Chapter 1

Decision Support for Agricultural Efficiency

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1. Introduction

The efficiency of agriculture has been one of the most daunting challenges confronting mankind in its need to manage natural resources within the constraints of weather, climate, and other environmental conditions. Defined as maximizing output per unit of input, agricultural efficiency reflects a complex relationship among factors of production (including seed, soil, human, and physical capital) and the exogenous influence of nature (such as temperature, sunlight, weather, and climate). The interaction of agricultural activity with the environment creates another source of interdependence, (e.g., the effect on soil and water from applications of pesticides, fungicides, and fertilizer). Agricultural production has long been a large component of international trade and of strategic interest as an indicator of the health and security of nations.

The relationship between climate change and agriculture is complex. A changing climate can influence agricultural practices (e.g., climate-induced changes in patterns of rainfall could lead to changes in these practices). Agriculture is not only influenced by a changing climate, but agricultural practices themselves are a contributory factor through emissions of greenhouse gases and influences on fluxes of carbon through photosynthesis and respiration. In short, agriculture is both a contributor to and a recipient of the effects of a changing climate (Rosen Zweig, 2003; National Assessment Synthesis Team, 2004).

The use of Earth observations by the agricultural sector has a long history. The Large Area Crop Inventory Experiment (LACIE), jointly sponsored by the US National Aeronautics and Space Administration (NASA), the US Department of Agriculture (USDA), and the National Oceanic and Atmospheric Administration (NOAA) conducted from 1974 to 1978 demonstrated the potential for satellite observations to make accurate, extensive, and repeated surveys for global crop forecasts. LACIE used observations from the Landsat series of multi-spectral scanners on sun-synchronous satellites. The Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing (AgRISTARS) followed LACIE and extended the use of satellite observations to include early warning of production changes, inventory and assessment of renewable resources, and other activities (Congressional Research Service, 1983; National Research Council, 2007; Kaupp *et al.,* 2005). Today these data are used by agencies of the federal government, commodity trading companies, farmers, relief agencies, other governments, and essentially anyone with an interest in crop production at a global scale.

An approach, among others, to increasing agricultural efficiency is to expand and enhance uses of Earth observation data for (1) policy and resource management decision support, (2) monitoring and measuring climate change affects, and (3) providing policy and resource climate change decision support. The foremost example of the application of Earth observations in agriculture is found in the USDA's crop-monitoring decision-support system, the Production Estimates and Crop Assessment Division (PECAD) of the USDA's Foreign Agricultural Service (FAS). (Reorganization at USDA finds the PECAD functionality, but not the name, residing within the USDA's FAS as part of the Office of Global Analysis, Impact Analysis Division, International Production Assessment [USDA/FAS/OGA/IAD/IPA]). PECAD is now the world's most extensive and longest running (over two decades) operational user of remote sensing data for evaluation of worldwide agricultural productivity (NASA, 2001). A Description of the PECAD decision-support system, its functionality, its analysis style, how it deals with making decisions under uncertainty, and its future uses form the basis of this chapter.

2. Description of PECAD

The USDA/FAS uses PECAD to analyze global agricultural production and crop conditions affecting planting, harvesting, marketing, commodity export and pricing, drought monitoring, and food assistance. Access to and uses of PECAD are largely by the federal government, rather than state and local governments, as a means of assessing regions of interest in global agricultural production.

PECAD uses satellite data, worldwide weather data, and agricultural models in conjunction with FAS overseas post reports, foreign government official reports, and agency travel observations to support decision making. FAS also works closely with the USDA Farm Service Agency and the Risk Management Agency to provide early warning and critical analysis of major crop events in the US. (FAS OnLine Crop Assessment at http://www.fas.usda.gov/pecad2/crop_assmnt.html, accessed April 2007). FAS seeks to promote the security and stability of the US food supply, improve foreign market access for U.S. agricultural products, provide reports on world food security, and advise the US government on international food aid requirements. FAS bears the primary responsibility for USDA's overseas activities: market development, international trade agreements and negotiations, and the collection and analysis of statistics and market information. FAS also administers USDA's export credit guarantee and food aid programs.

PECAD's Crop Condition Data Retrieval and Evaluation (CADRE) database management system, the operational outcome of the LACIE and AgRISTARs projects, was one of the first geographic information systems (GIS) designed specifically for global agricultural monitoring (Reynolds, 2001). CADRE is used to maintain a large satellite imagery archive to permit comparative interpretation of incoming imagery with that of past weeks or years. The database contains multi-source weather data and other environmental data that are incorporated as inputs for models to estimate parameters such as soil moisture, crop stage, and yield. These models also indicate the presence and severity of plant stress or injury. The information from these technologies is used by PECAD to produce, in conjunction with the World Agricultural Outlook Board, official USDA foreign crop production estimates. (FAS OnLine Crop Assessment at http://www.fas.usda.gov/pecad2/crop_assmnt.html, accessed April 2007)

Figure 1 (Kaupp *et al.,* 2005, p. 5) illustrates the global data sources and decision support tools for PECAD. The left-hand portion of the figure shows sources of data for the CADRE geospatial DBMS. These inputs include station data from the World Meteorological Organization and coarse resolution data from Meteosat, Scanning Multichannel Microwave Radiometer (SSMR), and Geostationary Satellite (GOES). Meteosat, operated by the European Organization for the Exploitation of Meteorological Satellites (EUTMETSAT), provides visible and infrared, weather-oriented imaging. The SSMR and its successor, the Special Sensor Microwave/Imager (SSM/I), are microwave radiometric instruments in the US Air Force Defense Meteorological Satellite Program. Additional weather data come from the US GOES program.

Medium resolution satellite data include Advanced Very High Resolution Radiometer (AVHRR)/NOAA, Spot-Vegetation, and Terra/Aqua MODIS. AVHRR/NOAA, operated by NOAA, provides cloud cover and land, water, and sea surface temperatures at approximately 1-km spatial resolution. The Systeme Pour L'Observation de la Terre (SPOT) supplies commercial optical Earth imagery at resolutions from 2.5 to 20 meters (m); SPOT-Vegetation is a sensor providing daily coverage at 1 km resolution. The NASA Moderate Resolution Imaging Spectroradiometers (MODIS) on the Terra and Aqua satellites, part of the US Earth Observation System, show rapid biological and meteorological changes at 250 to 1,000 m spatial resolution every two days. NASA's Global Inventory Modeling and Mapping Studies (NASA/GIMMS) group processes data acquired from SPOT and Terra/Aqua MODIS. NASA/GIMMS provides PECAD with cross-calibrated global time series of Normalized Difference Vegetation Index maps from AVHRR and SPOT-Vegetation. Moderate-resolution Earth observation data are also used from the US Landsat program.

Sources of high resolution and radar altimeter satellite data include SPOT, IKONOS, Poseidon, and Jason. IKONOS is a commercial Earth imaging satellite providing spatial resolution of 1 and 4 m. Data from Poseidon and its successor, Jason, provide lake and reservoir surface elevation estimates. Poseidon, part of the TOPEX/Poseidon mission, and Jason-1, a follow-on mission, are joint ventures between NASA and the Centre National d'Etudes Spatiales (CNES) using radar altimeters to map ocean surface topography (including sea surface height, wave height, and wind speed above the ocean). These data enable analysts to assess drought or high water-level conditions within some of the world's largest lakes and reservoirs to predict effects on downstream irrigation potential and inform production capacity estimates (Birkett and Doorn, 2004; Kanarek, 2005). The assimilation of these data into PECAD is described in detail in a recent systems engineering report (NASA, 2004b).

PECAD combines the satellite and climate data, crop models (along the bottom portion of the figure), a variety of GIS tools, and a large amount of contextual information, including official government reports, trade and new sources, and on-the-ground reports from a global network of embassy attaches and regional analysts. The integration and analysis is attained by "convergence of evidence analysis" (Kaupp *et* *al.,* 2005). This convergence methodology seeks to reconcile various independent data sources to achieve a level of agreement to minimize estimate error (NASA, 2004a).

The crop assessment products indicated along the right-hand side of the PECAD architecture in figure 1 represent the periodic global estimates used to inform official USDA forecasts. These products are provided to the agricultural market, including farmers; agribusiness; commodity traders and researchers; and federal, state, and local agencies. In addition to CADRE, other automated components include two features providing additional types of information. The FAS Crop Explorer (middle of diagram) is a feature on the FAS Web site since 2002 (Kanarek, 2005). Crop Explorer offers near-real-time global crop condition information based on satellite imagery and weather data from the CADRE database and NASA/GIMMS. Thematic maps of major crop growing regions show vegetation health, precipitation, temperature, and soil moisture. Time-series charts show growing season data for agro-meteorological zones. For major agriculture regions, Crop Explorer provides crop calendars and crop areas. Through Archive Explorer, PECAD provides access to an archive of moderate- to high-resolution data, allowing USDA users (access is controlled by user name and password) to search an image database.

3. Potential Future Use and Limits

The most recent enhancements to PECAD/CADRE have included the integration and evaluation of MODIS, Topex/Poseidon, and Jason-1 products (NASA, 2006a). Figure 2 summarizes the Earth system models, Earth observations data, and the CADRE DBMS and characterizes their outputs. Several planned Earth observations missions anticipated when this image was prepared (indicated in italics) show how PECAD/CADRE could incorporate new opportunities, including those with additional land, atmosphere, and ocean observations. These would include space-based observations of atmospheric carbon dioxide (CO_2) from the Orbiting Carbon Observatory (OCO) and measurement of global sea surface salinity (Aquarius) to improve understanding of the links between the water cycle, climate, and the ocean. Other opportunities for enhancing PECAD/CADRE could include improvements in predictive modeling capabilities in weather and climate (National Aeronautics and Space Administration, 2006a).

In a recent evaluation report for PECAD, NASA has acknowledged that one of the largest technology gaps in meeting PECAD requirements is the design of NASA systems for research purposes rather than for operational uses (NASA, 2004a). PECAD analysts require dependable inputs, implying the use of operational systems that ensure continuous data streams and that minimize vulnerability to component failure through redundancy. The report also emphasizes that PECAD requires systems that deliver real-time or near-real-time data. Many NASA missions have traded timeliness for experimental research or improvements in other properties of the information delivered. Additionally, the report identifies several potential Earth science data streams that have not yet been addressed, including water balance, the radiation budget (including solar and long wave radiation flux), and elevation, and expresses concern about the potential continuity gap between Landsat 7 and the Landsat Data Continuity Mission.

A 2006 workshop convened at the United Nations Food and Agriculture Organization (FAO) by the Integrated Global Observations of Land (IGOL) team identified priorities for agricultural monitoring during the next 5 to 10 years as part of the emerging GEOSS. In summary, the meeting called for several initiatives including the following (United Nations Food and Agriculture Organization, 2006):

(1) the need for an international initiative to fill the data gap created by the malfunction of Landsat 7;

(2) a system to collect cloud-free, high resolution (10 to 20 m) visible, near-infrared, and shortwave infrared observations at 5 to 10-day intervals;

(3) workshops on global agricultural data coordination and on integrating satellite and *in situ* observations;

(4) an inventory and evaluation of existing agro-meteorological data sets to identify gaps in terrestrial networks, the availability of data, and validation and quality control in order to offer specific recommendations to the World Meteorological Organization to improve its database;

(5) funding to support digitizing, archiving, and dissemination of baseline data; and

(6) an international workshop within the GEOSS framework to develop a strategy for "community of practice" for improved global agricultural monitoring.

A recent study by the National Research Council (NRC) of the use of land remote sensing expressed additional concerns about present limits on the usefulness of Earth observations in agricultural assessment) (National Research Council, 2007). These include data integration, communication of results, and capacity to use and interpret data. Specifically, the NRC identified these concerns:

(1) inadequate integration of spatial data with socioeconomic data (locations and vulnerabilities of human populations and access to infrastructure) to provide information that is effective in generating response strategies to disasters or other factors influencing access to food or impairing agricultural productivity; (2) a lack of communication between remote sensing mission planners, scientists and decision makers to ascertain what types of information enable the most effective food resource management; and (3) shortcomings in the acquisition, archiving, and access to long-term environmental data and development of capacity to interpret these data, including maintaining continuity of satellite coverage over extended time frames, providing access to affordable data, and improving capacity to interpret data.

4. Uncertainty

Two aspects of PECAD provide means of validation and verification of crop assessments. One is the maturity of PECAD as a decision support system. Over the years, it has been able to benchmark, validate, verify, and then selectively incorporate additional data sources and automated decision tools. An example of the systems engineering review associated with a decision to incorporate Poseidon and Jason data, for example, is offered in a detailed NASA study (NASA, 2004b).

Another example demonstrates how data product accuracy, delivery, and coverage are tested through validation and verification during the process of assimilating new data sources, as well as to ascertain the extent to which different data sources corroborate model outputs (Kaupp *et al.,* 2005). Essential considerations included enhanced repeatability of results, increased accuracy, and increased throughput speed.

Another significant aspect of resolving uncertainty in PECAD is its extensive use of a convergence methodology to assimilate information from regional field analysts and other experts. PECAD seeks to provide accurate and timely estimates of production, yet must accommodate physical and biological influences (e.g., weather or pests), the fluctuations in agricultural markets, and developments in public policy impacting the agricultural sector (Kaupp *et al.,* 2005). The methodology brings a large amount of additional information to the PECAD forecasts, well beyond the automated outputs of the decision support tools. This extensive additional analysis may not fully correct for, but certainly mitigates, the uncertainty inherent in the data and modeling at the early stages. Figure 3, a simplified version of

Figure 1, shows the step represented by the analyses that take place during this convergence of information in relation to the outputs obtained from the decision support tools and their data inputs. Figure 4 further describes the nature of information included in the convergence methodology in addition to the outputs of the data and automated decision support tools. Official reports, news reports, field travel, and attaché reports are additional inputs at this stage. The process is described as one in which, “while individual analysts reach their conclusions in different ways, giving different weight to various inputs, analysts join experts from the USDA’s Economic Research Service and National Agricultural Statistics Service once a month in a ‘lock-up.’ In this setting, the convergence of evidence approach is fully realized as analysts join together in committee formed by (agricultural) commodity. Final commodity production estimates are achieved by committee consensus” (NASA, 2004a, p. 4).

The convergence methodology is at the heart of analysis and the final step prior to official world agricultural production estimates and suggests that uncertainty inherent in data and automated models at earlier stages of the analysis are “scrubbed” in a broader context at this final stage.

5. Global change information and PECAD

The relationship between climate and agriculture is complex. Agriculture is not only influenced by a changing climate, but agricultural practices themselves are a contributory factor through emissions of greenhouse gases and influences on fluxes of carbon through photosynthesis and respiration. In short, agriculture is both a contributor to and a recipient of the effects of a changing climate (Rosenzweig, 2003).

At present, PECAD is not directly used to address these dimensions of the climate-agriculture interaction. However, many of the data inputs for PECAD are climate-related, thereby enabling PECAD to inform understanding of agriculture as a “recipient” of climate-induced changes in temperature, precipitation, soil moisture, and other variables. If reliable climate change prediction of temperature, precipitation, soil moisture, and other necessary variables become available, then these variables can be used as input to PECAD and the results may be used to provide long-range planning of agricultural practices. In addition, spatial and geographic trends in the output measures from PECAD have the potential to contribute to understanding of how the agricultural sector is responding to a changing climate.

The output measures of PECAD also can serve to inform understanding of agriculture as a "contributor" to climate changes. For example, observing trends in PECAD's measures of production and composition of crops can shed light on the contribution of the agriculture sector to agricultural soil carbon sequestration.

The effects of a changing climate on agricultural efficiency as measured by PECAD:

PECAD relies on several data sources for agro-meteorological phenomena that affect crop production and the quality of agricultural commodities. These include data that are influenced by climate (e.g., precipitation, temperatures, snow depth, and soil moisture). The productivity measures from PECAD (yield multiplied by area) are also influenced by climate-induced changes in these data.

In addition, the productivity measures of PECAD can be indirectly but significantly affected by possible climate-induced changes in land use. Examples of such changes include the reallocation of land from food production to biomass fuel production or from food production to forestry cultivation as a means of carbon sequestration. In all of these cases, Earth observations can contribute to understanding climate-related effects on agricultural efficiency (National Research Council, 2007). Much of the research to integrate Earth observations into climate and agriculture decision support tools is relatively recent; for example, in FY05, NASA, and USDA began climate simulations using GISS GCM ocean temperature data and also completed fieldwork for verification and validation of a climate-based crop yield model (NASA, 2006b). The UN FAO has begun to coordinate similar research on integrating Earth observations and decision support systems to study possible effects of changing climate on food production and distribution (e.g., see United Nations Food and Agriculture Organization, no date).

The effects of agricultural practices and efficiency on climate:

In addition to consideration of the effects of climate on agriculture, the feedback from agricultural practices to climate has also been a topic of study (e.g., see http://www.fao.org/NES/1997/971201-e.htm, accessed April 2007). The crop assessments and estimates from PECAD, by revealing changes in agricultural practices, could play a role as early indicators to inform forecasting future agricultural-induced effects on climate. The Agricultural Research Service within USDA and NASA have undertaken research using Earth observation data to study scale-dependent Earth—atmosphere interactions, suggesting that significant changes in regional land use or agricultural practices could affect local and regional climate (NASA, 2001).