CHINESE GEOGRAPHICAL SCIENCE
Volume 9, Number 1, pp. 40 – 48, 1999
Science Press, Beijing, China

REMOTE SENSING BASED ESTIMATION SYSTEM FOR WINTER WHEAT YIELD IN NORTH CHINA PLAIN

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(Received 15 January 1998)

ABSTRACT: This paper presents the applications of Landsat Thematic Mapper (TM) data and Advanced Very High Resolution Radiometer (AVHRR) time series data for winter wheat production estimation in North China Plain. The key techniques are described systematically about winter wheat yield estimation system, including automatically extracting wheat area, simulating and monitoring wheat growth situation, building wheat unit yield model of large area and forecasting wheat production. Pattern recognition technique was applied to extract sown area using TM data. Temporal NDVI (Normal Division Vegetation Index) profiles were produced from 8 – 12 times AVHRR data during wheat growth season dynamically. A remote sensing yield model for large area was developed based on greenness accumulation, temperature and greenness change rate. On the basis of the solution of key problems, an operational system for winter wheat yield estimation in North China Plain using remotely sensed data was established and has operated since 1993, which consists of 4 subsystems, namely databases management, image processing, models bank management and production prediction system. The accuracy of wheat production prediction exceeded 96 per cent compared with on the spot measurement.

KEY WORDS: yield estimation, remote sensing, winter wheat, operational system, North China Plain

1 INTRODUCTION

China is a big agricultural country with a very large population. Chinese government attaches great importance to food production. An obvious application of satellite remote sensing, with its regular synoptic coverage, is to monitor agricultural performance. Crop yield estimation has been one of the main applications of space remote sensing technology since the launching of high resolution satellite-Landsat. For gaining information of crops production in time, State Planning Commission set up a national key project during the eighth five year plan period (1991 – 1995) called Research on Main Crops Yield Estimation by Remote Sensing in Principal Food Production Regions of China. The objective of the study was to monitor the crop sown area, growing situation and forecast the output of rice, winter wheat and maize in major food production regions such as Northeast, North China and the low and middle reaches of the Changjiang (Yangtzi) River using satellite remotely sensed data. The work presented here was one of the core sub-project which was carried out on China's largest wheat production region——the North China Plain, covering 569 000 square kilometers and accounting for 51 percent of national wheat output. It includes 4 provinces (Hebei Province, Henan Province, Shandong Province and Northern Anhui Province) and 2 autonomous citites (Beijing and Tianjin).

Beginning from the middle seventies, many studies on wheat production forecasting were conducted under controlled conditions to understand the spectral behavior of crops and relate remote sensing derived parameters with yield and yield attributes. The Large Area Crop Inventory Experiment (LACIE) was the first comprehensive operational crop monitoring study at regional/country level wheat production forecasting using satellite data (Colwell, 1983).

Similar studies have since been carried out in many counties, e.g., Argentina (Redondo *et al*., 1985), Australia (Dawbin, 1988), Brazil (Moreira et al., 1986), Italy (Ascani, 1987), Canada (Pokrant, 1990), India (Dadhwal *et al*., 1991).

Use of remotely sensed data for crop inventory and production forecasting in China, presents a higher level of complexity due to small field sizes, varied topography, large number of crops and field-to-field variability in crop phenology. Some studies have been conducted since the 1980s. In 1984, National Meteorological Bureau organized Comprehensive Winter Wheat Production Inventory in Northern 11 Provinces using meteorological satellite data (Li, 1992) and built a operational system for wheat yield forecasting. However, sown area was not obtained for just using low spatial resolution AVHRR data, while crop planting area has changed obviously with the development of economy and urban extension. The remote sensing based estimation system for winter wheat yield described here was a research result during the eighth five-year plan period, which is an integrated system combining remote sensing with geographic information system (GIS). All working procedures of wheat production forecasting are carried out in computer system. Yield estimation and results output could be processed automatically.

2 KEY TECHNIQUES OF WHEAT YIELD ESTIMATION

Crop production prediction, using remotely sensed (RS) data, including two major components, acreage estimation and yield forecasting. To meet the needs of wheat production prediction and system operation, a series of key techniques must be solved previously, such as area extraction, crop growth situation monitoring, yield model establishment and total output calculation.

2.1 Automatic Extraction of Wheat Area

The work of area estimation was conducted on SUN workstation using Landsat TM as main information source. Because of the large amount of TM data and demand of wheat output prediction prior to harvest, area extraction should not only take quickness and precision into account, but also seek simple and efficient algorithm to curtail time of imagery processing. The study presented here selected suitable period of TM images according to the winter wheat growing feature, created multidimension greenness maps, and utilized pattern recognition technology to extract wheat area and interplanted wheat area separately. In North China, the growth period of winter wheat is from September to June of next year. The proper period of TM images is from middle November to middle December or from early March to early April.

2.1.1 Preprocessing of TM

Geometric and radiometric correction were conducted for every scene of TM tapes data. The map of 1:250 000 is the base map that was processed for projection transformation and marked many obvious ground objects, e.g. river, city, lake, which could conveniently select ground control points (GCP) for geometric registration.

2.1.2 Creating multi-dimension greenness map

Taking red band (R, TM3), near infrared band (IR, TM4) and difference vegetation index (namely greenness, G, G = IR − R) of TM image as X, Y and Z axis, built a three dimension greenness image, which different objects distribute on varied level of 3-D space. Using some planes parallel to IR − R plane to cut the 3-D image, we could distinguish different type of target.

2.1.3 Quantization of discriminate pattern

The core problem of quantitative remote sensing is identification of ground objects, while the quantization of discriminate pattern should be carried out before automatic recognition. Previous research (Richardson, 1977) showed that in R − IR plane, vegetation points were above the soil spectral line, while water points were below the soil line. Expressed with G are:

vegetation: $$g_1(x) = IR - R > 0$$

water: $g_2(x) = IR - R < 0$

soil line: $g(x) = IR - R - b$

From the view of classification, the soil line equation can be regarded as discriminant function of water and vegetation. The relation of them is given by:

$$g_1(x) > g(x) > g_2(x)$$

Every point whose value is greater than $g(x)$ belongs to vegetation.

2.1.4 Determination of discriminant function

In order to get quantitative information, discriminant functions of wheat land and non-wheat land are represented by below standard equations:

$$g_1(x) = a_{11}x_{11} - a_{12}x_{12} + c_1b_1 \quad \text{(wheat)}$$

$$g_2(x) = a_{21}x_{21} - a_{22}x_{22} + c_2b_2 \quad \text{(non-wheat)}$$

where a_{11}, a_{12}, a_{21}, a_{22}, b_1, b_2, c_1, c_2 are uncertain coefficients. Bidirection approach method was taken to calculate $g_1(x)$ and $g_2(x)$ in computer so on and so forth until $g_1(x) \approx g_2(x) = G$. The value of G was the threshold value between wheat land and non-wheat land. Counting the pixels and deducting the pixel number of conifer and vegetable with the aid of GIS, wheat land area could be obtained automatically. Compared with 1:50˙000 visual interpretation map in test county, auto-extraction had less than 1 per cent deviation. The acuracy of utilization in large area is over 95 per cent at provincial level.

2.2 Growth Situation Simulation and Monitoring

2.2.1 Multi-temporal NDVI profile to simulate wheat growing process

The goal of growth situation simulation is to monitor wheat growing condition dynamically and forecast the wheat seedling situation for directing agricultural production. NOAA-AVHRR data is considered as an efficient information source for its high temporal resolution. Growth situation information of vegetation expresses in the variation of green characteristics. Normalized Difference Vegetation Index (*NDVI*, $NDVI = (IR - R)/(IR + R)$) is a generally recognized good indicator for vegetation growth condition, whose value increases nearly linearly with the raise of vegetation coverage. At any time, the greenness of a region is a function of wheat area and growth situation at that moment. Actually, the change of wheat area at county level among years is within 5 per cent generally. So the variation of greenness reveals mainly the differences of wheat growing condition. It is a practicable method using *NDVI* to monitor wheat growth situation, which well reflects the greenness characteristics of vegetation.

Real-time AVHRR data was obtained every ten days from turn green stage of wheat after winter sleep to the ripening stage, about eight to twelve periods during wheat growing season. Atmospherically and radiometrically corrected and sequentially co-registered using a second order polynomial transform with base map in GIS, AVHRR images during wheat growing season were processed into NDVI images. Mean *NDVI* value of each county was extracted to create *NDVI* temporal curve. For the purpose of simulation of wheat growth situation, the range of *X* axis had to be determined firstly according to the local crop calendar,. For example, in Shijiazhuang region, capital of Hebei Province, seeding time is in early October and harvest on June 10 next year, total 253 days. Hence, the start of *X* axis is on Oct. 1 and the maximum value is 253.

It is should be pointed out that multi-temporal NDVI should form a continuous and integrable curve on the theoretical plane. However, NDVI value usually varies greatly due to the changes of satellite posture and atmospheric transmission, even up to 20 per cent sometimes. This is a public difficulty faced with scientists around the world while using NOAA-AVHRR data. A number of strategies were taken to overcome it. Moving average is one of the main types of smoothing approaches, which includes running weighted means, running medians and combination of mean and median smoothing filters (Van *et al.*, 1987). Another type of approaches is high enveloping procedure, which low *NDVI* values can be regarded with suspicious and the highest observed value are likely to be those least affected by atmospheric contamination and can be taken to be the most representative. The high *NDVI* values were kept through enveloping procedure smoothing (Quarmby *et al.*, 1993). These two methods are not very ideal in practical applications. We developed bi-enveloping curve smoothing and least square method to smooth the *NDVI* time-series profiles and obtained nice results. The smoothed *NDVI* curve had 'S' shaped feature of vegetation dry-matter accumulation and could simulate wheat growing process well. Figure 1 shows the simulated curve using least square method.

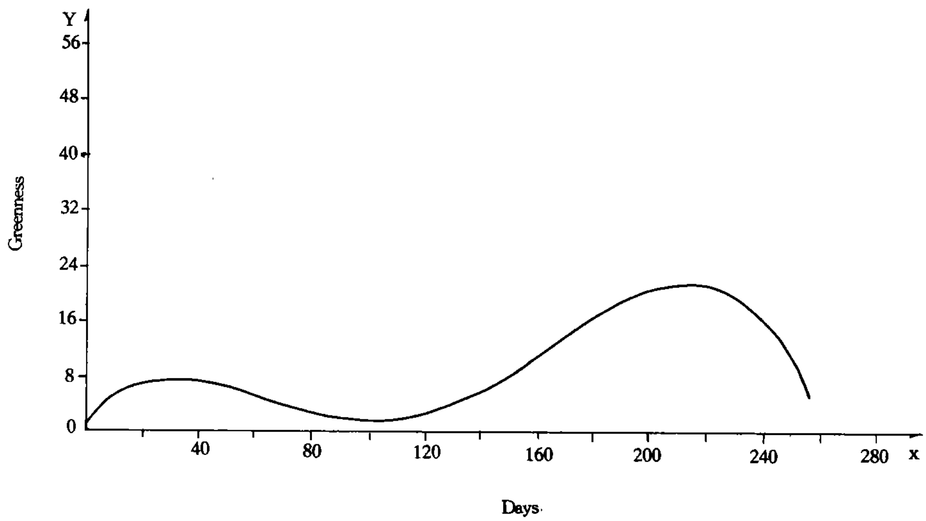

Fig. 1 Greenness-time simulated curve of wheat growing period

2.2.2 Verification of growth condition simulation for winter wheat

The process of wheat growth is also the period for dry matter accumulation. Therefore, whether the growing process simulation corresponds to reality could be tested with accumulation process of wheat dry matter. The matter production of wheat is mainly fulfilled by plant photosynthesis, which is directly related to the photosynthetic area of wheat canopy. Correlation analysis was conducted between the average growth rate (AGR) of wheat in different growing stage and corresponding *NDVI* values (Table 1). The correlation coefficient of two group of variables was 0.997 and average close degree of growth simulation was 0.92, among which there were 62 per cent sampling spots exceeded 0.90. Hence, the method of application of *NDVI* temporal curve for wheat process simulation tallied with the dry matter accumulation process. Experiments showed it is an efficient and practicable method to monitor wheat growth.

Table 1 Average growth rate (AGR) and corresponding NDVI values in different growing stages of winter wheat (Shijiazhuang region)

	Seeding	Germination	Tillering	Turn green	Jointing	Heading	Flowering/ Grain-filling	Ripening	All stages (exp. hibernation)
Days	16	8	27	18	19	22	33	9	152
AGR($g/m^2 \cdot d$)	1.2	6.2	3.3	10.2	18.7	42.7	40.5	7.8	20.0
Mean *NDVI*	2.1	4.1	2.8	7.6	12.2	23.7	21.4	5.2	11.8
$ax_i + b$	1.21	5.10	2.96	11.89	20.81	43.14	38.67	7.23	
Close degree	0.99	0.82	0.90	0.84	0.89	0.99	0.95	0.94	0.92

2.3 Modeling Winter Wheat Yield Using Remotely Sensed Data

There are several factors should be taken into account when establishing the wheat yield model for large area. The first problem is the biological characteristics of each stage during crop biomass formation period, the second is effects to wheat yield caused by selected model parameters, and then the model variables should be acquirable.

After analyzing the growth features of winter wheat in North China Plain, phase based modeling method was applied with the analysis of three essential factors to crop production formation, namely ear number of unit area, grains of ear, and weight of a thousand grains. We developed a wheat yield remote sensing model for large area using greenness accumulation, temperature and greenness change rate taking the requirement of necessity for wheat growth, such as sun light, brightness temperature, water and fertilizer. The model is described as:

$$Y = a\sum G \cdot b\frac{T_0}{T_i}(D_0 - D_i)[Q/K + C] + W$$

where Y is unit yield, $\sum G$ is *NDVI* integral value from turn green to heading stage, T_0 is required temperature accumulation (℃) for wheat growth from the beginning of heading to grain filling, or perennial average value of ground temperature, T_i is current year temperature accumulation (℃) from the beginning of heading to grain filling period, D_0 is start date (days) of wheat grain filling, D_i is start date (days) of heading, Q is standard kilo-grains weight (g) of wheat breed, K is a parameter showed by

$$K = \sqrt{1 + (\frac{\Delta G}{\Delta T})^2}$$

ΔG is greenness difference between the start and end of grain filling period, ΔT is days from start of grain filling to the end, a, b and c are experimental constants and W is a free item representing the expert suggestion.

Among the variables, T_0, D_0, D_i and Q reflected regional difference law, while G, T_i, ΔG and ΔT were dynamic parameters, a, b, c and W were adjustable according the actual situation. To meet the requirement of operational system for forecasting wheat production, we developed several novel techniques in variable acquirement and model calibration. Main variables were derived from NOAA-AVHRR data. Temporal *NDVI* profiles smoothed to simlate wheat growth process were produced in computer automatically, model variable could be acquired through *NDVI* curve (see Fig. 2) and inversion ground temperature from AVHRR data. There were some changes for variables in models with the different physical condition and crop prediction regionalization. With the three years' operation on large area, this RS yield model has been proved a practical and precise model.

3 DESIGN AND OPERATION OF WHEAT YIELD ESTIMATION SYSTEM

Crop yield estimation is a complex system engineering including many technological links and a vast amount of data both of remote sensing and auxiliary data. The steps of yield prediction are interrelated and interactive. The goal of building an estimation system for wheat production is to integrate remote sensing, GIS and ground measurement data into computer system to carry out quick, accurate prediction for wheat yield and reach automatic processing in computer step by step.

The objective of system design was to establish a practical remote sensing based estimation system for winter wheat yield in large area combining satellite data, GIS with ground data, which consists of a series of subsystems. It could conduct real-time monitoring of wheat growth, forecast wheat area and total output of current year and provide accurate data before harvest to central and local governments for food trade and food policy decision.

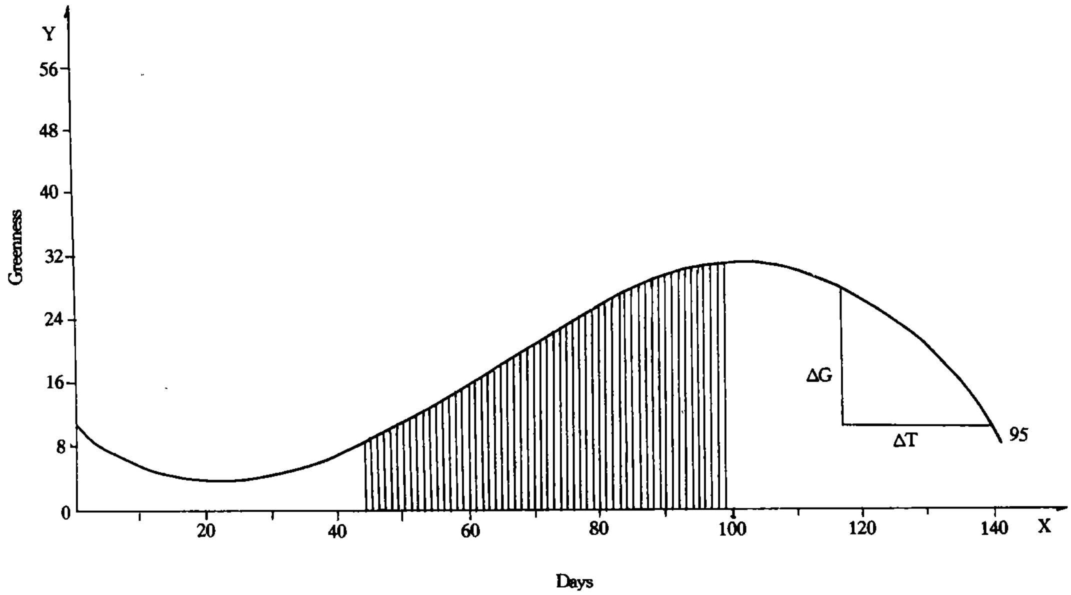

Fig. 2 Aquiring value of $\sum G$ and K from temporal *NDVI* curve

3.1 Logic Structure of System

Remote sensing based estimation system for wheat yield takes satellite data as main information source, which are Landsat TM and NOAA-AVHRR, to conduct area estimation and output prediction with the aid of other background data. It is an integrated system combining computer technique, remote sensing technique, with GIS technique. The processing flow is described as Fig. 3.

3.2 Information Flow in the System

For the sake of proper system structure design, it is the first step that make clear the flow direction of various data in the process of wheat yield estimation with remotely sensed data. Figure 4 demonstrates the information flow at each procedure.

From the flow chart, some cognition should be obtained as below.

1) Supported by background information, image processing is carried out using TM and AVHRR images to acquire the data of wheat area and growth situation. The estimation results were stored into database for the utilization of other step.

2) Using wheat growth condition monitoring data and other relative information in database, built wheat yield model. The calculation results of model operation were also laid in the database for total output prediction.

3) Derivation of data of wheat area and unit yield, to forecast wheat production of each region and put the results into database for the statistical analysis and output.

Background database plays an important role in the whole process of wheat yield estimation. It provids all kinds of data to each procedure for yield estimation and renews itself continuously with the input of result data.

3.3 Function and Operation of Wheat Yield Estimation System

Remote sensing based estimation system for wheat yield consists of 4 subsystems according to their functions, namely management system for background database, image processing system, management system for models bank and production forecasting system. Each subsystem is independent and works on its own function, however, they are interrelative and interdependent connected with a local area network (LAN).

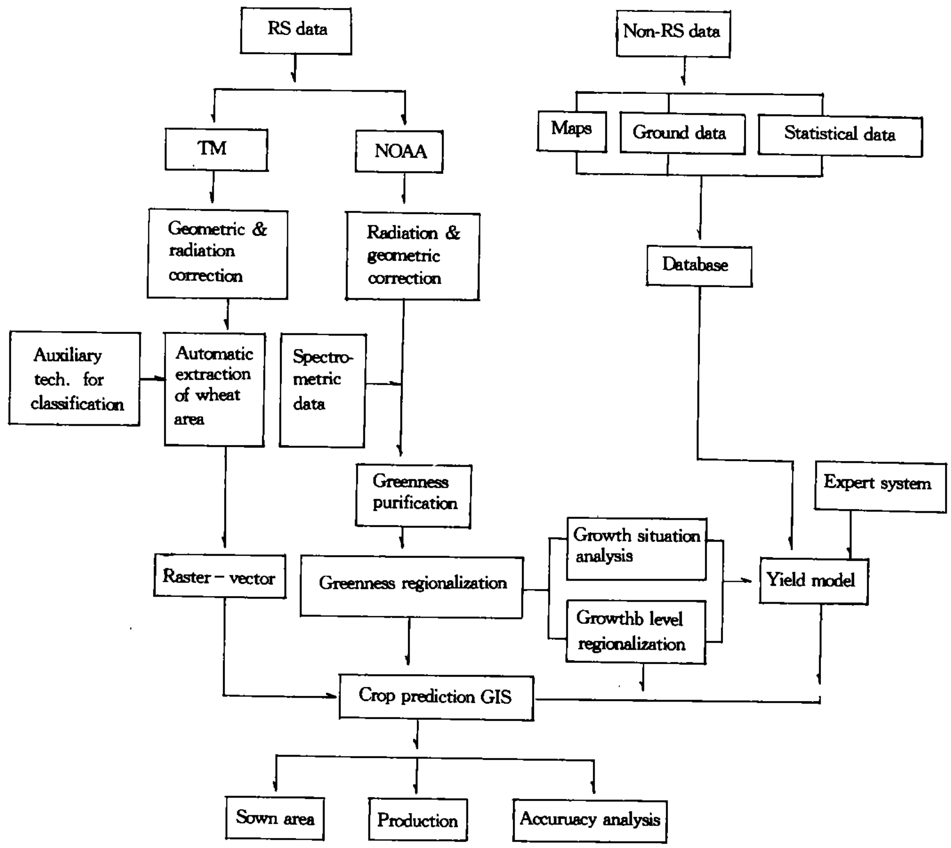

Fig. 3 Flow chart of winter wheat yield estimation using RS data

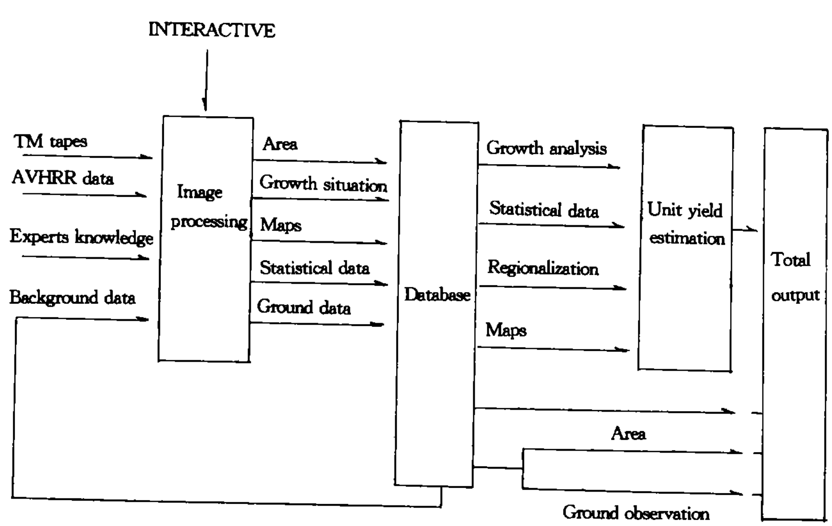

Fig. 4 Information flow in wheat yield estimation system

3.3.1 Management system for background databases (MSBD)

MABD carries out united management of various background databases, which are composed of types of databases related crop yield estimation, such as statistical data, ground observation data and spatial data for the calculation of yield model and imagery classification. Many operation results of other subsystems are also stored in MSBD, e.g. area estimation data at county level and unit yield data of different region of each year.

3.3.2 Image processing system (IPS)

IPS mainly fulfills two tasks: wheat area extraction and wheat growth situation monitoring.

1) Conducts analysis of TM data for wheat area estimation supported by background GIS. NOAA-AVHRR 1.1 km data was used with TM and GIS to extract wheat area as well.

2) Taking advantage of AVHRR high temporal resolution, to carry out wheat growth process simulation and produce NDVI temporal profiles to monitor wheat growth condition. During some key stages of wheat growth, e.g. turn green period, jointing stage, heading stage and milky ripeness, real time AVHRR data was processed and combined with ground observation data to forecast output trend and provide data for yield model operation.

3.3.3 Management system for models bank (MSMB)

MSMB provides methods for the establishment of yield model through model tool bank, and operates all models supported by expert system. The calculation results will be input MSBD for the production estimation.

3.3.4 Production forecasting system (PFS)

PFS conducts production trend prediction, total output forecasting and relevant results export.

1) There are two times production trend prediction during winter wheat growing season, one in March (turn green to jointing stage), the other in April (jointing to heading stage), whose content was amount of increase or drop in production compared with last year based on analyses of AVHRR greenness data, agricultural condition, agro-meteorological data and disaster evaluation.

2) Transferring data of unit yield and current year wheat area from MSBD, we could easily calculate total output. The output prediction was on county level and then could provided results to district or provincial government for local policy decision, while gathering counties production data to provincial scale will be important scientific basis for central givernment making food policy.

3) The exported results includes distribution maps of unit yield and total output, data of area and production and spatial distribution map of wheat area.

4 CONCLUSIONS

The following conclusions can be drawn from the research and operation of remote sensing based estimation system for winter wheat yield in the North China Plain:

1) The system has a series of functions such as monitoring of wheat growth situation and soil moisture content, automatic extraction of wheat area, yield model development and variables acquirement, output prediction and results export.

2) Area extraction accuracy has reached the demand of production estimates by automatic computation in workstation. The method of area estimation has obtained some improvement through 3 year's application in large area, while operation speed is faster and accuracy is higher than before.

3) Wheat unit yield estimation achieves success using RS yield model based on greenness integral, temperature and greenness change rate and other auxiliary wheat yield models.

4) The system has experimentally run in North China Plain since 1993. Production prediction accuracy exceeded 96 per cent at provincial level compared with ground measurement using multi hierarchy statistical sampling technique. The study results indicate that, for large area in China, crop yield estimation using remote sensing data is practicable on an operational basis.

5) With the system continuous operation, the estimation accuracy will be improved gradually while costs of system will reduce simultaneously year by year.

Acknowledgments

The study was carried out under national key project during the eighth five-year plan period (1991 – 1995) named Winter Wheat Yield Estimation by Remote Sensing in the North China Plain (85 – 724 – 02 – 02) funded by State Science and Technology Commission of China.

REFERENCES

Ascani F., 1987. Agri-program the operation use of remote sensing for wheat and corn production at national level. *International Symposium on Remote Sensing of Environment*, *20th Proceedings*, Vol. 1, 287 – 292.

Colwell R. N., 1983. *Manual of Remote Sensing* (2nd edition). Virginia: American Society of Photogrammetry.

Dadhwal V. K., *et al.*, 1991. Wheat acreage estimation for Haryana using satellite digital data. *Journal of Indian society of Remote Sensing*, 19: 1 – 15.

Dawbin K. W., Evans J. C., 1988. Large area crop classification in New South Wales, Australia, using Landsat data. *Int. J. Remote Sens.*, 9, 295 – 301.

Moreira M. A. *et al.*, 1986. Wheat area estimation using digital Landsat MSS data and aerial photographs. *Int. J. Remote Sens*, 7: 1109 – 1120.

Redondo F. V. *et al.*, 2985. Estimating wheat cultivated area with large productivity region in Argentina using Landsat data. *Proceedings 19th International Symposium on Remote Sensing of Environment*. Ann Arbor, Michigan. Ann Arbor. pp. 361 – 367.

Richardson A. J., Wiegand C. L. 1977. Distinguishing vegetation from soil hackground information. *Photogrammetric Engineering & Remote Sensing*. 43: 1541 – 1552.

Li Yuzhu, 1992. The operational system for winter wheat yield monitoring and forecasting by satellite remote sensing in North China. *Meteorology*, 11. (in Chinese)

Mahey R. K., *et al.*, 1993. Pre-harvest state level wheat acreage estimation using IRS – IA LISS – 1 data in Punjab (India). *Int. J. Remote Sens.*, 14: 1099 – 1106.

Pokrant H. T., 1990. The Canadian World Crop Monitoring System: the formative years. *Canadian Symposium on Remote Sensing*, *13th Proceedings*, 3911.

Sridhar V. N. *et al.*, 1994. Wheat production forecasting for a predonminantly unirrigated region in Madhya Pradesh (India). *Int. J. Remote Sens.*, 15: 1307 – 1316.

Van Dijk K. A., Collis S. L., Sakanmoto C. M. and Decker W. L., 1987. Smoothing vegetation index profiles: an alternative method for reducing radiometric disturbance in NOAA-AVHRR data, *Photogrammetric Engineering and Remote Sensing*, 53: 1059 – 1067.

Wang Naibin, Qin Ping and Zhou Yingchun, 1993a. A study on extracting winter wheat area automatically from TM imagery using pattern recognition. *Remote Sensing Technology and Applications*, 3 (3). (in Chinese)

Wang Naibin, Zhou Yingchun, Lin Yaoming and Deng Kunmei, 1993b. Study on modeling winter wheat yield of large area using remotely sensed data. *Remote Sensing of Environment*, 8: 250 – 259. (in Chinese)