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Wheat Yield Prediction Using Remotely Sensed Agromet Trend-Based Models for Hoshiarpur District of Punjab, India

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Abstract: Estimation of crop production in advance of the harvest has been an intensively researched field in agriculture. The aim of present study was to predict wheat yield using different agrometeorological indices, spectral index (NDVI, Normalized Difference Vegetation Index) and Trend Estimated Yield (TEY) in Hoshiarpur district of Punjab for the years 2001-02 and 2002-03. On the basis of examination of Correlation Coefficients (R), Standard Error of Estimate (SEOE) and Relative Deviation (RD) values resulted from different agromet models, the best agromet subset were selected as Minimum Temperature (T_{min}), Maximum Temperature (T_{max}) and Accumulated Heliothermal Units (HTU) for Hoshiarpur district. In order to improve model accuracy the above mentioned agrometeorological indices together with NDVI and TEY were used as independent variables for yield prediction at reproductive stage (2nd week of March) of wheat. It was found that Agromet-Spectral-Trend-Yield model could explain 96% (SEOE = 87 kg ha^{-1}) of wheat yield variations for Hoshiarpur district.

Key words: Wheat yield prediction, spectral index, agrometeorological indices

INTRODUCTION

Various government agencies and private institutions have provided a great deal of fundamental information relating spectral reflectance and thermal omittance properties of soils and crops to their agronomic and biophysical characteristics. This knowledge has facilitated the development and use of various remote sensing methods for non-destructive monitoring of plant growth and development. Estimation of crop production in advance of the harvest is of great utility in farming. Temporal spectral pattern of any crop summarizes the phenology as well as growth features of the crop. The integrated models incorporating satellite based vegetation indices, agro-meteorological indices, biophysical indices and time trend predicted well the crop (Pinter *et al*., 2003; Deosthali and Akmanchi, 2006). Since crop yield is the culmination of many temporal plant processes and is affected by various external factors related to soil, weather and technology, parameterization of these factors and investigation of their relationship with yield are essential for crop yield modeling. Remotely sensed data have emerged as a promising tool for yield modeling because of their unique advantages such as, possibility of obtaining crop specific objective information with adequate spatial and temporal coverage. The integration of agrometeorological and spectral indices derived from remotely sensed data may provide more reliable pre-harvest crop yield estimates (Dadhwal and Ray, 1998). The wheat yield prediction improved where Trend Estimated Yield (TEY) parameter (showing the combined effect of technological development on yield) was incorporated in agromet-spectral-yield relations in Punjab (Kalubarme *et al*., 1995; Medhavy *et al*., 1995) and Haryana (Verma *et al*., 2003) states. The present study is an attempt to relate spectral, agrometeorological indices and TEY for wheat yield prediction in Hoshiarpur district of Punjab.

MATERIALS AND METHODS

Seventeen years (from 1984-1985 to 2000-2001) historical yield data published by Bureau of Economics and Statistics (BES) for Hoshiarpur district were used to develop agromet-spectral-trend-yield models. To integrate various agromet and spectral indices over different growth phases, wheat growing season was divided into four phenological stages, starting from the sowing of crop on 12th of November up to harvesting on 15th of April including: i) Early Seedling stage (Meteorological

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Standard Week Numbers (MSWN) 46-50), ii) Active Vegetative (AV) stage (MSWN 51-7), iii) Reproductive (RP) stage (MSWN 8-11), iv) Maturity stage (MSWN 12-15). Besides, AV + RP and overall crop growth were used.

Spectral index

Archived spectral index of Normalized Difference Vegetation Index

$$NDVI = (NIR-R)/(NIR+R)$$

Where:

NIR = Near infrared reflectance band
R = Red reflectance band

corresponding to the maximum vegetative growth stage (maximum leaf area index, LAI) of wheat were collected from Space Applications Centre (SAC), Ahmedabad from 1988-89 to 2002-2003 for Hoshiarpur district.

Meteorological parameters: Weekly meteorological data of Ballowal Saunkhri meteorological observatory located in the study area were used from 1984-1985 to 2002-2003. Weekly maximum (T_{max}) and minimum (T_{min}) temperatures, accumulated rainfall (ARF) and evaporation data of US Weather Bureau Class A Pan Evaporimeter were used as meteorological parameters.

Agrometeorological indices: Growing Degree Days (GDD): The heat unit or growing degree-days concept was proposed to explain the relationship between growth duration and temperature. This concept assumes a direct and linear relationship between growth and temperature (Nuttonson, 1955). It has been reported that accumulated GDD is the best index to predict various phenophases in wheat crop under Punjab conditions (Hundal *et al*., 1997).

A degree-day or a heat unit is the mean temperature (T_{mean}) above base temperature. Mathematically, it can be expressed as:

$$GDD = \sum_{a}^{b} \left\{ \left[\frac{T_{max} + T_{min}}{2} \right] - T_b \right\}$$

Where:

GDD = Growing degree-days (°C day)
T_{max}/T_{min} = Daily maximum/minimum temperature (°C)
T_b = Base temperature i.e., the lowest temperature below which it is assumed that there is no growth. A base temperature of 5°C was selected to determine GDD for different growth stages of wheat (Sharma *et al*., 2004; Dubey *et al*., 1987). If $T_{mean} < T_b$, GDD = 0
a = Starting date of phenophase
b = Ending date of phenophase

Temperature Difference (TD): Temperature difference was computed using following expression:

$$TD = \sum_{a}^{b} (T_{max} - T_{min})$$

Where:

TD = Temperature difference

Photothermal Units (PTU) and Heliothermal Units (HTU): Because of the phasic changes taking place due to the influence of both temperature and photoperiod, it is better to calculate Photothermal Units (PTU) instead of heat units for accurate prediction of flowering and maturity. Therefore, photothermal units are proposed, where in, the degree days are multiplied by length of the night in case of short- day plants and length of the day for long-day plants (Reddy and Reddi, 2003).

In general, PTU is product of GDD and day length (maximum possible sunshine hours, N) and HTU is the product of GDD and bright sunshine hours (actual sunshine hours, n). Therefore, they can be computed using following expressions:

$$PTU = \sum_{a}^{b} (GDD \times N)$$

$$HTU = \sum_{a}^{b} (GDD \times n)$$

Where:

PTU = Photothermal units (°C day hours)
HTU = Heliothermal units (°C day hours)
GDD = Growing degree days (°C day)
N = Maximum possible sunshine hours which collected from Doorenbos and Pruitt (1975)
n = Actual sunshine hours

Vapour Pressure Deficit (VPD): Vapour pressure deficit plays a significant role in crop evapotranspiration. At constant temperature, changes in atmospheric humidity affect transpiration by changing actual vapour pressure of the air (e_a) and modifying the vapour pressure gradient from leaf to air (Rao, 2003; Kramer, 1997). The difference between the saturation vapour pressure (e_s) and its actual water vapour pressure is termed as vapour pressure deficit and it can be worked out using following expressions:

$$e_a = (RH_{mean} \times e_s)/100$$

$$VPD = e_s - e_a$$

Where:

e_a = Actual water vapour pressure (millibar)
Rh_{mean} = Mean relative humidity (%)
e_s = Saturated water vapour pressure (millibar) as a function of mean air temperature which collected from Michael (1978)
VPD = Vapour pressure deficit (millibar)

Potential Evapotranspiration (PET): Baier and Robertson (1967) demonstrated that the yield of a crop was closely related to the physical environmental parameters, like evapotranspiration (ET) and soil moisture than to simple meteorological variables, such as rainfall or temperature. CropWat for windows package version 4.2 developed by Clarke *et al.* (1998) was used to compute PET during different phenological stages. CropWat for windows is a programme that use the modified Penman-Monteith method for calculating reference crop evapotranspiration. The method supersedes the FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1975). Monthly maximum and minimum temperature (°C), mean relative humidity (%), sunshine hours and wind speed (m sec^{-1}) at two meter height above the ground were used to run the model.

Trend Estimated Yield (TEY): The district-wise data on wheat yield for Hoshiapur reported by Bureau of Economics and Statistics (BES) from the year 1984-1985 to 2000-2001 was used for the trend analysis. Scatter plots of year vs. yield was created for evaluating the time trend used in fitting a regression line. In this trend analysis time was used as a dummy variable (Draper and Smith, 2003). The trend-predicted yields were computed using the following equation:

$$Y = a + bT$$

Where:

Y = Yield (kg ha^{-1})
a = Intercept
b = Regression coefficient
T = Time (years, 1985 = 1)

In order to evaluate the performance of different yield models for prediction of yields, predicted yield for the years 2001-2002 and 2002-2003 were compared with corresponding BES estimates using Relative Deviation (RD) as a measure of accuracy of prediction.

$$RD\,(\%) = \frac{\text{(Model Predicted Yield-BES Estimate)}}{\text{BES Estimate}} \times 100$$

In order to have sufficient information about the order of importance of the independence variables in predicting the dependent variable y, a forward stepwise regression method was used. The independent variables X_1, X_2,....X_p are entered one-by-one into the equation according to criterion of a minimum F-to-enter value equal to 3.5. For the variables, a minimum F-to-remove was also set equal to 3.2. Once a variable was in the equation, it may be swapped with a variable not in the equation or it may be removed from the equation altogether. The meteorological variable used to calculate the different indices (GDD, TD, HTU, PTU, VPD and PET) were checked for collinearity and it was found from their low correlation values among these variables that there was no problem of multicollinearity.

RESULTS AND DISCUSSION

Various possible ways using meteorological parameters/ agrometeorological indices and NDVI for wheat yield modeling have been attempted. The simple, multiple-linear and stepwise regression analysis have been developed. Table 1 shows simple linear correlation coefficient values between wheat grain yield (kg ha^{-1}) and meteorological parameters/agrometeorological indices for Hoshiarpur district.

The results obtained from simple linear regression analysis will be discussed under various wheat growth stages:

Early seedling stage: It was observed that among different meteorological parameters/agrometeorological indices, minimum temperature (T_{min}), accumulated Temperature Difference (TD), accumulated Evaporation (E) and Potential Evapotranspiration (PET) were significantly correlated with wheat grain yield. The model with PET yields the highest correlation coefficient (r) of 0.831. TD showed positive relationship with yield while T_{min}, E and PET had negative relationship with yield. Baier and Robertson (1967) reported that high minimum temperatures from emergence to heading may be responsible for reduction in yields.

Active vegetative stage: In Active Vegetative (AV) stage significant correlations were obtained between wheat grain yield and T_{min}, accumulated Growing Degree-Days (GDD), Photothermal Units (PTU), accumulated vapour pressure deficit (VPD), E and PET (Table 1). In addition, a significant r value was found between wheat grain yield and accumulated Heliothermal Units (HTU) in Hoshiarpur district. The highest r values were obtained in the model

Table 1: Simple linear correlation coefficient values between wheat grain yield (kg ha^{-1}) and meteorological parameters/agrometeorological indices for Hoshiarpur district

	Wheat growth stage					
Predictor variable	Early seedling	Active vegetative (AV)	Reproductive (RP)	Maturity	AV+RP	Overall crop growth
T_{max}	0.290	-0.245	-0.079	0.167	-0.153	0.074
T_{min}	-0.539*	-0.603*	-0.712**	-0.519*	-0.786**	-0.785**
TD	0.557*	0.247	0.517*	0.537*	0.385	0.553*
GDD	-0.220	-0.737**	-0.445	-0.100	-0.666**	-0.529*
HTU	-0.110	-0.502*	0.033	0.069	-0.399	-0.204
PTU	-0.217	-0.738**	-0.447	-0.100	-0.729**	-0.507*
VPD	-0.316	-0.661**	-0.330	-0.121	-0.577*	-0.431
ARF	0.009	0.015	-0.193	0.107	-0.095	-0.035
E	-0.729**	-0.841**	-0.598*	-0.492*	-0.794**	-0.748**
PET	-0.831**	-0.860**	-0.675**	-0.700**	-0.830**	-0.834**

*: $\alpha = 0.05$, **: $\alpha = 0.01$, n =17

between yield and PET, which explained 74% of yield variation. These results showed the importance of temperature based indices and day length in vegetative stage which are in conformity with the results obtained by Angus *et al.* (1981). They obtained a fairly straight line, suggesting that a day-degree system could adequately account for the different rates of development in wheat crop.

Reproductive stage: In Reproductive (RP) stage significant correlations were found between wheat grain yield and T_{min}, TD, E and PET in Hoshiarpur district and among which the highest correlation coefficient (r = -0.712) was obtained with T_{min}. High value of correlation coefficient between wheat grain yield and minimum temperature (T_{min}) in reproductive phase (from February 19 to March 18) might be due to the fact that RP coincides with the transitional period in which change in T_{min} from lower to higher values may influence the rate of respiration process during night. These results indicated the importance of high night temperature and confirmed the findings of Peters *et al.* (1971).

Maturity stage: Significant correlations were found between wheat grain yield and T_{min}, TD, E and PET during maturity stage. The highest r value (-0.700) was obtained between yield and PET for Hoshiarpur district. These results are in confirmation with the earlier work conducted by Bairagi and Hassan (2002). The higher correlation coefficient values between yield and PET indicated that temperature and water use play an important role and influence grain yield of wheat crop.

Active vegetative to reproductive stage: In combined Active Vegetative (AV) and Reproductive Period (RP), significant correlations were obtained between wheat grain yield and T_{min}, GDD, PTU, E and PET. Besides, a negative significant correlation was observed between grain yield and VPD.

Overall crop growth: For entire wheat growth season, in Hoshiarpur district, significant correlations were found between grain yield and T_{min}, TD, GDD, PTU, E and PET among which the highest r value (r = -0.834) was obtained with PET followed by T_{min} (r = -0.785). Jand (1999) also found a negative correlation between wheat grain yield and GDD and PTU for Ferozepur district of Punjab.

The best agromet subset were selected on the basis of examination of correlation coefficients (R), Standard Error of Estimate (SEOE) as well as RD values resulted from different agromet models including simple/multiple linear and stepwise regression analysis (Data not given due to brevity) to develop agromet-spectral-trend-yield models. Accordingly, the suitable time of prediction was found to be at the end of reproductive stage i.e., 2nd week of March (11th week after sowing). The best agromet subset to incorporate in agromet-spectral-trend-yield models were selected as T_{min}, T_{max} and HTU for Hoshiarpur district. The final regression equations of different models are given below:

Model (1), Agromet- Yield

$$Y = 4300.32-228.54\, T_{min}-16.76\, T_{max} + 0.47\, HTU$$

($R = 0.779$, $R^2 = 0.607$, $R^2_{adj} = 0.516$, SEOE = 293.26, F =6.69**, n = 17)

Model (2), Agromet-Spectral-Yield

$$Y = 1081.08 -134.68\, T_{min} + 100.16\, T_{max} + 0.22\, HTU +485.37\, NDVI$$

($R = 0.944$, $R^2 = 0.891$, $R^2_{adj} = 0.804$, SEOE = 126.80, F= 10.23*, n =10)

Model (3), Agromet-Spectral-Trend-Yield

$$Y = 1277.36-88.89\, T_{min}+ 25.57\, T_{max} + 0.25\, HTU-520.39\, NDVI + 0.51\, TEY$$

($R = 0.979$, $R^2 = 0.959$, $R^2_{adj} = 0.908$, SEOE = 86.92, F=18.75**, n=10)

Variation explained by models ranged from 61-96% and standard error of estimate ranged from

Table 2: Performance evaluation of different agromet-spectral-trend-yield model at reproductive stage of wheat for the years 2001-2002 and 2002-2003 in Hoshiarpur

Model	2001-2002 BES Estimate (kg ha^{-1})	2001-2002 Predicted yield (kg ha^{-1})	2001-2002 RD (%)	2002-2003 BES Estimate (kg ha^{-1})	2002-2003 Predicted yield (kg ha^{-1})	2002-2003 RD (%)
Agromet	3616	2762	-23.6	3439	2873	-16.5
Agromet-Spectral	3616	3093	-14.5	3439	3104	-9.7
Agromet-Spectral-Trend	3616	3350	-7.4	3439	3417	-0.6

87-293 kg ha^{-1}. The results revealed that in case of agromet-yield model, both minimum and maximum temperature showed negative relationship with grain yield. It might be due to the fact that higher day time temperature decreases the period available for photosynthetic activity before grain maturation and hence will affect the yield adversely (Marcellos and Single, 1972; Asana and Williams, 1965). Moreover, high night time temperature associated with accelerated respiration, which decreases translocation of photosynthates from leaf to grain and hence reduced the yield.

Heliothermal Units (HTU) showed a positive relationship indicating the flowering response to bright sunshine hours prevailing during the reproductive period of the crop growth. The agromet-yield model explained 61% of yield variability while, the coefficient of determination (R^2) value improved from 61-89% when NDVI was included in agromet-yield model. Similar results have been reported by Dubey *et al.* (1994). Agromet-spectral-trend-yield model accounted for 96% of variations in wheat grain yield over reproductive stage. It might be due to the fact that trend-incorporated relation gives better correlation with grain yield than agromet/agromet-spectral-yield models. Since trend predicted yield is a integrated factors of technological advancement, improvement in fertilizer insecticide /pesticide/weedicide use and increased use of high yielding varieties (Verma *et al.*, 2003; Jand, 1999).

Model validation: In order to evaluate model validity, model predicted yields were compared with corresponding BES estimates using relative deviation values for the years 2001-2002 and 2002-2003 (Table 2), for Hoshiarpur district.

The predicted wheat yield obtained from these models ranged from -23.6 to -0.6% deviation from actual yield in different years. The model developed using agromet parameters underestimated yield 16.5% during 2002-2003. With the incorporating of spectral parameters into this model improved its predictability by reducing the relative deviation between model predicted and actual observed wheat yield to -9.7% with reduced SEOE. Similarly, incorporating the trend parameters into these models, further improved the model with just -0.6. RD values and reduced SEOE. The performance comparison between wheat yields prediction and its corresponding BES estimates (Table 2) using different models revealed that the predicted wheat grain yield computed for the year 2002-2003 were always closer to actual yields than 2001-2002. It might be attributed to the fact that the model is not likely to give a very realistic estimate in years of extreme weather conditions as evident from actual yields in Hoshiarpur district in the year 2001-2002 which were 3616 kg ha^{-1} as compared to its difference from normal yields during 1985 to 2003 (2987 kg ha^{-1}) whereas, in 2002-2003 yield was 3439 kg ha^{-1}, respectively. The response of crop meteorological conditions is not always the same during the entire life cycle of the crop and also during different ranges of the parameters (Mahey, 1999). It can be concluded that wheat yield prediction was better when Agromet and spectral indices in the models were used in combination rather than when used individually. However, Agromet-Spectral-Trend-Yield models at reproductive stage of wheat crop give the highest R values of 0.98.

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