

AN INTEGRATED CROP CONDITION MONITORING SYSTEM WITH REMOTE SENSING

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ABSTRACT. *This article introduces an integrated crop condition monitoring system with remote sensing in China. The system can provide accurate and timely global-scale crop condition information. Two crop condition monitoring methods were evaluated and adopted: instantaneous monitoring and crop growth process monitoring. The objective of instantaneous monitoring is to acquire the spatial variation of crop condition, while crop growth process monitoring is used to capture its temporal variation. Instantaneous monitoring evaluates crop condition at a specific time during the growing season by computing a difference image of normalized difference vegetation index (NDVI) images comparing the specified 10-day period and with the same period in previous years. These difference images can provide the spatial distribution of different crop conditions. Crop growth process monitoring extracts crop growth profiles from time-series NDVI images during the crop growing season. These extracted crop growth profiles are then compared to different years with known yields. The two monitoring methods were used jointly to assess production prospects prior to harvest. In addition, environmental condition analysis was implemented to assist crop condition monitoring. An operational system was developed to integrate the two crop condition monitoring methods and environmental condition analysis to provide an integrated crop condition analysis platform. The monitoring results have been delivered to a number of Chinese government agencies and have made significant and timely contributions to their decision-making to help avoid food shortage and market volatility.*

Keywords. *Crop growth profile monitoring, Instantaneous monitoring, Integrated crop condition monitoring system, Remote sensing.*

Crop condition information is important for users at different levels, from individual farmers to national decision-makers. Crop condition monitoring can provide an objective foundation for large-scale crop management, as well as early information on crop yield estimation. The acquisition of early crop condition information can assist decision-makers in adopting measures for averting potential large-scale grain surpluses and shortages (Wu and Liu, 2000). In addition, accurate and timely assessment of crop condition in a natural disaster, such as a drought or pest infestation, can be critical for countries whose economy is dependent on crop production.

Crop condition can be evaluated using remote sensing (RS) technology (Doraiswamy et al., 2004). Crop condition monitoring with RS has been studied extensively during the past several decades. It is one of major domains in agricultural monitoring with remote sensing, which is different from agricultural statistics. Bauer (1985) summarized the underlying premise of using optical remote sensing for crop condition assessment. Specifically, multi-

spectral reflectances and temperatures of crop canopies relate to two basic physiological processes: photosynthesis and evapotranspiration. A spectral vegetation index (VI), which is a ratio, or linear combination, of reflectances in the red and near-infrared (NIR) wavebands, is particularly sensitive to the amount of vegetation (Jackson and Huete, 1991) or the amount of photosynthetically active plant tissue in the plant canopy (Wiegand et al., 1991). A commonly used VI is the normalized difference vegetation index (NDVI), which is the difference between the red and NIR measurements divided by their sum. It has been shown that NDVI is highly correlated with crop growth and health, and can be used to monitor crop condition (Badhwar, 1980). Research on monitoring crop condition with RS began as early as the 1970s. Different methods and different RS data have been used in crop condition monitoring (Crist and Malila, 1980; Schneider et al., 1981; Philipson and Teng, 1998; Doraiswamy et al., 2004). A strong correlation was found between accumulated NDVI values over the entire crop growing season and the final crop biomass (or yield). Thus, a quantitative analysis of crop condition could be realized by the inter-annual comparison of accumulated NDVI values, which also provides indicators for crop yield estimation (Rao et al., 1982).

Based on the experience gained by the LACIE (Large-Area Crop Inventory Experiment; Macdonald and Hall, 1980) and AgRISTARS (Agriculture and Resource Inventory Surveys Through Aerospace Remote Sensing) programs, jointly initiated by NASA, USDA, and NOAA efforts, the USDA Foreign Agricultural Service (FAS) established the GLAM (Global Agriculture Monitoring Program) system for monitoring, in near-real-time, global agriculture. The VI

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dataset of the previous eight years was used to define the average crop growing status, and the instant VI image could then be compared to that of a certain previous year or to the average of the previous years to describe crop growth status. The European Commission Joint Research Center (EC JRC) MARS (Monitoring Agriculture with Remote sensing) program developed a crop condition monitoring method based on the crop NDVI process with full use of the CORINE land cover database in which crop condition monitoring is carried out every ten days at three scales: EU, regional, and country. This system has been applied in African and Asian countries (Genovese et al., 2001). The FAO developed GIEWS (Global Information and Early Warning System) to provide crop condition information at a global scale. In addition to VI images, remotely sensed meteorological images (precipitation) are used to evaluate crop condition (Hielkema and Snijders, 1994). The crop condition monitoring results of the FAO system can be acquired from the FAO's website (www.fao.org/giews/english/index.htm) or from its official report, titled "Crop Prospects and Food Situation". The Canadian Statistics Bureau has carried out crop condition monitoring with a comparison map and NDVI profile for each week since 1996. Crop condition maps are produced by comparing the instant VI image with images from the last several weeks, from the same period of the preceding year, and from the average of all past images (Reichert et al., 2000). A flexible inter-annual comparison can be made with weekly average cloud-free NDVI images of farmland and grassland (Reichert et al., 2000; McNairn and Brown, 1999).

With 20 years of research experience, a comprehensive remote sensing crop monitoring system named CropWatch was developed by the Institute of Remote Sensing Application (IRSA) of the Chinese Academy of Sciences (CAS) (Wu, 2004). The objective of this system is to provide independent, timely, comprehensive crop information, including crop condition, crop yield, crop acreage, cropping index, and crop planting structure. The crop condition monitoring system, a component of CropWatch, provides crop condition information at a large scale, which contributes to policy outcomes by supporting water resources management and reducing vulnerability to risk of grain production declines and food shortages.

The objective of this article is to introduce this operational crop condition monitoring system and its utility for crop monitoring. The methodology of the system development is introduced first, followed by an introduction of the system. Then the results of the system on data processing, crop condition monitoring, and its application are provided. Three case studies on how the monitoring results were used in the decision-making process are also presented.

DATA AND METHODOLOGY

Two methods were developed and adopted for assessing crop condition: instantaneous monitoring and crop growth process monitoring. In instantaneous monitoring, a rank map of crop condition is produced through inter-annual comparisons of RS images for a specified time period. In crop growth process monitoring, time-series RS images are used to extract crop growth profiles at county scale and are then aggregated to other larger scales. While instantaneous crop

condition monitoring reflects the spatial variability of crop condition at a specific time, crop growth process monitoring reflects the crop condition through the crop growing season. A standardized RS data preprocessing procedure was developed to provide accurate and timely input data for the system. A comparison of the instant environmental condition with a reference mean condition was implemented to provide supplementary information.

DATA

Large-scale and daily RS data are needed in order to effectively monitor crop condition as the growing season develops. NOAA AVHRR, SPOT VGT, and TERRA MODIS are the major datasets used. NOAA AVHRR has been used for domestic monitoring with collected and archived data since 1991. The AVHRR data were acquired through the IRSA-CAS ground station and the National Satellite Meteorological Center of China. Daily data were processed for radiometric calibration, atmospheric correction, geographic correction, and bi-directional reflectance distribution function (BRDF) correction. Daily NDVI was computed, and a ten-day composite was produced. The simplified method for atmospheric correction (SMAC; Rahman et al., 1994) was applied in preprocessing the AVHRR data, which is a simplified model of 6S (Vermote et al., 1997). The CLAVR method (Liu and Wu, 2004) was applied for cloud identification. The spectral reflectance of all five bands was used to identify cloud-contaminated areas (Liu and Wu, 2004). The harmonic analysis of time series (HANTS) method (Roerink et al., 2000) before 2008 (Zhang et al., 2003) and the Savitzky-Golay filter method (Meng et al., 2009) after 2008 were used to reconstruct cloud-contaminated time-series NDVI data.

SPOT VGT was used for global monitoring with data collection starting in 1998 and ending in 2003 due to charging policy. The SPOT VGT data can be ordered through the VITO website (www.vgt.vito.be) and are delivered with a one-week lag, while historical data can be downloaded directly free of charge. The SPOT VGT data from VITO were preprocessed for radiometric calibration, atmospheric correction, and geographic correction. The standard VITO NDVI data product is provided in tiles and has global coverage at 1 km resolution.

MODIS has become a major data source for both domestic and global monitoring since 2004. For domestic monitoring, data were acquired through the IRSA-CAS ground station and preprocessed with geo-correction, atmospheric correction, cloud identification, NDVI computation, and ten-day composition. The MODIS data for global monitoring were downloaded from the MODIS website (<http://wist.echo.nasa.gov/api>) with a 10 to 15 day delay. The reason for using different data sources for domestic and global monitoring is that a higher timeliness could be achieved with self-preprocessed data, which is important for early delivery.

The meteorological data were used to provide crop growing environment information. Domestic data were obtained from the China Meteorological Administration, and global data were downloaded from the NCDC (National Climatic Data Center) website (www.ncdc.noaa.gov/oa/ncdc.html). After 2004, precipitation data from TRMM, as well as the FPAR (fraction of absorbed photosynthetically active radiation) and LST (land surface temperature) datasets from MODIS were used to replace the meteorological

dataset. The variation of environmental status for crop growth was evaluated through inter-annual comparison of remotely sensed parameters.

To enhance the information on crops, 1:100,000 cropland data for China (Liu et al., 2005) and JRC GLC2000 (Neumann, et al., 2007) were used to mask non-cropland pixels. Due to the spatial variation in crop phenological phase throughout China and worldwide, crop phenophase data for major crops were collected (Joint Agricultural Weather Facility and USDA, 2005). These data were converted into contour maps that can be overlaid on the condition map to understand the crop phenological stage of the monitoring result.

METHODS

Instantaneous Crop Condition Monitoring

The instantaneous monitoring method compares the NDVI values of croplands at a specific time with those of the same period in a previous year or with the historical average (Meng and Wu, 2008). The differential image can provide the spatial distribution of crop condition at that period relative to other years with known production values. The differential image can be categorized into different crop condition grades to evaluate the regional crop growing status (Rao et al., 1982). In this system, the crop condition was categorized into five grades: excellent, good, normal, poor, and very poor. The percent area of each grade was computed to evaluate the crop condition quantitatively. A cropland map was used to mask non-agricultural lands.

To lessen the influence of cloud contamination, a cloud mask from the cloud identification was used to mask cloud-contaminated areas. Labeled cloud-contaminated pixels were excluded from the computation of the percentage of different crop condition ranks.

Crop Growth Process Monitoring

The crop growth process monitoring method constructs the crop growing profile with time-series NDVI images and evaluates the crop condition by comparing inter-annual crop growth profiles (Meng and Wu, 2008), i.e., the current year was compared with the profiles of other years with known production. The variation in greenness measured by the time-series NDVI images over the crop growing season was used to track the crop condition dynamics. Crop condition and yield prospects were assessed based on the similarities and differences with the profiles derived from previous years (Genovese et al., 2001). Parameters from the crop growth profile, including green-up rate, senescence rate, and seasonally accumulated NDVI values, were extracted to evaluate crop growth process and yield prospects (Ren et al., 2008; Kastens et al., 2005; Mkhabela et al., 2005).

Due to the uncertainty in pixel matching, a method was developed to extract the crop growth profile at county scale. The crop growth profile at county scale is composed of the weighted average of NDVI values of all pixels within a county boundary. The contribution proportion of a pixel to a county crop growth profile is proportional to the crop acreage in that pixel. Thus, the area of cropland in a pixel is taken as its weight in computing the weighted statistical average NDVI. To reduce the influence of non-crops area to the weighted NDVI average, two filtering thresholds were set for selecting valid crop pixels: (1) the percentage of farmland had to be greater than 10%, and (2) the NDVI value had to be

greater than 0.1 (Zhang et al., 2003, 2004). Pixels that did not meet these requirements were assigned a weight of 0. This filtering increased the contribution of NDVI signal from crops in the time-series NDVI profiles. Croplands were further divided into dryland and paddy fields. Crop growth profiles were extracted separately for these two types of cropland to provide specific monitoring results. The county-scale profile can be aggregated to acquire large-scale (provincial and national) crop growth profiles.

Environmental Condition Evaluation

Environmental condition is the main driver of crop condition and has a primary influence on agricultural production. The analysis of environmental condition can help to explain the crop condition derived from RS. Therefore, regional environmental anomalies were produced by comparing the current data with the historical averages, including precipitation, FPAR, and LST. The anomaly images of environmental parameters were classified into three grades: higher, normal, and lower.

CROP CONDITION MONITORING SYSTEM

Crop condition monitoring is a time-consuming process. The system described here can (1) manage all data used, including RS data, land-use data, environmental parameter, and phenological data; (2) provide timely crop condition information for different countries and counties over China; (3) provide an analysis platform to produce a comprehensive assessment of crop condition and production prospects by integrating environmental information, crop phenophase, and crop condition; and (4) generate and export graphs.

The system was designed, developed, and integrated originally in the ArcView 3.0 environment and later changed to the IDL environment with support of Oracle as the database management system and ArcSDE as the spatial data engine. The system is composed of six parts:

- Data preprocessing model, which implements the preprocessing of RS data including calibration, correction, cloud identification, NDVI computation, and composite.
- Data management model, which manages the crop growth profile data, environmental data, crop phenological data, vector data of regionalism, and time-series RS data.
- Instantaneous monitoring model, which computes the differential image between inter-annual NDVI images, produces the crop condition rank map, and counts the percentage of different crop condition grades.
- Crop growth profile monitoring model, which reconstructs the crop NDVI profile and extracts the crop growth profile for different scales.
- Analysis model, which provides a platform to integrate the results from the instantaneous crop condition monitoring, the crop growth process monitoring, and administration boundary to produce timely crop assessments at a range of different scales.
- System configuration model, which configures the system parameters.

Figure 1 is a screen shot of the system user interface; it is through this interface that the different models can be launched for crop condition monitoring by clicking the corresponding button on the panel, as well as through the menus. Each model has a GUI to carry out corresponding

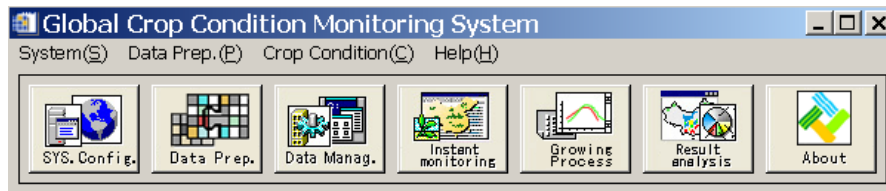


Figure 1. User interface of crop condition monitoring system (original in Chinese).

functions. Figure 2 is a screen shot of the GUI for the analysis model.

Periods of the crop growing season can be selected based on the phenological information for different crops. Monitoring extent (country or county) and farmland types can be assigned by the user. In the center of the GUI, a crop condition map and a crop growth profile chart are displayed together to provide a comprehensive understanding of crop condition. The differences in crop condition either at different periods or in different areas can be analyzed.

Vector layers, such as country, province, or county borders, can be overlaid on the output crop condition map, with the labeling of these layers at the user's discretion. Other basic thematic maps, such as crop phenophase, land use, and environmental condition, can be overlaid on the crop condition map. These options increase the analysis capacity of the system.

In upper center of figure 2, the instantaneous crop condition map had been overlaid with province borders and a cropland mask, which shows the spatial anomalies indicative of crop condition at a specific period over the growing season. The comparison chart of inter-annual crop growth profiles is displayed in the lower center, which reflects the variation in crop condition at different times

through the crop growing season. Through comprehensive analysis of the data, a complete understanding can be acquired about where, when, and why the crop condition differs from a previous year or from the historical average.

The crop calendar varies among different areas of the world, and therefore an operational monitoring plan is necessary. Plans for both domestic and global crop condition monitoring were established. Monitoring for China, India, U.S., Canada, North Africa, and most European countries is carried out from March to October. In Southeast Asia, monitoring is carried out throughout the year, and in South Africa, Australia, and South America, monitoring is carried out from September to May. The monitoring is at ten-day frequency (Wu, 2000).

The system development and deployment ensure timely delivery of the monitoring results. The system reduces the time and labor needed to carry out the task, and global-scale monitoring can be implemented routinely as planned. The monitoring results from this system are routinely delivered to government bodies, such as the State Council, Ministry of Agriculture, State Grain Administration, State Development and Reform Commission, Ministry of Civil Affairs, National Disaster Reduction Center, and so on.

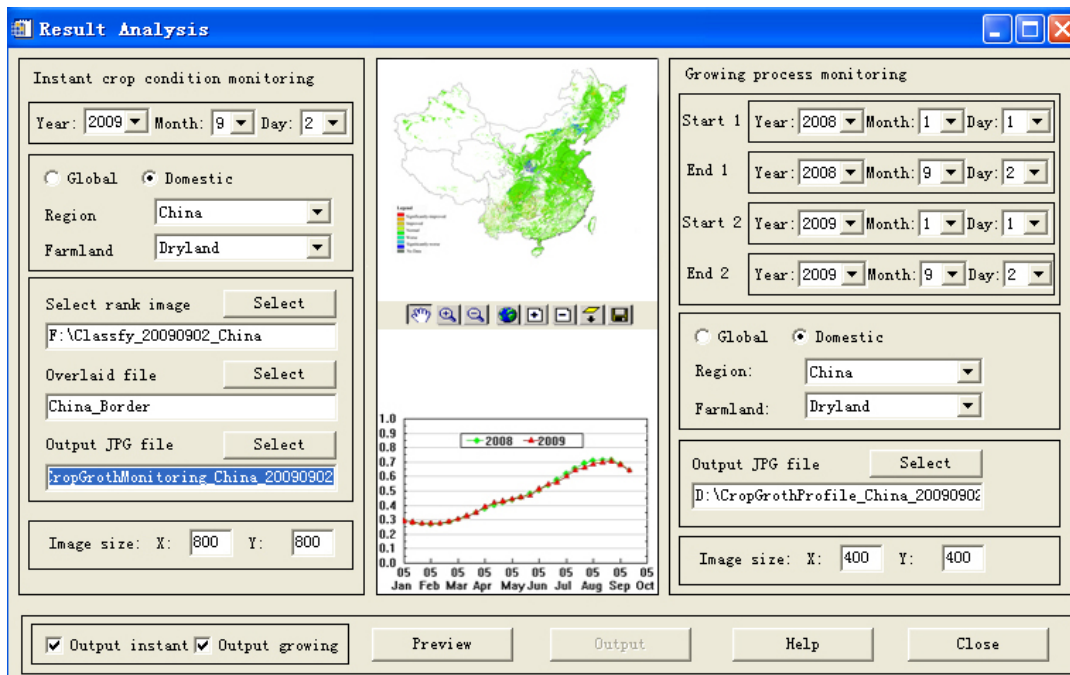


Figure 2. GUI of the analysis model (original in Chinese).

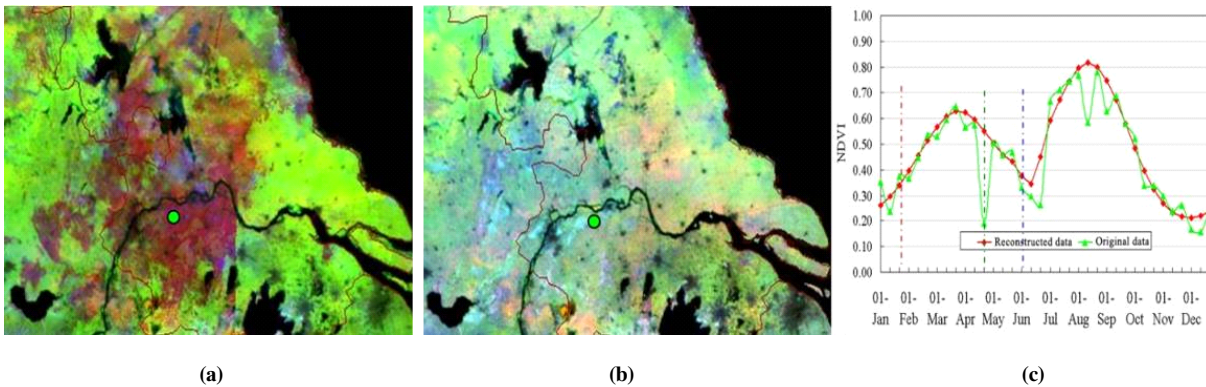


Figure 3. Effect of cloud elimination for time-series NDVI images: (a) cloud-contaminated NDVI images, (b) reconstructed images using HANTS method, and (c) graph of NDVI over the growing season.

RESULTS AND DISCUSSION

CLOUD IMPACT ELIMINATION

Cloud contamination has a severe influence on remote sensing data. Cloud elimination with the HANTS or G-Z method was adopted for the time-series NDVI reconstruction. The images in figure 3 were composed with the band combination of NDVI of different times (R: end of February; G: end of April; and B: end of May). Most of the area in the image was cropland; thus, the NDVI of crops in the above three periods determined the color of the image. The NDVI in January was rather low, yet a peak appeared in April at the flowering stage of winter wheat; after that, the crop entered a period of filling and senescence. The NDVI continued to decrease until it reached a valley in June, when the summer crops were harvested (fig. 3c). Cloud-contaminated areas (an abnormally low NDVI at the end of April) can be recognized as the red area in figure 3a. The HANTS method was applied to reconstruct the cloud-contaminated NDVI image, which worked quite well in figure 3b. The reconstructed NDVI profile (fig 3c) at the pixel (green point near the center of figs. 3a and 3b) was a smoothed curve that can express the periodicity and variation of greenness in the crops.

CROP CONDITION

Crop condition monitoring was first implemented to estimate the agricultural consequences of the big flood in China in 1998. Since then, with the development of an operational system, the monitoring has become a routine task. Monitoring reports are generated every ten days for China and monthly for 26 countries around the world. The monitoring results are in three forms: crop condition map, crop growth profile chart, and environmental condition map. Monitoring results for September 2009 are presented in figures 4 through 6.

Crop Condition Map

According to the crop condition map of China in September 2009, 13.5% of farmland had better crop condition, 16.1% had worse crop condition, and 70.4% had the same crop condition as that of the previous year (fig. 4). To evaluate the overall crop condition relative to a previous year, the following classification criteria were used:

- When 6% to 20% of cropland (in terms of area) in the year being assessed was below (or above) the crop

condition of the reference, the analysis concluded little worse (or little improved) crop condition.

- When the difference was greater than 20% relative to the reference year, conditions were considered worse (or better).
- When the difference was between 0% and 6%, conditions were considered normal. Thus, in September 2009, the crop condition of China was considered normal.

Crop Growth Profile Chart

Crop growth process monitoring was carried out at five spatial scales: county, stratum, province, main production region, and country. Figure 5 presents an example at country scale. According to figure 5, a worse crop condition was observed between June and August, while a normal crop condition was observed at other times. The crop growth process monitoring result is consistent with the result of instantaneous crop condition monitoring.

Environmental Condition Map

Environmental condition is analyzed once per month over the crop seasons beginning in April. Figure 6 is an anomaly map of China in September 2009 for LST, precipitation, and FPAR. According to the inter-annual variation map of LST, precipitation, and FPAR, the LST in the most southwestern area of China was higher in September 2009 than in the previous year, the central northern area was lower, and the other areas were the same. The northwestern and eastern areas of China received abundant precipitation, while some parts of the southern and western areas suffered a continuous shortage of precipitation. Most areas maintained the same level of FPAR from the previous year, except a part of southern China that had higher FPAR.

EFFECTS OF SEVERE EVENTS

Three case studies are presented to demonstrate the contribution of the crop condition monitoring system during crucial moments when timely and accurate agricultural information was needed by Chinese decision-makers in order to avert potential food-crisis situations.

2006 Drought in Southwest China

In 2006, a severe drought hit southwestern China from early July to late August. The most severe drought condition in over 50 years was reported in the southwestern region of Chongqing and neighboring Sichuan province. To provide an

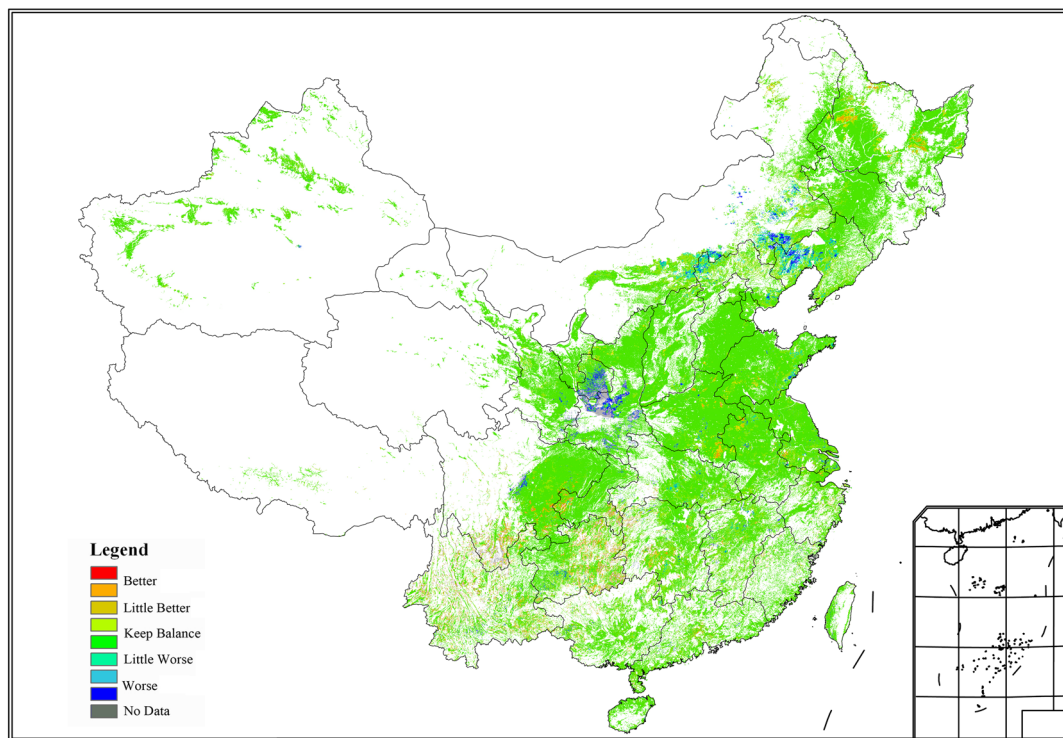


Figure 4. Crop condition map of China in September 2009.

early estimation of production losses due to the drought, a report was produced based on the monitoring results of the system, together with field surveys used to calibrate the results (fig. 7). A serious deterioration of crop condition was observed from the crop condition map of the area (fig. 7). The monitoring result showed that approximately 60% to 70% of farmland in the area was affected by the drought and that 20% to 25% of farmland would suffer no harvest. A 30% reduction in crop production was predicted. A detailed report was produced that explained the influence of the drought on the different crop types that were affected. Estimations of loss of different crops were also made by combining the crop condition monitoring result with the crop proportion data (from field survey with GVG; Wu and Liu, 2004) in different drought-affected areas. This report was instrumental in helping the government make the appropriate decision.

2008-2009 Drought in North China

A prolonged drought hit north China in October 2008 and persisted to late February 2009. The drought emergency

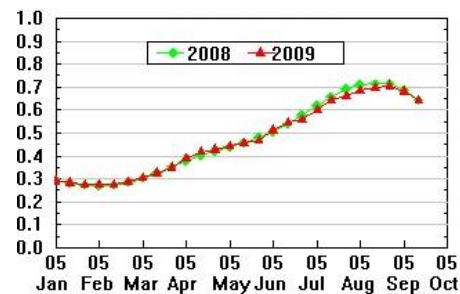


Figure 5. Crop growth process monitoring chart of China in September 2009.

status was raised to the highest level for the first time ever. According to the report of the Chinese Ministry of Agriculture, the drought parched more than 40% of the nation's wheat land. A loss of winter wheat production was anticipated by most of the local governments and was reported to the central government. A plan for providing

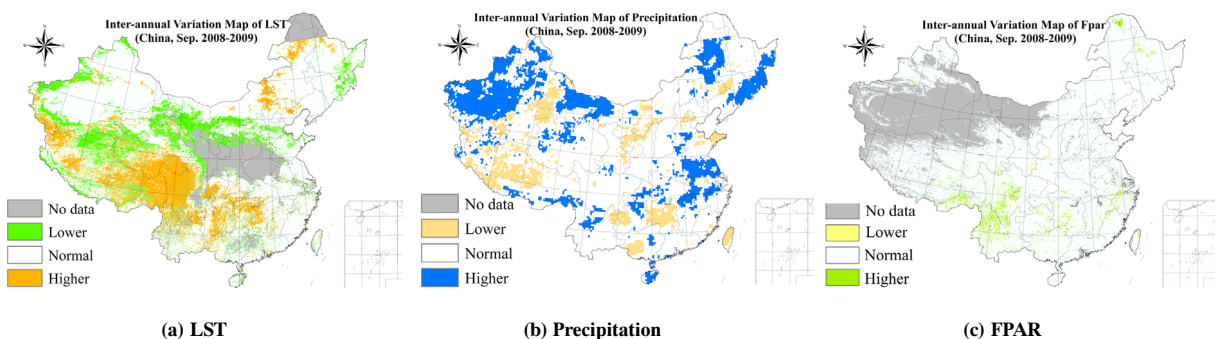


Figure 6. Inter-annual variation map of environmental condition in September 2009.

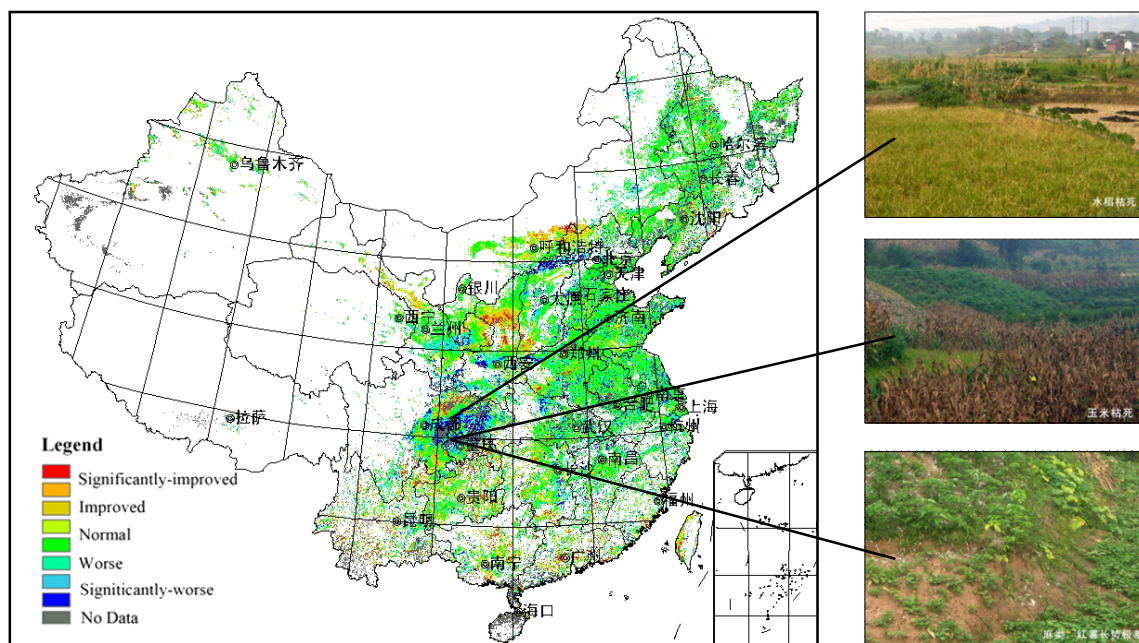


Figure 7. Crop condition map of China in mid-September 2006.

subsidies to the disaster-affected farmers and transporting grain products to deal with post-drought shortages was in discussion.

The analysis report from the crop condition monitoring system was delivered to the central government (fig. 8). According to the crop growth profile charts of the three selected provinces, although the crop condition was much worse in 2009 than it was in the previous year from January to March, which could be judged from the lower crop growth profile, an acceleration in crop growth was witnessed from the beginning of March to mid-April due to the relief in the

drought conditions. By mid-April, a normal or even better crop condition was observed in most of the drought-affected provinces. The crop condition map of China (fig. 8, left) in mid-April also showed that the crop condition in the drought-affected areas had improved to normal relative to the previous year. Therefore, a conclusion was drawn that the drought would not have obvious negative impacts on winter wheat yields in north China.

The report was adopted by the central government for drought mitigation. Timely and accurate assessment of the crop condition helped to avoid unnecessary subsidy.

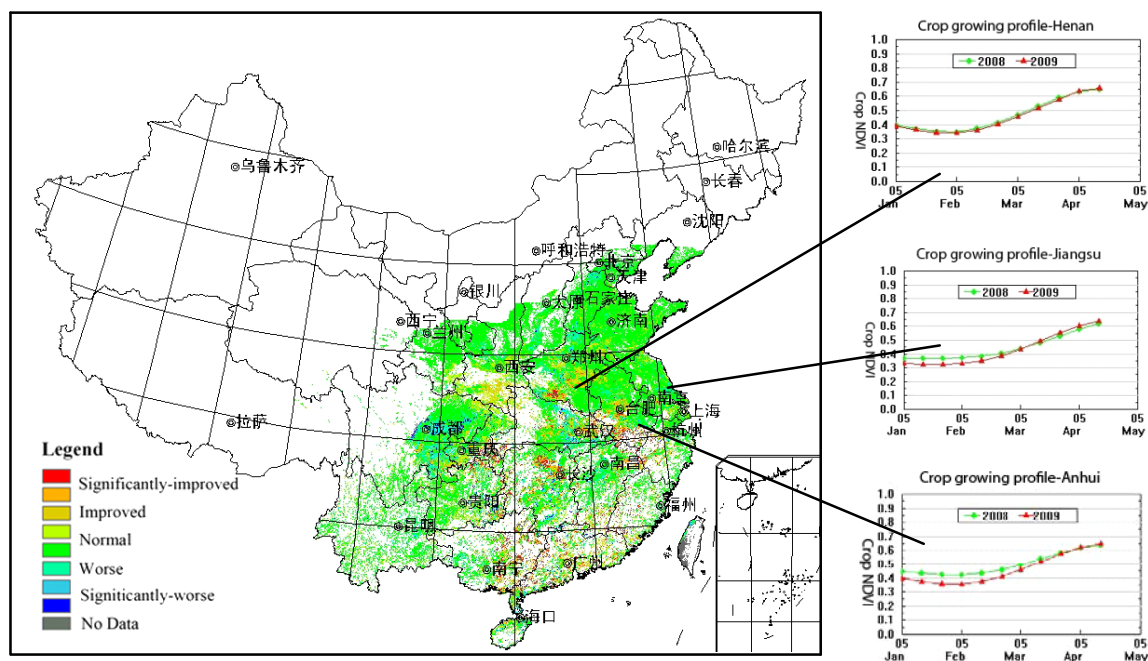


Figure 8. Crop condition map of China and crop growth profile charts of typical provinces in north China (2009).

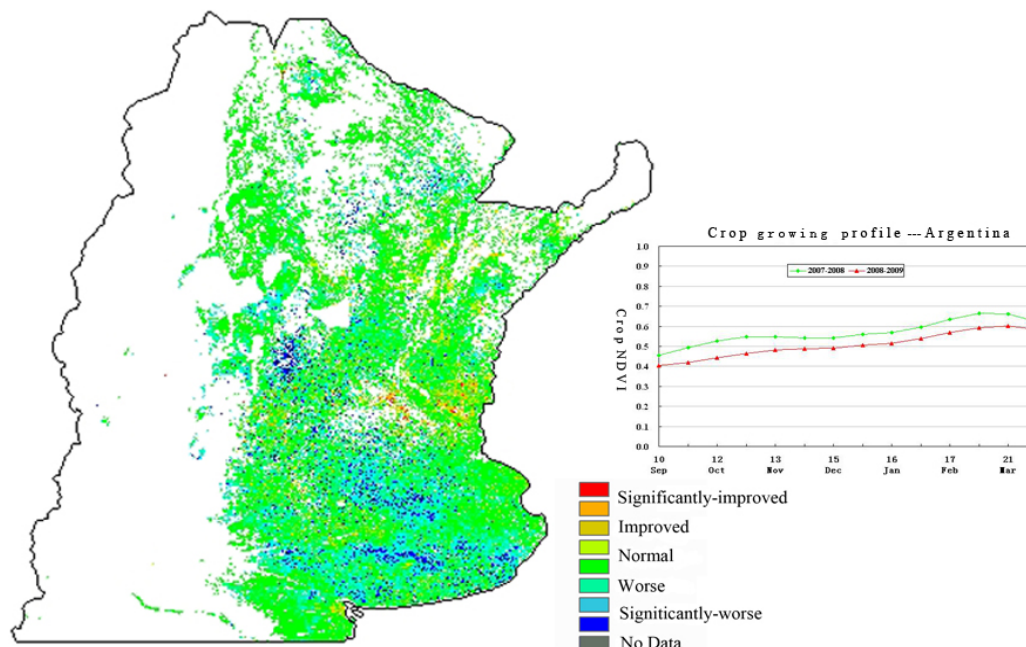


Figure 9. Crop condition map and crop growth profile charts of Argentina in late March 2009.

2008-2009 Drought in Argentina

A drought in Argentina severely affected corn and soybean crops from September 2008 to March 2009. Total rainfall after December was far below normal in most areas. Soybean production in Argentina accounted for 20% of world production. According to the crop growth profile charts (fig. 9, right), the crop condition was much worse throughout soybean season than in the previous year (2007-2008), and the crop condition map shows that the southern and middle parts of Argentina, which is the major soybean production region, had an obviously worse crop condition. A large decrease in Argentina's soybean production was predicted. The result and the analysis were submitted to the central government in the form of a bulletin.

PERSPECTIVES

Crop condition can be evaluated with the current system, but some false information was also induced due to reasons such as the inter-annual crop planting structure. A new method needs to be developed to avoid (or reduce) this false information in crop condition monitoring.

The emergence of new sensors, especially the HJ (for *huan jing*, which means "environment" in Chinese) of China, makes it possible to acquire land surface spectral information at 30 m resolution and two-day frequency. This will enable 30 m crop condition evaluation with a delay less than two days. Small differences can be better captured with these new sensors.

NDVI is the main index of the system, but NDVI alone is not enough. The applicability of other RS indices, such as temperature condition index, vegetation condition index, and enhanced vegetation index, are to be studied. An integrated drought monitoring system would also be helpful in explaining the influence of drought on crop condition.

Research is to be conducted on how to better relate crop condition monitoring with crop yield estimation. Yield is the final indicator of crop condition at different periods, and crop condition at each crop growing stage has its own way to

influence the final yield. Therefore, the influence of crop condition on crop yield also needs to be assessed in crop condition monitoring.

CONCLUSIONS

This article described the development of a crop condition monitoring system in the framework of CropWatch. The methods, system structure, monitoring results, as well as some application cases, were introduced. The objective of the system is to provide timely and accurate crop condition information to serve agricultural management and relevant decision-making.

With standard RS preprocessing, instantaneous crop condition and crop growth process monitoring were adopted by the system. An integrated crop condition monitoring and analysis system was developed to provide comprehensive and timely crop condition information.

Significant progress has been made since 1998 in terms of the methods, quality, monitoring extent, and monitoring frequency of the crop condition monitoring system. A technical framework including RS image preprocessing, integrative crop condition monitoring, and environmental condition analysis was developed. The monitoring is carried out at five scales in China, and the monitoring range has been expanded from China to global coverage. The monitoring results are included in the monthly bulletin of CropWatch and make a significant contribution to large-scale decision-making.

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REFERENCES

- Badhwar, G. D. 1980. Crop emergence date determination from spectral data. *Photogram. Eng. and Remote Sensing* 46: 369-377.
- Bauer, M. E. 1985. Spectral inputs to crop identification and condition assessment. *Proc. IEEE* 73(6): 1071-1085.
- Crist, E. P., and W. A. Malila. 1980. Temporal-spectral analysis of technique of vegetation applications of Landsat. In *Proc. 14th Intl. Symp. on Remote Sensing of Environment*, 1031-1041. Tucson, Ariz.: International Center for Remote Sensing of Environment.
- Doraiswamy, P. C., J. L. Hatfield, T. J. Jackson, B. Akhmedov, J. Prueger, and A. Stern. 2004. Crop condition and yield simulations using Landsat and MODIS. *Remote Sensing Environ.* 92(4): 548-559.
- Genovese, G., C. Vignolles, and T. Negre. 2001. A methodology for a combined use of normalized difference vegetation index and CORINE land cover data for crop yield monitoring and forecasting: A case study on Spain. *Agronomie* 21(1): 91-111.
- Hielkema, J. U., and F. L. Snijders. 1994. Operational use of environmental satellite remote sensing and satellite communications technology for global food security and locust control by FAO: The ARTEMIS and DIANA systems. *Acta Astronautica* 32(9): 603-616.
- Jackson, R. D., and A. R. Huete. 1991. Interpreting vegetation indices. *Prev. Vet. Med.* 11(3-4): 185-200.
- Joint Agricultural Weather Facility and USDA. 2005. *Major World Crop Areas and Climatic Profiles*. Honolulu, Hawaii: University Press of the Pacific.
- Kastens, J. H., T. L. Kastens, D. L. A. Kastens, K. P. Price, E. A. Martinko, and R. Lee. 2005. Image masking for crop yield forecasting using AVHRR NDVI time series imagery. *Remote Sensing Environ.* 99(3): 341-356.
- Liu, C. L., and B. F. Wu. 2004. Application of cloud detection algorithm for the advanced very-high resolution radiometer. *Chinese J. Remote Sensing* 8(6): 677-687.
- Liu, J., M. Liu, H. Tian, D. Zhuang, Z. Zhang, W. Zhang, X. Tang, and X. Deng. 2005. Spatial and temporal patterns of China's cropland during 1990-2000: An analysis based on Landsat TM data. *Remote Sensing Environ.* 98(4): 442-456.
- Macdonald, R. B., and F. G. Hall. 1980. Global crop forecasting. *Science* 208(4445): 670-679.
- McNairn, H., and R. J. Brown. 1999. Remote sensing in support of crop management. In *Seminars of the United Nations Programme on Space Applications*, 49. New York, N.Y.: United Nations.
- Meng, J. H., and B. F. Wu. 2008. Study on the crop condition monitoring methods with remote sensing. *Intl. Archives Photogram., Remote Sensing, and Spatial Info. Sci.* (Beijing, China) 37(part B8): 945-950.
- Meng, J. H., B. F. Wu, Q. Z. Li, X. Du, and K. Jia. 2009. Monitoring crop phenology with MERIS data: A case study of winter wheat in North China Plain. In *Proc. Progress in Electromagnetics Research Symposium*, 1225-1228. Beijing, China.
- Mkhabela, M. S., M. S. Mkhabela, and N. N. Mashinini. 2005. Early maize yield forecasting in the four agro-ecological regions of Swaziland using NDVI data derived from NOAA's-AVHRR. *Agric. and Forest Meteorology* 129(1-2): 1-9.
- Neumann, K., M. Herold, A. Hartley, and C. Schmullius. 2007. Comparative assessment of CORINE 2000 and GLC2000: Spatial analysis of land cover data for Europe. *Intl. J. Applied Earth Obs. and Geoinfo.* 9(4): 425-437.
- Philipson, W. R., and W. L. Teng. 1998. Operational interpretation of AVHRR vegetation indices for world crop information. *Photogram. Eng. and Remote Sensing* 54(1): 55-59.
- Rahman, H., and G. Dedieu. 1994. SMAC: A simplified method for the atmospheric correction of satellite measurements in the solar spectrum. *Intl. J. Remote Sensing* 15(1): 123-143.
- Rao, M. V. K., R. S. Ayyangar, and P. P. N. Rao. 1982. Role of multispectral data in assessing crop management and crop yield. In *Proc. Machine Processing of Remote Sensed Data Symposium*. West Lafayette, Ind.: Purdue University.
- Reichert, G. C., P. R. Nixon, and R. N. Dobbins. 2000. Statistics Canada's near real-time crop condition assessment program (CCAP) utilizing NOAA AVHRR data, remote sensing, GIS, and the internet. In *Proc. Intl. Conf. on Agric. Statistics*, 142-148. Washington, D.C.: USDA National Agricultural Statistics Service.
- Ren, J., Z. Chen, Q. Zhou, and H. Tang. 2008. Regional yield estimation for winter wheat with MODIS-NDVI data in Shandong, China. *Intl. J. Applied Earth Obs. and Geoinfo.* 10(4): 403-413.
- Roerink, G. J., M. Menenti, and W. Verhoef. 2000. Reconstructing cloud-free NDVI composites using Fourier analysis of time series. *Intl. J. Remote Sensing* 21(9): 1911-1917.
- Schneider, S. R., D. F. McGinnis, and J. A. Gatlin. 1981. Use of NOAA AVHRR visible and near-infrared data for land remote sensing. NOAA Tech. Report NASS84. Washington, D.C.: USDA.
- Vermote, E. F., D. Tanre, J. L. Deuze, M. Herman, and J. J. Morcrette. 1997. Second simulation of the satellite signal in the solar spectrum, 6S: An overview. *IEEE Trans. Geosci. Remote Sensing* 35(3): 675-686.
- Wiegand, C. L., A. J. Richardson, D. E. Escobar, and A. H. Gerbermann. 1991. Vegetation indices in crop assessments. *Remote Sensing Environ.* 35(2-3): 105-119.
- Wu, B. F. 2000. China crop growth monitor and production estimate operational methods. *Chinese J. Geography* 55(1): 25-35.
- Wu, B. F. 2004. China crop watch system with remote sensing. *Chinese J. Remote Sensing* 8(6): 481-497.
- Wu, B. F., and C. L. Liu. 2000. Crop growth monitor system with coupling of NOAA and VGT data. In *Proc. Vegetation 2000*, 355-360. Lago Maggiore, Italy.
- Wu, B. F., and C. L. Liu. 2004. 1-km AVHRR China land dataset. *Chinese J. Remote Sensing* 8(6): 529-550.
- Zhang, F., B. F. Wu, and C. L. Liu. 2003. An advanced tool for real-time crop monitoring in china. In *Proc. IEEE Intl. Geosci. and Remote Sensing Symposium (IGARSS)*, IV: 2245-2247. Piscataway, N.J.: IEEE.
- Zhang, F., B. F. Wu, C. L. Liu, Z. M. Luo, S. W. Zhang, and G. L. Zhang. 2004. A method to extract regional crop growth information with time series of NDVI data. *Chinese J. Remote Sensing* 8(6): 515-528.

