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The potential of remote sensing data for decision makers at the state, local and tribal level: experiences from NASA's Synergy program

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Abstract

NASA's Earth Observation System (EOS) satellite data are contributing to the development of policy relevant, remote sensing applications. To promote the use of EOS data for application development, NASA funded the Synergy program in 2000 in partnership with academia, end users, and industry. Three examples of remote sensing applications from the Synergy program are presented here and include agriculture, range management, and water resource management. These examples show that remote sensing products have the potential to be useful to a variety of decision makers and policy makers because of the opportunity to reduce chemicals in the environment, improve crop yields and better manage range lands and water resources. Transitioning from research and development to successful applications must overcome challenges such as the lack of awareness by end users of these technologies, inadequate feedback mechanism between application developers and end users, and unproven cost benefits of remote sensing data. Experience from the Synergy program indicates that these issues could be mitigated by educating and training end users, demonstrating the utility of remote sensing data in improving decision making, and establishing and maintaining a continuous dialogue between developers and end users. Sustainability of remote sensing applications ultimately depends on users continuing reliance on products and benefits from remote sensing data. The Synergy program also demonstrates that remote sensing data sets that are collected primarily for global change research contribute to the development of applications in a variety of disciplines at the regional and local level.

Keywords: Remote sensing applications; Precision agriculture; Range management; Water resources management; Synergy program; EOS data

1. Introduction

Remote sensing data from NASA's Earth Observing System (EOS) satellites are valuable for understanding global change, particularly at decadal time scales. The EOS program consists of a constellation of satellites such as Landsat 7, Terra, Aqua, and Aura, which are designed to continuously collect measurements of the earth's land surface, atmosphere, cryosphere, and the oceans to understand earth system science (Asrar et al., 2001; King, 1999). With the maturity of remote sensing algorithms and techniques over time, these data have found increasing use in decision making at regional and local scales. One of the goals of NASA's Earth Science Enterprise Application Division's Strategy is to expand and accelerate the realization of societal and economic benefits from earth science, information, and technology (NASA, 2002).

Over the years, applications of remote sensing have emerged in agriculture, urban planning, disaster mitigation and monitoring, forestry, hydrology, and operational meteorology among others. The traditional sources of coarse (>250 m) and moderate resolution (10–250 m) satellite imagery within the United States have been federal agencies such as NASA and the National Oceanic and Atmospheric Administration (NOAA). Several commercial companies (e.g. Space Imaging and Digital Globe) are now providing high spatial resolution (<10 m) satellite data. With this combination of data types, users have a variety of options to choose the data that best suits their needs and budget. A brief list of earth observing satellites launched by NASA and other organizations within the US that are suitable for developing applications for state/local/tribal agencies is given in Table 1 along with their main characteristics.

Remote sensing applications are growing at a rapid pace. Several studies have been conducted primarily by NASA and NOAA to understand the requirements and barriers for adoption of this technology by state and local governments. For example, NASA organized four workshops during 2000–2001 to better understand the information and technology requirements of state/local/tribal governments within the United States (NASA, 2001). These workshops indicated a strong desire among different user agencies to replace conventional field or aerial photography with faster,

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Table 1
Characteristics of different earth observing satellite instruments that have potential use in application development for decision makers at the state/local and tribal level

Satellite	Instrument	Spectral bands (μm)	Spatial resolution	Temporal resolution	Cost[a]
Landsat 7	ETM+	3 Visible 1 NIR 2 SWIR 1 TIR 1 Panchromatic (B&W)	30 m 60 m 15 m	16 days	$600 per scene
NOAA-K, L, M	AVHRR	1 Visible, 1 NIR, 1 SWIR, 1 MWIR, 2 TIR	All at 1.1 km	Daily	Free
Terra, Aqua	MODIS	1 Visible and 1 NIR 5 Visible, NIR, SWIR 29 Visible, NIR, SWIR, MWIR, TIR	250 m 500 m 1 km	1–2 days	Free
Terra	ASTER	2 Visible 1 NIR 6 SWIR 5 TIR	15 m 15 m 30 m 90 m	16 days	Free
IKONOS	IKONOS	1 Panchromatic (B&W) 3 Visible 1 NIR	1 m 4 m 4 m	3 days	$10.50/km^2 for archived data (geo)
QuickBird	QuickBird	1 Panchromatic (B&W) 3 Visible 1 NIR	0.61 m 2.4 m 2.4 m	2–6 days	$18/km^2 for archived data (standard)
GOES	GOES Imager	1 Visible 1 MWIR 1 Thermal 2 Thermal	1 km 4 km 8 km 4 km	30 min	Free
SeaStar	SeaWiFS	6 Visible, 2 NIR	All at 1.1 km	Daily	Free to NASA researchers

Satellites launched by NASA and other US organizations only are shown here. Visible = 0.4–0.7 μm, NIR = 0.7–1.3 μm, SWIR = 1.3–3 μm, MIR = 3–5 μm, LWIR (thermal) = 5–14 μm. Abbreviations: ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; AVHRR, Advanced Very High Resolution Radiometer; ETM+, Enhanced Thematic Mapper+; GOES, Geostationary Operational Environmental Satellite; MODIS, MODerate resolution Imaging Spectroradiometer; SeaWiFS, Sea-viewing Wide Field-of-view Sensor.

[a] The prices quoted here are those that are published on the internet by data providers at the time this manuscript was written. These prices are given for the sake of information and comparison purposes only and are not guaranteed. Prices vary by level of processing, date of acquisition, and location. People interested in acquiring these data should contact the data providers directly for more accurate and up to date pricing.

cheaper, and/or more accurate remote sensing methods. This NASA study also indicated that state, local and tribal users want to use remote sensing data primarily to improve monitoring and prediction capabilities of the local environment for regulatory compliance. The cost of remote sensing data and software, lack of personnel skilled in these technologies, and unproved cost/benefit ratios for investment in remote sensing data were noted as some of the common barriers for adoption of this technology.

The Space Studies Board of the National Research Council (NRC, 2001) conducted a similar study to identify the opportunities, approaches and bottlenecks for adoption of remote sensing data by state/local agencies. This study focused on the use of remote sensing data for management of coastal environment to determine barriers and opportunities in transferring remote sensing technology and applications to end users. Several factors such as education and training of end users, and successful demonstration of cost benefits from investment in remote sensing technology by end users were identified as potential activities that need to be undertaken by federal and private agencies that develop these technologies to promote useful, operational applications of satellite remote sensing data.

Even though EOS data were designed primarily to collect global change research measurements, these data could be potentially used to develop various applications that are relevant to policy makers at state and local governments. To explore the use of remote sensing data collected by the EOS satellites for the development of applications that are relevant to state, local and tribal agencies as well as individual users, the Synergy program was started in 2000. The Synergy program is funded by NASA through its Application Division and is managed by Raytheon Company. Six application areas were identified under the Synergy program and include agriculture, urban planning, natural resource management, water resource management, disaster management and weather, climate and human health (http://www.earth-outlook.com).

The Synergy program is a partnership between end users, academia, and industry. This program has a three-fold objective:

- Identify issues at the state/local/tribal governments that can be addressed by using remote sensing data and determine their requirements.
- Develop sustainable remote sensing applications using EOS data and demonstrate benefits.
- Educate and train the end users in using these technologies to promote these data sets within their communities.

As a part of the Synergy program, scientists at different universities in the USA have been developing products primarily from NASA's remote sensing data based on the analysis of specific user requirements. These products are then distributed through interactive web-based tools hosted at 11 centers called InfoMarts. This paper will highlight some of the impacts on policy and decision making by end users and discuss lessons learned in promoting NASA's remote sensing technologies for application development. The main objectives of this paper are to:

- Describe the applicability of EOS sensors for state/local/tribal users.
- Highlight impacts on policy and decision making by end users who are using NASA's remote sensing data.
- Identify opportunities and barriers to adoption of remote sensing data by these users.
- Identify ways to promote remote sensing technologies and applications within state/local/tribal agencies.

Presenting results from each of the six remote sensing applications within the Synergy program would be duplicative. Instead, we will focus on three application themes and present findings from a broad spectrum of remote sensing applications. The material presented here is based on authors meetings with application developers and end users, and annual progress reports from InfoMarts over a 3-year time period since 2000. To date, there are no other published independent reviews of the Synergy program or comparative assessment of experiences from the Synergy program with other similar activities within NASA.[1]

2. Remote sensing applications in precision agriculture in the Northern Great Plains

Historically, agronomic practices such as the application of fertilizers and pesticides, and irrigation have largely been made at a field level without taking into consideration spatial variability of soil properties and crop condition. The adoption of precision agriculture, where crop variability is actively managed, optimizes fertilizer and pesticide applications and reduces environmental contamination while maximizing profitability.

A typical example of environmental benefits of precision farming is the potential to decrease anthropogenic contributions of nitric oxide and nitrous oxide into the atmosphere, which are both considered as greenhouse gases. Atmospheric concentration of nitrous oxides has reached its highest recorded levels in recent years (316 ppb in year 2000) since the pre-industrial era (Watson et al., 2001). Volatilization of inherent organic soil nitrogen and that applied as fertilizer release these greenhouse gases from agricultural areas through denitrification. Emissions of nitrous oxides from cultivated agriculture are estimated to contribute 50 to 70% of the anthropogenic sources to the environment (Nakicenovic and Swart, 2000). Typically, 10–30% of the total nitrogen input to common grain-production systems is lost through leaching of water-soluble nitrates (Meisinger and Delgado, 2002), which could lead to contamination of surface and ground water (Follett and Delgado, 2002).

During the past 35 years, global food production doubled, and if past trends in fertilization were to continue, global nitrogen fertilization would be 1.6 times greater than present amounts by 2020 (Tilman et al., 2001). Several factors such as the rate and amount of fertilizer application, tillage practices, irrigation, cropping systems, and soil and weather variability determine the amount of nitrogen that is transported from the soil to the environment. Among these factors, the uniform fertilizer treatment of entire fields, without taking into consideration inherent variability in soil and historic yield patterns, is a major factor for nitrate leaching and diffusion into the environment (Power et al., 2000).

The adoption of precision agriculture, where crop variability is actively managed, optimizes fertilizer and pesticide applications and reduces environmental contamination. Precision farming has created a growing need for geospatial data, and remote sensing techniques are appropriate for collecting such data.

Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) derived from polar orbiting instruments such as the Advanced Very High-Resolution Radiometer (AVHRR) are routinely used for operational crop condition assessment over large areas (Hutchinson, 1991; Kogan, 1997). These vegetation indices are mathematical transformations of visible and near IR reflectances, and have been used to derive variables related to crop growth such as the fraction of photosynthetically active radiation (0.4–0.7 μm) absorbed by crops (FPAR) and leaf area index (Asrar et al., 1984). These variables are then used as inputs to deterministic crop growth models (Moulin et al., 1998). Temporal profiles of vegetation indices are used to monitor crop growth and, furthermore, seasonally integrated values are known to correlate with crop yields. NDVI measurement

[1] The authors are not involved either in developing specific applications or in the day-to-day management of these activities at the universities (InfoMarts). The analysis presented here is intended to be a candid and critical assessment of remote sensing application development based on the authors experience in managing a broad spectrum of applications at different University InfoMarts.

from the Moderate Resolution Imaging Spectrometer (MODIS) at 250-m spatial resolution provide significant spatial detail compared to AVHRR (1 km). Not surprisingly, several AVHRR users have begun to adopt MODIS data sets (see for example, Townshend and Justice, 2002).

While these coarse and moderate resolution data sets are valuable tools for crop condition assessment at county, regional, and state levels, they are not adequate for operational monitoring of crops at the individual field level. Farmers with large land holdings are interested in precision crop management tools that help them identify and monitor variations in crop condition within the field, so that they can selectively apply herbicides, pesticides, fertilizer, and seed for maximum benefit at reduced cost. With the availability of unrestricted, low-cost, high-quality imagery from Landsat 7 Enhanced Thematic Mapper (ETM+) and high spatial resolution satellite imagery from commercial sensors such as Ikonos and QuickBird, new opportunities have emerged for remote sensing in agriculture. Images generated from combinations of reflectance bands from these satellites are being made available to the farmers by various organizations. These images are ideal for examining variations in crop growth within the field. Additionally, these images can be integrated with field data such as soil properties, irrigation, and fertilizer practices using Geographic Information Systems (GIS), and Global Position System (GPS) technology to generate field maps and databases for optimum allocation of resources and investment.

As a part of the Synergy program, the University of North Dakota (http://www.umac.org) has provided several farmers, ranchers, and land managers from the Native American community with frequent near real-time remotely sensed data throughout the growing season. As of August 2003, 246 farmers and ranchers have been receiving NDVI composite imagery from AVHRR and MODIS, as well as visible and near IR imagery from Landsat 7 ETM+ over their farms in North Dakota, South Dakota, Wyoming, and Montana. A few farmers have been receiving visible and near IR reflectances from the Ikonos satellite as well (Fig. 1).

Farmers located in remote rural areas do not have access to high-speed Internet connectivity. Not surprisingly, delivery of large image files (typically in the order of several megabytes) to them via 56 kB modems is an obstacle. To overcome this problem, end users were connected via a

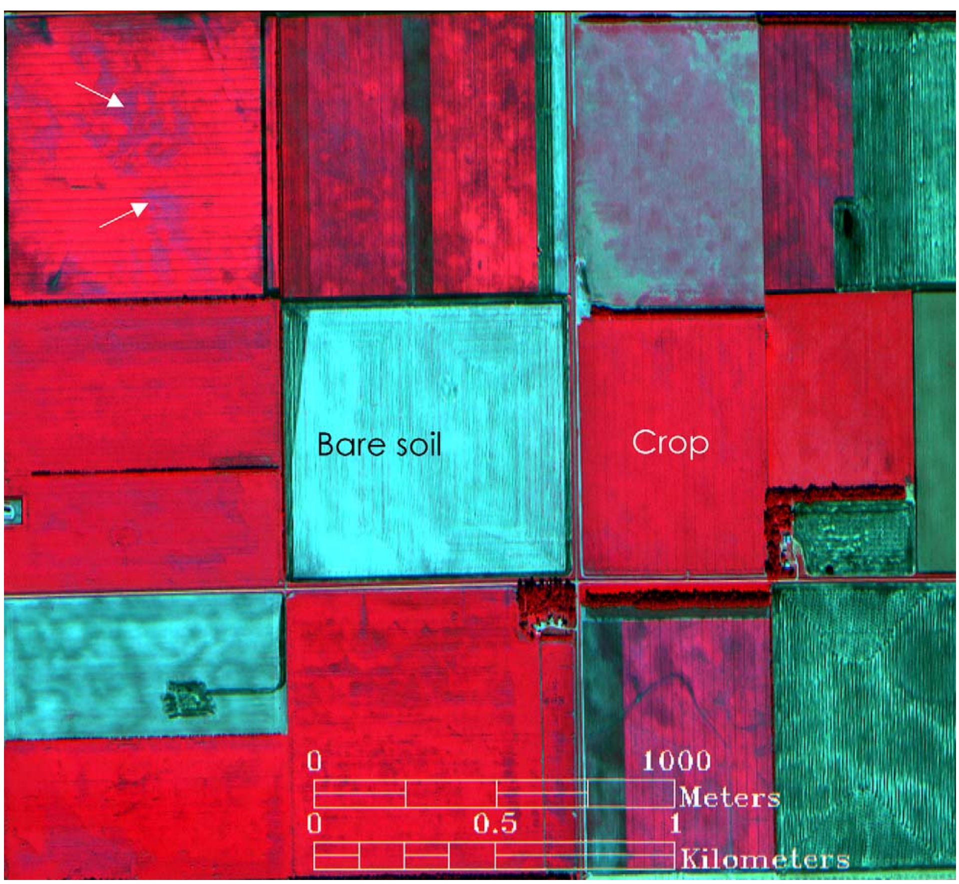

Fig. 1. False color composite image from IKONOS acquired over an agricultural area in N. Dakota taken on September 27, 2001. The red, green, and blue colors show reflectances in the near IR, red, and green wavelengths, respectively. Crops appear as red in this image, because of their high reflectance in the near IR wavelength. Different tones of brightness in the near IR wavelength are associated with differences in crop condition, vigor and maturity. Arrows indicate areas where there are problems with crop condition as indicated by low near IR reflectances. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

high-bandwidth satellite link to a central distribution center at the University of North Dakota. End users were provided training in the basics of remote sensing, image interpretation and manipulation and were given free software to visualize satellite imagery on a PC.

The users of these data sets can be classified as innovators and early adopters depending on their level of use of the products. Innovators among the farmers started using imagery when the technology was first introduced in their community and are now integrating the geo-referenced imagery into a GIS for variable rate application of fertilizer and herbicide. Early adopters, motivated by the innovators, are now beginning to use imagery for crop condition assessment through mostly visual interpretation methods. Farmers are able to determine fertilizer and herbicide allocation based on crop condition determined from the image of their farm during the growing season. Farmers then apply these resources at variable rates across their field using a GPS receiver mounted on a combine sprayer for navigation.

By integrating field data such as yield, moisture, and soil condition with positional information sampled uniformly on an evenly spaced, two-dimensional grid across the farm, farmers create zone maps and identify areas that require higher resource inputs. When data from several growing seasons are combined into a database and analyzed, spatial patterns of yield variability within a field emerge. Farmers in Montana who relied on satellite imagery for variable rate application of Nitrogen reported a saving of $12 per acre in fertilizer costs. Variable rate application, therefore, minimizes the cost of fertilizer and herbicide applied.

Selective application of chemicals on farms reduces atmospheric contamination as well (NRC, 2000a). In addition to the economic benefits accrued to farmers, is the decrease in the amount of fertilizer, pesticides, and fungicides that is leached into the soil, thereby reducing the contamination of streams and rivers from run-off. This has further economic benefit in terms of fishing and recreation activities as well as contributing to the health of environmental habitats, and in some cases, drinking water (Shortle and Abler, 2001).

Some other uses of remote sensing data by farmers participating in this project have been to map tillage practices using Landsat 7 ETM+ data, and estimating losses in acreage due to water inundation for insurance claims. Conventional tillage practices lead to reduction in soil organic matter, increase soil erosion by wind and runoff, and destroys macropores which are conduits of water flow in the soil. Zero or low-till practices can, over time, lead to storage of more carbon and nutrients in soils by preserving residue from previous crops. These practices are more cost effective than conventional tillage since less energy is used (Padgitt et al., 2000; Calderón et al., 2001). Satellite imagery can be used indirectly to determine tillage practice by monitoring the level of the senescent residues in the field.

Several farmers who were using remote sensing data actively were interviewed for feedback to determine the suitability of satellite data for precision farming. Farmers were willing to use the imagery on an ‘experimental basis’ and were enthusiastic to participate in the program as long as data were free. They were not willing to change farm practices based on image data alone until the technology was proven in the field. Since their livelihood depends upon making the right decision at the right time, decisions based solely on unproven technologies were considered high risk.

Farmers initially compared patterns in satellite imagery collected during the growing season with yield data after harvest to determine relationships. Subsequently, a farmer treated a small part of the field differently with fertilizers and fungicide compared to the rest of the crop to determine how it would appear in a satellite image. Quantitative comparison of chemical application rates with yield data and associated patterns of reflectances observed in remote sensing imagery helped the farmers in relating imagery to field conditions. Farmers gained confidence in the technology through repeated studies. Use over several growing seasons appears to be necessary before any new technology is fully adopted by this community of users. Information products derived from satellite data which show spatial patterns in a field associated with properties such as moisture, nitrogen content, crop vigor, etc. were considered more valuable than raw imagery by the farmers. It was also evident from the users that product diffusion could be highly successful if the derived products were accompanied by specific recommendations on improving crop productivity through prescriptive spraying of chemicals over problem areas identified in the imagery. Creation of peer learning communities in which advanced users share their experiences and demonstrate benefits within a community enhances potential user’s confidence and promotes faster product penetration.

Farmers in the US Northern Great Plains typically manage their fields using spraying, planting, and harvesting equipment that typically has a swath of 10 m. The minimum farm management unit in these studies can thus be considered as 10 m wide. Imagery with a 10-m spatial resolution was, therefore, considered appropriate for precision farming by the farmers interviewed. Even though commercial satellite imagery from Ikonos and QuickBird provides multispectral imagery at spatial resolution larger than 10 m, the high cost of these data make them financially impractical at present for routine use in precision farming. Nevertheless, high spatial resolution imagery is needed for defining drainage needs and assessment of damage due to wind, water, pests, hail, overspray, etc. The high cost of these data become affordable only if groups of farmers share the cost of imagery. However, the use of Landsat ETM+ data (30-m spatial resolution) has been successful in introducing remote sensing technology to a large number of farmers. In this project, Landsat ETM+ data has been demonstrated as a valuable tool in identifying broad anomalies within fields to help in management decisions particularly since its cost per scene is less than half of the commercial satellite data that provide higher spatial resolution. While the existing suite of NASA’s space-borne sensors has limitations for precision farming, the most promising approach would be a combination of data from multiple instruments using physical models to provide the necessary information (Moran et al., 1997).

3. Range management in the southwest

Even though similar remote sensing principles and data sets could be used to monitor both agricultural fields and rangelands, the requirements for each application differ because agricultural lands are managed more intensely. Rangelands in the Western US support a variety of uses such as cattle ranching, recreation, forestry, and watershed. Most rangelands in the West are public lands (NRCS, 1999). Thus, several federal, state, and tribal agencies are responsible for managing the rangelands and often there is competition between different user communities for limited resources. Competition for grazing between cattle and native wildlife on rangelands is one of many important issues that evokes considerable debate in the West among ranchers, hunters, environmentalists, and developers. The potential for conflict among varying uses emphasizes the need for an integrated strategy to manage rangelands effectively, and remote sensing data provide valuable information on rangeland conditions. Managing rangelands requires routine surveys to monitor range conditions for determining the carrying capacity of land and remote sensing is an appropriate tool for such analysis (Tueller, 1989). Of particular need are tools that can capture vegetation dynamics through time and over large areas. Through the Synergy program, the Office of Arid Land Studies at the University of Arizona set up a web-based information system called RangeView (http://www.rangeview.arizona.edu) that provides web-based user access to near real-time vegetation indices derived from AVHRR and MODIS at 1-km and 250-m spatial resolutions, respectively. This activity is specifically designed to provide accurate and timely geospatial information about vegetation dynamics to natural resource managers including ranchers and members of federal, state and tribal government agencies responsible for rangeland resources in the Western US Users can plot and visualize temporal trends in greenness and deviations from long-term averages. Multi-temporal vegetation indices computed as bi-weekly maximum value composites can be used as a surrogate for vegetation response to climate and other influences along a 1-km grid (Fig. 2). Internet map server technology permits the users to interactively map an area of their interest along with ancillary vector data layers to help locate and monitor a particular forest, ranch, or watershed.

Several workshops and training sessions were held to inform the county extension agents, agency personnel and ranchers about the tools available through the RangeView project and to get their feedback on product use. Natural resource managers from government agencies listed (a) comparing current greenness to long-term normal levels, (b) forecasting greenness based on historical patterns, and (c) understanding historical variations in greenness as the most important benefits they would derive from the web-enabled, spatially dynamic, time-series animations. Ranchers indicated that the RangeView products would allow them to (a) monitor the immediate response of vegetation to rainfall, (b) monitor overall range conditions, (c) determine the relative amount of vegetation growth between pastures that will occur in response to rainfall or climate events such as El Niño, and (d) observe patterns of vegetation growth during a year. Users wanted the ability to either print a professional looking map from the images displayed on the screen or to download the images to their computers for further modification and use. Ranchers and agency personnel both emphasized the role RangeView could play in encouraging dialogue when disagreements over vegetation trends occur, particularly during periods of drought or wildfire risk, or where elk and cattle might be expected to use the same pasture in the months ahead. The high temporal resolution and landscape coverage helped in longer term planning as well as shorter term identification of areas that needed specific ground monitoring. Moreover, the coarse spatial resolution was actually applauded by agency personnel and ranchers alike: too coarse to be used in regulatory applications, and yet powerful enough to provide visual insight on vegetation trends as a basis for dialog where resource management strategies were in dispute. There are 770 million acres of rangeland in the United States (NRC, 1994), and the RangeView approach could enhance natural resource management and vegetation monitoring activities at scales that would not be practical to monitor with medium or high spatial resolution imagery.

Rangeland management requires a concerted effort among natural resource agency personnel, ranchers, other land users, and developers for a longer term, sustainable use of public land in the Western US bridging the knowledge gap among these groups in terms of new tools and technologies is key to effective communication and management. The role of a new Cooperative Extension program initiated by a NASA-Land Grant partnership was critical to the success of the project. Termed the “Geospatial Extension Program,” a university extension specialist focused on bridging the gap between geospatial research/technology and its use by the general public and was central to the technology transfer strategy pursued by the RangeView team. The “diffusion of innovation” model embraced by the project required a marketing research component to identify the key factors facilitating and constraining adoption. This project identified the pivotal role university extension Agents within natural resource programs would have to play in introducing RangeView to lead users among both agency personnel and ranchers.

Typical extension agents are not experts in remote sensing data and technologies, and thus RangeView initiated a “train the trainer” scheme to train extension agents, a crucial element in promoting remote sensing products to uninitiated users. Holding frequent regional workshops and training sessions was essential to enhance product use.

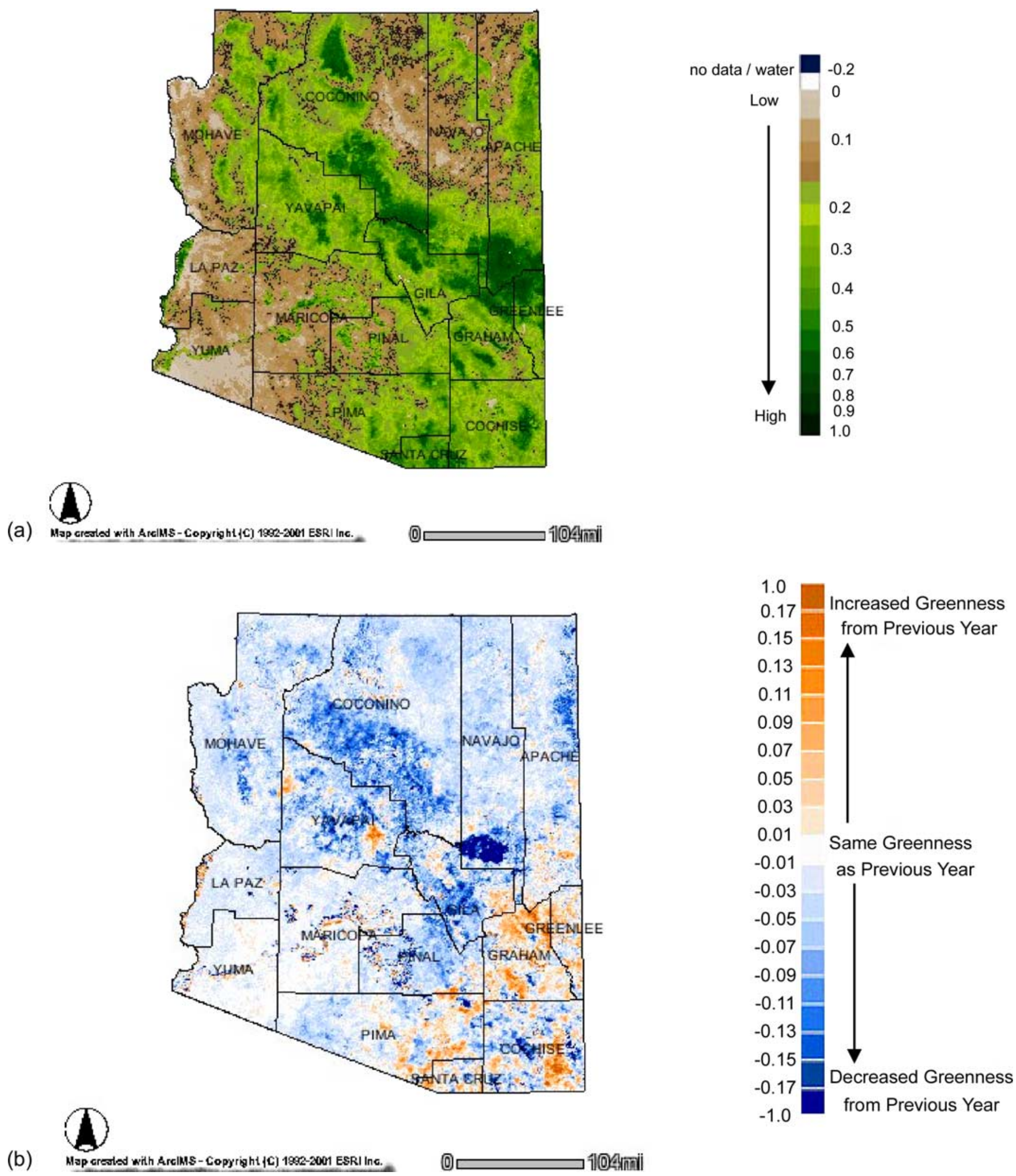

Fig. 2. The image on the top (a) shows the maximum NDVI or maximum greenness over Arizona for the 2-week period ending September 19, 2002 as observed by the Advanced Very High-Resolution Radiometer (AVHRR). The image on the bottom (b) shows the deviation in NDVI relative to the same time during previous year. Images like these help track and monitor range conditions. These images are available at http://www.rangeview.arizona.edu.

Involvement of user communities in product development from the beginning of the project and soliciting periodic feedback that aided in enhancing the services and products was critical for a broader adoption of remote sensing data. Lack of access to faster Internet connectivity was one of the technological hurdles in product use, but the users themselves have provided solutions: community library access, and the proposal of special RangeView kiosks in local Cooperative Extension offices.

The use of EOS data in this project, despite being much coarser in spatial resolution compared to commercial data, allowed prototyping and demonstrating practical benefits of remote sensing data at a low cost. By providing open and free access to geospatial information regarding rangeland health and vegetation dynamics, the RangeView web site allows different federal and state agencies as well as individual ranchers to identify and synoptically visualize areas that are under stress due to abnormal weather patterns. This allows informed decision making for sustainable and ecologically sound management of rangeland resources by optimizing plant growth and grazing.

4. Water resources management in the northwest

A variety of remote sensing techniques continue to evolve for estimating different components of the terrestrial hydrological cycle, particularly precipitation (Sorooshian et al., 2000), evapotranspiration (Choudhury, 1994), and runoff (Hsu et al., 1995). Three applications have been funded under the Synergy program in the field of water resource management: monitoring evapotranspiration (ET) in the Snake River aquifer in Southern Idaho, estimating snow water equivalent in Arizona, and determination of runoff coefficient maps for use in models to compute peak flood discharges in Missouri. Here, we present experience from estimating ET in Southern Idaho.

Water availability played a key role in the settlement of the American West. Population pressure causes an increase in both demand and price of water (NRC, 1996). Precipitation, snow water melt, ET, land use, extraction of ground water, and stream flow are important factors that affect water management. When surface water from streams and reservoirs does not meet irrigation demands, tapping aquifers for groundwater is a common practice. Therefore, water resource managers have to model and monitor surface and ground water conjunctively for a planned, reliable, and coordinated water supply (Winter et al., 1998; NRC, 2000b).

In general, States west of the Mississippi award the right to use water to individuals based on the principle of prior appropriation. According to this doctrine, a person does not have the right to own ground water by virtue of owning the land from which the water is pumped. Individuals need to obtain permits from the state governments, and the allocation of water rights is issued through the maxim "first in time, first in right." This means that the first person to obtain a right (senior appropriator) has priority to pump water compared to another person who acquired water right at a later time (junior appropriator). During times of water shortage, water pumps of junior appropriators could be shut down before the senior's (Idaho Code, §42-106). Because of intense competition for water, administering water rights has profound socioeconomic, environmental and legal implications.

In areas where irrigation is the main source of water supply to crops, ET can be used as a good indicator of water use. In fact, it is a common practice to use estimates of actual and potential ET to implement irrigation scheduling in several parts of the world (Allen et al., 1998; Shuttleworth, 1991). Knowledge of depletion and recharge rates from aquifers is important for calculating water balance.

The Idaho Department of Water Resources (IDWR), a Synergy partner, has been investigating the use of Landsat data to estimate ET in the Snake River System in Idaho. The intent is to use ET as an indicator of water depletion from the aquifers. Traditionally (before ground water and surface water rights were administered conjunctively), IDWR directly measured and regulated surface water, but not ground water. Identifying irrigators who are using water "in excess of the elements or conditions of a water right" has become necessary in order for IDWR to conjunctively administer water rights. Estimating ET would help IDWR assure pumpage in compliance with the terms of water rights.

To estimate ET from Landsat data, IDWR adopted an energy balance model called SEBAL (Surface Energy Balance Algorithm for Land; Bastiaanssen et al., 1998a,b). Since IDWR is a regulatory and planning agency with limited resources for remote sensing research and application development, IDWR teamed with scientists from the University of Idaho who have previous experience in this field to help in developing viable ET models that use remote sensing data.

Before the SEBAL method could be adopted, the model had to be validated and demonstrated to show that the satellite estimates of ET were at least as good and less costly than traditional methods that IDWR is currently using. Among the various instruments and methods that are available to measure ET, measurements made by lysimeters are considered to be the most accurate (Rosenberg et al., 1983). ET was computed using data from Landsat 5 TM sensor for seven overpass dates in 1989, and the results were compared with coincident measurements collected using a lysimeter in Idaho. The absolute error of daily ET between the satellite derived estimates and ground data was 14%. A similar comparison of ET for four days in 1985 showed an error of 15% between Landsat estimates and lysimeter measurements (Allen et al., 2001). Encouraged by these results, IDWR has begun to utilize ET estimates from Landsat ETM+ for monitoring water use in irrigated areas of the Snake River Basin on an experimental basis (Fig. 3).

Several training sessions were held by the University of Idaho scientists who developed the ET algorithm to train the IDWR personnel in the basic principles of remote sensing, theory of surface energy balance and ET, and methods to derive ET from satellite data. These training classes were designed to ensure a smooth transfer of technology from the academic community to the user domain.

The State of Idaho spends nearly half a million dollars annually to monitor water use in the irrigation districts using labor intensive field surveys. Considering the cost of imagery and processing, water use in the Snake River plain can be predicted through ET estimates from Landsat data for a fraction of that cost in a growing season. About 15 Landsat scenes are required to monitor water rights in the Snake River Plain during the growing season, and the cost of acquiring, processing and modeling ET from these scenes is estimated to be about $30,000 annually including staff time.

Using satellite estimates of ET, water masters, selected by communities to administer water rights, will be able to tell whether or not water has actually stopped being used for irrigation after a well has been ordered to shut off. Spatial and temporal estimates of ET offer other benefits as well. Estimates of actual and potential ET are useful for yield modeling and to accurately characterize the hydrological cycle and water balance.

Critical to the success of this project was the buy-in and continuous involvement of the end user agency from the initiation of the project. Several factors contributed to the success of the project: the end user had a critical need for a technology for decision making; the end user has some initial

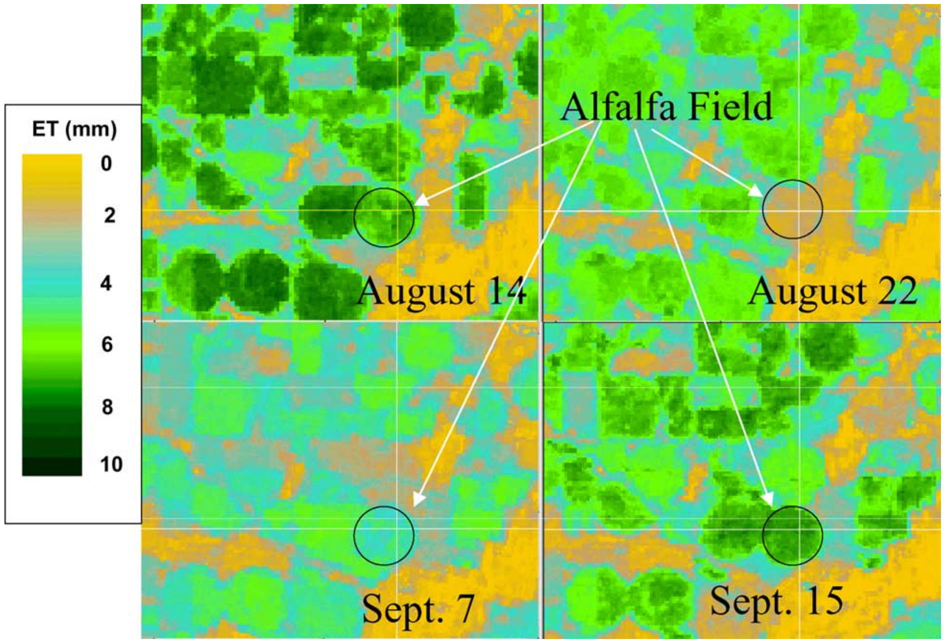

Fig. 3. These images show evapotranspiration (ET) estimates from Landsat 5 and 7 derived over an area in South Jerome county in Idaho during 2000. The circular areas show the sequence of ET for four dates over a hay field and indicate harvest and regrowth during this period. ET computed from these images can be directly related to water use. (Image courtesy: Tony Morse, Idaho Department of Water Resources.)

experience and capacity to understand and process remote sensing data; the end user already had an established working relationship with scientists from a university for collaboration; and most importantly, the spatial, spectral, and temporal and economic aspects of remote sensing data were suitable to address the issues faced by the end user. There is, however, one important factor that determines the adoption of any new technology by users, and it relates to data continuity. Users of any new technology should be assured of longevity of a data stream before they can make permanent changes to their decision-making procedures. Thermal measurements from the Landsat ETM+ sensor are critical to ET estimates for this project. Future Landsat data continuity missions are not likely to collect thermal measurements and that could significantly impact the long-term sustainability of this application by IDWR. This issue is not unique to this project alone. Not surprisingly, users are unwilling to adopt data products from experimental sensors that do not have longevity.

5. Lessons learned

Based on the case studies that were reviewed here, the findings in promoting remote sensing technologies for decision making by state/local users can be summarized as follows.

5.1. User involvement

Early and continuous involvement of the users is critical for the success of application development, and ultimately for realizing an impact on decision-making. The products and datasets that are developed have to be driven by a compelling requirement by the user community. Adequate feedback mechanisms should exist through periodic meetings and workshops between developers (e.g. scientists in academia and government, industry) and product users for continuous innovation and improvement. Workshops with users from multiple agencies help in overcoming institutional barriers by bringing together different user groups with similar requirements and facing similar challenges. Such workshops provide a forum for exchange of ideas among various groups. The product developers should ensure progressive alignment of products between meetings with the end users. There is a strong tendency to conduct user surveys through postal and email survey questionnaires, and while these mechanisms are useful, they are not as effective as regular face-to-face dialogues between application developers and their users, where the users have the opportunity to engage in a collective discussion.

Within a technology adoption life cycle, users can be classified as innovators, early adopters, early majority, late majority and laggards based on their level of adoption (Moore, 1999). Adopters of remote sensing applications can be similarly classified as well. Winning the support of the early adopters who can showcase the benefits of remote sensing technology over conventional methods of resource analysis is essential to a wider adoption by a larger user group. Users must, therefore, be involved as stakeholders within the life cycle of the project, and the application developers should factor in stakeholder's interests for successful transfer of technology from application to decision making or policy making.

5.2. Training and education

At present, remote sensing technologies are not widely used within state/local/tribal agencies, and training and educating these users is critical for successful adoption of these technologies. Users familiarity in remote sensing techniques also helps in building an informed consensus between end users and developers on the product specifications.

After the development of a technique or a data product, routine operational activities should be handed off to the end users or some other intermediary, thereby freeing up the research community to pursue additional investigations. The basic model adopted for the Synergy program was that the scientists from academia would develop and prototype an application by working closely with the end users. After successful demonstration of the benefits of remote sensing products, these products and methods would then be transferred to the agencies who would then adopt and maintain them. Training and education are, therefore, critical to transfer of technology and knowledge from the application developers to the end users within state/local/tribal agencies.

Establishing peer learning groups, in which an advanced user of a product teaches his peers within the same user community enhances product diffusion. For example, a group of farmers is more comfortable adopting a product when a fellow farmer endorses it and shares his positive experiences with them compared to marketing by an outsider.

5.3. Data accessibility, continuity, and formats

Remote sensing imagery often consists of large digital files. Fast network connectivity is, therefore, essential for efficient transfer of imagery among data providers, developers, users, and decision makers. Applications that rely on continuous, operational satellite data require real time acquisitions. In response to user demand for immediate data access, NASA has developed "data pools," which are large, online caches of real-time satellite data collected within the US (Carr et al., 2003).

Similar to other technologies, remote sensing technology is evolving. NASA is continually improving sensors with each generation of satellites. A number of remote sensing applications require data collected over multiple years for temporal analysis to observe patterns, trends and changes. NASA's EOS satellites are often precursors to operational monitoring satellites managed by NOAA. Since NASA is not an operational agency, there is rarely a redundancy in data collection or backup satellites in case an operating sensor or satellite fails within its planned lifetime. Also, some EOS instruments (e.g. Advanced Spaceborne Thermal Emission and Reflection Radiometer, Multi-angle Imaging Spectro-Radiometer) are unique and experimental in nature, and data continuity is not always assured. In some cases, transitioning research missions that have demonstrated opportunities for practical applications in to operational missions has been either slow or have gone unrealized altogether (NRC, 2003).

Users expect consistency in data format and content over time and need to be assured of data longevity before they are willing to switch to remote sensing data products and techniques for operational decision making. Decision makers and policy makers require datasets and techniques that can provide consistent results each time the tool is used. It is also critical that the remote sensing data have the right spectral, spatial and temporal characteristics and be economically viable in terms of cost for successful application development. Because of these factors, EOS data may face difficulties in being accepted universally by all decision-makers who rely on remote sensing data unless data continuity is assured.

Remote sensing data and products are generated by various agencies in a variety of formats. These formats may be suitable for researchers, but end users in non-research organizations require data in a format that can be readily displayed and analyzed using simple software packages. End users at the state/local/tribal level typically do not have access to high-end image processing software and tools. Products from remote sensing imagery should, therefore, be generated in formats that can be readily ingested into a variety of popular low cost image visualization and GIS packages and should be compatible with user's existing systems and infrastructure. To promote wider use of EOS data, NASA and its partners are developing translation tools that convert data into a variety of formats and projections for input to existing image processing and GIS packages.

5.4. Proven benefits

One of the major obstacles to date for adoption of remote sensing data for applications has been the lack of proven benefits, particularly in relation to cost. Adopting remote sensing imagery requires investment in hardware, software, and training. Before a group of users adopt this technology as an alternate to existing methods, they need to be convinced that remote sensing solutions are economically viable and save time and money or enable the realization of other environmental benefits. Using traditional financial cost benefit analysis models, it is feasible to show the monetary savings for applications that directly use remote sensing techniques for regulation and allocation of resources and where there is direct impact on marketable products such as crops and timber. It is, however, more difficult to assign a monetary value to benefits to the environment and quality of life which resulted from policy changes. Monetizing indirect benefits from using remote sensing data is complex and challenging. Nevertheless, demonstrating tangible benefits of remote sensing through either cost savings or cost avoidance would build a strong case for investing in these technologies by government agencies.

5.5. Incubation period

New users of remote sensing technology are not willing to invest unless the application has been proven to be a viable alternative to current practices. Experiences from the Synergy program show that 3–5 years are required before the end users gain confidence in using remote sensing data and institutionalize their use. Diffusion and adoption of these technologies is faster in agencies that have prior experience (even if limited). During the initial phases of application diffusion, the end users need hands-on training and advice, access to free data and processing software, technical support, and sometimes access to equipment as well. The rate of diffusion is directly related to the perceived value that remote sensing data has by users responsible for policy development or implementation.

5.6. Collection of metrics

“One can manage only what can be measured.” This maxim is true to remote sensing applications development, although there is no set of universally accepted metrics for all applications due to their specific context. Nevertheless, the collection of metrics for reporting externally to funding sources and to improve internal management of applications development is receiving growing interest since Federal agencies such as NASA must demonstrate the value of their investment to the public.

Metrics play an important role in determining the success of application development. Synergy metrics have evolved from a simple monitoring of product development (e.g. numbers of remote sensing files accessed, maps or statistics produced) in year 2000 to capturing outcomes from product application in decision support for resource management in 2003. Examples of these metrics are given in Table 2. Indeed, one lesson from our work is that project managers should incorporate this change in focus in their project strategies.

Some generalized metrics such as the impacts of remote sensing on policy, cost savings or cost avoidance, changes in the numbers of users of a specific data set, the demand for a specific dataset or application, and indicators of willingness of end users to invest in remote sensing technology could be used to gauge the performance and diffusion of application development. Metrics associated with policy impact are most difficult to quantify, but would have the most significance. Other metrics such as web transaction logs showing the number and volume of data sets distributed from a data center are easy to quantify and help in tracking the number of users and the datasets that are more popular.

Some of the measurable impacts of an application on decision making include factors such as the reliability and quality of decisions, time saved in using these new techniques, and the number of instances a decision has been made as a direct use of the new product compared to existing approaches to decision making. Improvements in the quality of the environment as a result of policy changes due to the adoption of remote sensing products can be readily measured and quantified.

Firm, time-bound goals, and project milestones can be difficult to define, implement, and maintain for a science and research project. However, if the goal of application development is to take established remote sensing algorithms or datasets and turn them into applications, then time-bound goals and milestones help set expectations between application developers and end users, and prevent the project from drifting off course on personal research agendas. Collection of metrics to improve internal project management may appear initially burdensome to applications developers. However, these metrics can help towards long-term sustainability of the project by ensuring that resources stay focused on applications that are most likely to succeed.

5.7. Sustainability

The long-term goal of the Synergy program is to make applications sustainable through a combination of private/public funding sources beyond NASA. The Synergy experience suggests that 3–5 years of project life span are required to advance from gathering user requirements to prototyping and developing an application, training users in

Table 2
Example of qualitative and quantitative metrics collected within the Synergy program

Metrics for external reporting to funding agencies		Metrics for improving internal management of applications development	
Quantitative	Qualitative	Quantitative	Qualitative
• Volume of data distributed in a given period	• Institutional collaboration in data sharing	• Numbers of repeat customers	• Clear project objectives, goals and existence of time-bound milestones
• Numbers of peer-reviewed articles published	• New/improved policies for managing the environment, natural resources and anothropogenic changes	• Numbers/kinds of training activities	• Maintenance of project’s internal skill base
• Numbers of graduate degrees awarded; students supported	• Local success stories from users who benefited from remote sensing data	• Numbers and kinds of contacts with user community	• Clear definition of user needs
• Income ($$) from alternative (new) funding sources		• Number of web hits from different sources	• Existence of user feedback loops
• Cost savings or avoidance ($$)			

the appropriate use of products and winning user confidence. Factors such as proven benefits, ease of use, timeliness of data, and continuity of data contribute to the sustainability of remote sensing applications. Among various applications of medium and coarse spatial resolution remote sensing data, numerical weather forecasting, disaster mitigation, and climate prediction have found markets within public and private sectors because of recognizable economic and social benefits (Williamson et al., 2002). Other applications such as urban planning and precision agriculture are more localized, and require imagery at a higher spatial resolution, which are more expensive than medium or coarse resolution data (Table 1).

There is no single model for reaching sustainability because of the uniqueness of each application and its user group. However, within the Synergy program three distinct categories of sustainability models have begun to emerge based on the type of users and sources of funding:

- Federal/state/local/tribal/non government organizations—State agencies such as IDWR or federal agencies such as the US Forest Service that have been benefiting from remote sensing data for monitoring large areas for environmental quality and compliance policies have invested in medium resolution remote sensing applications. Some agencies have started to acquire high-resolution imagery over selective areas, but the higher cost remains an issue.
- Private organizations—Commercial entities responsible for managing large land holdings such as timber companies fall within the second group of users. Private companies convinced of the benefits of remote sensing data for their operations eventually begin to build the infrastructure and technical capability within their organizations to process remote sensing data. They, however, would likely depend on universities and NASA for research and development of data processing algorithms.
- Private individuals and community-based organizations—Individual users such as farmers and ranchers have shown great interest in using remote sensing data for making informed decisions in managing their lands for better productivity. Sustainability of remote sensing applications within these user groups is more challenging since this group typically does not have the technical and financial resources to readily absorb remote sensing technologies. This user group tends to rely on well-established remote sensing data centers in the government, universities or the private sector companies to receive remote sensing data and products. Nevertheless, private individuals have the ability to influence public agencies in providing remote sensing data as they gain awareness of the value of these data for their particular need, which in turn could foster sustainability of an application. Community-based organizations such as farmer cooperatives or local environmental groups also play an active role in influencing federal, state, and local governments in setting funding priorities for remote sensing activities.

As the user base for remote sensing products is dynamic, application developers should be flexible in their approaches to sustain their operations. For example, working with individuals requires an effective outreach or extension campaign, whereas targeting a state agency might involve a detailed analysis of current organizational processes.

Remote sensing technology is still dominated by academic institutes and government organizations pursing research. Adopting models for achieving sustainability that are based on user interaction at each step in the development process suggests a shift away from the more traditional, technology-driven, research process in applying remote sensing.

6. Summary

Remote sensing data collected for research purposes by NASA's EOS satellites have been shown to be extremely valuable for a variety of applications development. Experience of the Synergy program demonstrates that partnerships among government, academia, end users, and industry help in fostering the success of remote sensing applications for a wide variety of users within state/local/tribal communities. Results from the Synergy program indicate that remote sensing data could have positive impacts on the environment through improved decision making and policies. The term "Crossing the Valley of Death" is often referred to in the transition from research and development to applications (NRC, 2000c). Several bottlenecks and hurdles such as lack of awareness by end users in remote sensing technology, lack of proper feedback mechanisms between application developers and end users, institutional barriers, and unproven cost benefits have to be overcome to cross this valley. Nevertheless, frequent dialogue between application developers and end users, education and training of end users, delivering products and data to end users in formats that best suit them, and collection of metrics and using them to manage application development ensure the success of application development using remote sensing data.

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