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Article

Digital Northern Great Plains: A Web-Based System Delivering Near Real Time Remote Sensing Data for Precision Agriculture

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Abstract: The US Northern Great Plains is one of the world's most agriculturally productive areas. Growers in the region are eager to adopt modern technology to improve productivity and income. Use of information derived from remote sensing satellites to better manage farms and rangelands while reducing environmental impacts has gained popularity in recent years. However, prohibitive costs and non-availability of near real time remote sensing imagery has slowed the adoption of this technology for in-field decision making. Digital Northern Great Plains (DNGP), a web based remote sensing data dissemination system, was developed to address these drawbacks. It provides end users easy and free access to a variety of imagery and products in near real time. With delivery of archived and current data, DNGP has helped farmers and ranchers reduce operational costs and increase productivity through a variety of innovative applications. Moreover, negative environmental impacts were lessened.

Keywords: remote sensing; precision agriculture; Digital Northern Great Plains; croplands; agricultural productivity; decision-support; MapServer

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1. Introduction

Growing demand globally for food over the past 40 years has improved economic returns for the agricultural industry, but producers face higher risks because input costs and land values have also increased significantly [1]. To reduce risk, increase energy efficiency, enhance productivity, improve profitability, and minimize environmental impacts agricultural producers are increasingly resorting to the use of information technologies to aid their decision making processes [2]. In addition to land, labor, and capital, which have been agriculture's traditional assets, information management has become increasingly important [3]. The management strategy that uses information technologies to bring data from many sources for precise application of inputs to increase crop production has come to be known as precision agriculture.

Remote sensing imagery acquired from satellites and aircraft provides information in both the spatial and temporal dimensions that can potentially assist crop management. To maximize value to producers, the information has to be easily accessible in a timely manner and useable with a minimum of training [4]. These challenges were magnified in the northern Great Plains region, where limited bandwidth available to producers in the vast and sparsely populated rural areas previously hindered information access. Recent technological advancements, however, have alleviated this problem. Adoption of remote sensing technology is also affected by the depths of scientific and technical knowledge required to analyze and interpret the data [5], and producers are likely to have limited skills and/or interest in this area [6]. One way to lower the barrier to adoption is to develop low or no-cost value-added products that can be easily interpreted. To a producer, the value of remote sensing images and derived products occurs when they enable management decisions that enhance productivity and reduces unwanted environmental impacts.

In response to these challenges, the Upper Midwest Aerospace Consortium (UMAC, http://www.umc.org), a consortium of seven universities in the US Upper Midwest, executed a project that included the following: delivery of remote sensing data products of no-cost to the farmers and ranchers in the region; training of farmers and ranchers in the use of satellite imagery and derived products such as Normalized Difference Vegetation Index (NDVI) [7]; and development and promotion of applications through a learning community approach [8]. At the outset we realized that the dynamic nature of agriculture meant remote sensing products and services are useful only when made available in a timely manner and in an easy-to-use format. During the late 1990s and early 2000s, UMAC's end users who lacked fast internet access were provided with DirecPC satellite internet connections to ensure timely delivery of products [8]. In subsequent years, we designed and developed a web-based system, Digital Northern Great Plains (DNGP, http://dngp.umac.org), to deliver archived and near real time remote sensing data and products. In this paper, we will describe the DNGP system and offer examples of how the system has been used by agricultural producers to lower costs, enhance productivity, and minimize environmental impacts.

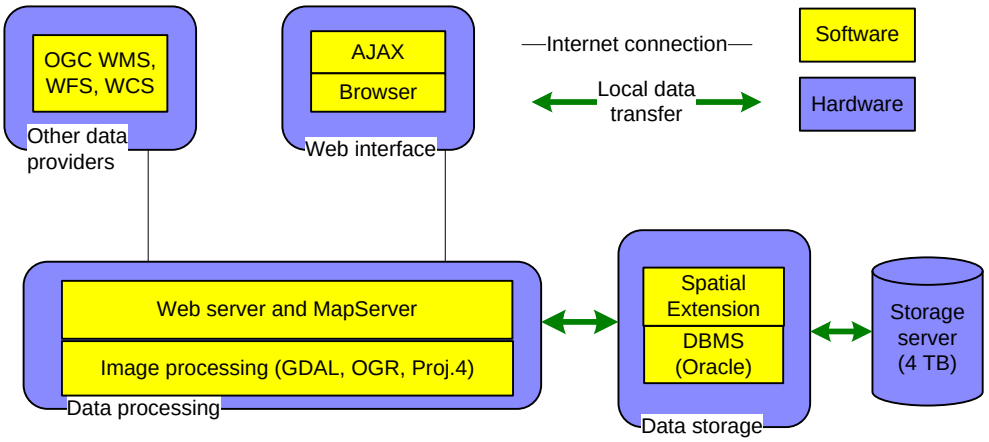
The DNPG system represents one of our ongoing efforts to deliver societal benefits to a major regional user community by taking advantage of modern technologies. We are constantly evolving the DNGP system with an ultimate goal of providing an information infrastructure enabling a variety of decision-support systems.

2. Digital Northern Great Plains

UMAC has collected a rich archive of remote sensing imagery over North and South Dakota, Minnesota, Montana, Wyoming and Idaho spanning more than 30 years. Data include medium resolution (20–250 m) multispectral images from Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Moderate Resolution Imaging Spectroradiometer (MODIS); surface relief from the Shuttle Radar Topography Mission (SRTM); and high resolution (1–2 m) images from AeroCam [9], a multispectral airborne camera that was developed and is operated by UMAC. To ensure consistency in temporal and spatial comparisons, all images have been geo-referenced and atmospherically corrected using the ATCOR software [10].

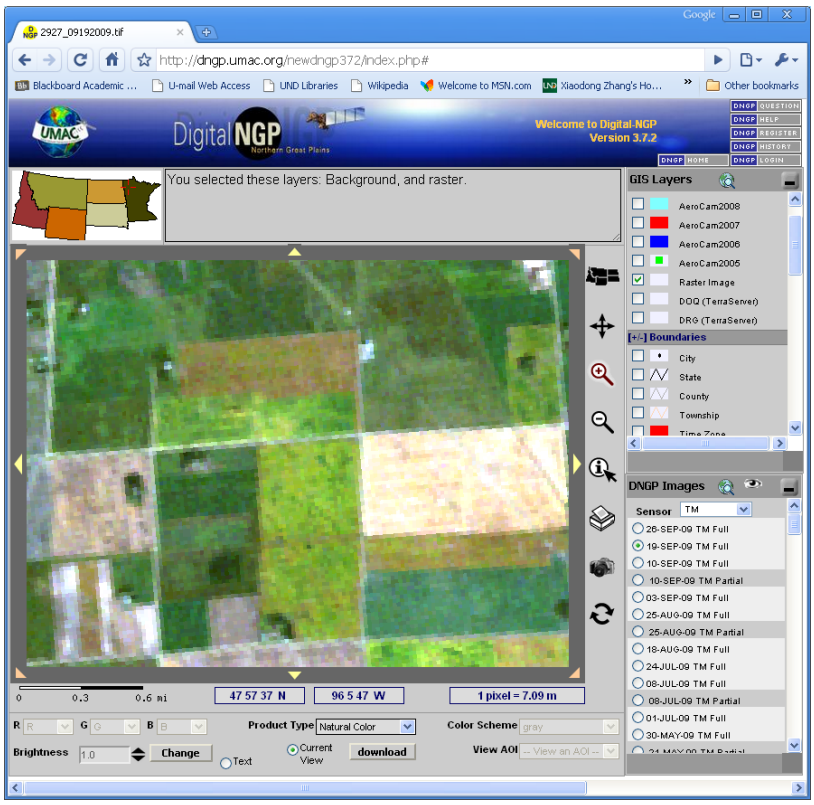
In designing the DNGP system we adopted "thin-client" architecture to ensure the minimum footprint on a client computer; all computing and analyses are carried out by the host server and results presented through a web interface accessible *via* a web browser. The architecture has three tiers: client presentation, data processing, and data storage (Figure 1).

Figure 1. Schematic diagram of DNPG system architecture.



The client tier is a web interface, through which users interact with DNGP and its database. The web interface features a modularized design with three independent panels for image display, image list, and GIS layers (Figure 2). Each panel communicates with the server through Asynchronous JaveScript and XML (AJAX) technology individually. With AJAX, only the web contents that need to be updated are refreshed, avoiding downloading redundant information, saving bandwidth and giving users a smoother viewing experience. For example, if a user navigates to a different area, both the view of the current image and the list of images covering the new area will be updated automatically, while the GIS layers panel remains unchanged.

Figure 2. Screen-shot of the DNGP system displaying a Landsat TM image (color composite with bands 3, 2, and 1) acquired on September 19, 2009 farmland in Minnesota. Panels list available GIS layers (upper right) and all the images covering the area (lower right).



The data processing tier, the main component of the DNGP implementation, is where the server side processing takes place, interacting with both the client and the database. This tier was implemented using Open Source applications. Raster and vector data are processed using the Geospatial Data Abstraction Library (GDAL) and OpenGIS Simple Features Reference Implementation (OGR) library, respectively. Various raster and vector layers are combined into a final image using another open source package, MapServer. We also used the PROJ.4 Cartographic Projections Library for coordinate conversion between different projections and datums.

All images are stored in a storage server and managed through an Oracle database system with a spatial operation extension. While Oracle allows storage of binary data such as images in the database, we chose to store images as external GeoTIFF files and to link the images to the database through their regular and spatial attributes. This barely affects the database performance, but offers advantages of containing the database's size and hence the cost of managing it. Spatial operations such as intersection or containment enable images to be searched geographically. Spatial information on users' areas of interest and the geographic extents of images is saved. The latter are detected automatically by an algorithm we have developed. This is particularly important for geo-referenced Landsat-type images, because they are tilted relative to North and therefore often covers a smaller area than the geo-extent of the file which is aligned with North.

The DNGP system has several features that enable users with low-bandwidth Internet connections to search and download remote sensing data and products easily and quickly. These features include:

(1) An intuitive user interface to allow users to conduct searches *via* spatial coordinates. This is critical because essentially a farm is a spatial object. With thousands of images archived, this allows a user to focus quickly on his or her area of interest.

(2) Capability to subset remote sensing images either spatially or spectrally. For example, a typical Landsat scene covers ~740,000 acres whereas a farm typically spans ~3,000 acres, or only $1/250^{th}$ of a scene. Dynamic subsetting helps achieve timely delivery by eliminating data of no interest to a user and saving a significant amount of bandwidth.

(3) Products generated on the fly, which not only simplifies the database design but also allows users to access the improved or new products quickly. Currently, the data products include color and false-color composites, NDVI, green NDVI, and sugar beet yield [11]. The differences in spectral response functions affect the estimate of vegetation indices [12]. But for the sensors whose imagery is hosted in DNGP, the differences are <10% and therefore are not considered in the current products.

(4) Compatibility with a wide range of application software. In addition to GeoTIFF format, in which the original images are saved, images or products can also be rendered as ASCII text files.

(5) A multitude of vector layers, including township, highways, lakes, rivers, and other geographic features has been incorporated into the system to help users identify their targets.

(6) A single interface design with dynamic content update to provide a smooth user experience.

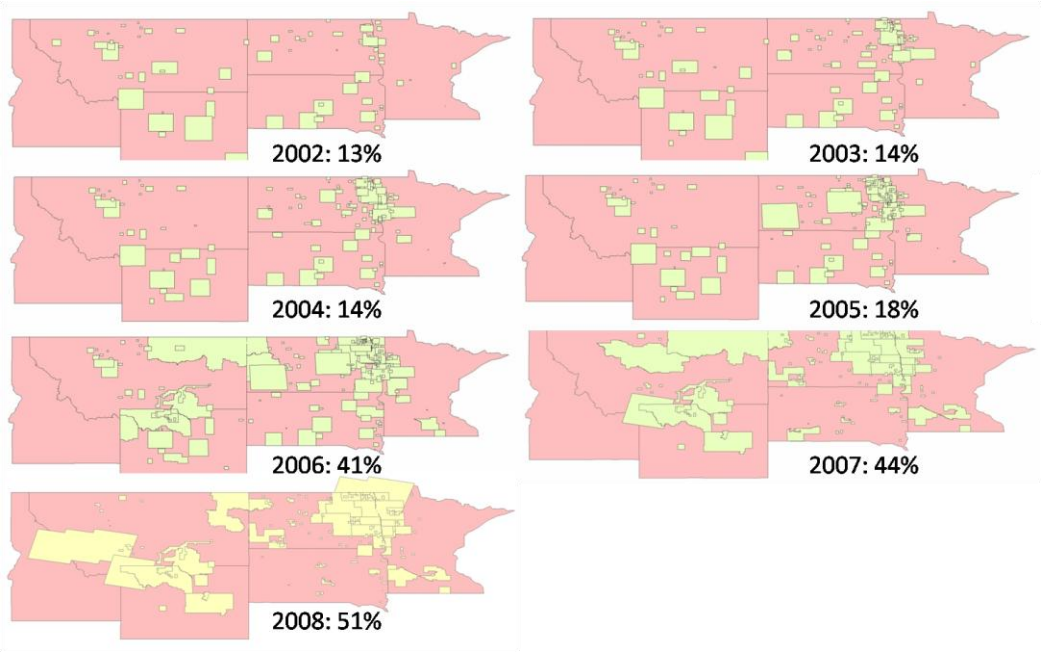
A user of DNGP can have seamless access to images hosted by other data providers through Open Geospatial Consortium, Inc. (OGC) Web Map Service (WMS), Web Feature Service (WFS), or Web Coverage Service (WCS) [13]. Currently, DNGP provides access to 1 meter Digital Ortho Quarter Quads (DOQQ) aerial photographs hosted by TerraServer [14]. Through these web services, users have access to a much wider range of data and information than a single system, such as DNGP, could possibly provide.

From designing the DNGP system to promoting its use among the end user community, we followed the innovation adoption/diffusion model of Rogers [15]. While remote sensing technology's potential for improving productivity is generally accepted by agricultural producers, endorsement of the technology by a few key early adopters accelerated widespread adoption of the innovation. To identify and engage early adopters, we followed a learning community approach [8], where producers were treated as full partners and not as clients of researchers. This led to the design of DNGP to be practical with tools and products that end users need. For example, many software applications still being used by agricultural producers cannot ingest geo-referenced raster images directly. Permitting users to download images in ASCII text format extended the functions of these legacy applications while saving the expense of acquiring and the investment of time learning new software. Also, information on cost-benefits is freely shared within the learning community, leading to trust and confidence in the use of the technology. Training workshops were conducted regularly across the UMAC region to expand the learning community by assimilating more early adopters.

The success of DNGP is illustrated in Figure 3, showing steady growth in areas of interest for which users have requested images. Prior to the development of the DNGP system, FTP and postal mail were the primary means for delivery of imagery and the coverage of images requested amounted to only about 14% of the total UMAC region. Since its initial release in 2004, the DNGP system has enabled more and more agricultural producers to apply remote sensing technology in practice. The

total areas of interest have expanded steadily from <20% of total UMAC area before 2005 to ~50% in less than four years.

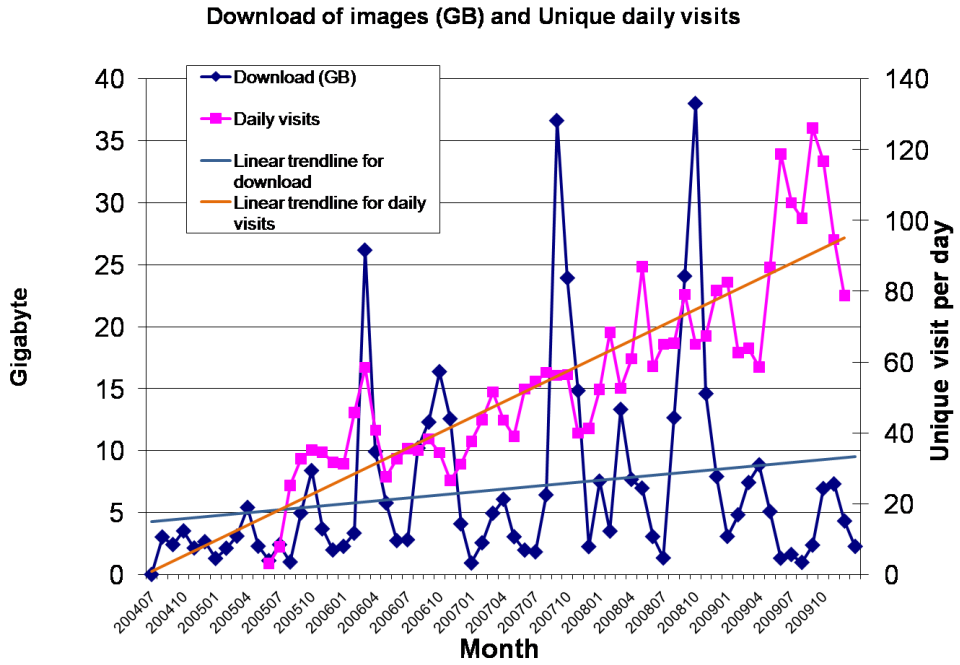
Figure 3. Areas of interest for which users have requested remote sensing images between 2002 to 2008 are overlaid on a map of six states of North and South Dakota, Minnesota, Montana, Wyoming, and Idaho. Numbers after each year indicate the percentage of AOI relative to the total geographic area.



While remote sensing images hosted in DNGP have provided services to a broad community ranging from K-12 teachers to government agencies, the majority has been used for agricultural management. Figure 4 shows the number of unique daily visits, averaged monthly, to the DNGP website as well as the total quantity of data downloaded in Gigabytes. In addition to the overall growth trends, these two parameters also exhibit a strong seasonal pattern, with two peaks occurring around April and October annually. These peaks coincide with the spring planting and fall harvesting seasons in UMAC's region. Comparison of Figures 3 and 4 indicates that the significant increase in actual download of images during 2006–2008 was due to the great expansion in the number of users and their area of interests. For example, for the four months from July to October in 2008, a total of 72 GB of images and products were downloaded, with an accumulated area about half the size of the UMAC's region.

The two parameters shown in Figure 4 have diverged since 2009: the daily visits continue to rise, but the quantity of data downloaded has decreased as compared to the previous years. The reason is because UMAC released a new extension to DNGP in 2008, Zone Mapping Application for Precision-farming (ZoneMAP) [16]. ZoneMAP further expanded the service by DNGP in two aspects: (1) the source of data was extended to include field measurements by end users; and (2) instead of raw data, management zones can be delineated automatically based on the selection of data. The decrease in downloading images was accompanied by an increase in use of ZoneMAP. The divergence is explained by the fact that producers are more interested in value-added products that can be used directly for decision making than in the images themselves.

Figure 4. Unique daily visits averaged monthly and total downloads of DNGP images in Gigabytes between July 2004 and December 2009.



The design of DNGP allows value-added products to be added easily and quickly, because only imagery is permanently saved and all imagery products are generated on the fly. Our ultimate goal is to use DNGP as a backbone for delivering remote sensing data and information, from which various specific decision-support systems can be developed. In the following, we will describe several applications using the DNGP system which have the potential to evolve into decision-support systems targeted for specific applications.

3. Applications Using the DNGP System

As described earlier, a farmer or rancher is able to use DNGP to define an area of interest, usually his or her own farm or ranch, and to download all the remote sensing data and products available for that area of interest. The Landsat TM image shown in Figure 2 covers a farm field in Minnesota for which a list of images covering the area at various times was generated automatically for display and download. The archive of past data serves as a reference against which the current status of farms or ranches from near real time data can be compared. For example, the farmer interested in the field shown in Figure 2 would have instant access to 143 Landsat (MSS, TM, ETM+) images since 1974, 12 ASTER images since 2003, and 210 MODIS images since 2005. This has resulted in applications leading to economic and environmental benefits. Some of the typical farming applications include zoning for variable rate fertilizer application; identification of areas of poor growth; assessment of damage due to pests, hail, wind, spray drift, flooding *etc.*, for insurance adjustments; assessment and improvement of drainage conditions; and purchasing decisions based on quality of land. Some of the typical ranching applications include identification of invasive weeds and their control, estimation of livestock carrying capacity, and wildlife management. The following sections provide case studies of farmers and ranchers who used remote sensing data downloaded from DNGP.

3.1. Zoning Fields and Applying Nitrogen Credits for Precision Farming

A farm field in the US Upper Midwest is typically 100 to 150 acres in size, making remote sensing an ideal tool for studying in-field variation. Since productivity is impacted by soil, nutrient levels, moisture content, topography, and other factors [17], precision farmers integrate as many of these parameters as they have measurements for into maps defining zones within their fields. After a careful zoning is done based on these factors, soil samples are taken to determine the amount of fertilizer each zone requires.

Closely related to zone-mapping is determination of nitrogen credits. When sugar beets are harvested, only the sugar-laden root is removed, leaving the biomass of above-ground canopy in the field. The leftover leaves and stems decompose, releasing nitrogen back to the soil. Remotely sensed NDVI imagery permits site-specific estimates of the above-ground biomass, from which one can calculate nitrogen credits. When applying fertilizers for the next crop, farmers subtract these credits from the amount of fertilizer estimated initially.

A farmer in the Red River Valley in Minnesota downloaded the Landsat TM derived NDVI product from DNGP at the peak growth stage of sugar beets and used it to create zones (Figure 5) to estimate site-specific nitrogen credits. He then carried out soil testing to determine the amount of nitrogen already available. Where NDVI was higher (dark green) the field had larger nitrogen credits. Accordingly less fertilizer had to be applied in those zones for the following year's crop. The application rates of nitrogen fertilizer developed based on Figure 5 are listed in Table 1. The farmer reported a saving of $12 per acre and a total saving of $1,800 for the entire field through the use of products derived from imagery. Over four years, the farmer, planting 1,010 acres of sugar beet, was able to reduce the application of nitrogen fertilizer by 60 pound per acre on average with a total saving over $51,000.

Figure 5. Landsat TM derived NDVI map of sugar beet canopy. Biomass increase from yellow (least) through progressively darker shades of green. A map of nitrogen credits is created from the available biomass.

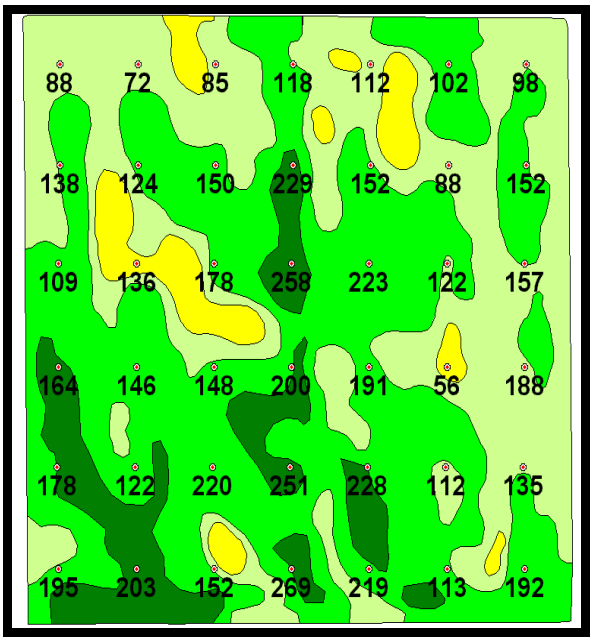


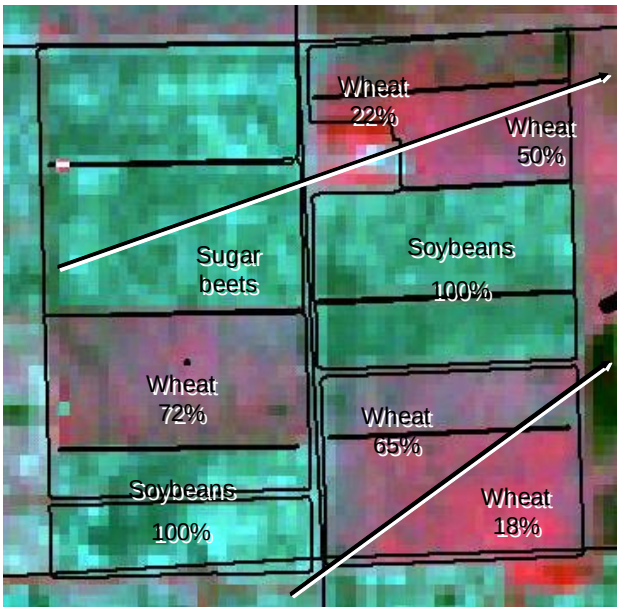
Table 1. Application rates of N fertilizer for the field shown in Figure 5.

Zone	Area (acre)	Application rate (lbs/acre)
Yellow	9.03	130
Yellow green	53.8	110
Green	73.5	80
Dark green	15.34	60

3.2. Hail Damage Assessment

Damage to crops due to hail is a common phenomenon in the US Upper Midwest. A farmer in Crookston, Minnesota used Landsat TM imagery available from DNGP to delineate areas of wheat, sugar beets and soybeans that were destroyed by a hail storm. Standard false color composite imagery (Figure 6) reveals the path of the hail storm. Darker shades of red indicate undamaged wheat while the lighter shades of red or pink indicate areas damaged by hail. These variations within the mature wheat fields coupled with field verifications enabled an accurate estimate of area of crops damaged. This enabled a quick, uncontested settlement with the insurance company. Besides the standard false color composite imagery, NDVI maps are also often used by farmers to determine damage to crops. By comparing an NDVI map obtained before the damage with one obtained shortly after, the extent of any damage is defined.

Figure 6. Percentages of crop damage due to hail, determined using standard false color composite imagery (bands 4, 3, and 2) from Landsat TM sensor available through DNGP.



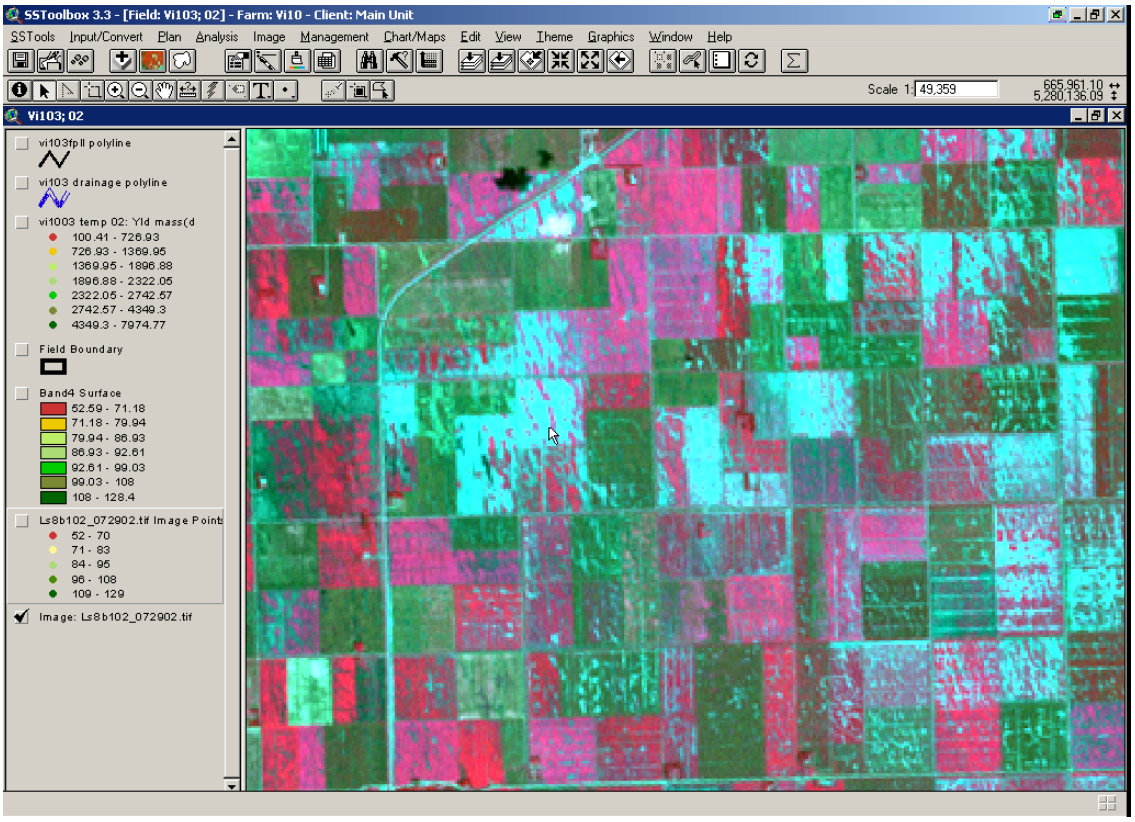
3.3. Water Damage Assessment and Decision on Leasing Land

The Red River Valley in North Dakota and Minnesota, a major agricultural region in the Upper Midwest, often experiences flooding and waterlogging due to its flatness and sluggish drainage.

Farmers use drainage ditches and tile drainage methods to drain water out of their farms, so that crops can be grown. Some fields are in low lying areas and are chronically waterlogged, making drainage ineffective or expensive.

During one growing season when 10 inches of rain fell in 6 hours, some farm lands were heavily affected and a number of fields were "drowned out", totally destroying the crops. Because the fields became too wet to access, farmers used satellite imagery to identify the affected fields and to map the spatial extent of the damage for insurance claims. One farmer searched DNGP and found a Landsat TM image acquired shortly after the event. The waterlogged fields could easily be identified as light blue areas in the standard false color composite image (Figure 7), and the extent of damage therefore accurately quantified. He also downloaded from DNGP Landsat images from previous years taken during major rainfall events. By combining historical images with ground elevation data using SSToolbox software (SST Software, Stillwater, OK, USA) he was able to identify fields that are chronically affected by waterlogging. This information was used in leasing land for future operations and in planning drainage requirements.

Figure 7. Waterlogged fields shown in light blue in this Landsat TM standard false color composite image (bands 4, 3, and 2) downloaded from DNGP by a farmer.



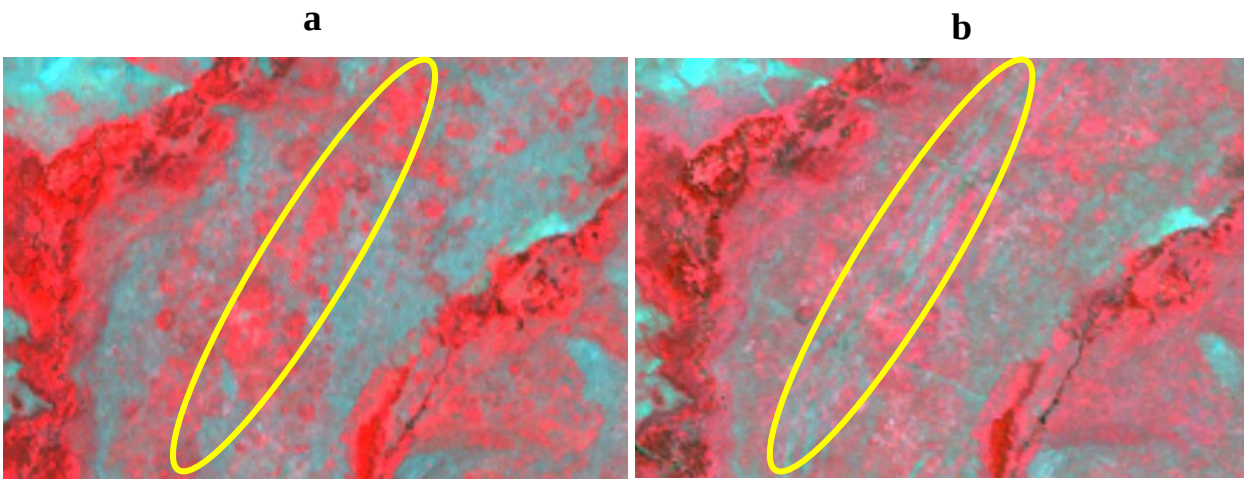
3.4. Weed Detection and Control in Rangelands

Knowledge about quantity and location of grass within a ranch is of critical importance in management of livestock grazing on rangelands. Grass is harvested for winter-feed as well as grazed directly by livestock throughout the growing season. Therefore, it is in the best interest of a rancher to monitor the grass's growth, move cattle accordingly to prevent over-grazing, and track weed

infestations. Ranchers who download imagery from DNGP routinely monitor forage production throughout the season to make decisions on stocking rates, and when to buy/sell grass for winter feed according to market prices.

A rancher in Montana on one occasion detected healthy vegetation on late-season imagery when he expected the grass to have already senesced. The healthy vegetation, on ground inspection, was determined to be buckbrush and wildrose weeds. Figure 8-a shows the late summer Ikonos standard false color composite (bands 4, 3, and 2) image of 2001 where the yellow oval highlights the area with concentrated weeds. Note, Ikonos imagery was made available only on specific cases, and it is not distributed routinely through DNGP. The rancher was able to estimate the approximate acreage and percentage of the non-productive portion of his pasture using ArcView software (ESRI, Redland, CA).

Figure 8. Standard false color composite Ikonos images (bands 4, 3, and 2) in 2001 (a) and 2002 (b). The yellow oval highlights greatest concentration of weeds on valley floor. The dark red regions on the northwest and southeast corners are forested areas on ridges not used for grazing. The 2001 image shows significant weed biomass in red, whereas the 2002 image shows reduced weed biomass following application of herbicide from an ultra-light aircraft.



Concerned by the extent of weed infestation and armed with exact locations of the invasive weeds, the rancher implemented a weed control program in spring of the following year. He purchased his own ultra-light aircraft and began aerial weed control applications. Ikonos imagery taken in the summer of 2002 after herbicide had been applied shows that the weeds had been largely controlled (Figure 8b). The grazing area that was salvaged was about 25 acres worth $200 each, for a total benefit worth about $5,000. In the following summer, he applied weed control over a larger area of 200 acres and recovered land worth $40,000 for grazing. In subsequent years, he was able to use Landsat imagery to monitor not only his ranch but his neighbors' as well and assist them in weed control.

4. Conclusions

An ultimate goal of remote sensing is to use the technology for societal benefits. Here, we described a few examples from many of applying the technology in agriculture to help farmers and ranchers benefit economically, and all of us to benefit environmentally. The acquisition of remote sensing imagery is just the beginning, but a key towards successful application of such imagery is the

timeliness of its delivery and of the delivery of information derived from it to actual end users. The Digital Northern Great Plains successfully achieved this goal.

With the DNGP system, users have access to satellite and aerial imagery not only geo-referenced and atmospherically corrected but also in near real time. As a result, farmers and ranchers are using remote sensing images in production, from planning for seeding to scheduling for harvest, from mapping nutrient availability to delineating weeds, from identifying standing water to claiming storm damage. In the meantime, we are constantly evolving the system. Our ultimate goal is to transform DNGP from a standalone delivery system to a data delivery backbone driving various decision support systems.

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