaining the requisite number of usable (cloud-free) images during the growing season to inform management objectives. Based on preliminary results from a 2014 study of Landsat users in the United States, 50 percent of agricultural Landsat users indicated that they need usable imagery every 5–8 days to meet breakthrough requirements (the level at which significant improvement is realized; Holly Miller, USGS, oral commun., 2015). Currently, with Landsats 7 and 8 in operation, new scenes are collected every 8 days. Cloud cover, particularly over agricultural regions during the growing season, means the number of usable images each season is far lower, with sometimes only one or two cloud-free images obtained each season.

Two benefits of Landsat imagery not previously mentioned are the imagery's high degree of accuracy and the historic depth of the data archive. Jason Miller points out that he uses Landsat imagery to confirm higher resolution imagery such as NAIP, and he relies on the historic archive of Landsat imagery when NAIP imagery is unavailable, such as for previous crop conditions or in areas where the crop was already harvested when NAIP imagery was gathered.

Although all of the consultants and producers contacted for this study continue to use Landsat imagery, especially as it is available free of charge, many of them noted difficulty with the significantly larger file size of Landsat 8 scenes. Currently, scenes are available as compressed archives averaging around 1 gigabyte each. The large file size requires additional download time and processing power. Several users noted that the file size would likely be less of an issue if scene cropping were available. This type of service was offered by the Upper-Midwest Aerospace Consortium and a number of the consultants and producers previously used this service. In addition to scene cropping services, the consortium offered a number of image analysis services. As of 2014, however, the Upper-Midwest Aerospace Consortium did not have any funding and was no longer able to provide services to its prior users.

Environmental protection and conservation are also important components of agricultural policy. In particular, high levels of reactive nitrogen (the type that is applied as fertilizer to crops) have major ramifications for air and water quality. A study conducted by the USDA's Economic Research Service concluded that the best management practices for reducing levels of reactive nitrogen in the environment are to more closely match the rate, timing, and method of nitrogen delivery to crop requirements (Ribaudo and others, 2011). VR application has made significant advancements in regard to application rate, along with lesser improvements in application timing. Timing of application requires the ability to continuously monitor crop status so that fertilizer may be applied at the most effective stages of growth. Although the multi-spectral capabilities of Landsat imagery are well suited to deriving vegetation status, the low-acquisition interval makes timely responses to changes difficult. Despite potential issues with acquisition frequency, Landsat imagery still holds major potential for reducing nitrogen in the environment through refinement of VR application. Corn, which is the most intensive user of nitrogen and accounts for the greatest acreage in the United States, is currently in need of the greatest improvement in best management practices for nitrogen application. Reducing the rate of nitrogen application to a point where limited excess nitrogen is applied is the most effective single method for reducing nitrogen emissions (Ribaudo and others, 2011).

Conclusion

Ultimately, the utilization of technology such as Landsat imagery for broad-scale agronomic management depends on a number of factors including perceptions of costs and benefits by end users, sufficient education and expertise to apply the technology, and capability of the technology itself to provide timely and accurate information at sufficient detail to inform management decisions.

For private producers, the adoption of Landsat imagery and other higher-precision technologies is increasing. Historic evidence on adoption rates of agricultural technologies in general suggests growth will likely increase in the near future. Currently, Landsat imagery provides crop consultants and producers with a valuable tool for increasing yield, increasing revenue, decreasing negative environmental effects, and in general, optimizing the resources required for agricultural production. The future of Landsat imagery's use in field-level production management is dependent upon its ability to continue providing, and possibly even enhancing, these benefits.

For agencies such as the U.S. Department of Agriculture, the value of Landsat imagery has been well established and future use is primarily dependent on the continuing availability of multi-spectral imagery. The recent launch of Landsat 8 in 2013 has helped ensure the continuity of the Landsat mission. Between 2003 and 2013, the primary challenge facing agencies like the U.S. Department of Agriculture was uncertainty in the long-term outlook of the Landsat program and the pending data gap due to an aging Landsat 5 and the scan line corrector-off issue with Landsat 7. Although Landsat 8 became fully operational in 2013, a number of challenges related to agricultural monitoring remain. The primary challenge is low global repeat frequency, which continues to result in data gaps for global agricultural monitoring. Occlusion of the land surface by clouds remains the main challenge. In high rainfall or tropical areas such as Brazil's soybean region bordering the Amazon forest or the Ethiopian Highlands, generally only one cloud-free image is acquired each year. Ethiopia remains one of the largest U.S. food aid recipients, and Brazil has become one of the largest soybean producers in the world. Since agricultural production in high rainfall areas means frequent occlusion of imagery by clouds, prioritization of agricultural monitoring needs within the Landsat 8 acquisition plan could potentially increase the number of usable Landsat images obtained within major agricultural regions worldwide.

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