

# Predicting Wheat Grain and Biomass Yield Using Canopy Reflectance of Booting Stage

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**Abstract** Field experiment was conducted in a sandy loam soil of Indian Agricultural Research Institute, New Delhi during the year 2011–13 to see the effect of irrigation, mulch and nitrogen on canopy spectral reflectance indices and their use in predicting the grain and biomass yield of wheat. The canopy reflectances were measured using a hand held ASD FieldSpec Spectroradiometer at booting stage of wheat. Four spectral reflectance indices (SRIs) viz. RNDVI (Red Normalized Difference Vegetation Index), GNDVI (Green Normalized Difference Vegetation Index), SR (Simple Ratio) and WI (Water Index) were computed using the spectral reflectance data. Out of these four indices, RNDVI, GNDVI and SR were significantly and positively related with the grain and biomass yield of wheat whereas WI was significantly and negatively related with the grain and biomass yield of wheat. Calibration with the second year data showed that among the SRIs, WI could account for respectively, 85 % and 86 % variation in grain and biomass yield of wheat with least

RMSE ( $395 \text{ kg ha}^{-1}$  (15 %) for grain yield and  $1609 \text{ kg ha}^{-1}$  (20 %) for biomass yield) and highest d index (0.95 for grain yield and 0.91 for biomass yield). Therefore it can be concluded that WI measured at booting stage can be successfully used for prediction of grain and biomass yield of wheat.

**Keywords** Wheat · Booting stage · Canopy reflectance · Water · Nitrogen

## Introduction

Wheat is one of the most important *rabi* (winter season) cereal crop in India, which contributes nearly one-third of the total food grain production. Water and fertilizer (nutrients) are the two most important inputs, which contribute to wheat productivity (Lenka et al. 2009). The response of wheat crop to nitrogenous fertilizer depends on the availability of soil water (Hati et al. 2001). Now a days, availability of water for irrigation is limited because of urbanization, industrialization, rainfall variability etc. (Chakraborty et al. 2008). So in order to maintain favorable soil moisture in the crop root zone various moisture saving agronomic measures like mulching are practiced. Straw mulching is preferably used for its easy availability and improving soil health through addition of organic matter. Effect of mulching on conserving moisture and increasing productivity of wheat has been reported by several workers (Verma and Acharya 2004a, b; Li et al. 2005; Huang et al. 2005; Rahman et al. 2005; Sidhu et al. 2007). In season pre-harvest estimation of crop yield under these diverse water and nitrogen management conditions is really a challenge through simulation models (Clevers 1997; Ma et al. 2001). Simulation models are known to predict yield relatively accurately on a large scale under ideal conditions but not quite satisfactorily when biotic factor influence yield or for small research plots of size  $5\text{--}8 \text{ m}^2$  (Ma et al. 2001). Remote

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sensing techniques in general and hyperspectral remote sensing in particular, can provide quantitative, instantaneous and nondestructive assessment of crop growth status on a regular basis over a large area. The input of remote sensing derived parameters such as LAI in crop growth models is known to improve yield estimates (Clevers 1997; Sehgal et al. 2005). The canopy reflectance pattern is the reflectance/absorption of specific wavelengths of the EMR spectrum, which is influenced by specific plant traits (Reynolds et al. 1999). For example the strong absorption in the visible wavelengths is due to leaf pigments like chlorophylls, xanthophylls and carotenoids and the strong reflectance of the near-infrared wavelengths is due to scattering and diffusion of light by different leaf tissues. Hence measurement of canopy spectral reflectance can be used for the assessment of green biomass, photosynthesis, relative water content, nutrient and environmental stresses through spectral reflectance indices (SRI) which are empirical equations based on simple operations like sums or ratios or differences between the reflectances at given wavelength (Aparicio et al. 2000; Prasad et al. 2007). SRI is used for predicting grain and biomass yield of various crops in advance (Babar et al. 2006; Prasad et al. 2007; Li-Hong et al. 2007). Simple ratio (SR) and Normalized differential vegetation index (NDVI) are the most commonly used SRI for the estimation of crop dry mass, leaf area index, green area index, fraction of absorbed photosynthetically active radiation. Ma et al. (2001) observed high positive correlation between grain yield of soybean (*Glycine max* L.) and NDVI at all stages of measurement (R2, R4 and R5 stages). The NDVI has also been reported to predict grain yield in winter wheat (Raun et al. 2001), and in durum wheat (*Triticum turgidum* L.) (Aparicio et al. 2000). The other vegetation index SR has also been used for wheat yield prediction (Aparicio et al. 2000; Serrano et al. 2000). In one study, Aparicio et al. (2000) observed higher correlation of SR with durum wheat yield than did NDVI. However, NDVI becomes less sensitive to biophysical parameters when LAI value reaches above 3 (Prasad et al. 2007). Under these conditions, Gitelson et al (1996) has suggested green band is more sensitive than red band and proposed green normalized differential index (GNDVI) for assessing biomass. Many researchers have reported that green band in combination with NIR band i.e. GNDVI is more closely related with grain yield (Shanahan et al. 2001; Chang et al. 2005). The water based index i.e. Water Index (WI) used to predict relative water content and other characters related to water content of canopy (Peñuelas et al. 1993) can also be used to predict grain yield of wheat (Prasad et al. 2007). Prasad et al. (2007) observed better correlation between WI and grain yield compared to other SRI (RNDVI, GNDVI and SR). In this backdrop, the present investigation was carried out to see the effect of irrigation, mulch and nitrogen

application on canopy reflectance, spectral reflectance indices related to canopy photosynthetic area, viz., RNDVI, GNDVI and SR, and their use for early prediction of grain and biomass yield.

## Material and Methods

### Experimental Site

Field experiments were conducted during *rabi* (winter) 2011–12 and 2012–13 at the research farm of the Indian Agricultural Research Institute, New Delhi (77°89'N, 28°37'E, 228.7 m asl) with wheat (*Triticum aestivum*, L.) as the test crop. The climate is semi-arid with warm summer and mild winter. Summers are long (April–August) with the monsoon setting in between (July–September). The soil is sandy loam (Typic Haplustept) with medium to angular blocky structure, non-calcareous and slightly alkaline in reaction (pH=7.6). The soil (0–30 cm) has bulk density 1.56 Mg/m<sup>3</sup>; hydraulic conductivity (saturated) 1.02 cm/hr, saturated water content (0.40 m<sup>3</sup>/m<sup>3</sup>), EC (1:2.5 soil/water suspension), 0.37 dS/m; organic C, 5.2 g/kg; total N, 0.030 %; available (Olsen) P, 7.3 kg/ha; available K, 280.0 kg/ha; sand, silt and clay, 71.7, 12.0 and 16.3 %, respectively. Available soil moisture ranged from 26 to 29 % (0.033 MPa) to 8–11 % (1.5 MPa) for 0 to 1.20 m layers.

### Experimental Design and Crop Culture

The experiment was laid out in a split-split plot design with irrigation levels as the main plot, mulch as the sub-plot and nitrogen as the sub-sub-plot factors, replicated three times. The sub-sub-plot size was 4.5 m×4.5 m. Wheat (cv. PBW-502) was grown during the winter season (3rd week of November to 3rd week of April) of 2010–12. The irrigation levels were I2 (irrigation at CRI and flowering stage) and I4 (irrigation at CRI, tillering, flowering and grain filling stage) of 60 mm each. The mulching treatments are M0 (without mulch) and M1 (with maize straw mulch). The nitrogen treatments were N0: No nitrogen, N60: 60 kg N/ha and N120: 120 kg N/ha. Nitrogen was applied in three splits: 50 % at sowing, 25 % at CRI stage (21 days after sowing) and the rest 25 % maximum tillering stage (45 days after sowing). The whole amount of P and K fertilizers was applied as basal at the time of sowing. The recommended dose of fertilizers for wheat for the Northern India (120:60:60 kg N, P, K/ha) has been decided as per the package of practice suggested by the Division of Agronomy, Indian Agricultural research Institute, New Delhi. Two preparatory tillage operations by duck foot tine cultivator and leveling were applied for preparation of seed bed and mixing of fertilizers in all the treatments.

### Spectral Reflectance Measurements

The canopy reflectances were measured in the spectral range of 350–2500 nm with 1 nm bandwidth with the help of hand held ASD FieldSpec Spectroradiometer (Analytical Spectral Devices Inc., Boulder, CO, USA). The reflectance measurements were made on sunny days between 11.00 and 13.00 h. The field of view (FOV) was 25° and the distance between the optical head of the Spectroradiometer and the top of the plant was kept at 1 m for all observations. For optimization of ASD instrument, a Spectralon (Labsphere, Inc., Sutton, NH, USA) white panel was used to obtain reference signal prior to canopy reflectance measurement. The canopy reflectances were computed as the ratio of canopy radiances to the radiance from the white reference panel.

Spectral signatures of the wheat crop were recorded at six phenostages (Jointing, booting, flowering, milk, dough and harvesting stages) for the year 2011–12 and seven phenostages (CRI, tillering, booting, flowering, milk, dough and harvesting stages) for the year 2012–13. But in the present experiment the canopy reflectance of booting stages were only considered for the prediction of grain and biomass yield of wheat because of least changes in canopy reflectance spectrum (Chang et al. 2005). The spectral reflectance indices (SRI) viz., RNDVI, GNDVI, SR and WI were calculated from the spectral reflectance of each treatment. The description of SRI employed in this study are presented in Table 1.

### Crop Parameters

The net sub-plot areas were harvested for grain yield and final biomass. The grain yield was recorded after cleaning and drying and the result was expressed at 140 g/kg moisture basis. The grain weight and the above ground biomass dry weight were expressed in kg/ha.

### Model Development and Evaluation

Simple linear regression models were developed between grain and aboveground biomass yield as dependant variables and the spectral reflectance indices (SRI) as independent variables for the year 2011–12. Then these models were

evaluated with the help of independent datasets observed from the year 2012–13. Evaluation is an important step of model verification which determines how closely a model represents actual conditions. Following statistical indicators were employed to compare the estimated and observed data.

The coefficient of determination ( $R^2$ ) represents the percent of data that is the closest to the line of best fit.  $R^2$  equal to 1.0 indicates perfect fit, and lesser values indicating less agreement of data.

$$RMSE = \sqrt{\frac{1}{N} \sum_1^N (Pi-Oi)^2} \tag{1}$$

$$nRMSE = \sqrt{\frac{1}{N} \sum_1^N (Pi-Oi)^2} \times \frac{100}{M} \tag{2}$$

Where RMSE is absolute root mean square error, nRMSE is normalized mean square error expressed in %, Pi is the predicted value, Oi is the observed value, N is the number of observations and M is the mean of observed value. RMSE close to zero indicates better model performance. nRMSE is a measure (%) of the relative difference of estimated versus observed data. The prediction is considered excellent with the nRMSE <10 %, good if 10–20 %, fair if 20–30 %, poor if >30 % (Jamieson et al. 1991).

$$d = 1 - \left[ \frac{\sum_1^N (Pi-Oi)^2}{\sum_1^N (|Pi-M| + |Oi-M|)^2} \right]$$

Where “d” is the d index or index of agreement (Willmott et al. 1985). Closer the d index value to 1, the better the agreement between the predicted and observed value.

### Statistical Analysis

The data for the crop and soil properties were analyzed by analysis of variance as outlined by Gomez and Gomez (1984). The significance of the treatment effect was determined using

**Table 1** Description of the spectral reflectance indices (SRI) employed in this study

| S No | Spectral reflectance indices (SRI)                   | Estimation                                    | Function                   | Reference            |
|------|------------------------------------------------------|-----------------------------------------------|----------------------------|----------------------|
| 1    | Red normalized difference vegetation index (RNDVI)   | $\frac{(R_{780}-R_{670})}{(R_{780}+R_{670})}$ | Canopy photosynthetic area | Raun et al. 2001     |
| 2    | Green normalized difference vegetation index (GNDVI) | $\frac{(R_{780}-R_{550})}{(R_{780}+R_{550})}$ | Canopy photosynthetic area | Aparicio et al. 2000 |
| 3    | Simple ratio (SR)                                    | $\frac{(R_{900})}{(R_{680})}$                 | Canopy photosynthetic area | Gitelson et al. 1996 |
| 4    | Water index (WI)                                     | $\frac{(R_{970})}{(R_{900})}$                 | Canopy water status        | Peñuelas et al. 1993 |

R and the subscript numbers indicate the light reflectance at the specific wavelength (in nm)

F-test, and to determine the significance of the difference between the means of the two treatments, least significant differences (LSD) at 5 % probability level and Duncan's multiple range test were used. Correlations and regressions were determined using the data analysis tool pack of MS Excel (2003).

## Results and Discussion

### Grain and Aboveground Biomass Yield of Wheat

The grain yield of wheat was significantly ( $P \leq 0.05$ ) influenced by irrigation levels (Table 2). The grain yield of wheat was significantly higher in I4 treatment (4175 kg/ha for 2011–12 and 2837 kg/ha for 2012–13) than the I2 treatment (3322 kg/ha for 2011–12 and 2550 kg/ha for the year 2012–13). Averaged over the years, the grain yield of wheat was 16 % lower in I2 treatment than the I4 treatment. Similarly the aboveground biomass yield of wheat was significantly higher in I4 (8458 kg/ha) than the I2 (7625 kg/ha) for the year 2012–13. However, for the year 2011–12 the aboveground biomass yield of wheat was statistically similar between I2 (11083 kg/ha) and I4 (13028 kg/ha) treatments. Averaged over the years, the aboveground biomass of wheat was 13 % higher in I4 treatment than the I2 treatment. The higher grain and aboveground biomass yield with increasing levels of irrigation may be attributed to better water and nutrient availability. Similar results have been reported in wheat by many workers (Hati et al. 2001; Jat et al. 2008; Bandyopadhyay et al. 2010). Wheat grain and aboveground biomass yield were not significantly affected by the straw mulch application. Many authors have reported the advantage of organic mulching like straw mulching in improving grain and biomass yield of wheat by minimizing losses of soil

**Table 2** Grain and aboveground biomass yield of wheat 2011–12 and 2012–13

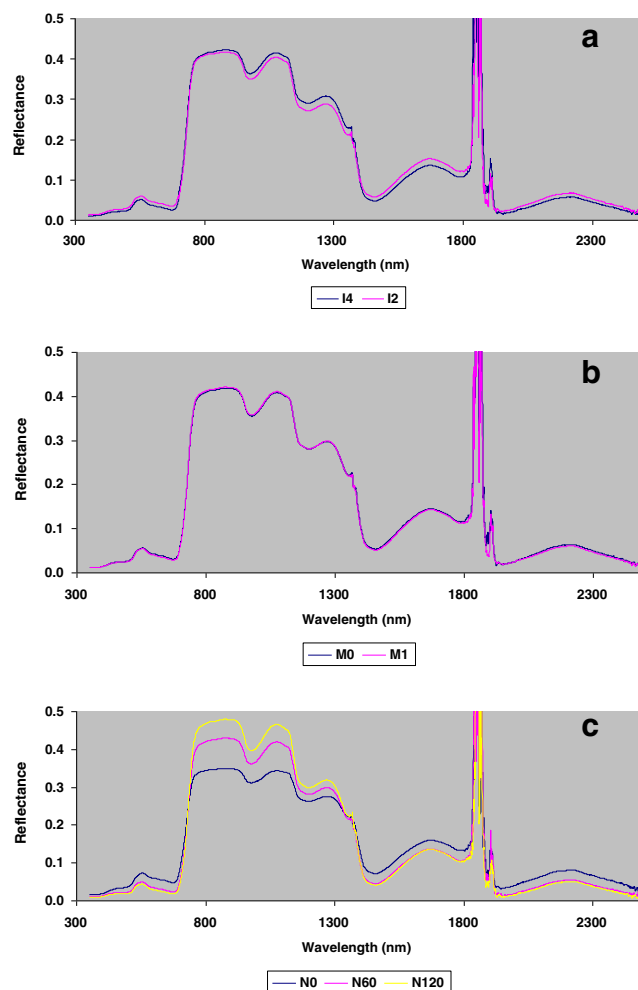
|                      | Grain yield (kg/ha) |         |      | Aboveground biomass (kg/ha) |         |       |
|----------------------|---------------------|---------|------|-----------------------------|---------|-------|
|                      | 2011–12             | 2012–13 | Mean | 2011–12                     | 2012–13 | Mean  |
| Effect of irrigation |                     |         |      |                             |         |       |
| I2                   | 3322b               | 2550b   | 2936 | 11083a                      | 7625b   | 9354  |
| I4                   | 4157a               | 2837a   | 3497 | 13028a                      | 8458a   | 10743 |
| Effect of mulch      |                     |         |      |                             |         |       |
| M0                   | 3657a               | 2628a   | 3143 | 12000a                      | 7986a   | 9993  |
| M1                   | 3822a               | 2759a   | 3290 | 12111a                      | 8097a   | 10104 |
| Effect of nitrogen   |                     |         |      |                             |         |       |
| N0                   | 2735b               | 1633b   | 2184 | 8417b                       | 5188b   | 6802  |
| N60                  | 4088a               | 3203a   | 3645 | 13333a                      | 9167a   | 11250 |
| N120                 | 4396a               | 3245a   | 3820 | 14417a                      | 9771a   | 12094 |

Letters followed by same letters are not significantly different at  $P \leq 0.05$  as per DMRT

water through evaporation and modification of soil thermal regime (Chakraborty et al. 2008), but in the present case, incidence of termite (40–60 % straw were eaten away) did not bring any positive effect on grain and aboveground biomass yield. The grain yield was significantly ( $P \leq 0.05$ ) influenced by nitrogen levels (Table 2). In both the years of study, grain yield of wheat was significantly lower in N0 treatment compared to N60 and N120 treatments. However, N60 and N120 were statistically at par with respect to grain yield. Averaged over the years N0 was 40 % and 43 % lower than the N60 and N120 treatments, respectively. It might have resulted from increased LAI, green spikes area and crop duration with greenness which resulted increased capture of radiation. Similar results have been reported by Latiri-Soki et al. (1998).

### Effect of Irrigation, Mulch and Nitrogen on Canopy Reflectance Spectra and SRI

Spectral reflectance curves of wheat as influenced by irrigation, mulching and nitrogen treatments at booting stage are



**Fig. 1** Effect of irrigation (a), mulch (b) and nitrogen (c) on canopy reflectance of wheat at booting stage

presented in Fig. 1(a, b and c). The spectral reflectance in visible region (400–700 nm) of irrigation treatments showed comparatively higher reflectance in I2 irrigation level than I4 irrigation level. This could be attributed to lower chlorophyll content because of lower nitrogen availability and uptake in lower irrigation levels. Nitrogen concentration in plants significantly affect pigment concentration and hence leaf colour. A reduction in the nitrogen would reduce pigment concentrations, which results increased visible reflection because of decreased radiation absorbance (Joseph 2005). The spectral reflectance in Near-infrared region (700–1300 nm) of irrigation treatment showed comparatively higher reflectance in I4 than I2 irrigation level. This could be attributed to the higher LAI in I4 than I2 irrigation level. Plant canopies strongly scatter photons in the near-infrared region compared to other regions of electromagnetic spectrum, which are ultimately measured by remote sensing instrument. The scattered photons which come from reflections of the vegetation canopy increase with increasing LAI (Asner 1998). However, the spectral reflectance in the Short Wave Infra Red (SWIR) region (1300–2500 nm) was comparatively higher in I2 than I4 irrigation level which might have resulted from lower leaf water content (Joseph 2005) due to lower amount of irrigation.

The canopy reflectance did not show any variation (Fig. 1b) between the mulched and no mulch treatment through the spectral region of study (350 to 2500 nm). As already explained, incidence of termite negated the benefit of mulching on plant growth with respect to chlorophyll content, LAI and leaf water content and hence on spectral reflectance curve.

The canopy reflectance of wheat in various nitrogen treatments (N0, N60 and N120) showed appreciable difference through out the spectral region of the measurement (350 to 2500 nm). The canopy reflectance of N0 treatment was highest in visible region (400–700 nm) followed by the N60 and N120 treatments. It is attributed lower green biomass and

**Table 4** Predictive equations of grain and aboveground biomass yield based on Spectral Reflectance Indices at booting stage (Developed from 2011 to 12 data)

|                           | Predictive equations   | R <sup>2</sup> | F     | SEE  |
|---------------------------|------------------------|----------------|-------|------|
| Grain yield               |                        |                |       |      |
| RNDVI                     | y=8175.6x-3380.8,N=12  | 0.69           | 22.7  | 558  |
| GNDVI                     | y=8887.2x-3076.7,N=12  | 0.73           | 27.6  | 519  |
| SR                        | y=74.243x+2025.1,N=12  | 0.88           | 75.9  | 344  |
| WI                        | y=-31039x+31362,N=12   | 0.79           | 35.1  | 474  |
| Aboveground biomass yield |                        |                |       |      |
| RNDVI                     | y=28551x-12810,N=12    | 0.79           | 38.3  | 1505 |
| GNDVI                     | y=31172x-11853,N=12    | 0.85           | 54.7  | 1298 |
| SR                        | y=249.45x+6295.3,N=12  | 0.93           | 141.9 | 848  |
| WI                        | y=-107476x+107701,N=12 | 0.87           | 69.3  | 1173 |

Significant at 1 % level of significance

lower total chlorophyll content in N0 treatment compared to N60 and N120 treatments (Lee et al. 2002; Chang et al. 2005). However the reflectance in the NIR region showed highest reflectance in the N120 treatment followed by N60 and N0 treatment. This is attributed to the lower LAI in N60 and N0 treatments compared to N120 treatment. Reflectance in the NIR region is directly related to leaf area which increases with the increase in nitrogen application (Guyot 1990; Asner 1998; Chang et al. 2005). But, SWIR region showed highest in the N0 treatment followed by N60 and N120 treatment. It may be attributed to lower canopy water content. N stress in N0 treatment behaved similar to water stress. N stress might have reduced transpiration, increased the canopy temperature resulting in low plant water status (Aggarwal et al. 2004). They have also reported that the effect of N stress is similar to water stress accelerating the phenological development. Among N and water stress, the one that was more prominent affects the rate of development. N stress affected the carbohydrate partitioning and senescence similar to water stress.

**Table 3** Variation of RNDVI, GNDVI, SR and WI at booting stage for the years 2011–12 and 2012–13

|                      | RNDVI   |         | GNDVI   |         | SR      |         | WI      |         |
|----------------------|---------|---------|---------|---------|---------|---------|---------|---------|
|                      | 2011–12 | 2012–13 | 2011–12 | 2012–13 | 2011–12 | 2012–13 | 2011–12 | 2012–13 |
| Effect of irrigation |         |         |         |         |         |         |         |         |
| I2                   | 0.86a*  | 0.79a   | 0.76a   | 0.68a   | 20.27a  | 12.89a  | 0.89a   | 0.93a   |
| I4                   | 0.88a   | 0.82a   | 0.77a   | 0.69a   | 25.92a  | 15.86a  | 0.89a   | 0.92a   |
| Effect of mulch      |         |         |         |         |         |         |         |         |
| M0                   | 0.86a   | 0.82a   | 0.76a   | 0.69a   | 22.46a  | 15.83a  | 0.89a   | 0.92a   |
| M1                   | 0.88a   | 0.79a   | 0.78a   | 0.68a   | 23.73a  | 12.92a  | 0.89a   | 0.93a   |
| Effect of nitrogen   |         |         |         |         |         |         |         |         |
| N0                   | 0.75b   | 0.64b   | 0.65b   | 0.54b   | 9.06c   | 4.94c   | 0.92a   | 0.97a   |
| N60                  | 0.92a   | 0.87a   | 0.81a   | 0.74a   | 26.60b  | 17.00b  | 0.88b   | 0.91b   |
| N120                 | 0.94a   | 0.91a   | 0.84a   | 0.78a   | 33.62a  | 21.19a  | 0.87b   | 0.90b   |

\*Letters followed by same letters are not significantly different at P<0.05 as per DMRT

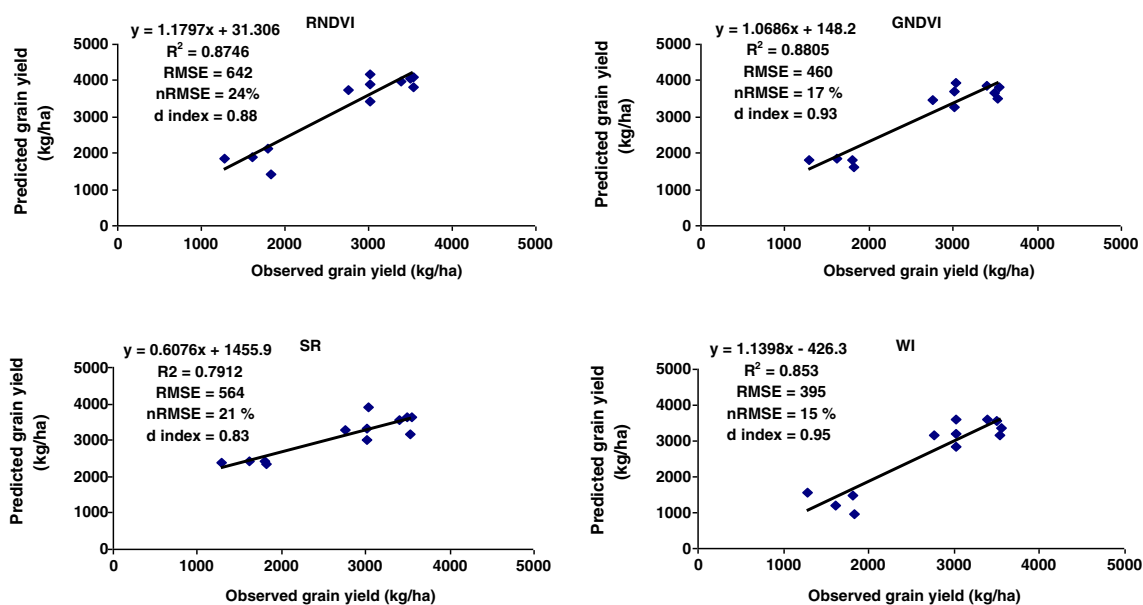


Fig. 2 Observed vs. predicted grain yield obtained using different SRIs (RNDVI, GNDVI, SR and WI)

The variation of SRI (RNDVI, GNDVI, SR and WI) of booting stage under various irrigation, mulch and nitrogen treatments are presented in Table 3 for both the years of study. Though the SRI values were numerically different between I2 and I4 treatments, they were statistically at par. Similarly the SRI values between M0 and M1 treatments were also statistically at par. However, the nitrogen treatment had significant effect on SRI. RNDVI, GNDVI and WI registered significantly lower value in N0 treatment compared to N60 and N120 treatments, but N60 and N120 treatments were statistically at par. However, SR showed significant difference between N0,

N60 and N120 treatments being highest in N120 treatment followed by N60 and N0 treatments.

#### Prediction of Grain and Aboveground Biomass Yield

The grain and aboveground biomass yield of wheat showed significant ( $P \leq 0.01$ ) and positive correlation with the RNDVI, GNDVI and SR, and significant and negative correlation with the WI (Table 4). Similar results have been reported by Prasad et al. (2007) and Li-Hong et al. (2007).

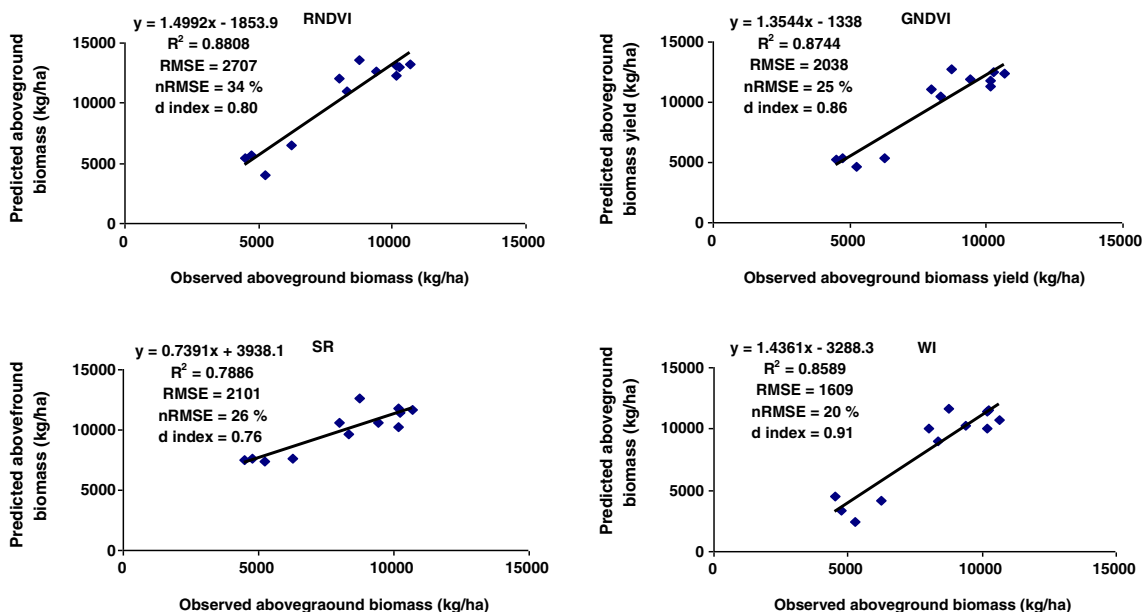


Fig. 3 Observed vs. predicted aboveground biomass yield obtained using different SRIs (RNDVI, GNDVI, SR and WI)

Regression models developed between the grain yield of wheat and the SRI of the year 2011–12 showed that RNDVI, GNDVI, SR and WI could account for 69, 73, 88 and 79 % variation in the grain yield of wheat (Table 4). These regression models were validated with the independent data sets of grain yield and SRI recorded during the year 2012–13 and presented in Fig. 2. It was observed that grain yield predicted by these regression models could account for 79 to 88 % variation in the observed grain yield of wheat (Fig. 2). Out of the four SRI based regression models, WI based model resulted in lowest RMSE (395 kg/ha), lowest nRMSE (15 %) and highest d index (0.95) compared to RNDVI (RMSE=642 kg/ha; nRMSE, 24 % and d index 0.88), GNDVI (RMSE=460 kg/ha; nRMSE, 17 % and d index 0.93) and SR (RMSE=564 kg/ha; nRMSE, 21 % and d index 0.83) based models. So it may be concluded that WI based model was the best predictor of grain yield of wheat. Similar results have been reported by Prasad et al. (2007).

The regression model between aboveground biomass and SRI revealed that RNDVI, GNDVI, SR and WI could account for 79, 85, 93 and 87 % variation in the aboveground biomass yield of wheat (Table 4). These regression models were validated with the independent data sets of aboveground biomass and SRI recorded during the year 2012–13 and presented in Fig. 3. It was observed that aboveground biomass yield predicted by these regression models could account for 79 to 93 % variation in the observed aboveground biomass of wheat (Fig. 3). Out of the four SRI based regression models, WI based model resulted in lowest RMSE (1609 kg/ha), lowest nRMSE (20 %) and highest d index (0.91) compared to RNDVI (RMSE, 2707 kg/ha; nRMSE, 34 % and d index 0.80), GNDVI (RMSE, 2038 kg/ha; nRMSE, 25 % and d index 0.86) and SR (RMSE, 2101 kg/ha; nRMSE, 26 % and d index 0.76) based models. So it may be concluded that WI based model was the best predictor of aboveground biomass of wheat.

## Conclusion

Thus it may be concluded that WI recorded at booting stage can be successfully used to predict grain and aboveground biomass yield of wheat in advance under various water and nitrogen management practices.

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