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Remote sensing based crop inventory: A review of Indian experience

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Abstract: This paper reviews the approach and techniques of Remote Sensing (RS) based crop discrimination and area estimation including single date approach based on maximum likelihood classification as well as hierarchical/ growth profile for crop classification. Uniqueness of both optical and microwave data for crop identification in operational scenario in Rabi and Kharif season is presented. In the past two decades, studies on RS based crop inventory of more than 20 crops at various spatial scales (village to national) have been conducted. In most of the studies a sampling-based approach using optimally acquired single date satellite data and a supervised classifier has been used. More recently, national scale inventory of wheat and rice using multidate WiFS and Radarsat, Synthetic Aperture Radar (SAR) data have been carried out. Studies on accuracies of area inventory led to understanding of effects of sensor characteristics such as spatial, spectral and radiometric resolution and scene characteristics such as field sizes, acquisition date etc. These experiences in Crop Area and Production Estimation (CAPE) project over past decade suggests that remote sensing inventory has matured in operational use. Future perspective such as utilization of multi-source data and merging techniques, fraction area estimation approaches, as well as integration of conventional field survey information with remote sensing data towards the FASAL concept is also presented.

Resumen: Este trabajo revisa el enfoque y las técnicas de discriminación de cultivos y de estimación de su superficie basadas en la Percepción Remota (PR), incluyendo el enfoque unitemporal - o de observación en fecha única- basado en una clasificación de Máxima Verosimilitud, así como una clasificación jerárquica por perfil de crecimiento para la clasificación de cultivos. Se presenta el carácter único de los datos ópticos y de los de microondas para identificar cultivos en escenarios de operación en la estación Rabi y Kharif. En las últimas dos décadas se han llevado a cabo numerosos estudios de inventario de cultivos basados en PR, para más de 20 cultivos y a varias escalas espaciales (poblado o nacional). En la mayoría de los estudios se ha utilizado un enfoque basado en un muestreo usando datos satelitales unitemporales adquiridos de manera óptima y un clasificador supervisado. Más recientemente se llevó a cabo un inventario a escala nacional de trigo y arroz usando datos multitemporales de tipo WiFS, Radarsat, y Radar de Apertura Sintética (RAS). Los estudios sobre la exactitud del área de inventario llevaron a entender los efectos de las características de los sensores tales como las resoluciones espacial, espectral y radiométrica, y las características de la escena tales como los tamaños de los campos, fecha de adquisición, etc. Estas experiencias en el proyecto Tamaño de Cultivo y Estimación de la Producción (CAPE por sus siglas en inglés) durante la década pasada sugieren que la realización de inventarios por medio de percepción remota ha madurado en su uso operativo. También se presenta una perspectiva hacia el futuro, incluyendo aspectos tales como la utilización de datos de fuentes diversas y técnicas de combinación, el enfoque de estimación de área fraccionaria y la integración de información convencional derivada del levantamiento de campo con los datos de percepción remota hacia el concepto de FASAL.

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Resumo: Este artigo revê a abordagem e técnicas de detecção remota (RS) na discriminação das culturas e estimação das suas áreas, incluindo o uso, numa única série de dados, baseados na classificação de plausibilidade máxima, bem como no perfil de crescimento/hierarquia para a classificação das culturas. A singularidade dos dados ópticos ou de microondas para a identificação de culturas num cenário operacional de uma estação em Rabi e Kharif é apresentada. Nas últimas duas décadas foram efectuados estudos usando a RS e baseados no inventário de mais de 20 culturas sob várias escalas espaciais (vila e nacional). Na maior parte dos estudos a abordagem teve por base uma amostragem que utilizou uma série optimizada de dados de satélite e um classificador supervisionado. Mais recentemente foi levado a cabo o inventário, a nível nacional, da cultura do trigo e do arroz utilizando a informação de dados múltiplos do WIFS, "Radarsat e do Synthetic Aperture Radar" (SAR). Os estudos sobre a exactidão da área inventariada conduziu à compreensão dos efeitos das características dos sensores tais como a resolução espacial, espectral e radiométrica e características espaciais como o tamanho dos campos, aquisição de dados, etc.. Estas experiências do projecto quanto ao inventário da Área das Culturas e Estimativas de Produção (CAPE), ao longo da última década, sugere que o uso da detecção remota é um instrumento operacional maduro. As perspectivas futuras, como sejam a utilização de informação de fontes múltiplas e de técnicas de amalgamação, abordagens de fraccionamento de avaliação de áreas, a par com a integração de informação convencional de inventário no terreno, com dados da detecção remota no sentido do conceito de FASAL, são também apresentadas.

Key words: Agricultural applications – India, crop acreage, crop identification, digital classification, remote sensing, sampling approach.

Introduction

The importance of agriculture for the Indian society can hardly be over-emphasized, as its role in economy, employment, food security, national self reliance and general well being, does not need reiteration. The need for timely and reliable information on crop area and production for tactical and strategic decision making by all stakeholders in agriculture, such as producers, processors, resource managers, marketing, finance and the government is well known. With the global shift in the market economies, reliable agricultural information has gained more importance than ever before. Remote Sensing (RS) using space-borne sensors is a tool, *par excellence*, for obtaining repetitive (with a range from minutes to days) and synoptic (with local to regional coverage) observations on spectral behavior of crops as well as their growing environment, i.e., soil and atmosphere. Use of this data could be made for a number of applications such as crop inventory, crop production forecasts, drought and flood damage assessment, range and irrigated land monitoring and management (Sahai & Dadhwal 1990). This review covers Indian experience on RS data use for crop inventory. A brief mention of conventional procedures of crop acreage estimation in India and the rationale of use of RS for crop inventory is made before reviewing the Indian experience.

Conventional procedures of collection of crop area statistics

The historic references to crop statistics generation in India date back to Kautilya's *Arthasastra* as well as Moghul era. The modern crop statistics form an uninterrupted series since the Government of India made a wheat assessment/forecast as early as 1884. Currently, the crop statistics cover 51 food crops and 15 non-food crops and are based on land revenue system. In three permanently settled states (Kerala, Orissa and W.Bengal), 20 percent sampling on rotation basis is used, north eastern states rely on ad hoc surveys, while multi season full enumeration approach is adopted in the remaining part of the country. Acreage estimates from these surveys have to pass through a hierarchy of aggregation of village, taluka, district and state level, which contributes to a delay in compilation of national forecasts. Shortcomings in the present crop information system in India include delay in reporting, rigidity of definition, non-sampling errors, inadequacy for forecasting and non-responsiveness to change in growing conditions or *episodic events*. Iyer (1991) reports about 20% of non-completion of enumeration in sample villages (mean for three years 1982-83 to 1985-85). In 67% of the survey numbers checked under Improvements of Crop Statistics (ICS) scheme by National Sample Survey Organisation (NSSO), there were no discrepancies in information filled by village functionaries. Non-reporting of crop sown occurred in 10-11%, whereas 3-4 % of survey numbers a crop not sown was reported. In 18-19 % of fields there was a discrepancy in reported crop area. The crop area ratio for village level worker and supervisor varied from 0.94 to 1.04 in the three years.

Global programs on crop inventory

Since the inception of civilian RS program in the U.S. in the early 1960s, a major research and development thrust has been agricultural crop identification and area estimation. A number of path breaking studies on use of aerial photographs and digital processing techniques were made before the launch of first earth observing satellite Landsat with its MSS (Multi Spectral Scanner) in 1972. Experiments such as Crop Identification Technology Assessment for Remote Sensing (CITARS) and Large Area Crop Inventory Experiment (LACIE) were conducted to demonstrate the capabilities of RS for crop inventory and forecasting (MacDonald 1984). CITARS demonstrated the usefulness of automated data processing techniques and space-borne data for corn, soybean inventory in U.S. LACIE was the first worldwide experiment to demonstrate the operational capability of RS technology for wheat production forecasting (MacDonald & Hall 1980). It featured use of Landsat MSS data for wheat acreage estimation and agrometeorological models for yield estimation. The results from LACIE were more reliable for the then USSR, and met the 90/90 accuracy criterion for the Great US Plains also. However, results for Canada, India, China, Australia, Brazil and Argentina, though encouraging, did not meet the 90/90 accuracy goal. United States Department of Agriculture as a user of RS technology took the initiative through Statistical Reporting Services (SRS) for integrating Landsat data in domestic crop estimation programme, which met 95/95 accuracy goal (Hanuschak *et al.* 1982). In this study RS data was used for stratification, for construction of area sampling frame and to classify the digital data of the sample segments.

Since then a large number of methodology development –cum- demonstration studies for crop monitoring have been carried out in Africa and Europe as well as in a number of other countries (Argentina, Australia, Brazil, Canada, Japan, etc.). Currently major operational programme is underway in Europe under Monitoring Agriculture through Remote Sensing (MARS) project. This project has, amongst its various objectives a rapid crop survey procedure, which uses a sampling approach, multi-date crop identification and field survey information for making Europe –wide crop area estimates (Sharman 1993).

Approaches of remote sensing based crop inventory

Crop discrimination is based on differential spectral response of various crops in a multi-dimensional feature space produced by different spectral bands, or time domain or both and is influenced by sensor characteristics as well as pattern recognition techniques. Interaction of electromagnetic radiation with crops is influenced by chlorophyll and water content in optical region, whereas crop geometry and dielectric property influences the response in microwave region. There are three broad approaches for use of remote sensing in generation of crop statistics: (1) RS forms a precious base for estimating parameters of spatial variablility, through area frame sample design. It provides an efficient and low cost stratification based on crop proportion derived from visual interpretation or digital classification of RS data. (2) Direct and independent estimation that uses RS data and pattern recognition technique to estimate crop area in the study region. (3) The use of RS data as an auxiliary variable which allows improving the precision of estimates based on ground surveys. It helps in reducing the amount of the field data to be collected, if the precision to be reached is fixed, On the contrary, if the sample size is fixed, this approach provides higher precision of the estimate. The steps involved in the crop acreage estimation using RS data are: (a) study area extraction, (b) crop discrimination/ identification from satellite data, (c) estimation of area under a crop in the study area, and (d) assessment of accuracy of crop identification and area estimates. A brief description of these steps is provided below:

Study area definition and extraction

As the satellite data is available in form of scenes covering fixed areas, the acreage estimates are obtained by overlaying the administrative boundary on the scenes and masking out pixels outside the boundary using a point-in-polygon algorithm. Although raw scenes could be used for overlaying boundaries by using control points, but the scene rectification is carried out for mosaicing map outputs or analysis in GIS system. Large area and rapid crop inventory requires, adoption of rigorous sampling approach and sample segments in form of square or rectangular subscenes are extracted for analysis.

The sampling approach requires the following parameters be defined for a study, segment size, spatial stratification, sample allocation, and sampling fraction. While LACIE adopted 5x6 nmi (9x11 km) segments and 2.5 % sampling fraction (MacDonald & Hall 1980), various other schemes have been adopted in other studies. Hallum & Perry (1984) have proposed an objective methodology for defining optimum sampling unit size which takes into consideration non-sampling errors in remote sensing as well as a model of sampling error variance as a function of segment size.

Crop discrimination

The crop discrimination/mapping using space data is carried out either by visual or digital interpretation techniques. Visual techniques generally are based on standard FCC (False Colour Composite) generated using green, red and near-IR bands assigned blue, green and red colours. Haack & Jampoler (1995) demonstrated that a colour composite formed by best three bands (TM bands 3, 4 & 5) gave better discrimination in comparison to standard FCC over a study site in Imperial valley, California. The digital techniques are applied to each pixel and use full dynamic range of observations and are preferred for crop discrimination.

A multi-temporal approach is used when single date data does not permit accurate crop discrimination. In this case, the procedure employs following three stages: (a) preprocessing, (b) data compression, and (c) *image* classification. The pre-processing includes multi-date registration and removal/ minimization of atmospheric effects through radiometric normalization or atmospheric correction. Although all the bands from multiple acquisition data set have been used in multi-date classification procedures (Bizzell *et al.* 1975; Bauer *et al.* 1979; Hixson *et al.* 1980). The data compression techniques are commonly adopted as for more than two dates the number of bands become very large. First four principal components (PC) from 3 date data from TM (15 bands, Band1 to Band5) in Germany (Mauser 1989) gave higher accuracies than various band combinations. The classification approach are similar to supervised or unsupervised as used in case of single date data, however, techniques involving graphical shape such as Profile modelling techniques, angular measures and Delta classifiers have also been used (Badhwar 1984). Campbell *et al.* (1987) has evaluated direct use of temporal spectral data for wheat acreage estimation in Australia. Use of discriminant function on total data set had improved separation than profile-based approach, with loss in separability occurring at both the data reduction steps, namely spectral to vegetation index (VI) and multi-date VI to spectral profile step. Belward & de Hoyos (1987) compared accuracy for crop classification between supervised Maximum Likelihood (MXL) and binary tree classification approaches. Although, similar accuracies were obtained by the two procedures, the ease or training in case of binary tree approach suggested that it is a viable alternative to MXL. Knowledge-based crop classification has been suggested by Janssen & Middelkoop (1992) where the crop rotation information about the area was formalised using Markov chains and transition matrix. These conditional probabilities and RS data were input for a Bayesian image classification.

Spatial-spectral procedures

While the traditional procedures adopt a per pixel approach, use of spatial information can improve accuracy of crop discrimination. The spatial information could be used in a number of ways such as field based classification, spatial-spectral segmentation and relaxation procedures. The most common being identification of a agricultural field by a spatial procedure, followed by classification of the field to a crop class. When the pixel size is much smaller than the field size, field demarcation followed by spectral classification based on mean spectral properties of the field has been shown to improve classification performance. Such an approach was adpoted in SECHO (Supervised Extraction and Classification of Homogeneous Objects) algorithm of Kettig & Landgrebe (1976). Meyer (1992) describes another approach which includes the steps of pre-processing (edge preserving filter), segmentation (region-based algorithm), symbolic descriptors of objects (of morphology and internal spectral data) which is followed by crop identification.

Spectral unmixing

Mixed pixels, which arise due to presence of more than one land cover type in a pixel, are a source of area error in conventional classifiers, which assign a pixel to a single class (Chhikara 1984). A number of spectral mixing models such as linear, probabilistic, geometric-optical, stochastic geometric and fuzzy have been proposed (Ichoku & Kanieli 1996) that describe spectral response of a mixed pixel. Inversion of these models, spectral unmixing, can resolve component landcover proportions. A number of studies have shown that such an approach gives improved land-cover estimation. For the purpose of crop inventory, Horowitz *et al.* (1971) applied probabilistic model to airborne data, while Quarmby *et al.* (1992) applied linear model to NOAA AVHRR data. Although, such models are promising tools, a number of validation and inter-comparison studies are needed for selecting an appropriate model for regular use in regional crop inventory.

Crop area estimation

The last step of crop inventory involves the estimation of crop area from the classified image generated by crop discrimination procedure. The following estimators are used:

Direct estimator

This is the simplest estimator, where in a study region of known total area D, the crop area (Z_c) is given as:

$$Z_c = D * (X_c/N_t)$$

Where, X_c and N_t are number of pixels in crop C and total number of pixels, respectively. Depending upon the classification accuracy the estimate could be biased. The information on the classification accuracy is used in the next set of estimators for obtaining improved crop area estimates (Maselli *et al.* 1990).

Global estimate using confusion matrices

If A is the confusion matrix on a test set, A_i the number of pixels classified into crop C_i (ground truth), A_j the number of pixels classified into land use C_j, and P_r and P_c matrices defined as:

$$P_{rji} = A_{ij}/A_{i.} \text{ and } P_{cij} = A_{ij}/A_{.j}$$

If P_r and P_c are unbiased estimators of the corresponding matrices for the whole population, the next area estimators are unbiased too (Hay 1988,1989; Jupp 1989):

$$Z_{dir} = D * (P_c{*}X/N_t) \text{ and } Z_{inv} = D * (P_r^{-1}{*}X/N_t)$$

This estimator exploits a larger part of information contained in the confusion matrix and give good results, but has not been widely adopted.

Regression estimator

Regression estimator uses both ground data and classified RS data for acreage estimation. The regression estimators are described in standard statistical texts (Cochran 1963). The formulation of separate form is:

$$\hat{Y}_R = \sum_{h=1}^{L} N_h \, \bar{y}_h \,(\text{reg})$$

Where,

$$\bar{y}_h(\text{reg}) = \bar{y}_h + \hat{b}_h\,(\bar{X}_h - \bar{x}_h)$$

b_h = regression coefficient for regressing ground-reported area on RS-derived area for stratum h and n_h segments.

$\bar{X}_h$ = average RS-based area for all frame units of stratum h (Thus entire area must be classified to obtain this mean of population, i.e., (X_{h_i}/N_h)

$\bar{x}_h$ = average RS-based crop area per sample segment of stratum h, i.e. (x_{hj}/n_h)

This approach has been extensively studied in USA where in June Enumeration Survey (JES) the crop data is collected on sample basis by questionnaire method. Other examples of application of regression approach are potato and canolarapeseed in Canada using Landsat MSS (Ryerson *et al.* 1985) and wheat in Brazil using Landsat MSS (Moreira *et al.* 1986). Gonzalez-Alonso & Cuevas (1993) show improved performance by using regression estimator with confusion matrix information over a test site in Spain. Gonzalez-Alonso *et al.* (1994) have compared results from regression approach using two different sampling approaches, namely square sample segments and irregular segments over a test site (900 sq km) in Spain. The weighted relative efficiency in case of square segment approach was higher than for irregular segment approach. Moriera *et al.* (1986) have used aerial photographs instead of ground survey and this could be replaced by use of very high spatial resolution satellite data (1-4 meter) which is becoming available now.

Indian experience on crop identification/discrimination

The first multi-spectral airborne study in the country in 1969 was jointly conducted by ISRO and ICAR and demonstrated identification of root-wilt disease in coconut using aerial false colour photograph over Kerala (Dakshinamurti *et al.* 1971). Since then, there have been many investigations on various aspects of crop identification and area estimation using air-borne to space borne sensors for different crops and agricultural regions in India.

Crop discrimination using RS data

A systematic study on crop inventory using CIR aerial data was carried out in the joint ISRO-ICAR Agricultural Resource Inventory and Survey Experiment (ARISE) project, which was conducted in Anantapur District (Andhra Pradesh) and Patiala District (Punjab) (Dhanju & Shankarnarayana 1978; Sahai *et al.* 1977). An interesting finding was under reporting of acreage of paddy, a levy crop by government agencies. In another aircraft-based experiment conducted in Karjan (Gujarat), it was possible to identify cotton cultivars and their vigour classes. In a multi-temporal study using 11-channel multispectral aerial scanner data over paddy and sugarcane growing area in Mandya (Karnataka), the NIR/Red ratio indicated different behavior due to crops, vigor and their stage. The spectral-temporal profiles with red and near infrared bands were used for crop identification and condition assessment (Ayyangar *et al.* 1980a, 1980b; Rao *et al.* 1982).

Early studies using space borne data employed visual mapping of crops such as wheat (Munshi 1982) and rice (Rao & Rao 1987; Singh 1983). Subsequently, the satellite based studies graduated from visual to digital analysis and by launch of IRS-1A, large projects such as Crop Acreage and Production Estimation (CAPE) were implemented covering large area crop inventory and yield modeling for important crops such as wheat, rice, cotton, groundnut, sorghum and mustard. A large body of experience has been gained in CAPE project on efficient sample design, factors affecting crop discrimination, spectral-yield relationships and realization of timeliness and accuracy for pre-harvest crop forecasts. Understanding of user requirements and various limitations in CAPE project has led to formulation of a proposal called FASAL (Forecasting Agricultural Output Using Space, Agrometeorology and Land-based Observations) to meet the stringent requirements of multiple, nation-wide and multi-crop forecasts. These developments have been summarized in the reviews by Navalgund & Sahai (1985), Sahai (1985), Sahai & Dadhwal (1990), Navalgund *et al.* (1991) and Dadhwal (1999).

There have been some efforts toward inventory of crops not covered in CAPE, and a summary of these studies is given in Table 1. A study to identify and map apple and almond plantations in Shimla district of Himachal Pardesh was carried out using IRS-1A & 1B, LISS-1 and LISS-II data. Overall accuracy for identification was 87% for 90 % confidence interval. Sharma (1995) delineated four vigour classes of coconut crop in Allepy district of Kerala. Panigrahy & Chakraborty (1996) reported mapping of potato crop using multi-date RS data. Vyas *et al.* (1993) reported RS based acreage estimate of chickpea using IRS-1A LISS-I data. The relative deviation of acreage estimate was 1.89% to that of official estimate by Bureau of Economics and Statistics (BES) in Hamirpur District of U.P. A study was conducted for identification and acreage estimation of *Mentha arvensis* using IRS –1C LISS – III data as no government estimates are made for this crop (Patnaik *et al.* 1998).

Microwave data has special significance for crop inventory in kharif (monsoon) season owing to its all weather capabilities. Exploratory studies were conducted for Kharif crops e.g. rice, groundnut, using ERS SAR data (Premlatha & Rao 1994;

Table 1. Experience of remote sensing studies on minor crops in India.

Crop	Distt./State	RS data	Approach*	Result/Accuracy	Reference
Apple	Shimla/H.P	IRS-1A, LISS – II, 1996	V. A, 1:50,000 scale	87% & 90% C.A.	1
Arecanut	Sirsi taluka/Uttar kannada	IRS-1A, LISS – II, Jan. 1991	V. A, 1:50,000 scale		2
Bengal gram	Hamirpur/U.P	IRS-1A, LISS – II, Feb. 1992	D.A, C.E	R.D. 1.89%	3
Coconut	Allepy / kerala	IRS-1A	D.A, C.E	Four vigour classes separable	4
Mango	Valsad / Gujarat	IRS-1B /LISS-II, 1993	D.A, C.E		5
Mentha	4 districts of U.P.	IRS-1C/LISS-III, 1998	D.A, C.E	89.7 to 95.1% C.A.	6
Mulberry	Malavalli/Mandya dist., Yelandur/Mysore dist.	IRS-1A, LISS – II, 1991	D.A at taluka level		7
Orange		IRS	D.A at taluka level		8
Potato	Bardhaman/ W.B.	IRS-1C/LISS-III, 1996	D.A, C.E		9
Soyabean	Chambal command area/ M.P.	IRS-1C/LISS-III, 1996	D.A, C.E		10
Tobacco					11
Tea	Nilgiri/ T.N.	MSS & TM of 1991	D.A, C.E	R.D 1.67 to 23.2%	12

* V.A. = Visual analysis, D.A. = Digital analysis, C.E = Complete enumeration method, C.A. Classification Accuracy, R.D.= Relative Deviation

1. Kimothi *et al.* 1997; 2. Hegde *et al.* 1994; 3. Vyas *et al.* 1993; 4. Sharma, R. 1995; 5. Ray *et al.* 1993; 6. Patnaik *et al.* 1998; 7. Nageswararao *et al.* 1991; 8. Sinha & Karale 1992; 9. Panigrahy & Chakraborty, 1996; 10. Kalra *et al.* 2000; 11. Adiga, S. 1992; 12. Sharma *et al.* 1993.

Patel *et al.* 1995) whereas RADARSAT data is currently being used for operational rice crop inventory at state and national scale (Panigrahy *et al.* 2000). Detailed studies using microwave data analysis show that rice and potato crop can be discriminated at better that 90% accuracy, and early detection with multiple forecast is possible (Chakraborty *et al.* 1997; Panigrahy *et al.* 1997). The overall accuracy of 70.35% was obtained for multi crop (wheat, potato) discrimination in Nalanda district, Bihar using two date SAR data (Dutta *et al.* 1998).

Indian studies on factors affecting crop identification

The accuracy of crop identification is determined by sensor parameters, scene characteristics as well as the analysis approaches. The crop inventory using space borne sensor data faces tougher technical challenges in India (Sahai 1985) due to (a) small field sizes, (b) a large diversity of crops sown in an area, (c) large field-to-field variability in sowing and harvesting dates, cultural practices and crop management, (d) large areas under rainfed/dryland agriculture with poor crop canopies, (e) practice of inter-cropping and mixed cropping, and (f) extensive cloud cover during kharif crop season. Some of the important studies describing effects of sensor and scene characteristics on crop identification are given below:

Sensor characteristics

The spectral, spatial and radiometric characteristics of the sensor affect crop identification. The narrow bands of TM and LISS-I and LISS-II can lead to higher classification accuracy than MSS (Dadhwal & Parihar 1988). The low radiometric resolution of 6 bits in MESSR resulted in lower classification accuracy than LISS-I (Dadhwal & Parihar 1990). Studies on MOS-B indicated improved discrimination as radiometric resolution increased from 4 to 6 bits as well as 6 to 8 bits (Singh *et al.* 2001). Higher accuracy of acreage estimate with TM in comparison to MSS has been noted for rabi sorghum in Solapur, Maharashtra (Potdar *et al.* 1991).

The spatial resolution and classification technique together have a bearing on classification accuracy since with higher spatial resolution per-field techniques give higher accuracy than per-pixel techniques. Higher crop classification accuracy using only three band data with SPOT in comparison to TM has been noted in Gujarat by Sahai *et al.* (1989). Higher inventory accuracy at village level for cotton has been noted for LISS-II in comparison to LISS-I in Haryana (Dutta *et al.* 1994). Singh *et. al.* (2001) studied the effect of spatial resolution on crop classification with help of IRS-LISS-III, LISS-II, LISS-I, WiFS and simulated data over central Madhya Pradesh and found that accuracy of wheat classification increased considerably from coarse resolution (188 m) to moderate resolution (100 m) and remained relatively flat over a range of higher spatial resolution (Fig.1) till it increased at 23 m resolution. The use of higher spatial resolution can sometimes lead to lower classification accuracy than moderate resolution especially when training sites and locations are kept constant due to increased variance of training sites (Dadhwal & Parihar 1988; Medhavy *et al.* 1993). Markham & Townshend (1981) have shown that two counteracting factors affect classification accuracy as a function of spatial resolution. With higher spatial resolution, spectral heterogeneity increases leading to higher overlap between classes and decreased classification accuracy but proportion of boundary pixels reduces which leads to reduced misclassification.

Inclusion of new spectral regions can bring more information that can be useful in crop discrimination. Thus, classification using MIR shows improved crop separability (Fig. 2) in wheat, gram and mustard growing region (Dadhwal *et al.* 1989). Similar results have been obtained for groundnut-other crop separation (Sharma *et al.* 1990) and rice-other vegetation separation (Panigrahy & Parihar 1992). Even in MIR region, better crop discriminability using TM5 in comparison to TM7 has been observed, which could be related to the higher within crop variability in TM7 (Dadhwal *et al.* 1996). Improved discrimination has also been reported with inclusion of MIR in simulated LISS-III (Patnaik & Dadhwal 1995) and IRS-1C LISS-III (Navalgund *et al.* 1996) data.

Scene characteristics

The important scene characteristics controlling accuracy of RS-based crop inventory are time of acquisition, soil and crop characteristics, field sizes, crop proportion and atmospheric conditions during satellite over pass. The field size was

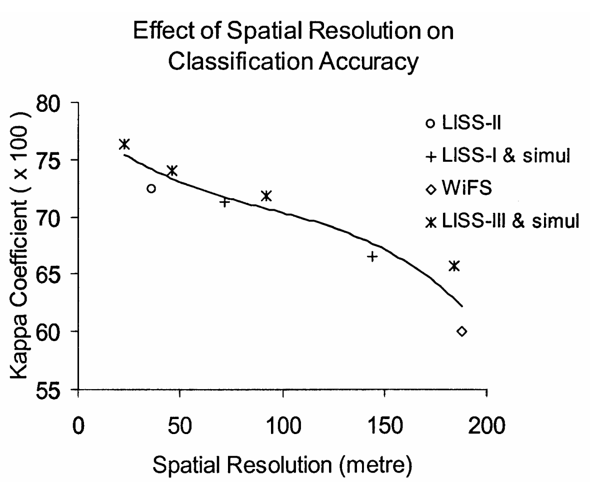

Fig. 1. Effect of crop classification accuracy assessed with IRS LISS-I, LISS-II, LISS-III, WiFS and simulated data over wheat dominated agricultural region in central Madhya Pradesh, India.

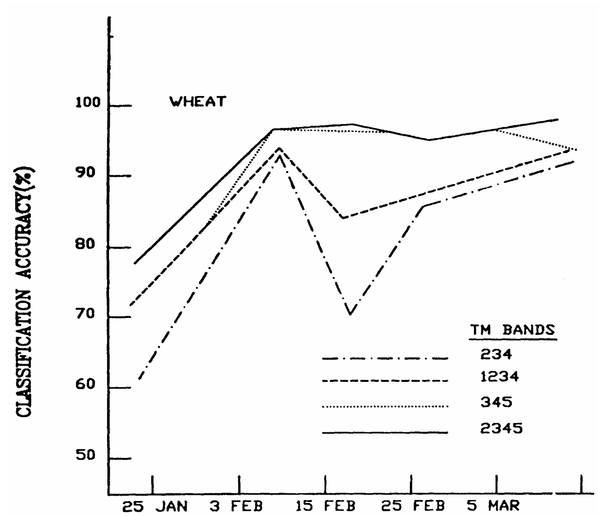

Fig. 2. Effect of different spectral band combinations and date of acquisitions on crop classification accuracy assessed using Landsat TM data over wheat dominated region in Haryana, India.

shown to have a strong effect on classification accuracy with small fields tending to have lower accuracies even when the effect of mixed pixels was eliminated (Batista *et al.* 1985; Buechel *et al.* 1989).

In a site having wheat, gram, mustard and lentil in Hisar (Haryana), large variation in classification accuracy (Fig. 2) has been demonstrated (Dadhwal *et al.* 1989; Dadhwal *et al.* 1996). Use of early acquisition, in comparison to peak vegetative growth stage, resulted in underestimation of wheat in Haryana (Dadhwal *et al.* 1990). The early stage data are associated with higher between-field as well as within-field spectral variability (Ruhal *et al.* 1988), which adversely affect crop discrimination using supervised MXL approach. A study on rice acreage estimation using NOAA AVHRR data (1989-90) season showed best inventory with October acquisition with overestimation of acreage in earlier dates and underestimation due to progressive ripening in later acquisitions (Panigrahy *et al.* 1992). In case of wheat and mustard acreage estimation in Rajasthan, late December/early January acquisition are optimal for mustard with large errors in wheat estimates while February acquisition is optimal for wheat and mustard area is underestimated as majority of crops have ripened (Purohit *et al.* 1997).

Approach and results of crop inventory at different spatial scales

Village level crop inventory

Studies on village level inventory have been conducted for accuracy estimation of RS based crop inventory. Studies on cotton in Badopal village, Hissar district , Haryana (Dutta *et al.* 1994), wheat and mustard in Khimara and Bangari village in Pali district, Rajasthan (Purohit *et al.* 1997) show that area deviations of less than five percent in comparison to field survey are observed. In a recent study conducted jointly by NSSO and SAC, village level inventory was carried out for six randomly selected villages in three districts (Karnal in Haryana, Kota in Rajasthan and Bhopal in Madhya Pradesh) during rabi 1999-2000. The accuracy of RS-based crop inventory was shown to be influenced by (a) data used for overlaying village boundary (IRS LISS-III or PAN), (b) availability of ground truth in village/ surrounding area and (c) target crop proportion. The results are summarized in Table 2 and indicate the area inventory accuracy of 90% using single date LISS-III data and use of PAN for overlaying village boundary. This highlights need for procedure upgradation for achieving higher accuracies. Chakraborty *et al.* (1995) also found that relative deviations in crop area estimations from digital anlysis of Landsat TM data and visual interpretation of CIR aerial photographs varied with crop proportion (Fig. 3) over a rice dominated region of Orissa. Since crop proportion had dominant influence on accuracy and all cropped fields were not resolved by LISS-III, the proposed LISS-IV on IRS-P6 would significantly improve accuracy of RS based village level inventory.

District level crop inventory

Munshi (1982) used Landsat MSS data and visual interpretation technique for wheat inventory in four districts of Punjab. Area under summer rice in Cachar district of Assam was estimated by visual interpretation of Landsat MSS data by Singh (1983) and analysis over areas in Andhra Pradesh by Rao & Rao (1987) indicated accuracies varying from 90 percent when rice oc-

Table 2. Crop area estimation in six villages carried out using Remote Sensing IRS-LISS-III data as well as detailed field survey by NSSO during rabi 1999-2000.

Village name, District, State	Village Area (ha)	Main crop	Other crop	Main crop Area (%) RS	Other crop Area (%) RS	Main crop area Field Survey (%)	Other crop Area Field Survey (%)
Baldi, Karnal, Haryana	236.97	Wheat	Fodder	51.24	-	44.73	11.58
Mainmati, Karnal, Haryana	316.98	Wheat	Fodder	63.81	-	66.28	13.6
Ranpur, Kota, Rajasthan	3868.23	Wheat	Mustard	5.36	7.83	4.37	7.18
Ghatoliya, Kota, Rajasthan	151.23	Wheat	Mustard	34.29	28.94	30.93	32.19
Anwala, Bhopal, M.P.	1450.77	Wheat	Gram	33.66	13.74	31.46	14.82
Gondakheri, Bhopal, M.P.	280.00	Wheat	Gram	33.34	13.34	30.77	23.03

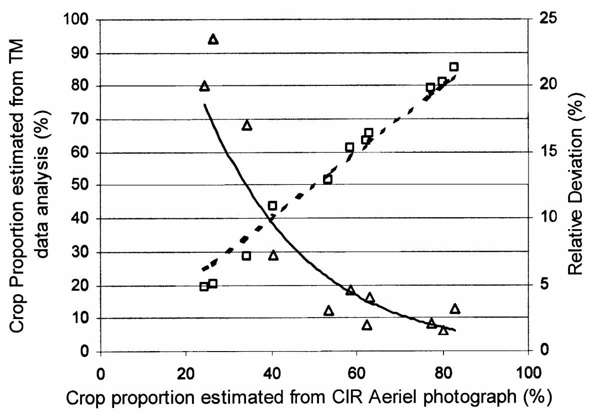

Fig. 3. Crop classification accuracy assessment based on digital analysis of Landsat TM data and visual interpretation of CIR aerial photographs in rice dominated agricultural region of Kalahandi district of Orissa state, India (Redrawn from Chakraborty *et al.* 1995).

cupied more than 50 percent of geographic area to 75 percent at lower crop proportions. The visual interpretation-based studies have not been pursued for large-scale adoption.

The investigations for use of spaceborne RS digital data for crop acreage estimation and production forecasting were taken up at Space Applications Centre with various collaborating agencies under IRS-Utilisation Programme in 1983. The studies were initiated in selected districts for wheat, rice and groundnut. The first study on wheat acreage estimation for Karnal was carried out in 1983-84 season (Dadhwal & Parihar 1985). The promising results led to an attempt to estimate state-level wheat acreage estimate using Landsat MSS data for Haryana and Punjab in 1985-86 (Dadhwal 1986) for which a sample segment based approach of 10x10 km segments and 10 per cent sampling fraction was adopted. The results were considered encouraging and a project called Large Area Crop Acreage (LACA) was initiated. It became a sponsored project by Ministry of Agriculture and yield forecasting was included and since 1988 is known as 'Crop Acreage and Production Estimation' (CAPE) project. It initially covered wheat, rice, groundnut and rabi sorghum in major growing districts and later mustard, sugarcane and cotton were also included for study.

The studies on crop inventory at district and state level were initiated with Landsat MSS data (Dadhwal & Parihar 1985; Dadhwal 1986) and it was the main sensor used in subsequent studies. With launch of IRS series, LISS-I was adopted (Dadhwal *et al.* 1991; Mahey *et al.* 1993; Panigrahy *et al.* 1991; Sridhar *et al.* 1994) as major data source. Use of Landsat TM has been made for some studies as for sorghum (Potdar *et al.* 1991) or as fall back option when cloud free acquisitions have not been available for the main sensor viz., rice in Orissa 1989-90 (Panigrahy *et al.* 1991), groundnut in Gujarat 1993-94 (Pokharna *et al.* 1994). In areas where more than one crop predominates, LISS-II has been preferred such as for mustard in Gujarat (Sharma *et al.* 1991), Assam (Sharma *et al.* 1993) and Rajasthan (Ravi *et al.* 1997). Use of NOAA-AVHRR data for crop acreage has been done to study feasibility of acreage estimation at state and group of districts level, when cloud free data from high spatial resolution sensors could not be acquired for rice in Orissa in 1989-90 season (Panigrahy *et al.* 1991) or for large areas with single crop such as rabi sorghum in Maharashtra.

The initial approach for district-level studies was to overlay district boundary by transforming it to image coordinates and study pixels inside the boundary. In this case a systematic sampling of alternate or every third pixel and scanline was adopted to reduce data load (Dadhwal & Parihar 1985). This was adopted in later studies for other crops (Ray *et al.* 1993). However, with improvements in computational facilities, such an approach seems no longer necessary. In order to estimate acreages for large study areas, a sample segment approach was first adopted for wheat in Haryana and Punjab (Dadhwal 1986). This approach has been followed in CAPE Project for district and state level studies and has also been adopted for national level studies with multidate WiFS data (Oza *et al.* 1996).

Supervised classification of single optimally acquired image using MXL is the standard classification approach followed in CAPE. Medhavy *et al.* (1993) showed that when supervised classification is adopted, use of training strategy based on selection of isolated pixels has higher classification accuracy than selecting blocks of pixels as training set. This is due to spatial autocorrelation amongst the digital counts of pixels, so that block training sites do not represent independent sets of observations to the classifier.

Interaction of classification techniques with sensor characteristics in controlling classification accuracy has been pointed out above. This is im-

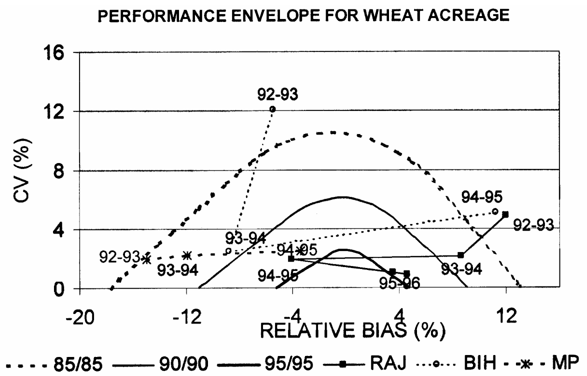

Fig. 4. Remote sensing based wheat area estimation performance in different years in Rajasthan, Bihar and Madhya Pradesh, India.

portant for higher spatial resolution data where per field techniques have been shown to perform better than per-pixel classification techniques. However, this would also depend upon the size of fields, as even with 20 m spatial resolution many of crop fields will not be individually identified in India (Dadhwal *et al.* 1990; Sahai *et al.* 1989). The procedures developed under CAPE used single-date high resolution RS data and provided estimates at district and state level. The performance of wheat area estimates for Madhya Pradesh, Bihar and Rajasthan states along with relative deviation and coefficient of variation is shown in Fig. 4.

National level wheat inventory

Use of coarse resolution and high repetivity WiFS data has been explored for national scale inventory of wheat and rice since 1995-96 season (Oza *et al.* 1996). The procedure uses a national-level sampling frame and coarse sample segment grids (20x20 km or 15x15 km). The most recent use of this approach was in 2000-2001 wheat season, during which multiple forecasts (total rabi crop-using data upto early February, mid season assessment-data upto end February and final forecast - March end) as well as inter-seasonal crop growth differences using multi-year WiFS data were demonstrated.

Use of Arc/Info GIS in National- level wheat estimation is made for making area sampling frame, storing segment-wise crop proportions for acreage estimation and computation of mean VI for condition assessment. The multi-date WiFS data is classified using a hierarchical decision-rule based classifier (Bhagia *et al.* 1997).

Improvements in crop discrimination

Multi-sensor data

The data from various sensors could be combined to produce products with higher information content and utility, requiring development of fusion as well as analysis procedures. The examples include, merging of multi-spectral (LISS-III) data with higher spatial resolution panchromatic data, merging multiple date SAR data or optical and SAR data, merging data from multiple view angles for BRDF extraction etc.

An attempt was made to compare various data fusion techniques for merging LISS-III and PAN at field / village level crop studies. The merged product based on Intensity, Hue and Saturation (IHS), Brovey and Wavelet transformation enhanced the image contrast and allowed the detailed identification of field boundaries as compared to the LISS-III image on visual inspection. In case of digital analysis, the techniques were evaluated with respect to preservation of multispectral signatures and NDVI of raw and fused products. Signature analysis indicated that except, IHS transformation, both the Wavelet and Brovey techniques preserved the NDVI signature.

Spectral unmixing

Crop area estimated from per pixel classification approaches holds good when the spatial resolution of the sensor is high enough to maintain the spectral purity of the pixels. As spatial resolution of the sensor designed for repetitive monitoring are coarser, approaches based on fractional estimation of crop area can be used in these conditions. Even for high resolution data, this technique can be adopted for very precise area estimation of land-cover classes. Singh *et al.* (1999) made an attempt to derive subpixel fraction wheat proportion from IRS-P3 MOS-B data using linear spectral unmixing. Sub-pixel wheat proportion estimated using all bands of MOS-B data showed high correlation (0.82) with wheat proportion estimated from corresponding WiFS pixels.

Integration of conventional and remote sensing techniques

The experience gained over more than a decade of implementation of CAPE project has been used in formulating a project FASAL (Forecasting Agricultural output using Space, Agro-meteorology and Land-based Observations) to meet requirement of timeliness, accuracy and nation – wide coverage of major crops. This project is likely to be implemented by Department of Agriculture and Cooperation with support from DOS in X[th] five year plan. It advocates an integrated approach, which uses inputs from the three types of observations namely field survey, weather and space to make multiple, in-season forecasts of desired coverage, accuracy, and timeliness. Development of technique and demonstration of national level wheat acreage estimate using multi-date WiFS and rice by multi-date RADARSAT forms a technological input to FASAL.

An approach for multiple in-season acreage estimates combining RS and weather based models as envisaged under FASAL has been investigated in Orissa. In the first step, it uses rainfall observations between June 1 to July 15 and a multiple regression approach for forecasting rice acreage for four agro-climatic zones (Northern plateau, Central tableland, Coastal delta and Eastern ghat). Subsequently, the forecasts use truncated weather upto August and later a SAR- based acreage estimate is obtained. The comparison of in-season forecast by models with estimates provided after harvest by Directorate and Economics and Statistics has shown deviation of three per cent at state level and larger at agro-climatic zone level (Fig. 5). This pilot study has demonstrated multiple forecasts of rice area and production in Orissa state as envisaged in FASAL (Patel *et al.* 1999).

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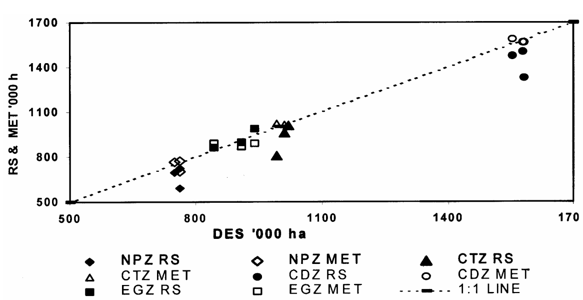

Fig. 5. Comparison of rice acreage forecasts using meteorological and SAR data with DES estimates for various zones in Orissa. (NPZ – Northern plateau zone, CTZ – Central tableland zone, CDZ – Coastal delta zone, EGZ – Eastern Ghat zone), RS – Remote sensing forecast, MET – Meteorological forecast).

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