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Prediction of wheat (*Triticum aestivum*) grain and biomass yield under different irrigation and nitrogen management practices using canopy reflectance spectra model

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ABSTRACT

A field experiment was carried out during *rabi* 2010-11 and 2011-12 to study the canopy reflectance and to predict the grain and biomass yield of wheat (*Triticum aestivum* L.) under different irrigation and nitrogen management practices using canopy reflectance spectra model. Wheat (cv. PBW 502) was grown with four levels of irrigation, i.e. 0.4, 0.6, 0.8 and 1.0 IW/CPE and three N sources, i e 120 kg N/ha as urea, 60 kg N/ha as urea + 60 kg N/ha as farmyard manure (FYM) and 120 kg N/ha as FYM. Three spectral reflectance indices, viz. Red Normalized Difference Vegetation Index (RNDVI), Green Normalized Difference Vegetation Index (GNDVI) and Simple Ratio (SR) were computed using the spectral reflectance data. It was observed that across the treatments, the RNDVI, GNDVI, and SR increased from crown root initiation (CRI) to booting stage and thereafter decreased progressively till harvest. The pooled yield data of both the years showed significantly higher yield in 0.8 and 1.0 IW/CPE irrigation levels than 0.4 and 0.6 IW/CPE irrigation levels. The pooled data of grain yield under different nitrogen practices showed significantly higher yield in urea treatment followed by urea+FYM treatment and FYM treatment. The biomass yield under different nitrogen management practices followed trend similar to grain yield. A significant and positive correlation coefficient was observed between grain and biomass yield and spectral reflectance indices (RNDVI, GNDVI, SR) for all the phenological stages except at CRI stage and maturity stage. Highest correlation coefficient (0.97 for grain yield and 0.93 for biomass yield) was observed for GNDVI measured at milking stage. The model could account for 79 % variation in the grain yield of wheat with root mean square error (RMSE) (%) of 17.1. Similarly the model could account for 86% variation in the biomass yield of wheat with RMSE (%) of 12.7. The models slightly underestimate the grain and biomass yield of wheat with coefficient of residual mass (CRM) value of 0.13 and 0.08, respectively.

Key words: Canopy reflectance, GNDVI, Irrigation, Nitrogen, RNDVI, Spectral index, SR, Wheat

Wheat (*Triticum aestivum* L.) is the second most important cereal crops in India which contributes nearly one-third of the total food grain production. Among the various inputs, water and fertilizer (nutrients) are the two most important inputs which contribute to wheat productivity (Lenka *et al.* 2009). Wheat covers an area of about 19–20 million hectares in India out of which 54% area is irrigated and this constitutes about 27% of the irrigated area of the country (Behera and Panda 2009). Wheat crop is highly responsive to nitrogen fertilizer and its response to nitrogen depends on the availability of soil water (Hati *et al.* 2001). To increase wheat production, excess application of nitrogenous fertilizer and irrigation is a common practice (Hussain and Al-Jaloud 1995) in India (Behera and Panda 2009). Nonjudicious and indiscriminate use of these resources has degraded soil and water quality besides raising the cost of production (Behera *et al.* 2003). Therefore, optimum application of nitrogenous fertilizer and irrigation water to meet the demand of crop as well as their improved management are essential for increasing the productivity and input use efficiency in crops. Prediction of wheat yield under different water and nutrient management scenario can help in optimal use of these inputs.

Knowledge of crop yield at an early stage is of immense value to agencies in government, trade and industry for planning distribution, storage, transportation, processing and export/import of crop produce. In order to get best result in

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estimation or prediction of crop yield, the growth of crops has to be monitored throughout the growing season. Remote sensing can provide information on the actual status of agricultural crops on a regular basis. Canopy spectral reflectance is used for predicting grain and final biomass in various crops (Aparicio *et al.* 2000; Araus *et al.* 2001, Royo *et al.* 2003, Babar *et al.* 2006, Prasad *et al.* 2007, Li-Hong *et al.* 2007, Raun *et al.* 2001, Serrano *et al.* 2000). The more commonly used spectral reflectance indices (SRI) for morphophysiological study of crop plants are simple ratio (SR) and normalized difference vegetation index (NDVI) (Araus *et al.* 2002). The NDVI has 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. Similarly, Shanahan *et al.* (2001) reported that the green normalized difference vegetation index (GNDVI) collected during midgrain filling stage of corn was highly correlated with the yield.

In this backdrop, the present investigation was conducted to compare the performance of three commonly used spectral reflectance indices (RNDVI, GNDVI and SR) based models for prediction of grain and biomass yield of wheat under varied irrigation and nitrogen management practices.

MATERIALS AND METHODS

Field experiments were conducted during *rabi* (winter) 2010-11 and 2011-12 at the Research Farm of the Indian Agricultural Research Institute, New Delhi (77°89'N, 28°37'E, 228.7m asl) with wheat 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 1.57 Mg/m^3; hydraulic conductivity (saturated) 1.03 cm/h, saturated water content (0.41 m^3/m^3), EC (1:2.5 soil/water suspension), 0.36 dS/m; organic C, 5.0 g/kg; total N, 0.032 %; available (Olsen) P, 7.1 kg/ha; available K, 281.0 kg/ha; sand, silt and clay, 71.7, 12.0 and 16.3 %, respectively. Available soil moisture ranged from 26–29 % (0.033 MPa) to 8–11 % (1.5 MPa) for 0 to 1.20 m layers.

The experiment was laid out in a split plot design with irrigation levels as the main plot and nitrogen sources as subplot factors, replicated three times. The subplot size was 3.5 m × 5.5 m. Wheat (cv. PBW 502) was grown during the winter season (3rd week of November to 2nd week of April in 2010-11 and 3rd week of November to 3rd week of April in 2011-12). The irrigation levels were I_1 (IW/CPE: 0.4, IW = 6 cm), I_2 (IW/CPE: 0.6), I_3 (IW/CPE: 0.8) and I_4 (IW/CPE: 1.0). The nitrogen sources consisted of N_1: 100 % N from urea, N_2: 50 % N from urea and 50 % N from farmyard manure (FYM) and N_3: 100 % N from FYM. 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 FYM, 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. The FYM was prepared mainly from cow dung and wheat straw, which is normally used as a bedding material in cowshed. The FYM had 9.6% C, 0.48% N, 0.17% P and 0.38% K. The FYM was applied on dry weight basis. Two preparatory tillage operations by duck foot tine cultivator and levelling were applied for preparation of seed bed and mixing of manures and fertilizers in all the treatments.

The canopy reflectances were measured in the spectral range of 350-2500 nm with 1nm bandwidth using 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 hours. 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 seven phenostages, viz. crown root initiation (CRI), tillering, booting, flowering, milking, soft dough and harvesting stage for the year 2010-11 and jointing, booting, flowering, milking, soft dough and harvesting stage for the year 2011-12.

Spectral reflectance indices were calculated using the formulae as follows,

Red normalized difference vegetation index $=\text{RNDVI}=\dfrac{R_{780}-R_{670}}{R_{780}+R_{670}}$ (Raun *et al.* 2001),

Green normalized difference vegetation index $=\text{GNDVI}=\dfrac{R_{780}-R_{550}}{R_{780}+R_{550}}$ (Aparicio *et al.* 2000),

Simple ratio $=\dfrac{R_{900}}{R_{680}}$ (Gitelson *et al.* 1996)

where R and the subscript numbers indicate the light reflectance at the specific wavelength (in nm). All the above mentioned vegetation based indices (i.e. RNDVI, GNDVI and SR) are related to canopy photosynthetic area. The range of RNDVI and GNDVI is from -1 to +1 and that of SR is 0 to infinity. The cumulative spectral reflectance indices (ΣRNDVI, ΣGNDVI and ΣSR) were obtained by multiplying by averaged SRI values between two spectral measurements by the time interval (in days) and summing for the whole growth period (from CRI to harvesting stage) as mentioned in Li-Hong *et al.* (2007).

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.

Simple regression models developed between grain yield and biomass yield as dependant parameter and the canopy spectral reflectance indices recorded for the year 2010-11. Then these models were evaluated with the help of independent data sets recorded for the year 2011-12.

Model evaluation is the process of comparing model output with the measured values. Evaluation determines how closely a model represents actual conditions.

The coefficient of determination (R^2) gives an indication of the quality of trend conformity, with values of $R^2 = 1.0$ indicating perfect fit, and lesser values indicating less agreement of data.

The root mean square error (RMSE, %) against the observed mean, was used to calculate the fitness between the estimated and measured results. RMSE (%) is defined as follows:

$$\text{RMSE (\%)} = \{\sqrt{[\Sigma(PV-OV)^2 / n]}\ \} \times (100/OM)$$

where PV is predicted value, OV is observed value, OM is observed mean and n is number of sample. RMSE (%) shows the relative difference between the predicted and observed data. The prediction is considered excellent with the RMSE < 10%, good if 10–20%, fair if 20–30%, poor if > 30% (Jamieson *et al.* 1991).

Coefficient of residual mass (CRM) statistics gives the degree to which the prediction is over or underestimated. Positive value of CRM indicates that the model underestimates the measured or observed. A negative value of CRM indicates a tendency to overestimate. The CRM is expressed as: $CRM = \Sigma\ (OV-PV) / \Sigma OV$ where OV is observed value and PV is predicted value.

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 F-test, and to determine the significance of the difference between the means of the two treatments, least significant differences (LSD) at 1% or 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

Weather

Mean monthly air temperature, relative humidity, bright sunshine hours, pan evaporation, wind speed and total rainfall are presented in Table 1. Mean monthly air temperature was 1°C cooler in February of 2011-12 compared to 2010-11. To be specific, the mean monthly minimum air temperature during February 2011-12 was 1.6°C cooler than the previous year, which coincided with the booting, flowering and milking stage of wheat. The mean monthly relative humidity was lower (drier environment) during February and March month of 2011-12 compared to 2010-11, which coincided with the reproductive and grain filling stage. During February month of 2010-11, crop received significantly higher rainfall (49.9 mm) than the year 2011-12. However there was good amount of rainfall (19.2 mm) during the month of March of 2011-12, which coincided with the grain filling stage. The higher mean monthly evaporation during February (1.3 mm/day) and March (1.1 mm/day) of 2011-12 compared to that of 2010-11 might have resulted from more sunshine hours, drier environment as indicated by lower humidity, higher wind speed and higher temperature (Table 1). As a whole the wheat crop of 2011-12 experienced cool and moist weather during vegetative growth period and warm and dry weather during grain formation stage compared to 2010-11, which is highly congenial environment for growth and development of wheat (Prasad 2004). This might have resulted in higher grain yield (5 462 kg/ha in 2011-12 and 3 624 kg/ha in 2010-11) and biomass yield (15 250 kg/ha in 2011-12 and 10 906 kg/ha in 2010-11) of wheat in the year 2011-12 than that of 2010-11.

Grain and biomass yield

Across the years, grain yield increased with the increase in levels of irrigation (Table 2). For the year 2010-11, no significant ($P<0.05$) yield differences in the grain yield of wheat were observed between 0.4 and 0.6 IW/CPE irrigation levels, and 0.8 and 1.0 IW/CPE irrigation levels. However, the grain yields were significantly ($P\leq0.05$) higher for IW/

Table 1 Weather conditions during wheat growth

	Mean T (°C)	Mean RH (%)	Rain (mm)	SSH (hr)	EP (mm)	AWS (km/hr)
2010-11						
Nov	20.0	70.5	10.6	3.3	2.8	0.9
Dec	13.6	67.3	0.7	3.0	2.2	1.0
Jan	11.7	67.3	0.0	3.8	2.8	4.6
Feb	16.3	69.7	49.9	5.4	2.9	3.0
Mar	21.1	61.8	2.3	6.9	4.4	2.7
April	26.4	44.8	2.2	7.9	6.3	3.1
2011-12						
Nov	20.7	60.7	0.0	4.2	2.9	2.9
Dec	14.2	67.2	0.0	3.2	2.2	2.3
Jan	12.1	72.6	14.8	3.4	2.1	3.9
Feb	15.3	54.4	0.0	6.6	4.2	5.8
Mar	21.3	50.4	19.2	6.8	5.5	5.5
April	27.4	54.1	9.0	7.4	7.1	5.7

CPE of 0.8 and 1.0 irrigation levels than IW/CPE of 0.4 and 0.6 irrigation levels (Table 2). In the year 2011-12, no significant yield differences were observed between 0.4 and 0.6, and 0.6, 0.8 and 1.0 IW/CPE irrigation levels. However, the grain yields in 0.8 and 1.0 IW/CPE irrigation levels were significantly higher than the 0.4 IW/CPE irrigation level. The pooled yield data of both the years showed significantly higher yield in 0.8 and 1.0 IW/CPE irrigation levels than 0.4 and 0.6 IW/CPE irrigation levels. It indicated that IW/CPE of 0.8 is sufficient enough for wheat under the present condition. The higher yield with increasing IW/CPE may be attributed to better water and nutrient availability which gave rise to better plant growth and hence yield. Similar results have been reported for wheat by Singh *et al.* (1987) in an Inceptisol, by Hati *et al.* (2001) and Bandyopadhyay *et al.* (2010) in a Vertisol. Grain yield was also significantly different ($P \leq 0.05$) in the three different nutrient management practices being lowest in FYM treatment in both the years of study. In the year 2010-11 significantly higher yield was observed in urea than urea+FYM treatment. However in the year 2011-12, the grain yields with urea and urea+FYM were statsistically at par. The pooled data of grain yield under different nitrogen practices showed significantly higher yield in urea treatment followed by urea+FYM treatment and FYM treatment. The poor grain yield in FYM treatment may be attributed to the low degree of nitrogen mineralization and hence its availability for plant growth during initial years of FYM addition.

Similar to grain yield, across the years, the biomass yield also showed increasing trend with increasing level of irrigation. In the year, 2010-11, there was significant ($P \leq 0.05$) differences in the biomass yield among the irrigation levels, being highest in IW/CPE of 1.0 and lowest in IW/CPE of 4.0. However, in the year 2011-12, no significant biomass yield differences were observed among irrigation treatments. The pooled biomass yield data of both the years showed that 0.4, 0.6 and 0.8 IW/CPE irrigation levels and 0.6, 0.8 and 1.0 IW/CPE irrigation levels are statistically at par. The biomass yield under different nitrogen management practices followed trend similar to grain yield (Table 2).

Comparing grain and biomass yield in both the years of study, it is seen that grain and biomass yield was significantly ($P<0.05$) higher in 2nd year than that of 1st year of study. This could be attributed to the highly congenial environment experienced by the wheat crop in 2nd year than 1st year of study (Prasad 2004).

Spectral reflectance curve

The canopy reflectance in visible (400-700 nm), near-infrared (700-1300 nm) and SWIR (1300-2500 nm) did not show much variation at CRI stage which might be due to the contribution of reflectance from the underlying water and soil as percent ground cover at CRI stage was < 20 % (Chang *et al.* 2005). The canopy reflectance in the visible region (400-700 nm) decreased from CRI to booting stage and thereafter increased till harvesting stage. The decreased reflectance in the visible region from CRI to booting stage may be attributed to absorption by pigments in general and chlorophyll in particular. The increased reflectance in the visible region from booting to harvesting may be attributed to the decreased chlorophyll concentration due to yellowing of leaves. The reflectance in the near-infrared region increased from CRI to booting stage and thereafter decreased progressively till harvesting stage. Leaf area index (LAI) increases from CRI onwards and gets stabilized at booting stage. Accordingly, reflectance in the near infra-red region increased rapidly till booting stage because of increased light scattering by leaves and stems (Asner 1998). After booting stage the decreased reflectance in near-infrared region resulted from decreased LAI and exposure of background soil (Chang *et al.* 2005). The reflectance in the SWIR region basically describes the plant water status. The highest reflectance in the SWIR region was observed during harvesting stage which could be attributed to lowest plant/leaf water status (Joseph

Table 2 Grain and biomass yield of wheat (2010-11 and 2011-12) under different irrigation and nitrogen treatments.

Treatment	Grain yield (kg/ha)			Biomass yield (kg/ha)		
	2010-11	2011-12	Pooled	2010-11	2011-12	Pooled
Effect of irrigation						
0.4 IW/CPE	3 336b*	5 139b	4 237b	9 361d	14 778a	12 069b
0.6 IW/CPE	3 276b	5 389ab	4 332b	10 764c	15 278a	13 029ab
0.8 IW/CPE	3 916a	5 583a	4 750a	11 506b	15 111a	13 308ab
1.0 IW/CPE	3 969a	5 736a	4 853a	11 992a	15 833a	13 913a
Effect of nitrogen source						
Urea	4 458a	6 219a	5 339a	13 615a	17 583a	15 599a
Urea+FYM	3 751b	6 125a	4 938b	11 123b	17 125a	14 124b
FYM	2 663c	4 042b	3 352c	7 979c	11 042b	9 517c

Numbers followed by same letter in a column are not significantly different at P=0.05 as per DMRT

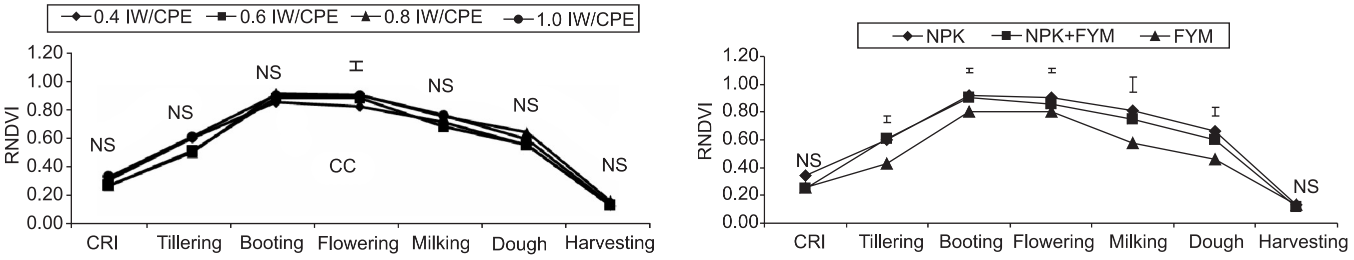
2005). Almost similar types of results were obtained during the second crop season (data not shown).

The spectral reflectance in visible region (400-700 nm) of irrigation treatments showed comparatively higher reflectance in lower irrigation levels (0.4 and 0.6 IW/CPE) than the higher irrigation levels (0.8 and 1.0 IW/CPE). 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 highest reflectance in 1.0 and 0.8 IW/CPE irrigation levels than 0.4 and 0.6 IW/CPE irrigation levels. This could be attributed to the higher LAI in 1.0 and 0.8 IW/CPE irrigation levels than 0.4 and 0.6 IW/CPE levels. Plant canopies strongly scatter photons in the near-infrared region compared to other regions of electromagnetic spectrum, which was ultimately measured by spectroradiometer. 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 higher in lower irrigation (0.4 and 0.6 IW/CPE) than higher irrigation levels (0.8 and 1.0 IW/CPE) which might have resulted from lower leaf water content (Joseph 2005) due to lower amount of irrigation.

Across the years, the canopy reflectance in FYM treatment was significantly less from urea and urea+FYM treatments. However, no significant differences in the reflectance spectra was observed between urea and urea+FYM treatments. The canopy reflectance of FYM treatment was higher in visible region (400-700 nm) than urea and urea+FYM treatment. It could be attributed to lower mineralization hence poor availability and uptake of nitrogen in FYM treatments during the dry season. The lower canopy reflectance of FYM treatment in near-infrared region may be attributed to lower LAI. However, in the SWIR region FYM treatment showed higher reflectance compared to urea and urea+FYM treatment because of lower leaf water content. This may be attributed to the fact that N stress in FYM 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. Almost similar types of results were obtained during the year 2011-12 (data not shown).

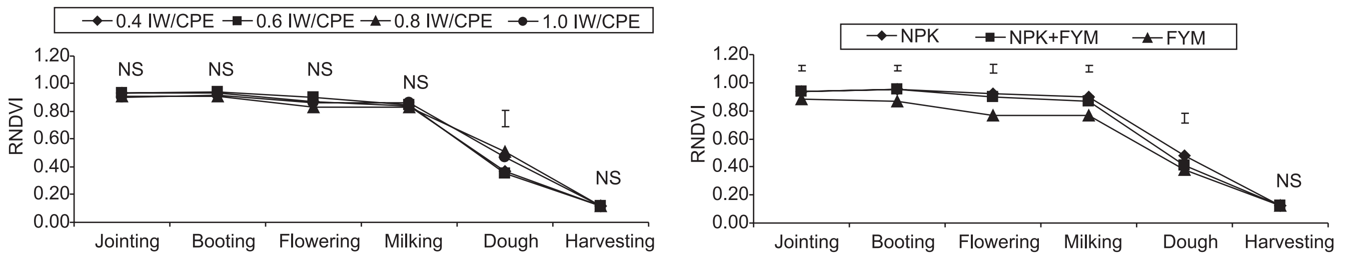
Temporal variation of RNDVI, GNDVI and SR

The temporal variation of spectral reflectance indices (RNDVI, GNDVI and SR) were calculated at each phenostages from the reflectance data and are presented in Fig 1 and 2 respectively. Across the treatments, the RNDVI, GNDVI, and SR increased from CRI to booting stage and there after decreased progressively till maturity in 2010-11. Similarly, all three spectral reflectance indices showed highest value at booting stage and decreasing trend at either side of



(a) Effect of irrigation levels, 2010-11

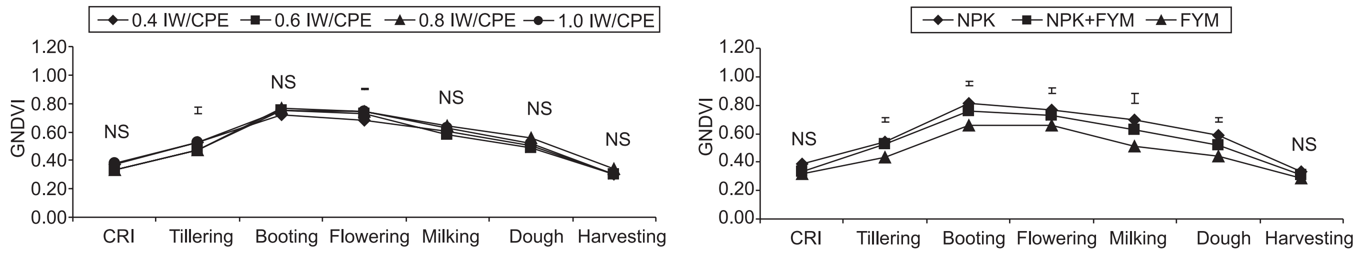
(b) Effect of nitrogen sources, 2010-11



(c) Effect of irrigation levels, 2011-12

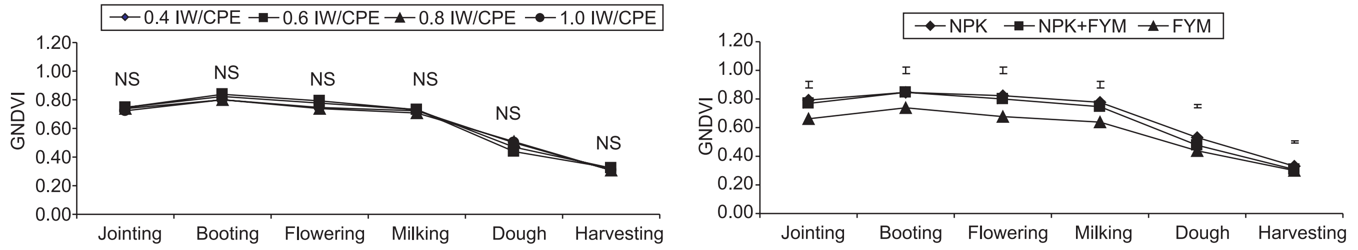
(d) Effect of nitrogen sources, 2011-12

Fig 1 Temporal variation of RNDVI under various irrigation (a,c) and nitrogen treatments (b,d) for the year 2010-11 and 2011-12. The error bars indicate LSD at P=0.05. NS indicate not significantly different at P≤0.05.



(a) Effect of irrigation levels, 2010-11

(b) Effect of nitrogen sources, 2010-11



(c)Effect of irrigation levels, 2011-12

(d) Effect of nitrogen sources, 2011-12

Fig 2 Temporal variation of GNDVI under various irrigation (a,c) and nitrogen (b,d) treatments for the year 2010-11 and 2011-12. The error bars indicate LSD at P=0.05. NS indicate not significantly different at $P \leq 0.05$.

booting stage. The decrease in RNDVI, GNDVI and SR from booting to grain filling stage of wheat has also been reported by Prasad *et al.* (2007). The primary reason for the decreasing trend of RNDVI, GNDVI and SR from booting to maturity is the reduced reflectance in the NIR region and increased reflectance in the visible region due to loss of green tissue with advancement of plant growth (Aparicio *et al.* 2000 and Prasad *et al.* 2007). The highest value of RNDVI, GNDVI and SR at booting stage may be attributed to the highest amount of green leaf area and the highest leaf area index observed at this stage (Prasad *et al.* 2007).

There was no significant variation in RNDVI, GNDVI, and SR values among irrigation treatments at all the phenological stages except at flowering stage for RNDVI, tillering and flowering stage for GNDVI, and booting and flowering stage for SR value in the year 2010-11. However in the year 2011-12, the dough stage for RNDVI and jointing stage for SR showed significant variation among irrigation treatments. GNDVI was not significantly different among irrigation treatments for all the phenostages of 2011-12.

Besides the CRI and harvesting stage, the RNDVI, GNDVI and SR values were significantly ($P \leq 0.01$) influenced by different nitrogen sources for the year 2010-11. However in the year 2011-12, besides RNDVI value at harvesting stage, all the spectral reflectance indices showed significant variation among nitrogen treatments. The highest value was observed in urea treatment followed by urea+FYM and FYM treatment. The release of nitrogen from FYM was relatively slower in the dry season, which might resulted in poor crop growth and less green leaf area in FYM treatments as observed by lower LAI and chlorophyll content (data not shown) in FYM treatment compared to urea treatment.

Table 3 Correlation coefficients (r) between grain yield, final biomass and grain protein content with three vegetation indices at different growth stages

Phenological stages	Grain yield (kg/ha)			Biomass yield (kg/ha)		
	RNDVI	GNDVI	SR	RNDVI	GNDVI	SR
CRI	0.449	0.549	0.45	0.454	0.507	0.458
Tillering	0.676*	0.734**	0.685*	0.585*	0.642*	0.583*
Booting	0.873**	0.896**	0.848**	0.894**	0.924**	0.862**
Flowering	0.734**	0.819**	0.838**	0.790**	0.886**	0.906**
Milking	0.954**	0.967**	0.927**	0.908**	0.930**	0.885**
Dough	0.894**	0.917**	0.918**	0.869**	0.894**	0.873**
Harvesting	0.444	0.793**	0.565	0.407	0.782**	0.545
Cumulative Indices	0.924**	0.954**	0.910**	0.888**	0.930**	0.921**

*Indicate significant at $P \leq 0.05$, ** indicate significant at $P \leq 0.01$

Table 4 Predictive models of grain and biomass yield of wheat (developed from 2010-11 data)

Parameters	Stage	Index	Predictive equation
Grain yield (GY in kg/ha)	Milking	GNDVI	GY = 10016 × GNDVI – 2512.6, R^2=0.94**, n=12
Biomass (BM in kg/ha)	Milking	GNDVI	BM = 28864 × GNDVI– 6852.1, R^2=0.86**, n=12

**Significant at P≤0.01.

Correlation between spectral reflectance indices and grain yield

The correlation coefficient between grain yield and spectral reflectance indices (RNDVI, GNDVI, SR) from CRI stage to maturity stage are presented in Table 3. Significant and positive correlations between grain yield and spectral reflectance indices are observed for all stages except at CRI stage and maturity stage, indicating that yield could be estimated well in advance of harvest. Similar results have been reported by Rudorff and Batista (1990), Li-Hong *et al.* (2007) and Prasad *et al.* (2007). The correlation coefficients were highest for the spectral reflectance indices measured at milking stage. Among the three spectral reflectance indices, GNDVI was having highest correlation coefficient with wheat grain yield. This indicated that the green band was better yield predictor than the red band. Li-Hong *et al.* (2007) and Royo *et al.* (2003) also observed milk ripe stage (mid-filling) stage was the most appropriate development stage for predicting wheat yield and the reflectance at green band explained the yield variability more precisely than the reflectance at red band. The strong dependence of yield and crop N status may explain this phenomenon. Cumulative spectral reflectance indices value from CRI to maturity didn't show any improvement in correlation coefficient compared to the correlation coefficient obtained at milking stage. This result is contrary to the earlier result of Pinter *et al.* 1981, Rudorff and Batista (1990), Serrano *et al.* (2000), Li-Hong *et al.* (2007), which state that cumulative spectral reflectance indices represents the intensity and duration of the photosynthetic activity of the crop and is better than a single SRI obtained at a given phenological stage. However, under present condition, in order to predict grain yield, GNDVI measured at milking stage was considered for the regression model and is presented in Table 4. It showed about 94% variation in grain yield of wheat can be accounted for by GNDVI at milking stage. The second crop season data was used for validation purposes and the relation between predicted and observed grain yield are presented in Fig 3. It was observed that the model could account for 79 % variation in the grain yield of wheat with RMSE (%) of 17.1. The model validation for grain yield shows that the model tends to slightly under-estimate its measured counterparts with CRM values pegged at 0.134.

Correlation between spectral reflectance indices and biomass

The correlation coefficient of biomass yield and spectral reflectance indices (RNDVI, GNDVI, SR) from CRI to maturity stage are presented in Table 3. Similar to grain yield, significant and positive correlations were observed between biomass and spectral reflectance indices for all stages except CRI and maturity stages which indicated that biomass yield could be estimated well in advance of harvest. Similar results have been reported by Verma *et al.* (2010) for wheat and Osborne *et al.* (2002) for corn. Similar to grain yield, the highest correlation coefficients between biomass yield and spectral reflectance indices were observed at milking stage. Verma *et al.* (2010) also observed highest correlation between SRI and biomass at milking stage. Among the three SRI considered, GNDVI was having highest correlation and SR the least correlation with wheat biomass yield (Table 3). Osborne *et al.* (2002) also observed higher correlation between corn biomass and reflectance in green band. So, GNDVI measured at milking stage was used for prediction of biomass yield (Table 4). It was observed that 86% variation in biomass yield could be explained by the model (Table 4). The relation between predicted and observed biomass yield is presented in Fig 4. The validation result of biomass yield

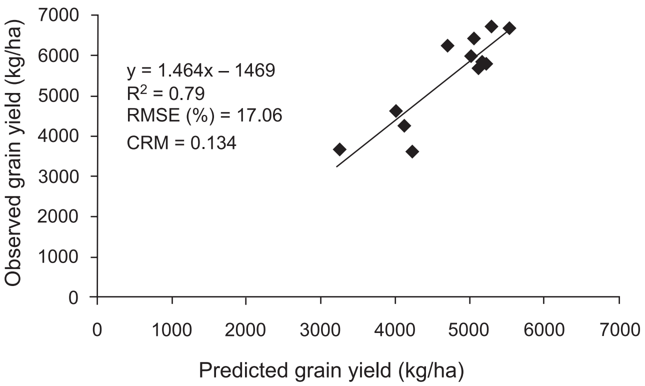


Fig 3 Relationship between measured and predicted grain yield.

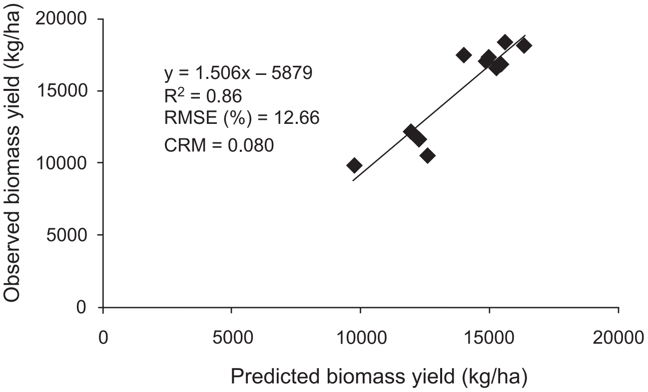


Fig 4 Relationship between measured and predicted biomass.

showed that 86% variation in the biomass yield could be accounted by the model with a RMSE (%) of 12.7. The model tends to slightly underestimate the biomass yield with CRM value pegged at 0.08.

Thus from this study it can be concluded that out of the three spectral reflectance indices (RNDVI, GNDVI and SR), GNDVI measured at milking stage can be successfully used for the prediction of grain and biomass yield under different irrigation and nitrogen management practices.

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