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THE BIG PICTURE – SATELLITE REMOTE SENSING APPLICATIONS IN RANGELAND ASSESSMENT AND CROP INSURANCE

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I. EXECUTIVE SUMMARY

Watts and Associates, Inc. (W&A) and TerraMetrics Agriculture, Inc. (TMAI) have proposed development of a new insurance plan for the Risk Management Agency (RMA) for rangeland, pastureland, and dryland hay. The program is intended to retain the administrative and moral hazard effectiveness of a county level Group Risk Plan (GRP) product while substantially increasing correlation with farm level perils by insuring perils at a sub-county level. The proposed methods to be employed involve the development of an insurable sub-county satellite remote sensing index. The product is being designed to capture the risk associated with perils occurring at the sub-county level, avoid moral hazard and adverse selection, and continue to be actuarially sound. In addition to the remote sensing index, a proxy index (a substituted crop or weather variable that has measurable yields or quantities that are used as a proxy for range production) will be developed at the county level. The remote sensing index at the sub-county level and the proxy index at the county level, if approved by the FCIC Board, will then be deployed as a dual trigger product, whereby the producer is paid the largest indemnity payment indicated by the dual trigger. The development effort is staged for testing initially in western rangeland region and then moved to the more seasonally complex and fractionated pastureland in the east.

W&A realizes farm level data associated with range production (similar to Actual Production History (APH) data) are largely nonexistent, even though satellite imagery is available nationwide. To enforce best management practices, many agencies have attempted to monitor animal days of grazing to enforce federal grazing leases. For an insurance plan to be successful, poor management practices such as overgrazing must be excluded as an insured cause of loss. Any plan based on agency or farm level verification of grazing pressure will be fraught with information asymmetries leading to insurmountable actuarial and underwriting problems. We are developing a plan that is not dependant on individual producer management strategies or potential hidden action. The use of satellite remote sensing to determine rangeland productivity at the sub-county level obviates the need to monitor individual producer actions.

For purposes of brevity, this paper will focus on the construct and design of the satellite remote sensing trigger and will not dwell on the construct of the proxy trigger. The design and construct of the proxy

trigger will be similar to the existing GRP Rangeland program. Statistical testing of the dual trigger indicated an increase in efficacy by using the proxy trigger in conjunction with the satellite remote sensing trigger.

The satellite remote sensing trigger was initially constructed using those methods and data determined to be most available and reliable. Numerous data sources were evaluated for inclusion in the trigger. After review, the Advanced Very High Resolution Radiometer-Normalized Difference Vegetation Index (AVHRR-NDVI) based trigger was chosen as the most reliable and best indicator of annual range condition. The NDVI element of the trigger provides a measure of vegetation "greenness" over time. Using weekly NDVI spatial data covering the conterminous United States, locale-specific phenological development of vegetation can be charted and deconstructed as needed for calculation of the optimal NDVI-based trigger. Other data sources and methods reviewed and rejected for this product include:

- Moderate Resolution Imaging Spectrometer (MODIS) and other high resolution sensors: Rejected due to lack of data history and no future operational guarantee.
- AVHRR: Data prior to 1989 were not used because of coarse resolution and insufficient archived imagery. Also, channel 4 thermal data were examined and found to not improve predictive capability.
- Doppler radar: Rejected because of lack of coverage and inabilities to capture precipitation estimates at the ground level.
- Parameter-elevation Regressions on Independent Slopes Model (PRISM): Rejected because the future funding for PRISM is not established.
- National Oceanic and Atmospheric Administration (NOAA)-National Weather Service (NWS) temperature data: Growing degree days (GDD) as a variable did not improve the predictive capability.

Historical and current research demonstrates that the imagery has informational content with respect to crop yields and, by association, production. We have identified three significant traits of range production estimation that should make this a more likely task than crop yield forecasting. These traits are: (1) locational stability of range over time (crop rotation is not a factor with rangeland); (2) distributional stability of range production over time (technology-induced trending is not a factor, i.e., genetics, fertilizer, etc.); and (3) lack of dependence of annual range production on end-of-season conditions, similar to harvest-time conditions for cultivated crops. In light of these reasons and in addition to the observed predictive relationship between AVHRR-NDVI and crop yields, we believe we have strong evidence in support of the use of AVHRR-NDVI for assessment of annual range productivity for the purpose of insuring against productivity losses.

II. SCOPE OF THE DEVELOPMENT EFFORT

The development effort is nationwide in scope. Western rangeland (and the attendant dryland hay base integral to western ranches) and eastern pastureland are considered in two separate phases of the project. It should be noted that dryland hay production is oftentimes intermixed in the production of pastureland and rangeland, and is managed by the same practices. The development effort does not address the risk management needs of irrigated pasture or irrigated hay acreage due to divergent management practices. The Natural Resource Conservation Service (NRCS) definition of pastureland and rangeland is used to define the proposed insurable acreage. The NRCS definitions are as follows:

> ***Rangeland:*** *Land cover/use category on which the climax or potential plant cover is composed principally of native grasses, glasslike plants, forbs or shrubs suitable for grazing and browsing, and introduced forage species that are managed like rangeland. This would include areas where introduced hardy and persistent grasses, such as crested wheatgrass, are planted and such practices as deferred grazing, burning, chaining, and rotational grazing are used, with little or no chemicals or fertilizer being applied. Grasslands, savannas, many wetlands, some deserts, and tundra are considered to be rangeland. Certain communities of low forbs and shrubs, such as mesquite, chaparral, mountain shrub, and pinyon-juniper, are also included as rangeland. [NRI-97]*

> ***Pastureland (and native pasture):*** *Land cover/use category of land managed primarily for the production of introduced or native forage plants for livestock grazing. Pastureland may consist of a single species in a pure stand, a grass mixture or a grass-legume mixture. Management usually consists of cultural treatments--fertilization, weed control, reseeding, or renovation and control of grazing. (For the NRI, includes land that has a vegetative cover of grasses, legumes, and/or forbs, regardless of whether or not it is being grazed by livestock.) [NRI-97]*

This first development effort is focused on western rangelands generally defined by the western borders (divisional line) of Minnesota, Iowa, Missouri, Arkansas, and Louisiana. While there is no bright line division between east and west, the border lines generally split the U.S. W&A considers the line as a convenience for discussion purposes.

Western rangelands are owned by private producers, businesses, or state or federal government. Determining the number of federal range and pasture holdings used for the production of livestock by ranchers and farmers in the U.S., in addition to private holdings, is no easy task. Private acreage estimates are more easily obtained than federal estimates of land holdings. There are conflicts among various informational sources for categorizing federal holdings into grazed or ungrazed, range or pasture. Exact acreages are not known due to changing land use (multiple use) and differing definitions. Federal holdings are not subject to inventory by national statistical sources such as the National Agricultural Statistical Service (NASS). Therefore, published information is generally from federal agencies that administer federal lands, user groups, or other sources involved with federal land multiple uses.

Federal acreage estimates may be established through records showing Payment in Lieu of Taxes acres for each state, NRCS publications, Bureau of Land Management (BLM) publications, United States Forest Service (FS) publications, or other sources connected to federal land stewardship. However, total quantity does not mean all grazing acres since federal lands are classified as multiple use and may exclude grazing in parks, wilderness, or other federal enclaves.

The U.S. encompasses approximately 2.27 billion acres of land across 50 states, 48 states being contiguous. Of the 2.27 billion acres, federal land comprises about 658 million acres (29 percent) of the total acreage. Of the 658 million acres of federal land, four agencies in the United States Department of Agriculture (USDA) and United States Department of the Interior (DOI) manage 615.2 million acres (93.5 percent) of the federal land area. Of the 615.2 million acres managed by two executive branch departments, the FS (USDA) manages 188.3 million acres (30.6 percent), BLM (DOI) manages 255.9

million acres (41.6 percent), the Fish and Wildlife Service (FWS) (DOI) manages 93.5 million acres (15.2 percent), and the National Park Service (NPS) (DOI) manages 77.5 million acres (12.6 percent).[1]

The responsibilities of the Bureau of Indian Affairs (BIA) include the administration and management of 55.7 million acres of land held in trust by the U.S. for American Indians, Indian tribes, and Alaska Natives. There are 562 federally recognized tribal governments in the U.S.[2] These lands may be forested, range, pasture, or put to other use. Trust lands are similarly leased out to procedures that occur between private parties but are regulated by specific federal statutes. The BIA administers these lands as a trustee, not as an owner. A large issue with lands on Indian reservations is the fractionalized ownership by many individuals of the same parcel. These lands may be unaccounted for in either trust or private totals. Therefore, determining an accurate inventory of available grazing lands under the purview of the BIA is extremely difficult.

Federal land sustains some level of livestock grazing pressure each year on 85 percent of the total federal land area.[3] However, this figure may not include areas unsuitable for grazing due to barriers caused by terrain, lack of water, or other impediment to access for domestic livestock use. Excluding NPS and FWS, the two key federal land management agencies manage 188.3 million acres (FS) and 255.9 million acres (BLM), respectively.

These two agencies administer 444.2 million total acres collectively. The 15 percent of federal land removed from the total may cover parks, monuments, federal enclaves, or agency land not subject to grazing leases and may total 92 million acres.

States own 196.9 million acres. Alaska owns 105.2 million acres, leaving 91.7 million acres (46.5 percent) spread over the other 49 states.[4] Exact acreage used for grazing is unknown; however, it is likely that approximately 50 million acres are grazed.

There are about 577.7 million acres of range (including grazed forest) and pasture in private ownership in the U.S.[5] Of this total acreage, there are 405.3 million acres of range, 117.3 million acres of pasture, and 55.1 million acres of grazed forest land.[6]

The general categorization of private and federal grazing land holdings demonstrates the enormous quantity of acres attached to the concept of the proposed insurance product for rangeland, pastureland, and the native dryland hay acres that accompany rangeland grazing. Collectively, between the Western and Eastern development efforts, there may be more than one billion acres of grazing acreage that could be insured under this development effort, which would represent nearly 45 percent of the U.S. total land area.

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[1] National Council for Science and the Environment. May 21, 2004. Congressional Research Service Reports.
[2] Bureau of Indian Affairs – Department of the Interior. Web Page. http://www.doi.gov/bureau-indian-affairs.html. (Accessed 1/10/2005).
[3] Sundquist, B. September 2003. “Grazing Land Degradation: A Global Perspective.” Online Article. http://home.alltel.net/bsundquist1/og0.html. (Accessed 11/2004).
[4] National Wilderness Institute. “State by State Government Land Ownership.” Web Page. http://www.nwi.org/Maps/LandChart.html. (Accessed 01/06/2005).
[5] National Resources Conservation Service. April 2004. “National Resources Inventory 2002.”
[6] The ability to reconcile NASS, CRSR, and NRCS sources for total grazing land (range, pasture, forest) acres grazed in the U.S. each year does not appear to exist.

W&A has summarized the questions of "what" and "approximately how much" range and pasture are in the U.S. The question of "how many" stewards there are of range and pasture acreage used for livestock production in the U.S. requires estimation, which is not without problems. The ability to classify producers is problematic because of nomenclature handicaps that seem to develop depending on which side of the divisional line one resides. The total acreage of native range east of the divisional line is small, and therefore the nomenclature adopted for this portion of the U.S. for grazing acreage is "pasture."[7] Grazing land west of the divisional line is predominantly native and the adopted nomenclature is "range." In the agricultural community as a whole, farmers are associated with pasture, and ranchers are associated with range. NASS uses the terms farms and farmers in the context of range and pasture, but does not refer to ranches or ranchers.

The 2002 Census of Agriculture indicates there were 850,913 operations that used 395.3 million acres of private pasture and range, excluding 31.1 million acres of private woodland pasture that were categorized separately.[8] There is no defined number of livestock producers the new plan may bring into the RMA insurance program. In 2002, there were 394,538 farms enrolled in crop insurance programs and 214.8 million acres covered.[9] The impact this new plan may have on total livestock operations and acres covered by insurance could be quite dramatic given federal and private range and pasture may exceed one billion acres of land, or nearly 45 percent of the entire U.S. land area. Current crop insurance coverage extends to less than 10 percent of the total land area of the U.S.

III. OVERVIEW OF THE DUAL TRIGGER APPROACH

Indemnifications in the new plan will be triggered when the smaller-than-county area satellite remotely sensed index falls below a percentage of its historical average, or when a county-based proxy index falls below a percentage of its historical average. The dual trigger approach will pay the producer the maximum of the indemnities respectively computed from the remotely sensed index and from the county level proxy index. The indemnification effects of the dual trigger mechanism are incorporated into premium rates. The dual trigger mechanism increases the likelihood that a producer receives an indemnity payment. As such, this product is more likely to pay an indemnity when a farm loss occurs than the typical Group Risk Plan (GRP) program. The dual trigger approach also provides a fail-safe mechanism in the unlikely event that several satellites should simultaneously fail.

The satellite remotely sensed index based on the AVHRR sensor is used to represent the level of annual range production. The AVHRR senses the "greenness" of vegetation throughout the growing season, and it returns values strongly correlated with accumulated live plant biomes. The surface reflectance data sensed by the AVHRR satellite are then converted to the NDVI. This index is a measure of relative plant productivity.

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7 Rainfall, climate, and soil morphology really are the driving factors in separating East from West. Generally, pasture is found where the Tall Grass Prairie existed before becoming farmland. The divisional line of the western borders from Minnesota south through Louisiana provides a convenient dividing reference.

8 Recall that the U.S. Government does not track statistics on Federal lands that are kept on agricultural commodities produced by U.S. producers.

9 United States Department of Agriculture–National Agricultural Statistics Service. "2002 Census of Agriculture." Vol. 1, Table 8: Land-2002 and 1997.

The proxy trigger is either based on countywide substitute crop yield or precipitation data. The substitute crop's yield should be correlated with range production. Non-irrigated crops having a reliable and current NASS data time series will be considered. Precipitation data are available from NOAA weather stations. Our experience suggests, in most cases, a substitute crop is a preferred proxy to precipitation. However, in some of the more arid areas of the West, proxy crop yield data are unavailable, leaving precipitation as the proxy.

Statistical procedures similar to those used in the W&A rating method will be used to merge longer term information from the county-based series with the shorter term, spatially diverse information from the satellite remotely sensed index. Also, for the redundant trigger, a county level proxy, similar to the process used in the GRP Rangeland Pilot Program, will be chosen and statistically tested for its efficacy.

IV. SATELLITE REMOTE SENSING OF VEGETATION CONDITIONS

In this section, the key concept to keep in mind is the sheer magnitude of the capability of satellite imagery to record observations in short time periods over large areas. This aspect of the trigger is the fundamental key in the development and application of the NDVI techniques for determining changes in range productivity, and the ability to administer a program covering large areas.

Early Application of Satellite Remote Sensing

Traditional vegetation mapping and assessment techniques have been based primarily on field observation and data collection methods. These traditional mapping and assessment techniques are time-consuming, subjective, and economically inefficient for relatively large areas. Range managers in the West have monitored range condition and trend based on aerial photographs, 7.5 minute quadrangular photos, or other differently scaled imagery taken of the range, and perhaps some close observation on the ground. However, the likelihood of obtaining meaningful vegetation monitoring is small, particularly on federally leased grazing lands. For these reasons, many rangelands in the U.S. monitored using the traditional approaches are seldom monitored at all by range managers, who are too few in numbers to inventory and assess rangeland directly.[10]

The use of satellite remotely sensed imagery has become a cost-effective method to identify and map various types and characteristics of grassland and agricultural land features. Previous studies have successfully used spectroradiometer and earth orbiting satellite data to estimate and assess biophysical characteristics of grassland ecosystems including biomass, plant net primary productivity (NPP), and

[10] United States Department of Agriculture. 1989. "State of the Land." August 1998. http://www.nhq. nrcs.usda.gov/land/home.html.

leaf area index (LAI).[11] Additionally, remotely sensed data have also been used to discriminate among land cover and grassland types.[12] In more recent years, several studies have shown the usefulness of multitemporal satellite imagery for improved classification of land cover types.[13] The use of multitemporal imagery has been shown to significantly improve the discrimination between cropland and grasslands in Kansas when compared to a single date approach employed in the Kansas Land Cover Mapping Project.[14]

Many past studies on resource management programs exist where remotely sensed data have been used to map, monitor, and characterize rangeland cover, composition, and trends. The literature on this topic is vast and comprehensive. A basic overview of the literature describing how satellite remotely sensed data have been used to study rangelands and other natural resources is useful.

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[12] Asrar, G., R. B. Myneni, Y. Li, and E. T. Kanemasu. 1989. "Measuring and modeling spectral characteristics of a tallgrass prairie." Remote Sensing of Environment, 27:143-155.
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[13] Buttner, G. and F. Csillag. 1989. "Comparative study of crop and soil mapping using multitemporal and multispectral SPOT and Landsat Thematic Mapper data." Remote Sensing of Environment, 29:241.
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[14] Egbert, S. L., K. P. Price, M. D. Nellis, and R. Lee. 1995. "Developing a land cover modeling protocol for the high plains using multi-seasonal Thematic Mapper imagery." Proceedings, ASPRS/ACSM Annual Meeting, Charlotte, North Carolina, February 27-March 2, Vol. 3. pp. 836-845.
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C.J. Robinove described one of the early remote sensing applications to rangeland.[15] Dr. Paul Tueller, at the University of Nevada, Reno was among the early range scientists to adopt satellite remote sensing as a means of studying rangeland dynamics. In one of the first applications of remotely sensed imagery to rangeland studies, Tueller used Earth Resources Technology Satellite (ERTS-1) imagery to map vegetation of the Great Basin. Tueller used Landsat Multispectral (MSS) imagery to map sagebrush distribution in northern Nevada.[16] Tueller also wrote a paper on remote sensing applications in arid environments[17] and published the first overview of remote sensing of rangelands in the *Journal of Range Management*.[18]

Researchers have used Landsat MSS imagery to examine arid vegetation community types in Rush Valley, Utah.[19] Landsat Thematic Mapper (TM) imagery has been used to study semiarid shrub communities,[20] shrub dieback in a semiarid environment,[21] and soil erosion in pinyon-juniper woodland.[22] Studies have examined the spectral characteristics of various rangeland plants and their surrounding abiotic factors in a sagebrush steppe ecosystem,[23] and the use of remotely sensed imagery for discriminating among grassland plant life forms and grazing intensity.[24] Work has been done to evaluate the use of remotely sensed data for discriminating among five grassland cover and land management practices.[25]

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[15] Robinove, C.J., P.S. Chavez Jr., D. Gehring, and R. Holmgrem. 1981. “Arid land monitoring using Landsat albedo difference images.” Remote Sensing of Environment, 11:133-156.

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[19] Price, K. P. M.K. Ridd, and J.A. Merola. 1985. “An integrated Landsat/ancillary data classification of desert rangeland.” American Society of Photogrammetry-American Congress of survey and Mapping (ASP-ACSM) Convention, Washington, DC. Technical Paper, 51st Annual Meeting, Vol. 2:538-545.

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[21] Price, K.P., D. Pyke, and L. Mendes. 1992. “Shrub dieback in a semiarid ecosystem: The integration of remote sensing and geographic information systems for detecting vegetation change.” Photogrammetric Engineering & Remote Sensing, 58(4):455-463.

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[24] Peterson, D.L., K.P. Price, and E.A. Martinko. 2002a. “Discriminating between cool season and warm season grassland cover types in northeastern Kansas.” International Journal of Remote Sensing 23:5015-5030.
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[25] Price, K.P., X. Guo and J.M. Stiles. 2002. “Comparison of Landsat TM and ERS-2 SAR data for discriminating among six grassland types in eastern Kansas.” 2nd special issue of Computers and Electronics in Agriculture. 37:157-171. (Invited paper).
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The research cited above focused primarily on the use of Landsat imagery for characterizing rangeland biophysical properties, land cover, and land use practices. This work focused mainly on the plant community or life form scales. Other work has focused on the natural resource dynamics, particularly of range and forestlands at the regional and continental scales in Africa, China, and Mongolia. C.J. Tucker initiated the early work at this scale in Africa using the AVHRR to look at dry matter production and desert expansion in Sahel.[26] In northern China, researchers used AVHRR imagery to assess desertification.[27] In separate studies, Price and Yu applied time-series analysis of AVHRR-NDVI composites to assess ecosystem variability[28] and to evaluate the effects of climate variability on grassland dynamics in Inner Mongolia.[29] Biomass in pastureland has been assessed in Mongolia using AVHRR-based vegetation health indices.[30]

Satellite Remote Sensing Overview

A basic understanding of remote sensing system resolutions is beneficial before assessing the advantages of one remote sensing system over another. System selection should be based on specific goals. There are numerous systems available. These include the U.S. Landsat TM, the French SPOT, the private sector IKONOS, OrbView-3, Quickbird, and the TERRA and AQUA systems that both carry the MODIS, and the Polar Orbiting Meteorological Satellite (POMS) that carries the AVHRR.[31]

Satellite Remote Sensing Resolutions

There are four resolutions that need to be considered when comparing remote sensing systems. These resolutions include: (1) spatial, (2) spectral, (3) radiometric, and (4) temporal. The four definitions describing resolutions are stated below:[32]

Spatial resolution is a measure of the smallest angular or linear separation between two objects that can be resolved by the remote sensing system. From a remote sensing standpoint, the picture element (pixel) size is often used to describe the spatial resolution. For example, Landsat has a nominal spatial resolution of 30 m; the SPOT sensor has a nominal spatial resolution for the multispectral bands of 20

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[26] Tucker, C.J. 1979. “Red and photographic infrared linear combinations for monitoring vegetation.” Remote Sensing of Environment, 8:127-150.

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[28] Price, K.P. F. Yu, R. Lee, and J. Ellis. 2004. “Characterizing Ecosystem Variability of Northern China Steppes Using Onset of Green-Up Derived From Time-Series AVHRR-NDVI Data.” GIS & Remote Sensing Journal, 41(1): 45-61.

[29] Yu, F, K.P Price, J. Ellis and P. Shi. 2003. “Response of seasonal vegetation development to climatic variations in eastern central Asia.” Remote Sensing Environment, 87:42-54.

Yu, F., K. Price, J. Ellis, J. Feddema, and P. Shi. 2004a. “Inter-annual variations of the Gobi Desert boundary in central Asia,” International Journal of Remote Sensing, 25(2), 327-346.

Yu, F., K.P. Price, J. Ellis, and D. Kastens. 2004b. “Satellite observations of seasonal vegetation growth in Central Asia: 1982-1990.” Photogrammetric Engineering & Remote Sensing, 70(4): 461-469.

[30] Kogan, F., R. Stare, A. Gitelson, L. Jargalsaikhan, C. Dugrajav, and S. Tsooj. 2004. “Derivation of pasture biomass in Mongolia from AVHRR-based vegetation health indices.” International Journal of Remote Sensing, 25(14):2889-2896.

[31] Jensen, J. R. 2004. “Introductory Digital Image Processing: A Remote Sensing Perspective.” Prentice Hall Series in Geographic Information Science, Keith C. Clark, Series Editor. 3rd Edition. 526 pp.

[32] Jensen, J. R. 2004. “Introductory Digital Image Processing: A Remote Sensing Perspective.” Prentice Hall Series in Geographic Information Science, Keith C. Clark, Series Editor. 3rd Edition. 526 pp.

m. Spatial resolution of space-borne satellites varies from less than 1 m to 50 km, with most sensors in the 10 m to 1,100 m range.

Spectral resolution is the number and dimension (size) of specific wavelength intervals (referred to as bands or channels) in the electromagnetic spectrum to which a remote sensing instrument is sensitive. Higher spectral resolution instruments have more bands, narrower bands, or both. Normal spectral resolution of space borne satellites is 3 to 36 bands. Hyperspectral sensors collect 126 to 256 bands.

Radiometric resolution is defined as the sensitivity of a remote sensing detector to differences in signal strength as it records the radiant flux reflected, emitted, or back-scattered from the terrain. It defines the number of just discriminable signal levels. The human eye can discriminate between 8 and 15 radiant intensity levels, or shades of gray ranging from white to black. The radiometric resolution of space-borne satellites varies from 256 to 1,024 intensity levels.

Temporal resolution refers to how often the sensor records imagery over a particular area. For example, the temporal resolution of the Landsat TM is 16 days. SPOT has a repeat time of 26 days, but greater temporal resolution can be obtained if off-nadir views of the terrain can be obtained and used. The temporal resolution of the near 1 m resolution systems is one to five days, but this is only if one can use surfaces viewed from an oblique or off-nadir angle. Nadir views are obtained on an infrequent basis. The temporal resolution of the NOAA-POMS that carries the AVHRR sensor is daily worldwide (except for 9 degrees from the north and south poles).

Swath width is the measure of width of the image for each pass as the satellite orbits the planet and is also a critical factor. Swath width influences how often the sensor captures data over an area on the earth. The smaller the pixel (greater the spatial resolution), the narrower the swath width. For example, the swath width of the meter to submeter measuring instruments is 8 to 11 km, compared to the 2,600 km width of the coarse resolution 1 km AVHRR data.

Satellite Remote Sensing System Classification

Other very important distinctions among remote sensing instruments are: (1) how long the data have been captured by the instrument; (2) whether the data have been saved or archived on a regular basis; (3) whether the data are available; (4) what are the future plans for the instrument; (5) the data cost; and (6) how accessible are the data.

When developing a national program having long-term implications, it is critical to ensure the data used for the program will be available in the future. If one is comparing current conditions to past conditions, it is likewise important that historical data from the instrument are also available. Satellite systems can be classified into three categories: (1) commercial; (2) experimental; and (3) operational.

Commercial satellite remotely sensed data are acquired by private companies that sell the imagery. In most cases, the cost of this imagery is expensive and often little historical data are available. Examples of commercially available imagery include all the very high spatial resolution instruments, such as IKONOS, OrbView-3, and Quickbird.

Experimental instruments are used to test remote sensing systems so improvements in future systems can be made. The National Aeronautics and Space Administration (NASA) often develops experimental remote sensing systems. These systems usually are one of a kind and plans for replacement of the system after it has become non-operational usually do not exist. NASA currently has many experimental systems in orbit. Two of the most recognized systems include the TERRA and AQUA satellites. Both of these systems have multiple remote sensing instruments onboard, including the MODIS sensor, which is a more advanced version of the AVHRR system primarily because it has 36 bands as opposed to the 5 bands offered by the AVHRR. MODIS also has multiple spatial resolutions including 250 m, 500 m, and 1 km.

Operational remote sensing systems are those that are planned to be in operation into the future. Replacement of the system after its failure is planned well in advance, and sometimes the replacement system is already in orbit so a failed system can be quickly replaced. There is only one "operational" remote sensing system currently in use–the NOAA-POMS that carries the AVHRR sensor.
The NOAA-POMS system has been in operation since 1960. The technology associated with this system is continually improved, but the number of bands measured, and their associated wavelengths, has remained constant since 1981. This continued operation of this system is planned through at least 2015.

AVHRR System History
Satellite imaging began in 1960 with the launching of the first meteorological satellite. The Television and Infrared Observation Satellite (TIROS-1) was launched from Cape Canaveral in Florida on April 1, 1960. This early space platform carried a Vidicon (television camera system), but later generations of this system included the AVHRR that was first placed on TIROS-N, launched on October 13, 1978. Since 1978, AVHRR digital imagery has been collected on a nearly continuous basis. In 1979, NOAA placed the AVHRR sensor on the NOAA-6 platform launched on June 27 of that year. Two years later, NOAA launched NOAA-7 with the AVHRR scanner onboard, but this scanner also included a third thermal band. Since 1981, the AVHRR sensor has remained the same with respect to the regions of the electromagnetic spectrum measured by the instrument. The sensor collects measurements in five regions of the electromagnetic spectrum: red (0.58–0.68 μm), near infrared (NIR) (0.73–1.10 μm), and in three thermal bands (3.55–3.93 μm, 10.3–11.3 μm, and 11.5–12.5 μm). The scientific community really did not apprehend the earth system science research value of meteorological satellites until the late 1980s and mid 1990s. The data used for this project spans from 1989 forward. Although the 1 km AVHRR imaging capabilities have been available since the early 1980s, meteorologists mostly used the coarser 4 km and 8 km imagery to study global weather conditions, and for this reason the 1 km imagery were archived on a less consistent basis until the late 1980s. Once scientists began to recognize the value of the 1 km imagery for studying earth surface phenomenon, the 1 km AVHRR imagery began to be systematically archived for the globe, making it possible to obtain enough imagery over an area to create the near cloud-free NDVI composites being used for this project. For these reasons, extending the 1 km near cloud-free composites back beyond 1989 is not possible, and matching the earlier 4 km and 8 km imagery to the 1 km imagery creates geometric registration and radiometric calibration challenges that would make it difficult if not impossible to merge these different datasets for comparison purposes.

No other remote sensing imaging system has such an extended history of collecting worldwide imagery on a daily basis as the AVHRR system. The long-term history of AVHRR data coverage on a daily basis using the same regions of the electromagnetic spectrum makes the data from this system truly unique and invaluable for a multitude of applications. Historical longevity was a primary factor in choosing a satellite system for this project, and AVHRR met this requirement.

Monitoring Natural Resources at the Continental Scale

In order to monitor natural resources on a continental scale, the remote sensing system must capture imagery on a regular basis, be able to cover the area of interest in a timely and cost effective manner, possess readily available historical data as far back as possible, and maintain operational status. Given all of these criteria, there is only one remote sensing system that meets all these requirements—the AVHRR sensor, orbiting as part of the NOAA-POMS system.[33] The NOAA Polar Orbiting Environmental Satellite System (NPOESS) that is scheduled for launch in 2009 represents a hybrid between the existing AVHRR and MODIS system. This system represents the future for continental scale natural resource monitoring through 2018. The SPOT Vegetation system and MODIS, however, are not suitable for monitoring natural resources on a continental scale. Data are available only since the late 1990s (SPOT) and early 2000s (MODIS). MODIS is not planned as an operational platform, and the commercial nature of SPOT means that continental-scale data would be very costly. The lack of a longer-term historical record from these systems and the uncertain future of operation of these satellites make them unsuitable for use in a long-term natural resource monitoring and condition assessment program.

The moderate spatial resolution sensors like Landsat and SPOT and the commercial satellites with meter to sub-meter resolutions are not practical for use in monitoring continental- to global-scale natural resources. This is because these data cannot be acquired on a sufficiently frequent basis over the entire region of interest to be useful for many applications, and the cost of purchasing and processing the data is also prohibitive.

TMAI has the capability of creating 14-day composite images. Presently, Earth Resources Observation Systems (EROS) Data Center (EDC) creates 14-day composite images, and these images are used in this project. Should EROS be unable to construct and provide the composite imagery, TMAI can fill the void.

Vegetation Indices

Researchers and managers have used remotely sensed data for more than 30 years to assess and monitor vegetation conditions. In particular, red and near infrared (NIR) reflectance have been used to measure vegetation health and vigor based on the inverse relationship between red reflectance and chlorophyll content and the direct relationship between leaf structure and NIR reflectance. During this time, scientists have examined various band combinations and transformations in an attempt to improve the ability to characterize biophysical and biochemical factors associated with vegetation. There are at least 21 vegetation indices dating from 1968 through 2003.[34] While each developer espouses the virtues of

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[33] MODIS provides continental coverage on a regular basis but is not planned to be operational and lacks historical longevity.

[34] Jensen, J. R. 2004. "Introductory Digital Image Processing: A Remote Sensing Perspective." Prentice Hall Series in Geographic Information Science, Keith C. Clark, Series Editor. 3rd Edition. 526 pp.

Perry, C.R. Jr. and Lautenschlager, L.F. 1984. "Functional equivalence of spectral vegetation indices." Remote Sensing Environment 14:169-182.

Price, K.P., D. Pyke, and L. Mendes. 1992. "Shrub dieback in a semiarid ecosystem: The integration of remote sensing and geographic information systems for detecting vegetation change." Photogrammetric Engineering & Remote Sensing, 58(4):455-463.

Eidenshink, J. C. 1992. "The 1990 conterminous U.S. AVHRR Data Set." Photogrammetric Engineering and Remote Sensing, 58(6), 809-813.

their index, others have found, for the most part, the indices are functionally equivalent in information content.[35]

One of the oldest indices is the NDVI.[36] This index is still the most widely used of all the indices and is the index selected by W&A and TMAI for use in this project. The NDVI is computed by taking the difference between the NIR and red spectral reflectance values, and then normalizing this difference by dividing it by the sum of the two reflectance values: NDVI = (NIR - RED) / (NIR + RED). The strong correlation between the NDVI and green photosynthetically active components of vegetation has caused some to refer to the NDVI as a plant "greenness" index.

Fourteen-Day Maximum NDVI Composite

One major advantage of using the AVHRR imagery is its high temporal resolution. While most remote sensing systems collect imagery at a nadir viewing angle over an area once every 16 to 26 days, the AVHRR sensor collects images over an area at least once daily. There is normally a morning and afternoon overpass by the NOAA polar orbiting platforms, providing AVHRR imagery often captured twice daily. Upper latitude regions may have as many as 14 images each day over the same area.

Unfortunately, most images contain varying degrees of cloud cover that obscure observation of the earth's surface. To overcome this problem, EDC began distributing cloud-free 1 km AVHRR-NDVI composite images of the conterminous U.S., southern Canada, and northern Mexico.[37] Presently, there are AVHRR 14-day NDVI cloud-free composites developed at EROS and distributed on a weekly basis. These composites date back to 1989 (prior to this date, sufficient 1 km AVHRR imagery were not available for compositing). This means any area in the conterminous U.S. can be monitored four times a month with minimal cloud obstruction. This relatively high temporal resolution, coupled with the availability of a substantial, multi-year, continuous dataset (more than 16 complete years at present, spanning 1989 through early 2005), makes these data truly unique and invaluable for monitoring vegetation dynamics over the growing season.

However, due to satellite changeover and physical limitations associated with any satellite remote sensing instrument (e.g., orbit drift and calibration inaccuracy), as well as processing problems (e.g., image registration and changes in atmospheric correction methods), time series satellite imagery inevitably has inconsistencies that manifest as data value drift. TMAI has substantial experience in dealing with satellite value drift. Drift adjustments will be made to the dataset as appropriate.

The only other comparable vegetation index datasets are the MODIS 16-day vegetation index sets. These datasets are created using the maximum NDVI and the maximum Enhanced Vegetation Index (EVI). The maximum NDVI and EVI composites are created using the MODIS 250 m, 500 m, and 1 km resolution images. These datasets have been produced since February 2000, and it is anticipated that these datasets will continue to be produced until the MODIS system becomes inoperable. Since the anticipated life expectancy of any satellite remote sensing system is normally five years, there is much

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[35] Perry, C.R. Jr. and Lautenschlager, L.F. 1984. "Functional equivalence of spectral vegetation indices." Remote Sensing Environment 14:169-182.
Price, K.P., D. Pyke, and L. Mendes. 1992. "Shrub dieback in a semiarid ecosystem: The integration of remote sensing and geographic information systems for detecting vegetation change." Photogrammetric Engineering & Remote Sensing, 58(4):455-463.

[36] Rouse, John W. "On radio science techniques for remote sensing." i, 9, [4] leaves; 28 cm, College Station, TX: Texas A&M University, Microwave and Infrared Systems Laboratory, 1973.

[37] Eidenshink, J. C. 1992. "The 1990 conterminous U.S. AVHRR Data Set." Photogrammetric Engineering and Remote Sensing, 58(6), 809-813.

uncertainty about the future availability of MODIS imagery. Uncertainty of the MODIS imagery is one reason for these data to be eliminated from consideration for the project in favor of AVHRR. The relatively brief length of the available historical MODIS data set was also cause for elimination.

There are ongoing discussions about the advantages and disadvantages of the EVI over the NDVI. Most of these discussions focus on the problem of saturation of the NDVI at high or dense levels of photosynthetically active biomass.[38] While saturation of the NDVI has been a problem for discriminating biomass differences in areas where dense vegetation is common, W&A and TMAI are not concerned about saturation of NDVI for the western rangeland, pastureland, and dryland hay project because the levels of biomass associated with these land cover types is generally well below the saturation point. The saturation is expected to generally increase from west to east across the U.S., with significant increases of saturation beginning where the tall grass prairies from Texas to eastern North Dakota historically existed, and continuing eastward from there.

The rangelands still existing in the U.S. are mostly located in regions too dry to cultivate.[39] The overall goal of this project is to develop methods for determining when drought has had a great enough impact on the vegetation to merit an indemnity payment. Conditions associated with low precipitation and abnormally low vegetation productivity are what W&A and TMAI aim to detect using the NDVI, which lessens the impact of saturation problems.

The procedures utilized in the Western testing phase implicitly assumed the mixture of grasses on a particular ranch are consistent with the mixtures of grasses within the sub-county insurable area. To the degree that this assumption holds, the NDVI profile of the sub-county area will implicitly capture and estimate the approximate mixtures of vegetative accumulations obtained from the producer's distribution of seasonal grasses.

If a given producer's distribution of seasonal grasses varies widely from the area's seasonal distribution, it is possible that a productivity index constructed with predetermined sub-period NDVI weights will not be as strongly correlated with a given producer's production. While possible, we believe the likelihood of such an event is small in the range areas of the West, where most grazing occurs on native vegetation.

The possibility of a producer having a divergent seasonal grass distribution is more likely in the heterogeneous and smaller developed pasture areas of the eastern U.S. In the eastern U.S. pilot phase, W&A will consult with interested parties and examine the extent of possibly disparate seasonal grass distributions. The efficacy of procedures that allow a producer to partially customize the production index will be determined. A possible approach that will be examined will provide the producer with options in selecting the NDVI-based sub-periods from which the NDVI-based production index is constructed.

<u>Satellite Remote Sensing System Requirements</u>

As stated in the previous section, the major purpose for using satellite remotely sensed imagery has been to assess the impacts of drought on rangeland, pastureland, and dryland hay vegetation for the

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[38] Didan, K. 2002. "MODIS vegetation index production algorithms." MODIS Vegetation Workshop, Missoula, Montana. July 15-18: Terrestrial Biophysics and Remote Sensing (TBRS) MODIS Team, Tucson: University of Arizona, www.ntsg.umt.edu/MO-DISCon/index.html.

[39] The Conservation Reserve Program is a program that the U.S. Government is using to revert cropland broken out on highly erodable lands back to grasslands. Western rangeland managers are the overwhelming recipients of these program benefits.

conterminous U.S. For this project, TMAI and W&A determined that there are six satellite system requirements that had to be met. These requirements include:

- Conterminous U.S. spatial coverage;
- Unobstructed (nearly cloud-free) imagery;
- Sufficient data history for estimation of “normal” conditions;
- Future data availability (continuity);
- Frequent sampling during the growing season; and
- Sufficient sensitivity to detect annual vegetative production variability.

Of the satellite remote sensing systems currently in place, the only one to meet all of these criteria was the AVHRR sensor flown on the NOAA-POMS system. In the next section, we present an overview of other data sources that were considered for use in this project.

V. DESCRIPTION OF DATA USED FOR DEVELOPING THE DUAL TRIGGERS

Given the paucity of ground level, site-specific range production, W&A considers only information and model designs that satisfy the following requirements. Note that some of these are similar to the satellite remote sensing requirements defined just above.

1. The information used must not be dependent upon a history or the future availability of producer-level range production data;
2. The information is expected to be correlated with producer-level range production;
3. Information must be available for any region containing potentially insurable land;
4. Information must be available in a timely, reliable, consistent, and ongoing manner;
5. There must be a mechanism and sufficient data so the prediction model can be estimated from a limited amount of ground level data from potentially spatially disparate locations;
6. Data must be sufficient to enable its reliable use in estimating both the model and a distribution of indemnification payouts (historical length and quality of data set); and
7. The model must be “translatable,” which means it must be determinable and applicable in any region containing potentially insurable land.

Historically, obtaining sufficient data to estimate a region-specific proxy trigger has required the corresponding region to be the area of a county or larger. The larger size of the area as compared to the typical ranch size is likely to decrease the correlation between the producer’s realized production and the regional instrument and thus decrease the effective demand for the insurance product. In this project, W&A developed a trigger for a smaller-than-county-sized region using satellite remote sensing, as well as a trigger for a county-sized region using proxy information. These two triggers comprise the dual trigger mechanism developed for this project.

After researching various available data sources, W&A found NDVI satellite data, NASS data, and NOAA precipitation data satisfied the above criteria. W&A examined other data for inclusion in modeling work, but determined that because some data did not meet the above criteria in some manner, the data were not used.

Data Obtained and Incorporated in the Trigger Testing

Any data obtained, evaluated, and eventually incorporated into the analysis to test the dual triggers for efficacy are discussed below. Direct observations of rangeland are not practical to determine range productivity to trigger indemnity payments to policy holders as previously noted. Therefore, various indicators of range productivity are used in lieu of a direct measure of range productivity. The data used to test the correlation between range indicators and productivity are discussed below. The indicators should be correlated with range productivity and be useful to implement as trigger mechanisms. Data that may be used for each of the two triggers are described below.

In this section, W&A evaluates the potential applicability of: (1) satellite-derived data; (2) NASS county or regional level crop data; and (3) weather data. The suitability of satellite and weather data in satisfying the data selection criteria is discussed below. NASS data are well known and meet the criteria.

Satellite Data

Several types of satellite data are readily available in nearly real time. These include the 1 km resolution satellite imagery used to develop a biweekly composite NDVI index. The AVHRR platform was the satellite used to capture the data used for NDVI. The AVHRR platform meets the data selection criteria. As discussed previously, the AVHRR has both a reasonable historical data record and will have continued longevity as a remote sensing platform.

NASS County or Regional Level Crop Data

NASS county or regional level yield data were used where available for the test areas. Crop statistics were incorporated into the proxy trigger testing. A crop was selected to be a proxy if there were sufficient crop data available and if the location of the crop information was in reasonably close proximity to each test area.

Weather Station Climatic Data

Several data sets containing weather-related information were thought to be potentially of use in estimating range productivity conditions. W&A investigated the potential usefulness of precipitation and temperature information obtained from NOAA's online weather station database. As discussed below, temperature data were not used. The NOAA database consists of historical daily weather observations from NOAA weather stations geographically dispersed over the western U.S. The data are usually available online three to four months after the date of the observation. The data consist of observations on a number of weather and climatically related variables. Precipitation data from the NOAA sites may be a proxy used to estimate range productivity where insufficient crop information is available or where crop acreage is too limited for accompanying crop yield data to be of general value for range productivity estimation.

While the weather station data are useful, one of its limitations is the fact that it is only available at a limited number of point locations within any given county or region. For example, there are counties in Texas with only one reporting weather station. As a result of the limited number of point locations, it is possible that weather events affecting a particular tract of land or smaller-than-county sized region may not be reflected in any weather station's data. In any case, spatially related extrapolation procedures or averaging may need to be applied if the weather station data are to be applied to estimating a particular site's weather conditions.

A second limitation of incorporating weather data into the smaller-than-county-based component of the proposed insurance product is the three- to four-month time lag before the weather station data are published. One of the objectives of this proposed insurance instrument is to provide an insurance mechanism whereby producers can receive insurance indemnifications in a timelier manner than under the current GRP NASS data-dependent products. If weather station data from the later part of the crop insurance year are used in constructing the production index estimation model, the producer would potentially not be able to receive indemnifications until well into the next calendar year.

Of the climatic data sets examined, it is believed that NOAA weather station data are the most applicable for this product. These data are available for a large number of sites, many sites have a long historical data set, and the data are available in a useable time frame when considered for use in the county-level proxy trigger.

Data Considered and Not Incorporated

Any data obtained, evaluated, and eventually not used to test the dual triggers for efficacy are discussed below. The basis for not using these data is that the data did not meet one or more of the data selection criteria previously discussed.

Doppler WSR-88D Radar Technology

W&A investigated the possible use of the NEXRAD WSR-88D Doppler radar system for collecting precipitation data for inclusion in one or both trigger development efforts. Ultimately, the results of the investigation revealed that Doppler technology was not a data source that could lend any assistance in forage production estimation in this project. Doppler radar lacks the spatial distribution of radar sites necessary to provide coverage to the rural areas where precipitation amounts are most required. Furthermore, even if there were adequate numbers of installations, the abilities of Doppler radar to quantify precipitation amounts reaching the ground is non-existent. The programming is not capable of dealing with reception problems from complex terrain, false returns (caused by virga, anomalous propagation, and ground clutter, for example), and diminished returns with increased distance of the beam from the installation. Doppler radar cannot estimate ground-level precipitation amounts over wide areas. Volumes of research have shown Doppler radar, on a systemic basis, has no predictive power for the needs of this program plan.

MODIS System

TMAI and W&A also considered the potential usefulness of higher resolution data from the MODIS system and other sources. TMAI and W&A judged that while the higher resolution MODIS data contained potentially useful information, the data were not processed in a timely manner and historical records were insufficient.

PRISM

Another climate-based indicator of range productivity is a variable developed by the PRISM data set. A description of PRISM follows:[40]

> *PRISM (Parameter-elevation Regressions on Independent Slopes Model) was developed by Dr. Christopher Daly of Oregon State University, and is a hybrid statistical-geographic approach to mapping climate. PRISM uses point measurements of climate data and a digital elevation model (DEM), a digital, gridded version of a topographic map, to generate estimates of annual, monthly and event-based climatic elements. These estimates are derived for a horizontal grid and are compatible for use on Geographic*

[40] Natural Resources Conservation Service, USDA. "The NRCS PRISM Climate Mapping Project." Web Page. http://www.ncgc.nrcs.usda.gov/products/datasets/climate/docs/fact-sheet.html. (Accessed 11/2004).

Information Systems (GIS). PRISM is not a static system of equations; rather, it is a coordinated set of rules, decisions, and calculations designed to mimic the decision-making process an expert climatologist would invoke when creating a climate map. PRISM was originally developed in 1991 for precipitation estimation but more recently has been generalized and successfully applied to other climate elements and derived variables, including temperature, snowfall, degree-days (heat units), and frost dates.

The PRISM system determines climate at grid cells by calculating linear relationships between the climate element in question (like precipitation) and elevation. The slope of these linear regression lines changes locally with elevation, as dictated by the available point climate data. Each grid cell estimate is then achieved by determining a separate regression function using data from many nearby climate stations. Each station in the multiple regression is weighted based on five factors: Distance, elevation, vertical layer, topographic facet, and coastal proximity. In short, the closer a given station is to a target grid cell in distance and elevation, and the more similar that station is in its climatology to the cell (given by the other three factors), the higher the weight the station will have on the final, predicted value for that cell. A technique within PRISM determines the lowest possible prediction error for the map as a whole (all cells). PRISM typically is configured to predict values approximately every 4 km horizontally. Mean annual precipitation maps were developed by first using PRISM to calculate mean monthly precipitation layers, and then summing these 12 layers. Each monthly precipitation layer was derived using all available and appropriate climate station data. Station data sources included the National Weather Service Cooperative Observing Network (NWS Coop), the Natural Resources Conservation Service's SNOTEL network, and local, state, regional, and federal networks.

W&A considered using PRISM as a data source for climatic variables. However, the PRISM data source did not meet one or more of the data selection criteria. Specifically, the PRISM data were not acceptable because the funding source to continue to generate this data was in question. According to the Oregon Climate Service (OCS), “there is little operational funding for maintaining and updating this web site or the data sets. They are provided as a public service for a limited time.”[41]

<u>Temperature Data</u>

Two sources of temperature data were considered. The data sources were from AVHRR satellite thermal band measurements and ground-based weather stations. W&A determined both sources of temperature data did meet the data selection criteria required to incorporate these variables into the project.

The GDD[42] computed from weather station-based temperature data added no significant information beyond that contained in the NDVI values and reduced the efficiency of out-of-sample forecasts in predicting range productivity. Given these results, growing degree data were excluded from the test area analysis.

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[41] Natural Resources Conservation Service, USDA. “The NRCS PRISM Climate Mapping Project.” Web Page. http://www.ncgc.nrcs.usda.gov/products/datasets/climate/docs/fact-sheet.html. (Accessed 11/2004).

[42] GDD is an index expressing relative temperature for plant growth each day.

The AVHRR sensor records reflectance data in three thermal bands, one of which (band 4 using conventional AVHRR numbering) possesses variation that can serve as a proxy for surface temperature variation. These data were rejected for use in testing areas due to excessive data noise. The thermal band data did not add any improvement to the modeling and were subsequently eliminated from use as a data source.

VI. CROP YIELD FORECASTING USING AVHRR-NDVI

This project uses advanced technology and statistical methods to develop a satellite remote sensing trigger of indemnity payments. TMAI and W&A have experience in using AVHRR-NDVI data for estimation of regional crop yields, and are now expanding the applications to range and pasture lands. The techniques and information learned from crop yield forecasting is a solid base for developing the application of remote sensing to range and pasture.

The earliest published research relating crop yields to AVHRR-NDVI appeared in the late 1970s and early 1980s. Since then, researchers have generated dozens of peer-reviewed scientific articles addressing this topic, most of which lend support to the use of AVHRR-NDVI for pre-harvest crop yield prediction. A brief history of the crop yield forecasting work TMAI and W&A have done prior to this project is useful.[43]

TMAI and W&A Crop Yield Forecasting

TMAI began development of its pre-harvest crop yield forecasting methods in 1995, and research has been ongoing since then. Though TMAI crop yield forecasting methods are continually scrutinized and refined, beginning in 2000, additional focus was placed on increasing the scope of TMAI forecasts to include more crops and more regions in an automated, real-time forecasting program. Consequently, during each of the last three years (2002 through 2004), TMAI has released, in real-time, eight biweekly pre-harvest crop yield forecasts for at least 1,383 region-crop combinations (see Table 1). In all instances, initial season forecasts were released more than one month in advance of initial USDA state-level crop production forecasts.

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[43] Crop yield forecasting using AVHRR-NDVI has been an ongoing effort at TMAI since 1995. A doctoral dissertation, (Lee, R., D.L. Kastens, K.P. Price and E.A. Martinko. 1999. "Forecasting Corn Yield in Iowa Using Remotely Sensed Data and Vegetation Phenology Information," Proceedings, PECORA 14, Land Satellite Information Regional Conference, American Society of Photogrammetric Engineering and Remote Sensing, Denver, Colorado, December 6-10.) and a master's thesis (Kastens, D. L. A. 2000b. "Forecasting winter wheat yields in Kansas using time-series analysis of remotely sensed data." Master's Thesis, Department of Geography, University of Kansas, Lawrence, Kansas. 103 pp.) have resulted from this work, along with SBIR Phase I and Phase II projects from the USDA (Kastens, D.L. 1998. "Estimating Wheat Yields from Time Series Analysis of Remotely Sensed Data," United States Department of Agriculture Small Business Innovative Research Phase I Grant (Grant Agreement Number 99-33610-7495)).

Kastens, D.L. 2000a. "Forecasting Pre-Harvest Winter Wheat Yields in the Great Plains using Remotely Sensed Data," United States Department of Agriculture Small Business Innovative Research Phase II Grant (Grant Agreement Number 00-33610-9453), as well as several academic proceedings and presentations (Lee, R., D.L. Kastens, K.P. Price and E.A. Martinko. 1999. "Forecasting Corn Yield in Iowa Using Remotely Sensed Data and Vegetation Phenology Information," Proceedings, PECORA 14, Land Satellite Information Regional Conference, American Society of Photogrammetric Engineering and Remote Sensing, Denver, Colorado, December 6-10.

Kastens, D.L., K.P. Price, J.H. Kastens and E.A. Martinko. 2001. "Using Crop Masks and Remotely Sensed Data to Develop Pre-harvest Forecasts of Winter Wheat Yields in Kansas." Proceedings, Annual Convention, American Society of Photogrammetric Engineering and Remote Sensing. St. Louis, Missouri, April 23 - 27. Kastens, J.H., K.P. Price, D.L. Kastens and E.A. Martinko. 2001. "Forecasting Pre-harvest Crop Yields Using Time Series Analysis of AVHRR-NDVI Composite Imagery." Proceedings, Annual Convention, American Society of Photogrammetric Engineering and Remote Sensing. St. Louis, Missouri, April 23 - 27., Kastens, J.H. 2003. "Yield Forecasting from Remote Sensing." PRX Summer Grain Meeting: World Grain Workshop. Invited presentation for the ProExporter Network. July 24-25, Kansas City).

Table 1. TMAI Annual Crop Yield Forecast Coverage

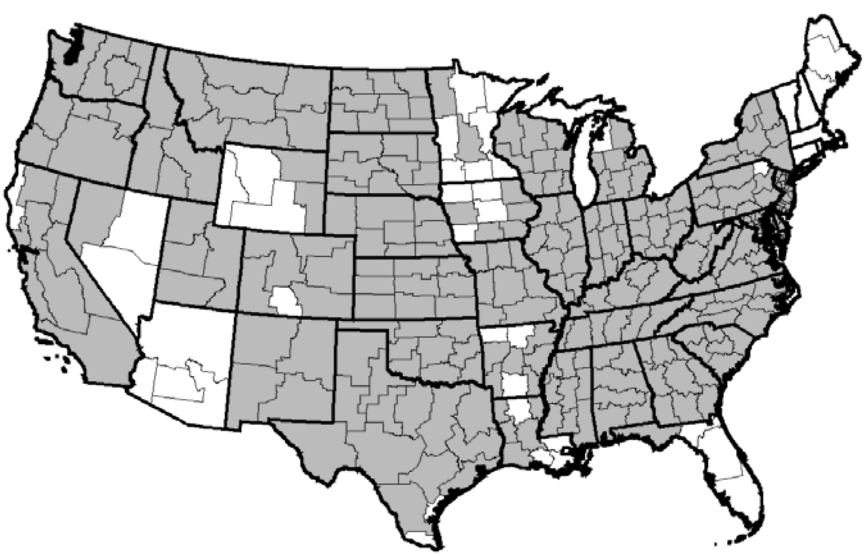
CROP	# STATES	# ASDs	# NATIONAL	TOTAL REGIONS
Winter Wheat	42	259	1	302
Corn	41	258	1	300
Soybeans	29	194	1	224
Oats	27	181	1	209
Barley	24	108	1	133
Sorghum	18	99	1	118
Spring Wheat	12	62	1	75
Durum Wheat	6	15	1	22
		Grand Total:		1383
		*8 updates per year:		11064

"ASDs" refer to agricultural statistics districts. The last quantity (11064) is the total number of unique yield forecasts generated annually by TMAI since 2002, corresponding to various (crop, region, time period)-triples.

Source: TerraMetrics Agriculture, Inc., 2005

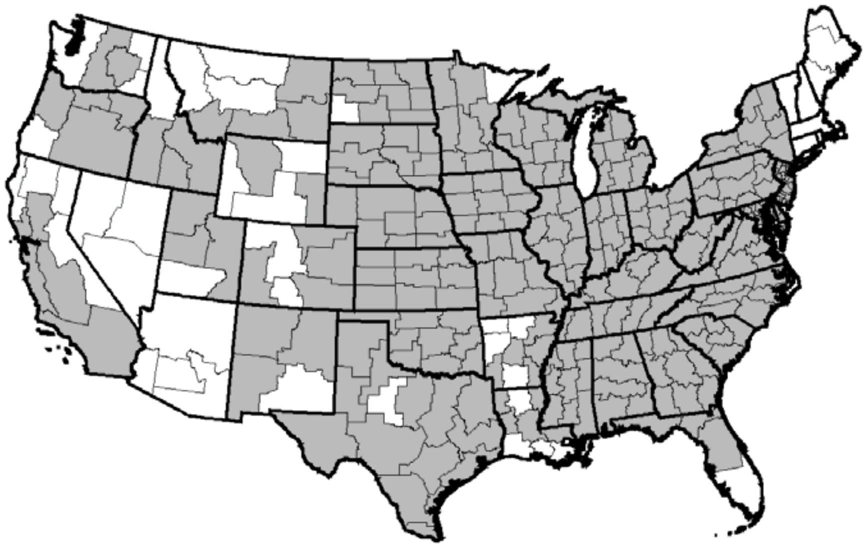
Figures 1 through 3 show the extent of the spatial coverage of TMAI forecasts at the agricultural statistics district (ASD) spatial scale for winter wheat, corn, and soybeans, respectively. The purpose of these graphics is to show the nationwide extent of TMAI forecasts. All ASDs possessing a complete history of NASS crop yields extending back to 1989 (matching the AVHRR-NDVI imagery) are shown in gray, and these are precisely the regions that are forecasted by TMAI. ASDs shown in white do not possess a complete yield history (typically due to low production in these ASDs), and these areas are not included in TMAI's forecast coverage.

Figure 1. TMAI Winter Wheat Agricultural Statistics Districts Forecast Coverage



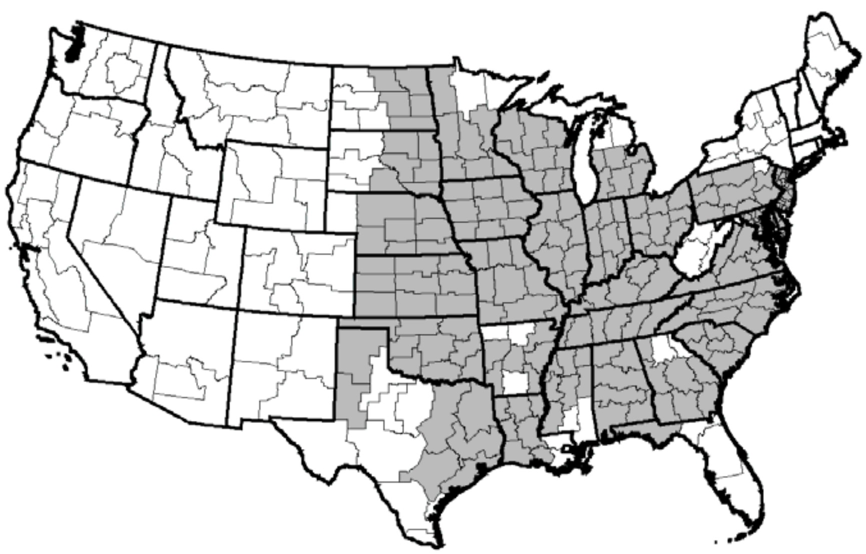
Source: TerraMetrics Agriculture, Inc. 2005

Figure 2. TMAI Corn Agricultural Statistics Districts Forecast Coverage



Source: TerraMetrics Agriculture, Inc. 2005

Figure 3. TMAI Soybean Agricultural Statistics Districts Forecast Coverage



Source: TerraMetrics Agriculture, Inc. 2005

The accuracy of some of TMAI's most important forecasts for winter wheat, corn, and soybeans in 2002 through 2004 are contrasted to USDA and simple trend forecasts in Tables 2 through 4. Though three years of forecasting results cannot fully confirm the efficacy of TMAI forecast methods, the results shown suggest some success in this regard.

Some interesting observations can be gleaned from the tables. First, for the 2002-2004 period, TMAI's national yield estimates made just prior to the USDA yield estimates have lower mean absolute errors than USDA estimates for each of the three crops. Looking at just winter wheat, this is true for all of the regions listed in the Table 1. For soybeans this is nearly the case. For corn, however, TMAI estimates did not consistently outperform USDA estimates. Although, it should be emphasized that all of the results shown are for TMAI forecasts generated prior to the release of USDA estimates, and TMAI estimates consistently outperformed trend model estimates in many of the cases when they failed to outperform USDA estimates. For winter wheat and soybeans, TMAI national estimates were, on average, more accurate than both initial-season USDA national estimates and trend estimates at all pre-harvest forecast periods.

Note that in many of the table rows, forecast accuracy increases as the season progresses. This demonstrates both the presence and increase of yield-predictive information in AVHRR-NDVI as the growing season progresses. The multi-state totals provide good examples of this phenomenon.

Observe that in just two instances, namely corn and soybeans in Minnesota, the latest TMAI estimates failed to outperform either the initial-season USDA estimate or the trend estimate. This was largely attributable to abnormal harvest time conditions that in one year (2002) resulted in a maximization of crop potential and in another year (2003) caused a severe reduction in realized potential. Generally speaking, pre-harvest forecasts are generated under the assumption that relatively average conditions will persist through harvest time, and forecast performance is affected by deviations from this assumption. Note that USDA initial season estimates for Minnesota corn and soybeans also were outperformed by the simple trend model, much for the reasons just described.

Table 2. Winter Wheat Yield Forecasting Error, 2002-2004

Region	Avg % Nat'l Production	TMAI				USDA	Trend
		26-Mar	9-Apr	23-Apr	7-May	11-May	
KS	23.64%	**5.47**	**4.17**	**2.63**	**2.50**	**5.33**	6.57
OK	8.81%	**3.20**	**1.77**	**1.13**	**0.60**	**3.00**	4.67
WA	8.00%	**2.57**	**1.90**	**1.50**	**1.03**	**4.67**	4.87
TX	6.13%	**2.33**	**2.90**	**2.93**	**2.60**	**2.67**	3.43
CO	5.03%	**6.27**	**5.70**	**4.60**	**4.27**	**5.33**	8.50
NE	4.46%	**4.83**	**4.33**	**4.17**	**4.53**	**4.67**	5.73
OH	4.11%	3.57	**2.07**	**2.07**	**2.87**	3.33	3.33
7-state total	60.18%	**4.32**	**3.38**	**2.53**	**2.36**	**4.45**	5.62
US	100.00%	**2.13**	**1.23**	**0.30**	**0.60**	**3.03**	3.37

This table shows average absolute error in bu/ac. For TMAI forecast errors, bold values indicate improved accuracy when compared to USDA initial season estimates (released in the USDA May Crop Production Report) or trend model estimates. For USDA forecast errors, bold values indicate improved accuracy compared to trend model estimates. "Trend" is the 2002-2004 average absolute error when using the 30-year linear trend model for prediction.

Source: TerraMetrics Agriculture, Inc., 2005

Table 3. Corn Yield Forecasting Error, 2002-2004*

Region	Avg % Nat'l Production	TMAI 4-Jun	TMAI 18-Jun	TMAI 2-Jul	TMAI 16-Jul	TMAI 30-Jul	USDA 11-Aug	Trend
IA	18.25%	19.17	**17.03**	**16.70**	**17.93**	**17.77**	**13.67**	18.93
IL	16.62%	**18.77**	**17.43**	**13.47**	**14.27**	**13.63**	**8.67**	19.00
NE	11.83%	13.33	**11.67**	**11.17**	**9.53**	**9.50**	**10.33**	12.60
MN	9.31%	14.03	14.17	17.97	17.50	17.43	11.00	7.60
IN	8.33%	17.50	18.07	**13.37**	**13.97**	**12.97**	**6.00**	16.80
5-state total	64.32%	17.03	15.87	**14.60**	**14.87**	**14.51**	**10.38**	15.87
US	100.00%	10.97	**9.47**	**8.07**	**6.50**	**5.57**	**5.90**	10.10

This table shows average absolute error in bu/ac. For TMAI forecast errors, bold values indicate improved accuracy when compared to USDA initial season estimates (released in the USDA August Crop Production Report) or trend model estimates. For USDA forecast errors, bold values indicate improved accuracy compared to trend model estimates. "Trend" is the 2002-2004 average absolute error when using the 30-year linear trend model for prediction.
* USDA November estimates have been used as a proxy for 2004 final estimated yield.

Source: TerraMetrics Agriculture, Inc., 2005

Table 4. Soybean Yield Forecasting Error, 2002-2004*

Region	Avg % Nat'l Production	TMAI 4-Jun	TMAI 18-Jun	TMAI 2-Jul	TMAI 16-Jul	TMAI 30-Jul	USDA 11-Aug	Trend
IA	17.31%	**7.10**	**6.43**	**6.60**	**6.80**	**6.83**	8.00	6.73
IL	17.09%	**4.63**	**4.20**	**3.57**	**3.47**	**3.60**	**5.17**	5.20
MN	9.66%	**6.37**	7.27	7.93	7.97	7.93	7.17	6.67
IN	8.98%	**5.87**	**5.47**	**4.60**	**4.23**	**4.40**	**4.33**	6.63
OH	6.79%	**5.83**	**6.17**	**4.90**	**4.70**	**4.47**	**5.33**	6.97
MO	6.34%	5.93	**5.53**	**5.63**	**4.67**	**3.87**	**5.33**	5.67
6-state total	66.16%	**5.95**	**5.73**	**5.47**	**5.34**	**5.30**	**6.12**	6.24
US	100.00%	**3.23**	**2.93**	**3.13**	**3.23**	**3.23**	**3.67**	3.70

This table shows average absolute error in bu/ac. For TMAI forecast errors, bold values indicate improved accuracy when compared to USDA initial season estimates (released in the USDA August Crop Production Report) or trend model estimates. For USDA forecast errors, bold values indicate improved accuracy compared to trend model estimates. "Trend" is the 2002-2004 average absolute error when using the 30-year linear trend model for prediction.
* USDA November estimates have been used as a proxy for 2004 final estimated yield.

Source: TerraMetrics Agriculture, Inc., 2005

TMAI methods are purely statistical in nature, and rely solely on AVHRR-NDVI data (spanning 1989 through to the present and covering the conterminous U.S.) and historical USDA regional crop yield and harvested acreage estimates.[44] Given that each year from 1989 through the present time provides a

[44] TMAI has nearly completed a manuscript (Kastens et al. 2005) exposing most of the underlying methods that TMAI uses for real time forecasting. This document will be submitted in February for peer-reviewed publication. The most recent version of the paper is available upon request.

Kastens, J.H., Kastens, T.L., Kastens, D.L.A., Price, K.P., Martinko, E.A., and Lee, R. (2005). "Image Masking for Crop Yield Forecasting Using AVHRR-NDVI Times Series Imagery." Photogrammetric Engineering and Remote Sensing. To be submitted February 2005.

Kastens, D. L. A. 2000b. "Forecasting winter wheat yields in Kansas using time-series analysis of remotely sensed data." Master's Thesis, Department of Geography, University of Kansas, Lawrence, Kansas. 103 pp.

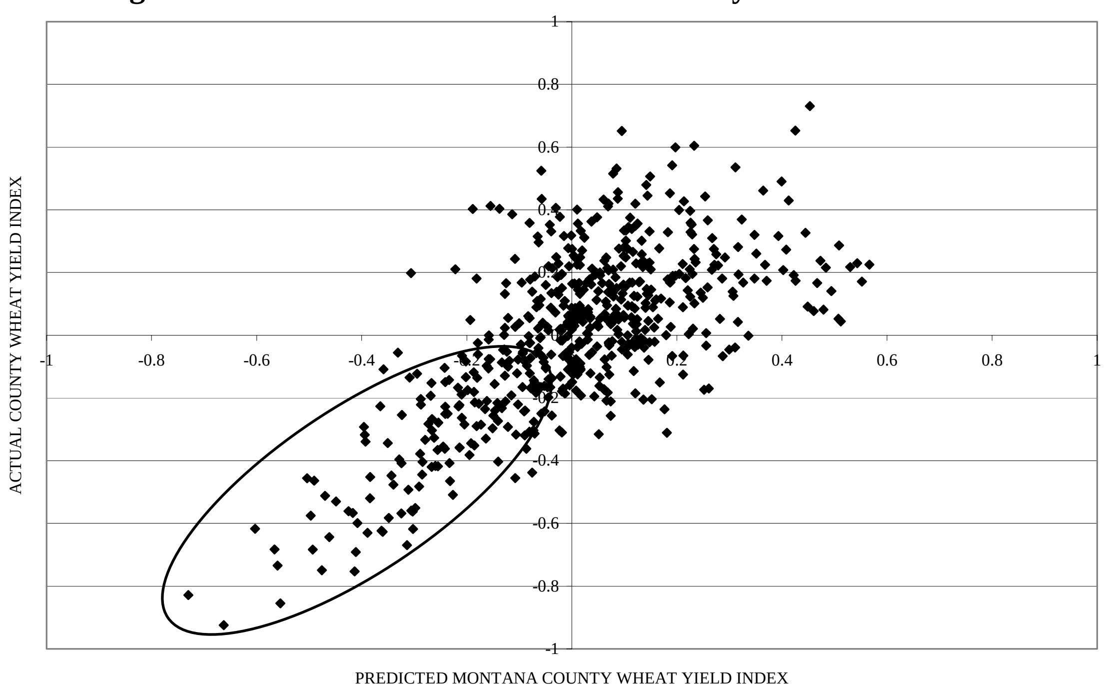
Lee, R. Y. 1999. "Modeling corn yields in Iowa using time-series analysis of AVHRR data and vegetation phenological metrics." Doctoral Dissertation, Department of Geography, University of Kansas, Lawrence, Kansas. 164 pp.

single observation of crop yield and AVHRR-NDVI data for each particular region-crop pair, TMAI crop yield prediction models are based on small samples. Consequently, TMAI scientists place great emphasis on statistical rigor and method robustness, as these characteristics are absolutely necessary for reliable numerical modeling in such situations.

Researchers at W&A and Montana State University have also been looking into the relationship between AVHRR-NDVI and crop yields, but from a different angle. Out-of-sample regression-prediction procedures were applied to examine the out-of-sample prediction performance of several model specifications. The out-of-sample procedures involved the sequential deletion of each year's data, the estimation of the model's parameters using data from the remaining years, using the estimated parameters to predict (out-of-sample) the yields of the deleted year, and repeating the process until a set of out-of-sample predictions were obtained for each year in the data.

Actual county wheat yield indices are contrasted to out-of-sample NDVI-based predictions in Figure 4. The scatter plot clearly demonstrates the ability of the NDVI model to identify below average yield events.

Figure 4. Predicted vs. Actual Montana County Wheat Yield Index



Source: Watts and Associates, Inc. 2005

Relevance of Yield Forecasting Efforts to PF&R Project

The realized success of crop yield prediction efforts (see Tables 2-4 and Figure 4) helps establish a relationship between a well-defined agricultural quantity (namely, regional crop yield) and AVHRR-NDVI, which indirectly but strongly supports the use of this data for assessment of rangeland annual productivity. Success in crop yield prediction helps support the notion that climatologic growing season characteristics influencing vegetation are indeed manifested in AVHRR-NDVI.

Assessment of rangeland yearly productivity is a more appropriate use of AVHRR-NDVI than is pre-harvest prediction of final crop yields. Due to the coarse resolution (approximately 250 acres/pixel, which is much larger than the typical cultivated field site) of the AVHRR-NDVI database, as well as the use of early- to mid-season NDVI for statistical modeling and prediction of yields, identification of pixels dominated by a particular crop is an improbable task. The fact that some crops have very similar NDVI signatures also serves as a barrier to crop pixel classification. Consequently, crop yield modeling methods relying on this database are forced to ignore the pervasive practice of crop rotation, which complicates extraction of information useful for prediction of crop yields. On the other hand, location of rangeland is much more stable over time and has already been delineated nationwide, which makes these lands easier to focus on when using spatial AVHRR-NDVI data.

An additional complexity entering into crop yield prediction is yield trending. Crop yield modeling methods must accommodate well-documented, non-stationary technology trends in crop yields. Such trends are typically less pronounced in terms of total plant biomass, and are thus less visible in NDVI. Because the genetic constitution of rangeland typically changes little over decades, annual productivity of such land is more distributionally stable over time than crop yields. This leads to more reliable statistical relationships between rangeland annual productivity and AVHRR-NDVI.

Finally, early- to mid-season AVHRR-NDVI cannot account for adverse or optimal harvest conditions, which can diminish the accuracy of crop yield predictions, and thus strain relationships between yields and NDVI. Estimation of annual range productivity is generally unaffected by this problem.

VII. SUMMARY

We have discussed the use of remote sensing data for the purpose of estimation of annual productivity of pastureland, rangeland, and dryland hay, with a focus on the latter two classes due to a focus on the western U.S. at the present point in time. Numerous remote sensing data sets have been examined and rejected, with the exception of the AVHRR-NDVI database. This vegetation condition database provides nearly cloud-free weekly coverage of the conterminous U.S. at 1 km (250 acre) spatial resolution, extends back through 1989, and will be continued well into the future due to the operational classification of the AVHRR sensor.

In addition to the remote sensing range indemnity payment trigger, a second component (the proxy trigger) was also briefly discussed. While the remote sensing trigger can be developed for sub-county regions, the proxy trigger will be implemented at the county level due to the nature of the data (NASS county yields and weather station precipitation) that will be used for the proxy trigger. These two triggers, the remote sensing trigger and the proxy trigger, form the basis of the dual trigger indemnity payment mechanism that is under development at W&A and TMAI. Producers receive the maximum of the payments specified by each trigger, which increases their chances of receiving payment in the event of a loss.

Historical and current research demonstrates that the imagery has informational content with respect to crop yields and, by association, production. We have identified three significant traits of range production estimation that should make this a more likely task than crop yield forecasting. These traits are: (1) locational stability of range over time (crop rotation is not a factor with rangeland); (2)

distributional stability of range production over time (technology-induced trending is not a factor, i.e., genetics, fertilizer, etc.); and (3) lack of dependence of annual range production on end-of-season conditions, similar to harvest-time conditions for cultivated crops. In light of these reasons and in addition to the observed predictive relationship between AVHRR-NDVI and crop yields, we believe we have strong evidence in support of the use of AVHRR-NDVI for assessment of annual range productivity for the purpose of insuring against productivity losses.