Applications of remote sensing to precision agriculture with dual economic and environmental benefits

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ABSTRACT

In the U.S. Northern Great Plains, growing seasons are short but extremely productive. Farms and ranches are large, so many of precision agriculture's early adopters reside in the region. Crop yield maps at season's end reveal sizable variations across fields. Farm management relying upon uniform chemical applications is ineffective and wasteful. We provided information about crop and range status in near-real-time, so that in-season decisions could be made to optimize final yields and minimize environmental degradation.

We created learning communities, in which information is shared among scientists, farmers, ranchers, and data providers. The new information for agricultural producers was satellite and aerial imagery. Value-added information was derived from ETM+, AVHRR, IKONOS, and MODIS sensors. The emphasis was on reducing the time between acquisition of data by a satellite and delivery of value-added products to farmers and ranchers. To distribute large spatial data sets in short times to rural users we relied upon satellite transmission (Direct PC).

Results include: (1) management zone delineation, (2) variable-rate fertilizer applications, (3) weed detection, (4) irrigation efficiency determination, (5) detection of insect infestation, (6) specification of crop damage due to inadvertent chemical application, and (7) determination of livestock carrying capacities on rangelands.

Keywords: precision agriculture, sustainability, information, biodiversity

1. INTRODUCTION

Future agricultural practices in the U.S. will not be a simple extrapolation from those in the past. Current economic stresses are too severe to allow "business as usual." Yet the long-term needs for food are so great that economic prospects should brighten for those who can survive the short-term crisis. This paper will discuss how **precision agriculture** can be one of the changes creating both a prosperous and an environmentally sustainable future.

The world's population is projected to increase by perhaps an additional 3 billion people before 2050. The combination of this many more mouths to feed and an enriched diet for others climbing the economic ladder will result in a global demand for 1.5-2 times more food by 2030.[1] New arable land cannot be increased by that amount. Most productivity increases will have to come from lands that are presently already among the most productive in the world. The need, therefore, is for better management of those lands.

Management of farming and ranching demands frequent decisions, always with less than perfect information and in the face of dynamic circumstances. Information's ability to enable knowledgeable decisions becomes a powerful economic resource. A management strategy based on uses of information technologies to bring data from many sources to bear on crop-production and livestock-raising decisions is one definition of precision agriculture.[2]

Economics is not the only stressor driving changes in agricultural practices. Environmental constraints are equally powerful. The two change-drivers are linked: a healthy economy is not possible in a deteriorating environment, nor is a healthy environment possible in a deteriorating economy. Some of the most pressing environmental constraints are:

- **Water**, its quantity, quality, and seasonal availability. The need to produce more food from land already under cultivation will severely strain water resources in many parts of the world. Efficient use of what water is available will be essential.
- **Soil Quality**. Erosion, compaction, depletion of minerals and organic matter cannot continue. Carbon sequestration by changing tillage, crop rotation, and fertilization practices–all through management founded on

better information–offers the potential to reverse soil's degradation.

- **Biodiversity Maintenance**. The natural world is an archive of plant genetic strains that might include next-generation crop varieties if a pest or disease outbreak should devastate today's dangerously narrow crop gene pool (approximately 90 percent of food production uses only 30 varieties of crop species). Farms and ranches can be managed to support ecosystem services in addition to their production of food and fiber.
- **Pollution**. Fertilizers, herbicides, and pesticides must be applied only where, in the exact amount, and precisely when needed to minimize both input costs and unwanted runoff to the air and water.

A summary of the challenge to farmers and ranchers is, produce more food from the same land using less water, and do so at reduced cost and with fewer producers; but do not adversely affect the environment or the safety of food. The new technologies upon which precision agriculture is based offer a partial response to this extraordinary challenge. Section 3 of this paper presents specific examples of practices that have dual economic and environmental advantages.

2. PRECISION AGRICULTURE

Information is the fundamental resource precision agriculture contributes to farm and ranch management, and various technologies are merely tools to acquire, synthesize, interpret, disseminate, and learn from information. Precision agriculture could be the basis for continuation of modern, large-scale, intensive farming practices, dependent on high inputs of nonrenewable resources to grow carefully bred cultivars, but it need not be. The choice depends on what the information dictates. A note of caution about the long-term viability of modern agriculture is appropriate, since its entire lookback time covers only the second half of the 20th century.

Among the information-enabling technologies our project has introduced to agriculture from outside its traditional knowledge base are the Global Positioning System (GPS), which defines a reference frame for all geospatial parameters; Geographic Information Systems (GIS), in which several data sets can be synthesized and the results presented in an easily comprehensible visual language; Remote Sensing (RS) to provide in-season, near real-time images revealing a crop's or range's health; and the Internet (or WWW) both to disseminate value-added products and to connect stakeholders and researchers alike into a problem-solving community.

The problem-solving or learning community concept is fundamental, for precision agriculture is a participatory process. Producers are full research partners, not clients. Farmers, ranchers, scientists, and other stakeholders all contribute to the common knowledge base from which all also draw. If the technologies mentioned above are ever to create successful business opportunities, cadres of people must understand the relationship between agronomic properties and parameters sampled by remote sensing. Our method of training producers who in turn train others is laying the base for a future industry.

Another change, not just in agricultural practices but also in agricultural research, is that scientific discovery and practical application occur simultaneously, not in isolated laboratories or experimental plots but on actual productive farms and ranches. Innovation and learning are continuous; traditional practices are continued only as long as they justify their value. The full complexities of multiple interactions occurring within agroecosystems are absorbed into a systems approach toward management. A difference in philosophy is that the focus shifts from average conditions to variations, because decisions about what action to take vary from place to place and time to time. [See reference 3, for a description of "Sustainability Science," of which precision agriculture could be considered a branch.] In sum, precision agriculture is multi-disciplinary, holistic, participatory, rooted in the real world, and continuously applying new lessons learned.

The tool that shifted focus from uniform to variable field practices was the GPS-guided yield monitor. Many farmers had a "feel" for which parts of their fields were most and least productive, but most were surprised at how big the variations were. The corn yield in Figure 1 from a South Dakota field had >3:1 variations; some portions would have been more profitable if not farmed at all. These variations, though, were quantified only during harvest, by which time, of course, nothing one does will change that season's yield. The promise of remote sensing is that it reveals conditions during a growing season–hopefully, throughout a season–when changes can be made that affect the final yield. Requirements, though, to make remote sensing useful are that it (1) provide frequent coverage (multiple times per growing season), (2) be delivered rapidly (1-2 days after acquisition), (3) have appropriate resolution (5-30 meters), and (4) be integrated with other information (often previous week's, year's, or decade's experience).

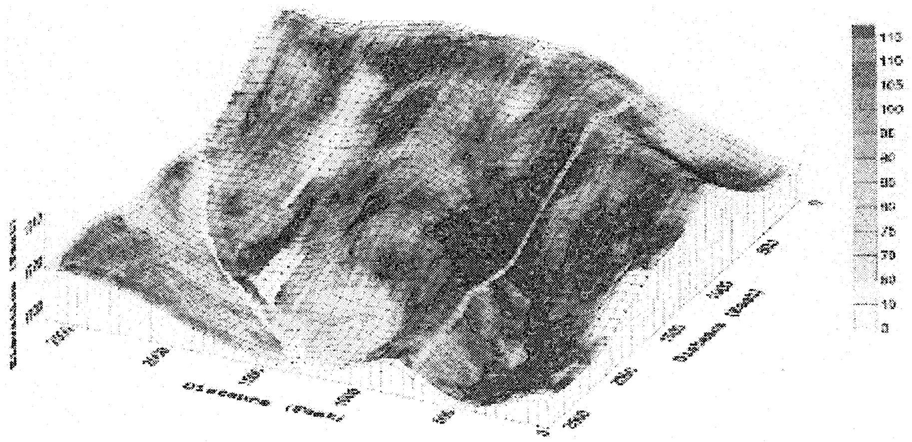

Figure 1: Yield of corn in bushels/acre for a SD field.

Images are merely pretty pictures unless some interpretation is provided. The complexity of ecosystems, even cultivated ones, demands expertise in many areas. One reason we have united into a consortium, the Upper Midwest Aerospace Consortium (UMAC, see Figure 2), is so that all can have access to a span of expertise broader than any of our single institutions can provide. Then, too, being distributed allows us to customize solutions to the localized variations that characterize our vast region.

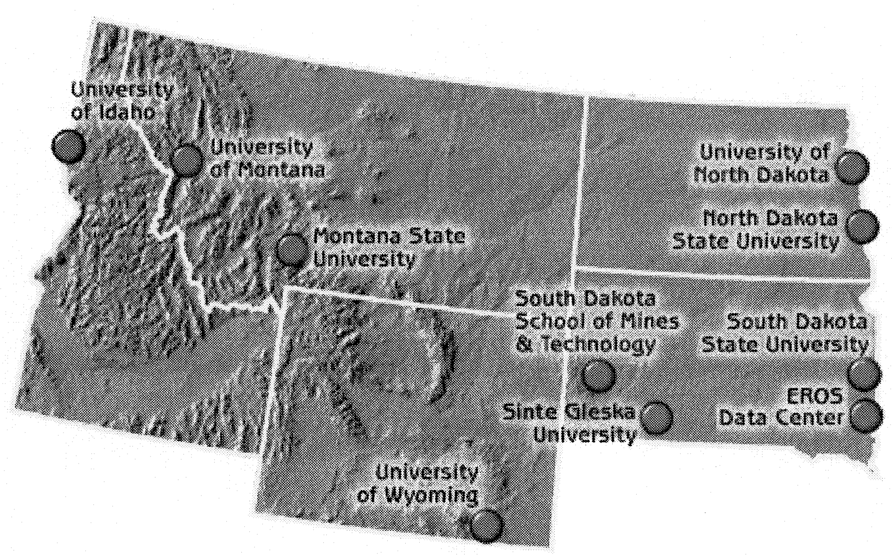

Figure 2: Region served by Upper Midwest Aerospace Consortium and UMAC's member institutions.

3. SPECIFIC EXAMPLES OF SUCCESSFUL APPLICATIONS

Success is judged by two criteria: (1) do the users benefit economically and (2) are the consequences benevolent to the environment? The answers are yes and yes to the examples we present. The successes occurred because information was provided at the scale and in the time series appropriate to the problem.

Satellite data came from the AVHRR sensor on GOES 8, the ETM+ sensor on Landsat 7, Space Imaging's IKONOS, the ADAR5500 on Positive System's airborne platform, and the MODIS sensor on Terra. The ways in which these data aided management are described below. Product distribution occurred over DirecPC, a satellite communications system having sufficient bandwidth to overcome the connectivity problem in rural America.

Management Zone Delineation. The principle is to rely on crops or natural vegetation as the integrator of the biophysical environment. Identifying patterns in satellite images of the Normalized Difference Vegetation Index (NDVI), made up of subfield areas having comparable biomasses, reveals regions either with similar soil characteristics or with productivities dominated by factors other than soil chemistry. In either case, soil samples need be acquired only once per identified subfield rather than on a uniform grid, yielding a significant cost savings to the producer. The delineated patterns also constitute the basis for variable-rate applications.

Variable-Rate Fertilizer Applications. Nitrogen management in sugar beets is critical: its addition can stimulate growth of both the canopy and the beet, but can, in excess, reduce the beet's sugar content. A Landsat ETM+ image taken one year reveals the spatial distribution of canopy biomass. During harvest, the canopy is shredded and left on the field. By the next Spring, decomposition of the residue supplies nitrogen that therefore need not be supplied by fertilizer. The amount to be supplied at each point varies according to the satellite map of the biomass. Figure 3 shows the results for one year. On a 1000-acre field, over the course of a 4-year crop rotation cycle, a beet farmer who used this precision management technique saved $51,000 and introduced 101 fewer tons of nitrogen into the environment.

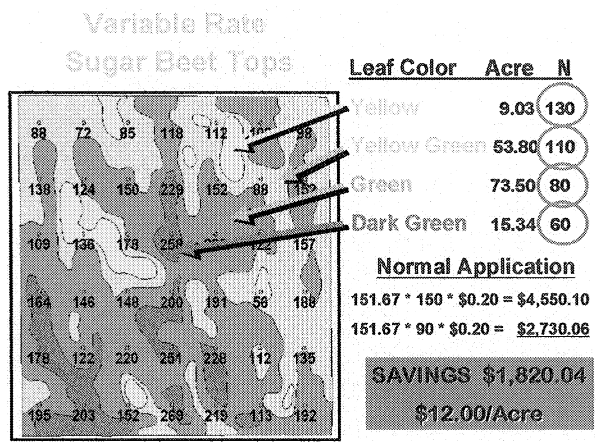

Figure 3: 152 - acre sugar beet field divided into 4 zones based on Lansat NDVI images. Ccanopy decomposed the following year, supplying soil nutrients. Amount of fertilizer applied was then reduced to values circled. Uniform application without precision information would have been 150 lbs/ acre, $12/ acre more expensive.

Wheat Protein Management. Wheat with a higher protein content commands a higher price. Nitrogen-based fertilizer can increase protein content, if an adequate nitrogen supply is not already available in the soil. Dryland wheat farmers cannot affect their soil's moisture content. If precipitation is well below average, wheat will grow poorly but be able to draw sufficient nutrients from the soil without supplement. Applying an amount of fertilizer based upon the average quantity applied over several years wastes it during those dry years. During years of normal or above-average precipitation, wheat will grow luxuriantly but will also exhaust the soil nutrients. An application of nitrogen fertilizer in those years could enhance wheat's protein content, hence price. Some Montana wheat farmers now apply approximately half the normally needed amount at the beginning of a season, monitor the vigor of the wheat's growth during the season via AVHRR NDVI observations, and then decide whether the accumulated precipitation warrants application of more fertilizer. Farmers either save money in reduced fertilizer costs or receive a price higher because of the additional protein than the cost of a second fertilizer application. The environment is spared runoff from fertilizer that was unnecessary in dry years.

Livestock Grazing and Rangeland Management. Figure 4 shows several fields on a few Montana ranches. Each field has three numbers for Animal Unit Months (the number of typical cattle who can graze for one month), depending upon whether the biomass is average or above or below. The biomass estimates are from a time series of NDVI maps derived from Landsat images. Using this time series, ranchers have a quantitative basis for determining (a) when and where to move cattle to another field, (b) whether to sell cattle or buy supplemental feed in below-average years, or (c) whether to buy cattle in above-average years. Furthermore, quantitative knowledge of the carrying capacity can avoid overgrazing.

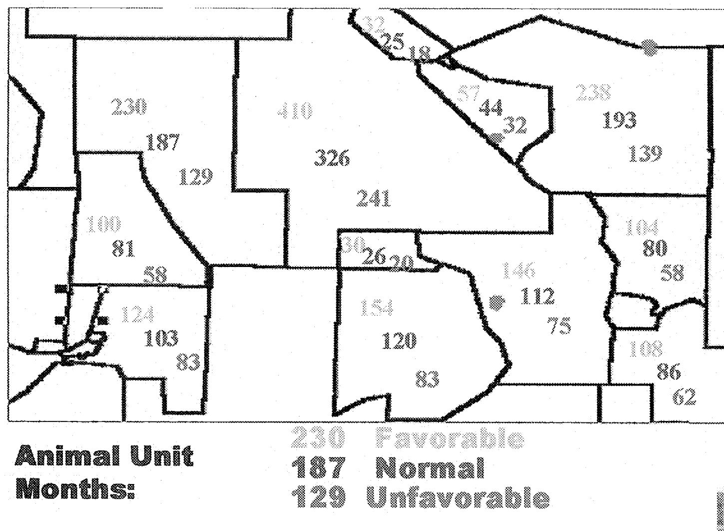

Figure 4: Cattle-grazing fields for which AVHRR NDVI calculates available animal unit months.

Fungicide Applications. A basic question is whether fungicides increase wheat productivity by an amount sufficient to cover the cost of the fungicide. In determining an answer–which really comes when yield maps are derived at harvest–farmers wondered whether remote sensing could verify whether chemicals had been properly applied. The answer is obvious: where no fungicide is applied in test strips, NDVI (from IKONOS) records its absence (see Figure 5). This illustrates well the learning community concept described in Section 2, for once wheat farmers learned the power of satellite images for managing fungicides, they built it into a decision-support tool. Savings of $33 per acre in reduced fungicide costs have been recorded. Simultaneously, runoff to the environment is reduced.

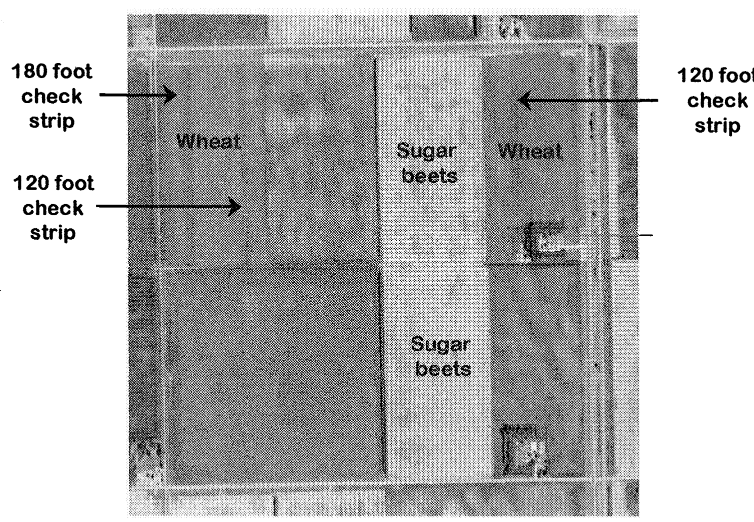

Figure 5: Check strips where no fungicide was applied to wheat fields.

Persistent Weed Spraying. Modern combines and other harvesters have GPS systems for location and field markers. The latter are push buttons the farmer can activate to mark a location where a particular problem occurs. An innovative farmer has marked the presence of wild oats, thistle, and quack grass separately while he harvests. Over the course of years, he noted where these weeds appeared persistently. He applied herbicides only in those locations, another dual economic-environmental benefit. In year 2000 on 1642 acres, cost reduction was $12,000 and about a thousand fewer acres were sprayed with herbicides.

4. LESSONS LEARNED

Precision agriculture--information-intensive and management-oriented--is promising economically and ecologically. It will one day be standard practice. Predicting exactly when that day is is difficult. The determining factor will be how rapidly cadres of producers acquire the knowledge to exploit the techniques. We see no alternative but to work collaboratively with early adopters whose successes will spread to others. Our experiences to date have taught the following lessons to the learning community we have created:

- Remote sensing supplements, but does not replace, all other sources of information. The power lies in a synthesis of a variety of sources of information into a decision-support tool.

- A commitment over several growing seasons is required. Any farmer or rancher who believes he or she will reap rewards from the acquisition of a single remotely sensed scene will be disappointed. The knowledge necessary to sharpen management accumulates only through iterations of comparisons of satellite and field data.
- Engaging producers means supplying images of their fields. Presentations of examples from others' farms or ranches do not trigger commitments.
- Most applications of the information have to be customized. Precision agriculture invokes a mix of technologies. Different suites of technologies must be exploited under different conditions, and those conditions vary geographically and within and between seasons.
- Information and a time series of it must be provided in near real-time. High-bandwidth data connectivity is therefore required.
- The proper resolutions–spatial, temporal, and spectral–depend on the problem. In general, the cost of information goes up with the quantity of it. Cost-benefit analyses must constantly recalculate, for example, the length of time information has value, as well as whether field practices can be implemented at a scale matching the spatial detail.
- Value only is derived if the information enables a decision that results in higher profitability and more responsible stewardship. There are years when weather disasters, as one example, render remote sensing useless, because it only tells producers over and over that their crops are poor–even though there is nothing they can do about it.
- When in-season predictions of final crop yield become more accurate, precision agriculture will have reached a new plateau.
- Farms and ranches provide more than food and fiber. They are managed ecosystems that can benefit society by providing essential services–water purification, soil stabilization, climate moderation, pollination, biodiversity preservation, and others. A system that rewards producers for these societal benefits could be based in the information provided by the practice of precision agriculture.[4]

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