

Wheat yield modelling using satellite remote sensing with weather data : Recent Indian experience

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सार – अंतरिक्ष वाहित दूर संवेदी आँकड़ों का उपयोग करके भारत में गेहूँ के उत्पादन के मॉडलों की नवीन पद्धतियों और विकास पर हाल में किए गए कार्य की इस शोध-पत्र में चर्चा की गई है। फार्म और जिला स्केल पर प्रत्यक्ष वानस्पतिक सूची (वी.आइ.) – उत्पादन आनुभविक निदर्श से उत्पादन में होने वाले महत्वपूर्ण परिवर्तन के बारे में पता चलता है। स्थान और सेंसर लक्षणों तथा फसल विभेदन के संबंध में इन निदर्शों की संवेदनशीलता निर्धारित की गई है। फार्म और जिला स्केल पर दाना बनने की अवस्था में मौसम के आँकड़ों सहित प्रत्यक्ष वानस्पतिक सूची-उत्पादन निदर्शों में हुए सुधार के बारे में इसमें बताया गया है। एल.ए. आई. के व्युत्पन्न के माध्यम से उत्पादन संबंधी माडुलन तथा दूर संवेदी आँकड़ों से स्पैक्ट्रल इमरजेंस और पीक वेजिटेटिव स्टेज के लिए भौतिक पद्धतियों के उपयोग के बारे में इसमें बताया गया है। सबसे सटीक पाई गई पद्धति फसल अनुकरण माडलों के उपयोग से संबंधित है जो अतिरिक्त दूर-संवेदी व्युत्पन्न एल.ए.आई. के साथ दैनिक मौसम आँकड़ों से फसल की प्रतिक्रिया को स्वभाविक रूप से समाकलित करती है। कृषि क्षेत्रों और क्षेत्रीय स्केल पर ऐसे अध्ययनों के परिणामों की इसमें समीक्षा की गई है।

ABSTRACT. Recent work on new approaches and development of yield models for wheat-using space borne remote sensing data in India is discussed. Direct vegetation index (VI)-yield empirical models at farm and district scale explain significant variation in yield. The sensitivity of these models to scene and sensor characteristics and crop discrimination has been quantified. Improvements in direct VI-yield models through addition of weather data during grain filling stage has been demonstrated at farm and district scales. Use of physical approaches for yield modelling through derivation of LAI and spectral emergence and peak vegetative stage from RS data has been presented. The approach showing most promise is to use crop simulation models that inherently integrate response of crop to daily weather inputs with additional RS-derived LAI. Results from such studies in farmer's fields and at regional scale are reviewed.

Key words – Leaf area index, Vegetation index, Remote sensing, Simulation model, GIS, Regional yield prediction.

1. Introduction

Crop yield is determined by a number of factors such as genetic potential of crop cultivar, soil, weather, cultivation practices (date of sowing, amount of irrigation and fertilizer) and biotic stresses. However, generally for a given area, year-to-year variability has been mostly modeled through weather as a predictor using either empirical or crop simulation approach. With the launch and continuous availability of multi-spectral (visible, near-infrared) sensors on polar orbiting earth observation satellites (Landsat, SPOT, IRS, etc) remote sensing (RS) data has become an important tool for yield modelling. RS data provides timely, accurate, synoptic and objective estimation of crop growing conditions or crop growth for developing yield models and issuing yield forecasts at a

range of spatial scales. RS data have certain advantage over meteorological observations for yield modelling, such as dense observational coverage, direct viewing of the crop and ability to capture effect of non-meteorological factors. Recent studies indicate that integrated use of RS and weather can be very effective tool for yield modelling. These RS-based yield forecasts can be combined with acreage estimates from RS-based crop inventory (Dadhwal *et al.*, 2002) for making pre-harvest production forecasts.

In this paper, recent research experience on the use of space-borne RS data with/without meteorological information for wheat yield modelling in India is presented. The studies covered are (i) direct use of vegetation indices (VI) and empirical form for yield

TABLE 1
Quantification of effect of various sources of error on estimated NDVI and predicted yield for Bhopal district, M.P., India

Sources of error	Error in (%)		
	NDVI	Predicted yield	
Sensor radiometry			
Noise equivalent change in reflectance ($\Delta\rho$)	0.25%	0.5	0.4
	2.0%	4.2	3.5
Date of acquisition			
Shift from peak vegetative stage	7 days	0.7	0.6
	12 days	2.1	1.7
Atmospheric effects			
Visibility	16 km	3.1	2.6
	5 km	13.6	11.4
Crop discrimination			
Relative deviation in area estimation	1%	1.0	0.8
	5%	5.0	4.2

models, (ii) combined use of RS and meteorological data for yield models, (iii) extraction of crop parameters [leaf area index (LAI), phenology] from RS data for use in yield models and (iv) use of crop simulation models (CSM) for yield modelling with RS inputs at field to regional scales. The emphasis is on studies on wheat, with details on recent work after the reviews of Indian experience on use of RS data by Dadhwal (1999) and Dadhwal and Ray (2000).

2. Direct VI -yield empirical models

Various VI have been used in RS literature by combining red and near-infrared and sometimes additional reflectances, in ratio or other algebraic expressions, as a means of expressing crop vigour, LAI or biomass. The direct VI-yield empirical approach is based on results from a large number of ground studies where high correlation between VI at specific stage and final grain yield has been observed. Barnett and Thompson (1983) demonstrated use of this approach with satellite data of both medium (MSS) and coarse (NOAA AVHRR) spatial resolution for wheat crop in USA. The scientific rationale for direct linear VI-yield relation is provided by Spectral Component Analysis (SCA) approach of Wiegand *et al.*, (1986), which relates asymptotic increase in both VI and yield to LAI, resulting in the following:

$$\text{LAI/VI} \times \text{YIELD/LAI} = \text{YIELD/VI} \quad (1)$$

This equation relates the two identities through LAI/VI and also indicates a direct VI -yield model.

2.1. Single-date RS data

Early studies on wheat in Haryana for 1983-84 season indicated significant correlation between Normalized Difference Vegetation Index (NDVI) and

average district yields (Dadhwal, 1986). This approach was adopted for developing district-level yield forecast models based on multi-year average wheat NDVI near peak vegetative growth stage. In order to account for variation in acquisition date or sensor, normalization to standard acquisition date and at sensor radiance was found necessary (Sharma *et al.*, 1993). This approach was adopted for regular in-season forecasting for study districts in Punjab, Haryana, Rajasthan, Madhya Pradesh and Bihar under the CAPE (Crop Acreage and Production Estimation) project (Navalgund *et al.*, 1991; Dadhwal & Ray, 2000). However, this approach could not regularly achieve reliable pre-harvest forecast (<10% bias) as (i) the effect of weather after the acquisition date of RS data was not captured, (ii) fixed acquisition date normalization approach could not capture the year-to-year crop phenology variations, (iii) errors of crop identification and classification resulted in uncertainty in wheat VI, (iv) the average wheat VIs were not corrected for the atmospheric effects and (v) since each regression model included RS data for a set of districts for few years, the models were not specifically sensitive to year-to-year variation in wheat yield.

The sensitivity of VI-yield empirical model to four major sources of error, namely, radiometric resolution, date of acquisition, atmospheric effects and misclassification, was investigated for Bhopal district (Singh *et al.*, 2002a). It was found that a sensor with radiometric resolution (noise equivalent change in reflectance) of 0.25% had an inherent uncertainty of 0.5% in NDVI estimation, which can result into 0.4 % error in yield prediction (Table 1) in this case. A shift in data acquisition by one week away from peak VI date introduced an error of 0.7 % in NDVI and 0.6 % in predicted yield. When atmospheric visibility decreased from the reference clear atmosphere (visibility 63 km), the relative error in NDVI gradually increased to 3.12% at a visibility of 16 km and reached 13.63% at a visibility of 4.72 km. These resulted in error in yield prediction of 2.6% and 11.4 %, respectively. It was also observed that there is 1.0 % change in the area weighted NDVI and 0.84 % error in yield estimation due to one percentage error in estimating crop area.

2.2. Multi date RS-data based models

An approach for using multi-date RS data for yield models using a non-linear form of VI-yield relation was suggested by Dadhwal and Sridhar (1997). Multi-date RS data from NOAA-AVHRR was used to model wheat spectral profile based on a model suggested by Badhwar (1980) and derived parameters related to district-level wheat yield in Punjab and Haryana (Dubey *et al.*, 1991;

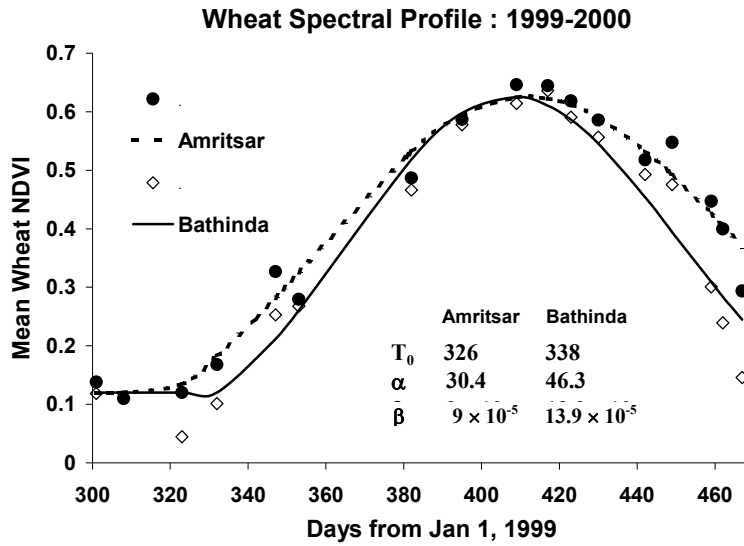


Fig. 1. Wheat spectral profiles for Amritsar and Bathinda districts derived from IRS WiFS data. (Eqn. 2 in text for meaning of symbols T_0 , α , β)

Kalubarme *et al.*, 1997). Badhwar (1980) described wheat growth profile by the following functional form:

$$G(t) = G_0 \quad \text{for } t < T_0 \quad (2)$$

$$G(t) = G_0 * (t/T_0)^\alpha * \exp [-\beta (t^2 - T_0^2)] \quad \text{for } t \geq T_0 \quad (3)$$

where, $G(t)$ is the wheat greenness (a form of VI) at time t , G_0 is the soil greenness at the spectral emergence day (T_0) and α and β are crop specific constants ($\alpha > 0$ and $\beta > 0$).

$G(t)$ attains peak value G_{max} at time T_{max} and is estimated as:

$$T_{max} = (\alpha/2\beta)^{1/2} \quad (4)$$

The width of the profile (σ) *i.e.* difference between first and second point of inflexions on the profile, is given by:

$$\sigma = (1 / \beta)^{1/2} \quad (5)$$

The Multi-date IRS Wide Field Sensor (WiFS) derived NDVI have been used to develop relationship between district-wise wheat yield and crop spectral profile parameters (Rajak *et al.*, 2002). Multiple acquisitions of WiFS data over Punjab were used for crop/wheat discrimination using a hierarchical decision rule based procedure (Oza *et al.*, 1996) and for developing spectral crop growth profile. District-wise crop spectral growth profile was parameterized using Badhwar (1980) crop

TABLE 2

Relating district level wheat yield for Punjab (1999-2000, $n=16$) to RS parameters from IRS WiFS

Model	Independent Variable(s)	R^2	Adj_ R^2	SEE
I	Max_NDVI (Observed)	0.412	0.370	0.309
II	G_{max} : Max_NDVI (Profile derived)	0.688	0.665	0.226
III	α , β , G_{max} , T_{max} , σ	0.863	0.794	0.177

Note : SEE: Standard Error of Estimate, Symbols in Model III refer to Eqns. 3-5.

spectral profile model on NDVI for 17 acquisitions of WiFS in Punjab for 1999-2000 season. Spectral wheat profiles for Amritsar and Bathinda districts are shown in Fig. 1. Wheat crop in Amritsar has earlier emergence and a longer duration as compared to Bathinda.

The results from linear regression between NDVI and district-level wheat yields of Punjab are summarized in Table 2. When the observed maximum NDVI were used as independent variable (Model I), a coefficient of determination (R^2) of 0.412 was observed. This increased to 0.688 when peak NDVI values estimated from crop spectral profile were used (Model II). A multiple linear regression analysis with all profile parameters (α and β) and the derived parameters (G_{max} , σ) gave a R^2 of 0.863 (Model III).

2.3. Combined VI-weather based models

An eleven years (1989-90 to 1999-2000) registered data set derived from IRS sensors (LISS II and LISS III) was created for Kota district, Rajasthan, India. Thirty-two images (25 LISS II and 7 LISS III) of December and February were registered to a LISS III geo-referenced scene. A stratified sample of 5 × 5 km segments was used for wheat acreage estimation using February date. Classification accuracies for different years ranged from 81-89 percent, and the estimated wheat acreage was within seven percent of Board of Revenue estimates, except for 1991-1992 where the deviation was around 20 percent. Wheat crop NDVI, after inter-sensor normalization, path radiance correction and acquisition date normalization could explain about 50 percent of the yield variations (Jaishankar *et al.*, 2001). However, when the mean night temperature during first fortnight of March (MNT) was used as an additional predictor, 80.5 percent of yield deviations [Y(dev)] from trend could be explained and the following model (Jaishankar *et al.*, 2002) was developed:

$$Y(\text{dev}) = 3.26 + 5.148 * \text{NDVI} - 0.173 \text{MNT} \quad (6)$$

The district level studies relate average wheat yield with estimated average vegetation indices over the district. The farm level yields are characterized by large variability due to variations in local soil and management practices. Since the farm level yields are known with higher confidence, they provide an opportunity for detailed analysis of yield characterization through RS inputs as well as possibility of application of the model at field scale for large area yield computations. While the sensors like Landsat MSS and IRS LISS-I lacked the required spatial resolution to resolve fields in India, which typically are in the range 0.05-0.5 ha, a large proportion of individual fields can be resolved with LISS-III sensors. Recently, studies have been carried out to study yield-VI relationship and effect of date of acquisition normalization and post anthesis temperature.

Farm-level wheat yield prediction using LISS-III was studied with field data spread over four crop seasons (1996-97 to 1999-00) for a total of 39 fields in the Seed Production Farm of Govind Ballabh Pant University of Agriculture and Technology (GBPUA&T), Pantnagar (Nain *et al.*, 2001). The sowing dates varied from November to January and yields between 1.27 and 5.16 tha^{-1} with mean yield being 2.99 tha^{-1} . The NDVI of individual fields was computed after LISS-III digital counts were converted to radiance (rad) and dark object subtraction (DOS) was applied to obtain red and near infrared reflectance. Although RS data was acquired in a narrow range between February 20 and March 2, these

dates and corresponding NDVI(raw) pertain to highly variable age of crop. Since sowing dates were known, CERES-Wheat was run to predict the date of “end of ear growth” (EEG) stage. Using the observed average days after sowing-NDVI profile, each NDVI was normalized to EEG, *i.e.*, NDVI(nor.). Three empirical VI-yield relations were then estimated, using (i) NDVI(raw), (ii) NDVI(nor.) and (iii) NDVI(nor.) and mean maximum and minimum temperature between end of vegetative growth to maturity as estimated by CERES-Wheat. The estimated relations were:

$$Y(\text{tha}^{-1}) = 3.256 - 7.057 \text{NDVI}(\text{raw}) + 8.888 \text{NDVI}(\text{raw})^2 \quad (R^2=0.464) \quad (7)$$

$$Y(\text{tha}^{-1}) = 4.373 - 11.166 \text{NDVI}(\text{nor}) + 11.979 \text{NDVI}(\text{nor})^2 \quad (R^2=0.526) \quad (8)$$

$$Y(\text{tha}^{-1}) = 4.54 + 2.568 \text{NDVI}(\text{nor}) - 0.0467 T_{\text{max}} - 0.1406 T_{\text{min}} \quad (R^2=0.605) \quad (9)$$

It was observed that coefficient of determination increased when NDVI were normalized to constant stage, and secondly when mean temperatures of the last growth phase were also used as predictors. The corresponding root mean square error (RMSE) were 0.638, 0.606, 0.537 tha^{-1} .

3. RS-based crop parameters as inputs to yield models

3.1. LAI retrieval

A number of studies on experimental farms have identified LAI, either at specific stages or as an integrated quantity, *i.e.*, Leaf Area Duration to be an important yield determining factor. The strong relationship of LAI of crop canopy to red and infrared reflectance provides basis for estimating LAI from space-borne sensors. The two commonly adopted procedures for estimating LAI from RS data are (i) empirical relations between vegetation indices and LAI, and (ii) use of canopy reflectance models. While empirical VI relations are vegetation type and location-stage specific, most of the models use reflectance as input and thus require atmospheric correction. The technique commonly used to invert a model is to adjust the model parameters in such a way that model – predicted values closely match with measured values (Qi *et al.*, 2000).

In a study on 22 farmer’s fields in Alipur block of Delhi, Sehgal (2001) related IRS satellite derived vegetation indices with ground measured field-wise LAI in two seasons of 1997-98 (Date: 4 February '98) and 1998-99 (Dates: 27 January 1999, 14 February 1999). For

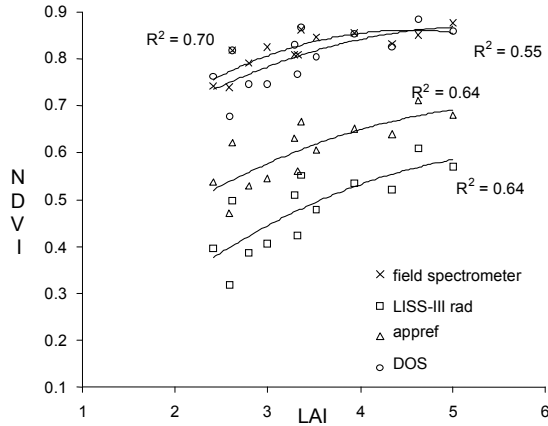


Fig. 2. Relationship between wheat LAI and NDVI derived from field spectro-radiometer and IRS-LISS-III data-based radiance (rad), apparent reflectance (appref) and atmospherically corrected reflectance (DOS) in farmer's fields on 14 February 1999, Bhopal district, Madhya Pradesh

4 February '98 and 27 January '99 data, the NDVI-LAI showed significantly higher R^2 (0.79; 0.83) than RVI-LAI relationship R^2 (0.67; 0.77) whereas for 14 February 1999 data, both the index relations were having comparable R^2 (0.55; 0.57). For each field, the value of reflectance based index was higher than its radiance based value but the basic nature of VI-LAI relation is saturating logarithmic. In 1998-99 season data, the VI-LAI relationship was highly significant for 27 January 1999 than the 14 February 1999 relation. It showed that the VI-LAI relationship was a function of crop growth stage. On 27 January 1999, wheat in most of the fields was in vegetative growth stage having lower LAI values than on 14 February 1999 when the wheat in most of the fields was in anthesis to post anthesis stage with high LAI values.

In another study in Bhopal during 1998-99, measurements of LAI and ground reflectance were made on wheat crop in farmer's fields contemporaneous to IRS LISS-III pass (February, 14, 1999) using LI-COR Canopy Analyzer-2000 and Field Spectro-radiometer, respectively. Empirical approaches for LAI estimation with different NDVI normalization procedures, *viz.*, radiance, apparent reflectance and DOS-based atmospheric correction were evaluated (Singh *et al.*, 2002b). The NDVI estimated using LISS-III radiance were lower than those estimated with reflectance. Atmospheric correction using DOS approach resulted in satellite derived NDVI to nearly match the ground measurements. However, due to spatial resolution effects, the NDVI-LAI polynomial regression had higher coefficient of determination in ground measurements in comparison to satellite observations (Fig. 2).

TABLE 3

Performance of simple radiative transfer model of Price for wheat LAI retrieval on farmer's fields using digital data from IRS-LISS-III.

Study area	Date of RS data	Observed LAI range	No. of observation	RMSE	Reference
Karnal	Feb 1997	1-4	8	0.78	1
Karnal	Feb 1997	4-6	5	1.25	1
Delhi	Feb 1998	1-4	16	0.87	1
Delhi	Feb 1998	4-6	7	1.50	1
Bhopal	Jan 1999	2-5	15	0.77	2

[1] Rastogi *et al.* (2000), [2] Singh *et al.* [2002b]

Price (1992) developed a two-stream model of the interaction of radiation with the plant canopy and soil background in which reflectance above canopy at wavelength λ is expressed in terms of reflectance of a dense canopy and LAI as:

$$R(\lambda) = (r_{\infty} + D/r_{\infty}) (1+D) \quad (10)$$

$$D = [(r_s - r_{\infty}) / (1/r_{\infty} - r_s)] \exp(-2cLAI), \quad (11)$$

where r_s is reflectance of soil, r_{∞} is reflectance of a thick (LAI_{∞}) vegetation canopy and c is attenuation constant for radiation in the canopy. Price (1993) reformulated the above models in terms of satellite digital numbers as:

$$DN_{si} = \frac{DN_i (e^{2c_i LAI} - r_{\infty}^2) + DN_{oi} (1 - e^{2c_i LAI})}{1 - r_{\infty}^2 e^{2c_i LAI} - DN_i \cdot r_{\infty}^2 (1 - e^{2c_i LAI})} DN_{oi} \quad (12)$$

where, DN_i is the measured value from sensor, DN_{si} is soil reflectance and DN_{oi} is reflectance of dense vegetation in terms of satellite measurements.

Rastogi *et al.*, (2000) tested Price model on farmers fields during 1996-97 season in Karnal and 1997-98 in Delhi using IRS LISS-III data and estimated wheat attenuation coefficients (c in Eqn.). The root mean square error (RMSE) between RS estimates and ground measured LAI ranged between 0.78-0.87 when LAI was in the range of 1-4, while for higher LAI range (4-6), the RMSE varied from 1.25 to 1.5 in two sites (Table 3). Using same attenuation coefficients, Singh *et al.*, (2002b) observed RMSE of 0.77 for wheat field in Bhopal during 1998-99 crop season. Thus, Price model could be applied over three sites in different years using common attenuation coefficients and new coefficients for other crops are necessary before it can be applied to a RS scene. The

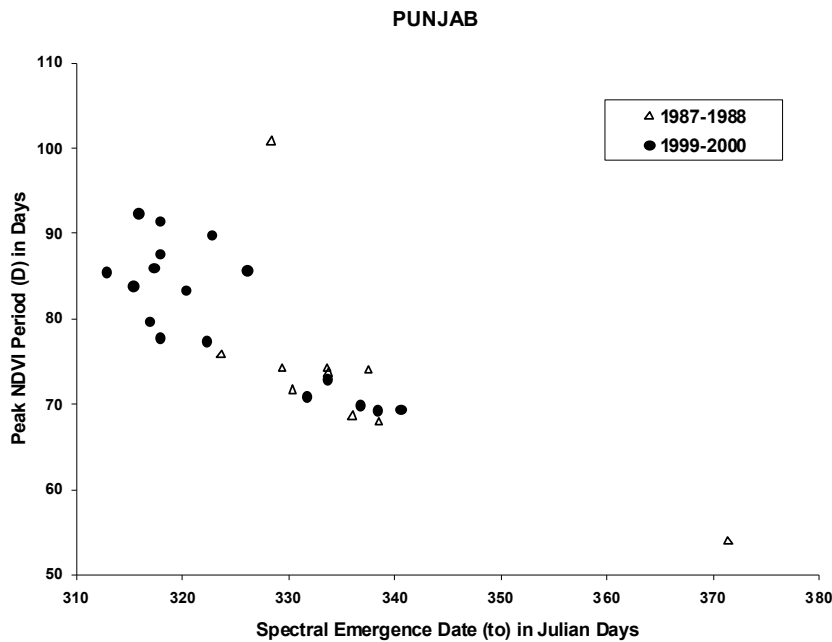


Fig. 3. Relation of spectral emergence date (T_0) to duration for attaining peak NDVI in Punjab from two studies [(A) – Dubey *et al.*, 1991; and (B) – Rajak *et al.*, 2002]

impact of observed errors in LAI estimates on yield prediction also needs investigation.

3.2 Crop phenology

The spectral growth profile modelling approach by Badhwar was proposed as a method to determine crop emergence date (Badhwar, 1980). Although, this spectral emergence date occurs after the ground observed seedling emergence date. The peak NDVI date is closely associated with ear emergence and/or anthesis stages. The period between emergence (T_0) to time to peak NDVI (T_{max}) is thus an indicator of pre-anthesis period. A scatterplot of district-level estimates of these two parameters for Punjab obtained by two studies based on different sensors, NOAA-AVHRR in 1988-89 (Dubey *et al.*, 1991) and IRS WiFS in 1999-2000 (Rajak *et al.*, 2002) is given in Fig. 3. Decrease in pre-anthesis duration as spectral-emergence is delayed is observed clearly. This matches with observations from field studies in which a delay in sowing in north-west India decreases the pre-anthesis period (Saini *et al.*, 1986) and delay in sowing have been related to yield reduction (Saini *et al.*, 1988). A comparison with earlier published results over Punjab indicated that crop phenology estimation was comparable across the sensors (Fig. 3).

4. RS inputs in crop simulation models at various spatial scales

Crop simulations models are based on physical plant processes and simulate the effects of change in growing

environment on plant growth and development on a daily basis. A number of simulation models have been developed for wheat crop and calibrated for various cultivars under different growing conditions using experimental plot data. Enough experience has been gained from these studies to use them for real world applications including yield forecasting (Nain *et al.*, 2002). The incorporation of RS inputs to CSM in the form of phenology, LAI, FPAR etc., could bridge the gaps between model outputs and actual crop growth in farmer's fields. The application of CSM at a field or lower scale would be useful for precision crop management while at larger scale be useful for regional crop growth monitoring and yield prediction.

Recently, use of two wheat CSM, WTGROWS and CERES-Wheat has been made for studying (i) the farm level yield prediction using CSM for phenology and normalization of RS derived VI (Nain *et al.*, 2001), (ii) wheat yield mapping in farmer's fields using RS derived LAI forcing in the model (Sehgal *et al.*, 2001a) and (iii) spatial wheat yield prediction using CSM and RS derived crop parameters in a GIS environment (Sehgal *et al.*, 2001b). The approach and major results for (ii) and (iii) are described here while (i) has been discussed earlier since it uses a direct VI-yield relation for yield prediction.

The study for generating the wheat yield maps for farmers' fields was undertaken during rabi 1998-99 in Alipur block (Delhi). The adopted procedure linked RS inputs in form of estimated LAI and wheat simulation model WTGROWS for yield mapping and results were

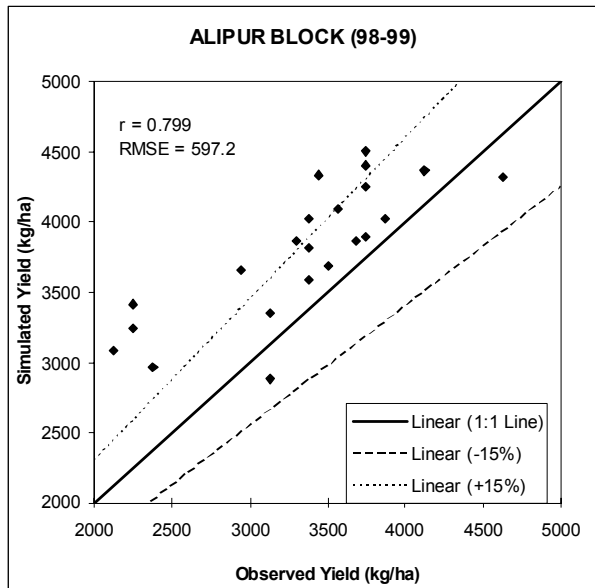


Fig. 4. Comparison of predicted grain yield by modified corrective approach and observed values for 22 farmers’ fields. The 1:1 line and its ±15 percent band lines are also shown

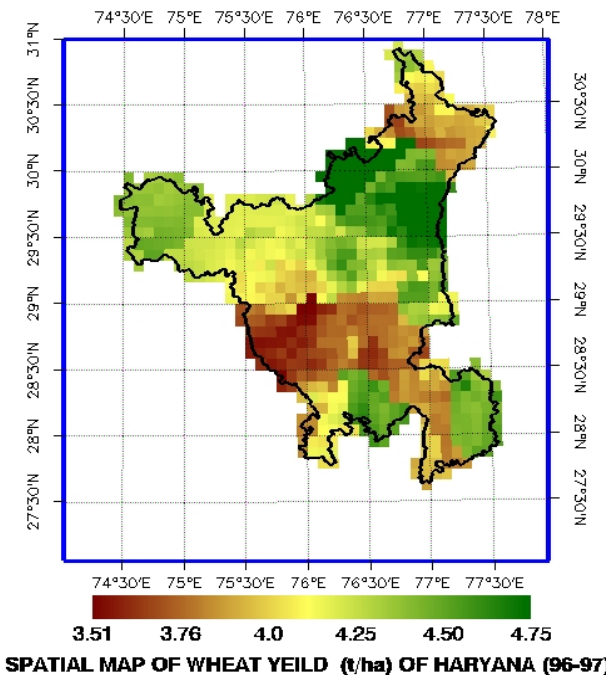


Fig. 5. Grid-wise simulated wheat yields by WTGROWS simulation model for 1996-97 season in Haryana

validated with yield observations on farmers’ fields. A new linking strategy, christened “Modified Corrective

TABLE 4

Range and mean of simulated crop growth and development characteristics for Haryana (1996-97) by CGMS

Parameters	Range	Mean
Pre-anthesis duration (Days)	85 – 100	93.3
Post-anthesis duration (Days)	29 – 33	31
Total above-ground Dry Matter (TDM t/ha)	8.13 – 10.73	9.27
LAI at anthesis	2.56 – 4.69	3.59
Grain yield (t/ha)	3.51 – 4.75	4.08

Approach” by Sehgal *et al.* (2001a), was adopted. This strategy is empirical in nature where biometric relation of grain yield and leaf area index (LAI) is derived from simulation model by running model for a combination of input resources, management practices and soil types occurring in the area. Then this biometric relationship is applied to all the crop fields of the study area for which the LAI is computed from remote sensing data.

The WTGROWS simulated grain yield for the combination of inputs showed yields varying between 1.1 and 4.9 t ha⁻¹. The corresponding range of simulated LAI on 27 January 1999 was 0.6 to 4.2. The regression equation fitted between simulated LAI on 27th Julian day (*i.e.* 27 January 1999) and simulated grain yield showed saturating logarithmic nature with a R² value of 0.81. The relationship is given below:

$$\text{Yield (kg/ha)} = 1571.2 * \ln(\text{LAI}) + 2033.6 \quad (13)$$

This empirical biometric relation was applied to the LAI map of the wheat pixels and grain yield map for farmer’s fields of Alipur block, Delhi, was generated. The predicted yields ranged from 2.1 to 4.8 tha⁻¹. The comparison of predicted grain yield and observed yield for the 22 farmers’ fields showed high correlation coefficient of 0.8 and a root mean square error (RMSE) of 597 kg ha⁻¹ which was 17 percent of the observed mean yield (Fig. 4).

A demonstration of regional wheat yield assessment by WTGROWS in a spatial framework of 5’ × 5’ geographical grid over Haryana for crop season 1996-97 was made by Sehgal *et al.*, (2001b). The inputs used were RS based wheat distribution map, daily weather surfaces, soil properties map and crop management input databases in a GIS environment. The issues related to framework design, generating various inputs in the required spatial format, and its implementation as a Crop Growth Monitoring System (CGMS) has been discussed. Further the study explored the possibilities and issues in linking

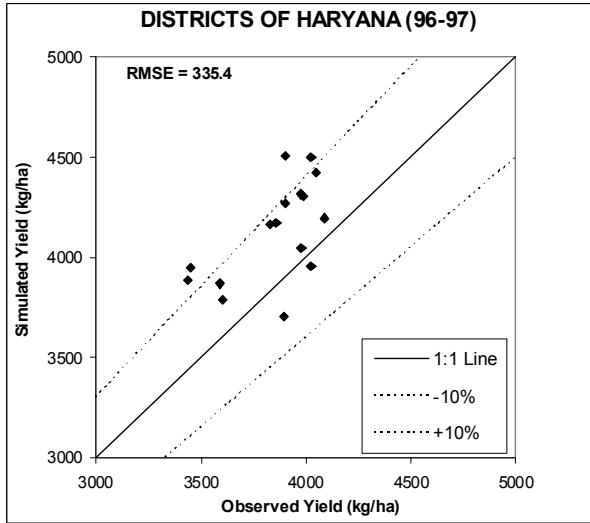


Fig. 6. Comparison of simulated district wheat yields by CGMS with observed values reported by the State Department of Agriculture Haryana for 1996-97 season. The 1:1 line and its ± 10 percent band lines are also shown

remote sensing inputs into the CGMS framework to improve its performance. The study is based on inputs and analysis over Haryana State for wheat season of 1996-97.

The CGMS framework was able to simulate daily crop and soil variables for 708 grid cells. The range and arithmetic means of crop parameters over the wheat grid cells are summarized in Table 4. The grid-wise simulated grain yields are shown in Fig. 5. The figure clearly indicates spatial patterns in yield variability. The high grain yields in Kurukshetra and Karnal and low yields in Bhiwani, Rohtak, Yamunanagar and Ambala are brought out clearly. The comparison of simulated grain yields aggregated at district level and estimates by the State Department of Agriculture is shown in Fig. 6. In general, the model simulated yields were higher than observed. This could be due to a number of yield reducing factors such as pest, weed, soil constraints, which operate in field but are not considered by the model. The model predicted yields were within $\pm 10\%$ of reported yields in 12 out of 16 districts. The RMSE of 335.4 kg ha^{-1} , which is less than 10 percent of the state mean yield, was obtained. Only in two districts, Mahendergarh and Bhiwani, the simulated district yields were lower than observed yields while for Kaithal, Karnal, Ambala and Yamunanagar, the simulated yields were higher than observed yields by more than 10 percent. Experience gained from this study will help in designing and implementing a multi-crop and multi-scale Crop Growth Monitoring System for real time crop growth assessment and yield forecasting using different types of RS-derived bio-geophysical products.

5. Future scenario

Recent advances in satellite sensor spectral, spatial and radiometric capabilities, modeling results and analysis approaches have opened new avenues for RS-based yield modeling. RS data can now be operationally used for monitoring crop growing environment such as ground insolation (Tanahashi *et al.*, 2001), rainfall (Thornton *et al.*, 1997) and soil moisture (Njoku and Entekhabi, 1996). The improved multi-spectral sensors allow computation of new vegetation indices that have lower noise from atmosphere, viewing conditions and soil background (Kaufman and Tanre, 1992; Major *et al.*, 1990). The retrieval of crop parameters is done operationally and 8-day global LAI product is now available from MODIS sensor onboard TERRA spacecraft. The computational and communication advances have been leveraged to make 10-day global vegetation index from SPOT VEGETATION sensor being produced operationally for monitoring global food security by FAO (Hielkema, 2000).

Proposed sensors onboard ISRO's new satellites to be launched in next two years, such as AWiFS (60m, 4 visible-NIR channels and 5 day repeat cycle) and LISS-IV (5.8m pixel, 3 visible NIR channels) on RESOURCESAT, VHRR and CCD on INSAT 3D will substantially improve the capability to make yield models at regional as well as local scales. While regional yield models will have crop assessment and forecasting applications, the local and field-scale models will be directly useful for farmers for improving input resource use efficiency by adopting techniques of 'precision farming'.

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