Yield prediction in wheat (*Triticum aestivum* L.) using spectral reflectance indices

N. S. Chandel*, P. S. Tiwari, K. P. Singh, D. Jat, B. B. Gaikwad, H. Tripathi and K. Golhani

ICAR-Central Institute of Agricultural Engineering, Bhopal 462 038, India

Influence of nitrogen on vegetative growth of wheat is significant, and can be monitored and assessed using vegetation indices derived from canopy reflectance at different phenological growth stages. The aim of the present work was to establish a regression model for yield prediction of wheat using spectral reflectance indices (SRIs), normalized difference nitrogen index (NDNI), normalized difference vegetation index (NDVI), normalized difference water index (NDWI) and soil adjusted vegetation index (SAVI) for selected phenological growth stages of wheat. The canopy spectral reflectance was recorded during three winter seasons (2014–2017) for irrigated wheat. A hyperspectral library of canopy reflectance was developed, which enables the study of spectra independent of different nitrogen management practices. It indicated that the precise level of nitrogen for irrigated wheat may be 90 kg ha^{-1} in vertisols under agro-climatic of central India. Coefficient of variation (CV) was determined based on significance test between eight levels of nitrogen and SRI values. On the basis of CV, NDVI and NDWI were selected among the four spectral indices for the study of correlation between grain and biomass yields and nitrogen levels for four growth stages, viz. tillering, booting, heading and milking. A regression model was developed to find the best representative stage for yield prediction among the four stages. The regression model indicated that the relations of NDVI with grain and biomass yields were stronger in the heading stage, and it resulted in 96% accurate estimation of grain and biomass yields in irrigated wheat.

Keywords. Nitrogen management, spectral reflectance, vegetation indices, wheat, yield estimation.

NITROGEN (N) is one of the critical macronutrients and its application is the most important factor in wheat production. Soil and plant analysis techniques have helped reduce N application rates without reducing grain and biomass yields. However, these estimation techniques are tedious, costly and labour-intensive[1]. Remote sensing is a non-destructive technique to estimate certain plant phenotypes, and has been frequently used to determine crop N status during the growing season[2–4]. Remote sensing may help estimate whether plants are able to acquire adequate N under a given management plan or not[5]. Precision N management in wheat crop using spectral reflectance indices (SRIs) may play a key role for instantaneous and accurate estimation of crop yield during growth stage. Determination of spectral characteristic of crop canopies provides an opportunity for on-field application of N fertilizer[6]. Spectral signature of the plants includes detailed data that may provide information regarding N management decisions. The reflectance wavelengths for determining N concentration change with time due to change in field cover, N application rate and growth stage[7]. Spectral reflectance for crop canopy can be used for plant nutrient measurement, plant environments monitoring at different stages and crop biophysical variables assessment[8].

The relationship of spectral indices with plant and environmental variables needs to be analysed using regression analysis[9]. The piece-wise multiple regression models used for discrete narrow bands provide flexibility in choosing bands that give more information at a particular crop growth stage. Various band arrangements have been used for variations in crop conditions due to agronomical practices, climatic factors, nutrient management and soil characteristics[10]. Temporal and spatial variability and crop growth can be described within the field during crop growing season by acquiring information from plant reflectance. Crop management information systems or empirical crop models based on vegetation indices can be developed with agronomic parameters, e.g. biomass[11]. Canopy spectral reflectance is helpful for predicting grain and biomass yields and grain protein content in various crops[12].

In order to establish the best regression model using spectral reflectance indices for estimation of grain yield and evolution of subsequent crop yield data, spectral indices such as normalized difference nitrogen index (NDNI), normalized difference vegetation index (NDVI), normalized difference water index (NDWI) and soil adjusted vegetation index (SAVI) have been widely used. NDVI is historically one of the first vegetation indices, which has been used by many researchers to predict crop greenness, production, biomass, main species, leaf area

*For correspondence. (e-mail: narendracae@gmail.com)

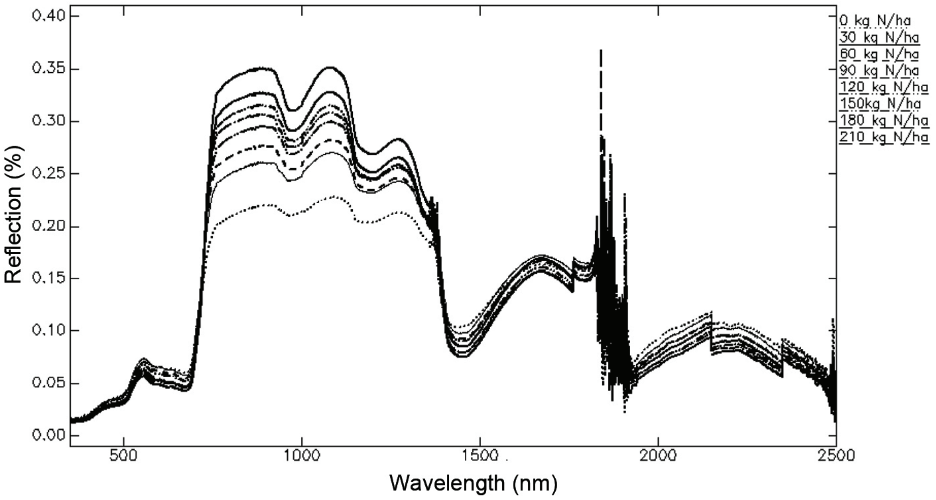

Figure 1. Spectral reflectance of different nitrogen treatments at heading stage.

index (LAI) and fraction of absorbed photosynthetically active radiation[13]. Huete[14] presented the concept of SAVI to minimize soil influence on canopy spectra. Gontia and Tiwari[15] reported the use of NDVI and SAVI-based models for predicting yield and water productivity of wheat crop. NDWI is considered as an independent vegetation index, but it is not a substitute for NDVI. Gao[16] found that NDWI is less sensitive compared to NDVI for environmental effects. NDNI has also been developed to retrieve N status of crop canopy[17]. The use of spectral techniques has provided a way for estimating N status of wheat; however these techniques have never been tried under vertisols of central India. Keeping these points in view, this experiment was planned to identify optimal dose of N fertilizer and the best phenological stage to establish a regression model for yield prediction using the best-suited SRIs among NDVI, SAVI, NDWI and NDNI for wheat crop under vertisols of central India.

Materials and methods

The experiment was conducted at the research farm of ICAR-Central Institute of Agricultural Engineering, Bhopal, Madhya Pradesh, India (77°24′7.50″E, 23°18′ 56.91″N) during the winter season of 2014–15, 2015–16 and 2016–17. Irrigated wheat crop (*Triticum aestivum* L.) variety HI-1544 was grown in vertisols with crop rows in the east–west direction. The granular urea as a source of nitrogen in eight different treatments, viz. T_1 to T_8 of N level 0 to 210 kg ha^{-1} respectively, with 30 kg interval was applied with three replications. The plot size for each treatment was 84 sq. m with randomized block design (RBD). The climate was favourable throughout the crop cycle for wheat growth and development. Spectral reflectance data were collected using a spectroradiometer (ASD FieldSpec3®; Analytical Spectral Devices Inc., Boulder, Co, USA) having spectral range of 350–2500 nm. The device was equipped with three sensors, VNIR (750–1000 nm), SWIR1 (1000–1830 nm) and SWIR2 (1830–2500 nm) with spectral sampling rate of 3, 10 and 10 nm respectively. White reference panel made of polytetrafluoroethylene was used to measure the reference spectrum. The observations were taken along the nadir view from 0.5 m above the wheat crop canopy using 25° field of view (FOV). Spectral data were recorded for seven phenological growth stages of the crop, viz. crown root initiation (CRI), tillering, booting, heading, milking, dough stage and harvesting using RS^3 software (Figure 1). Data were acquired between 11 : 00 and 1 : 00 IST under clear sky condition and appropriate sunshine. The View Spec™ Pro software was used for post-processing of spectra files that were saved using the spectroradiometer. These saved spectra files were averaged and exported to ASCII format. The ASCII format data were used for development of spectral libraries in ENVI 4.7 software. The spectral data (mean of three years) were arranged and saved in .xlsx format. Table 1 shows the formulation of different SRIs for the estimation of N. The data analysis including descriptive statistics, spectral indices and Duncan multiple range test (DMRT) was done using the SAS 9.3 software.

Results and discussion

Effect of N treatment on grain and biomass yields

The grain yield (Table 2) was found highest in treatment T_8 (4067 kg ha^{-1}) followed by T_7 (4037 kg ha^{-1}), T_5 (3793 kg ha^{-1}), T_4 (3748 kg ha^{-1}), T_6 (3743 kg ha^{-1}), T_3 (3224 kg ha^{-1}), T_2 (2361 kg ha^{-1}) and T_1 (1727 kg ha^{-1}). The biomass yield (Table 2) was found highest in treatment T_7 (5434 kg ha^{-1}) followed by T_8 (5383 kg ha^{-1}), T_5

Table 1. Spectral reflectance indices and formulation

Spectral reflectance index	Formulation	References
Normalized difference vegetation index	$NDVI = R_{864} - R_{671} / R_{864} + R_{671}$	25
Soil adjusted vegetation index	$SAVI = (1 + L) \times (R_{864} - R_{671})/(R_{864} + R_{671} + L)$	14
Normalize difference water index	$NDWI = (R_{864} - R_{1245})/(R_{864} + R_{1245})$	16
Normalized difference nitrogen index	$NDNI = (\log(1/R_{1510}) - \log(1/R_{1680}))/(\log(1/R_{1510}) + \log(1/R_{1680}))$	17

Note: R_{864}, Reflectance at wavelength 864 nm; R_{671} = Reflectance at wavelength 671 nm; R_{1245}, Reflectance at wavelength 1245 nm; R_{1680}, Reflectance at wavelength 1680 nm and R_{1510}, Reflectance at wavelength 1510 nm. L is the soil brightness correction factor = 0.5.

Table 2. Grain and biomass yields under different N levels (mean of three consecutive years' data)

Treatment	N level (kg ha^{-1})	Grain yield (kg ha^{-1})	Biomass (kg ha^{-1})
T_1	0	1727^a	2294^a
T_2	30	2361^b	3155^b
T_3	60	3224^c	4329^c
T_4	90	3748^{cd}	4888^{cd}
T_5	120	3793^{cd}	4988^{cd}
T_6	150	3743^{cd}	4960^{cd}
T_7	180	4037^d	5434^d
T_8	210	4067^d	5383^d

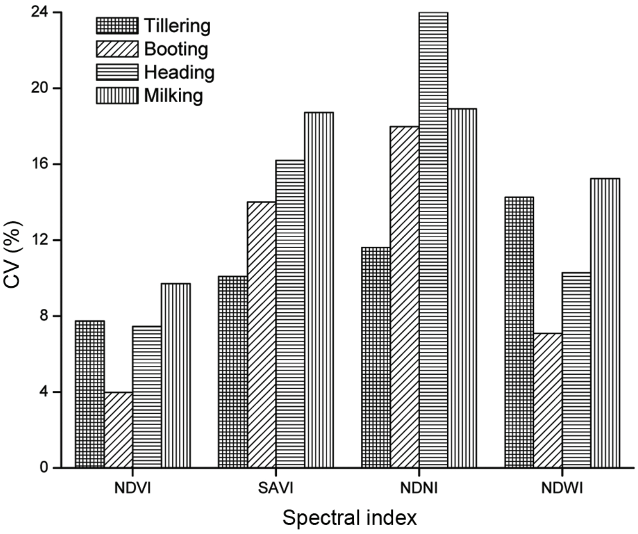

Figure 2. Comparative pattern of coefficient of variation for spectral indices under different growth stages.

(4988 kg ha^{-1}), T_6 (4960 kg ha^{-1}), T_4 (4888 kg ha^{-1}), T_3 (4329 kg ha^{-1}), T_2 (3155 kg ha^{-1}) and T_1 (2294 kg ha^{-1}). The grain and biomass yields were significantly affected by different levels of nitrogen applied (Table 2). DMRT showed that there were significant differences in the grain and biomass yields at 5% level of significance for treatments T_1–T_3. There were no significant differences between grain and biomass yields for treatments T_3–T_6. Similarly, grain and biomass yields for T_4–T_8 were at par. Thus, T_4 (nitrogen dose of 90 kg ha^{-1}) may be considered as the optimum N-rate for wheat in vertisols, where grain yield (3748 kg ha^{-1}) and biomass yield (4888 kg ha^{-1}) were found at par ($P < 0.05$) compared to other treatments with higher nitrogen doses. Baethgen and Alley[18] reported that 95 kg ha^{-1} was the adequate amount of N uptake for winter wheat in USA.

The spectral signatures of crop reflectance showed wide variation in canopy reflectance for different N treatments beyond the red region (Figure 2). In the visible range, the highest (7.5%) reflection was observed for T_2 at 550 nm wavelength. In the NIR range, the highest reflection (35%) was observed for T_8 at 850 nm. The hyperspectral reflectance was found to decrease in 350–675 and 1350–1750 nm and increase in 680–1300 nm. Thus different N applications were categorized with the help of spectral patterns. In the present study it was observed that higher N-rate gives higher reflection and lower N-rate gives lower reflection. With this technique over-fertilized fields can be identified in an early Feekes growth stage[19]. The spectra of T_4–T_6 coincided to each other. Therefore, we need not apply excess dose of N fertilizer beyond 90 kg ha^{-1}.

Effect of different treatments on spectral indices at different growth stages

Strong relationship between N concentration and grain yield was found at some critical growth stages of wheat crop. The grain yield could be predicted indirectly through the regression model between N concentration and spectral indices. The values for the selected spectral indices were analysed for different phenological growth stages. Significant differences ($P < 0.05$) were observed for values of spectral indices at all crop growth stages at different N levels (Table 3). DMRT was applied to differentiate these values. The spectral values for NDVI, SAVI, NDWI and NDNI increased from CRI to the booting stage were assertive from the booting to milking stage and decreased from the milking to harvesting stage (Table 3). Highest values at the booting stage may be due to the highest amount of green leaf area. Decreasing trend from booting to maturity can be attributed to reduced reflectance in the NIR region and increased reflectance in visible region. This is due to damage of green tissue from booting to harvesting stage of crop growth in wheat. Similar findings were reported by Prasad *et al.*[20] and Pradhan *et al.*[12].

Table 3. Temporal variation of spectral indices under different phenological stages (mean of three consecutive years' data)

Treatment	Growth stage						
	CRI	Tillering	Booting	Heading	Milking	Dough	Harvesting
NDVI							
T_1	0.426^{d}	0.633^{a}	0.890^{bc}	0.757^{a}	0.690^{a}	0.612^{a}	0.202^{a}
T_2	0.425^{d}	0.694^{ab}	0.833^{a}	0.815^{b}	0.780^{b}	0.760^{b}	0.255^{ab}
T_3	0.373^{bc}	0.710^{ab}	0.879^{b}	0.865^{bc}	0.861^{bc}	0.803^{bc}	0.259^{ab}
T_4	0.390^{cd}	0.684^{ab}	0.899^{bc}	0.892^{c}	0.857^{bc}	0.845^{bc}	0.282^{bc}
T_5	0.428^{d}	0.808^{b}	0.927^{bc}	0.899^{c}	0.898^{c}	0.873^{bc}	0.290^{bcd}
T_6	0.321^{a}	0.709^{ab}	0.931^{c}	0.903^{c}	0.919^{c}	0.903^{c}	0.338^{cde}
T_7	0.334^{ab}	0.746^{ab}	0.934^{c}	0.916^{c}	0.921^{c}	0.910^{c}	0.348^{de}
T_8	0.349^{abc}	0.780^{ab}	0.939^{c}	0.918^{c}	0.928^{c}	0.916^{c}	0.363^{e}
SAVI							
T_1	0.281^{d}	0.363^{b}	0.508^{ab}	0.408^{a}	0.372^{a}	0.313^{a}	0.116^{a}
T_2	0.281^{d}	0.403^{ab}	0.441^{a}	0.488^{ab}	0.433^{ab}	0.411^{b}	0.151^{b}
T_3	0.245^{bc}	0.400^{ab}	0.473^{a}	0.562^{bc}	0.523^{bc}	0.440^{b}	0.154^{b}
T_4	0.245^{bc}	0.398^{ab}	0.531^{abc}	0.619^{cd}	0.526^{bc}	0.482^{bc}	0.168^{b}
T_5	0.264^{cd}	0.493^{b}	0.599^{bcd}	0.606^{cd}	0.564^{cd}	0.486^{bcd}	0.170^{b}
T_6	0.1718^{a}	0.416^{ab}	0.608^{cd}	0.630^{cd}	0.631^{d}	0.547^{cd}	0.203^{c}
T_7	0.162^{a}	0.455^{ab}	0.639^{d}	0.654^{cd}	0.654^{d}	0.547^{cd}	0.213^{c}
T_8	0.225^{b}	0.473^{ab}	0.639^{d}	0.698^{d}	0.650^{d}	0.576^{d}	0.217^{c}
NDWI							
T_1	0.072^{d}	0.107^{a}	0.094^{a}	0.064^{a}	0.084^{a}	0.081^{a}	0.032^{a}
T_2	0.072^{d}	0.120^{ab}	0.127^{ab}	0.129^{b}	0.106^{ab}	0.106^{b}	0.043^{b}
T_3	0.064^{c}	0.121^{ab}	0.133^{ab}	0.143^{b}	0.128^{bc}	0.113^{bc}	0.043^{b}
T_4	0.061^{bc}	0.116^{ab}	0.148^{ab}	0.153^{b}	0.127^{bc}	0.121^{bcd}	0.0470^{bc}
T_5	0.073^{d}	0.152^{b}	0.167^{b}	0.152^{b}	0.137^{cd}	0.125^{bcd}	0.047^{bc}
T_6	0.042^{a}	0.123^{ab}	0.167^{b}	0.156^{b}	0.153^{cd}	0.135^{cd}	0.053^{cd}
T_7	0.040^{a}	0.139^{ab}	0.171^{b}	0.164^{b}	0.155^{d}	0.134^{cd}	0.054^{d}
T_8	0.056^{b}	0.139^{ab}	0.170^{b}	0.168^{b}	0.152^{cd}	0.139^{d}	0.053^{cd}
NDNI							
T_1	0.150^{e}	0.383^{a}	0.755^{bc}	0.550^{a}	0.500^{a}	0.357^{a}	0.036^{a}
T_2	0.149^{e}	0.443^{ab}	0.678^{a}	0.65^{b}	0.620^{b}	0.56^{b}	0.168^{b}
T_3	0.105^{c}	0.482^{ab}	0.735^{a}	0.726^{c}	0.739^{bc}	0.631^{bc}	0.176^{b}
T_4	0.110^{cd}	0.455^{ab}	0.760^{bc}	0.738^{c}	0.720^{bc}	0.698^{bcd}	0.218^{b}
T_5	0.144^{de}	0.601^{b}	0.811^{c}	0.759^{cd}	0.7918^{c}	0.740^{cd}	0.245^{b}
T_6	0.032^{a}	0.472^{ab}	0.815^{c}	0.765^{c}	0.813^{c}	0.798^{c}	0.307^{c}
T_7	0.018^{a}	0.51^{ab}	0.818^{c}	0.784^{c}	0.821^{c}	0.809^{c}	0.332^{c}
T_8	0.066^{b}	0.568^{ab}	0.828^{c}	0.766^{c}	0.829^{c}	0.814^{c}	0.308^{c}

Values with different lower-case letters are significantly different according to DMRT. The same letters are not significantly different in each row at 0.05 level.

Table 3 also presents canopy reflectance-based indices for different treatments at various growth stages of wheat. It can be seen that NDVI, SAVI, NDWI and NDNI show dissimilar trends for different treatments at different growth stages. Crops treated with higher N doses (T_6–T_8) showed higher NDVI compared to lower N doses (T_1–T_5). There was no trend observed at CRI stage with change in N dose in all indices. There was non-significant variation in NDVI, SAVI, NDWI and NDNI at tillering stage among all treatments. Significant variation in NDVI values was observed among some treatments at the harvesting stage. Results showed that values were not significantly different between NDVI, NDWI and NDNI at the booting to milking stage, whereas the milking and harvesting stages showed no significant difference ($P < 0.05$) in SAVI. No significant difference was seen at the heading stage in all indices, except SAVI. NDWI basically describes the plant water status seen in the VNIR and SWIR1 regions of reflectance. Significant difference in all treatments at the CRI stage was observed; however, reflectance difference was not significant at tillering stage among treatments except between T_1 and T_5. There was no significant difference ($P < 0.05$) in NDWI for T_2–T_5 from tillering to harvesting stages. There was no significant difference in NDVI for T_4–T_8 from booting to harvesting stages, except T_7 and T_8 at the harvesting stage. The highest reflectance in NDWI was observed during the booting stage at higher N doses,

Table 4. Descriptive statistics of spectral indices for different growth stages (mean of three years)

Growth stage	Minimum	Maximum	Mean	SD	CV%
NDVI					
CRI	0.32	0.43	0.38	0.04	11.41
Tillering	0.63	0.81	0.72	0.06	7.74
Booting	0.83	0.94	0.9	0.04	4.03
Heading	0.76	0.92	0.87	0.06	7
Milking	0.69	0.93	0.86	0.08	9.72
Dough	0.61	0.92	0.83	0.11	13.32
Harvesting	0.2	0.36	0.29	0.05	18.76
SAVI					
CRI	0.16	0.28	0.23	0.05	19.55
Tillering	0.36	0.49	0.43	0.04	10.36
Booting	0.44	0.64	0.55	0.08	13.86
Heading	0.41	0.7	0.58	0.09	16.19
Milking	0.37	0.65	0.54	0.1	18.89
Dough	0.31	0.58	0.47	0.09	19.68
Harvesting	0.12	0.22	0.17	0.03	20.09
NDNI					
CRI	0.04	0.07	0.06	0.01	21.6
Tillering	0.11	0.15	0.13	0.01	11.62
Booting	0.09	0.17	0.15	0.03	18.52
Heading	0.06	0.17	0.14	0.03	23.69
Milking	0.08	0.16	0.13	0.03	19.23
Dough	0.08	0.14	0.12	0.02	16.07
Harvesting	0.03	0.05	0.05	0.01	15.76
NDWI					
CRI	0.02	0.15	0.1	0.05	54.16
Tillering	0.38	0.6	0.49	0.07	14.26
Booting	0.68	0.83	0.78	0.05	6.76
Heading	0.55	0.78	0.72	0.08	11.03
Milking	0.5	0.83	0.73	0.12	15.89
Dough	0.36	0.81	0.68	0.16	23.29
Harvesting	0.04	0.33	0.22	0.1	43.68

SD, Standard deviation; CV%, Coefficient of variation.

which could be attributed to lowest plant/leaf water stress.

The highest CV of spectral indices was observed, especially during the CRI and harvesting stages (Table 4). Higher CV represented low spectral indices which might be due to low nitrogen accumulation and pigmentation in the plants. Lukina *et al.*[21] reported that as the vegetation coverage increased, CV of NDVI values decreased. In NDVI and NDWI, similar CV was recorded in tillering stage, viz. 7.74% and 14.26% respectively. However, increasing trend was observed from booting to harvesting stages in all the treatments. It is however established that the requirement of nitrogen is more in the tillering stage compared to later stages. Weisz *et al.*[22] observed that as the plant population or number of tillers increased, grain yield also increased and variation within the field was found to decrease. In SAVI, significant variation was represented in tillering and booting stages, viz. 10% and 14% respectively, and showed increasing trend of variation from booting to harvesting stages. In NDNI, variation was expressed by closely related values in all the stages (15–24%), except the tillering stage; CV was 11.62%. Based on the stability in CV, NDVI and NDWI were selected among the four spectral indices to study the correlation with grain yield and biomass yield for four growth stages, viz. tillering, booting, heading and milking (Figure 2). Arnall *et al.*[23] reported that prediction of crop yield improved by individually combining NDVI and CV. Raun *et al.*[24] reported that NDVI obtained from mid-season spectral reflectance data of crop might prove a better indicator and could be used to predict yield.

Relationship between spectral indices and yield attributes of wheat

A regression model was established for the relation between selected spectral indices, viz. NDVI and NDWI, and yield attributes from the experimental field, i.e. N level, grain and biomass yields affected by different phenological growth stages. The experiment was tested by correlation coefficient (r) and coefficient of determination

Table 5. Relationship between spectral indices and yield attributes at different growth stages

	Correlation coefficient (r)			Coefficient of determination (R^2)		
Growth stage	N level	Grain yield	Biomass yield	N level	Grain yield	Biomass yield
NDVI						
Tillering	0.78	0.76	0.75	0.60	0.55	0.56
Booting	0.90	0.76	0.76	0.82	0.57	0.57
Heading	0.91	0.98	0.98	0.89	0.96	0.96
Milking	0.97	0.94	0.95	0.94	0.88	0.90
NDWI						
Tillering	0.73	0.76	0.76	0.53	0.58	0.58
Booting	0.84	0.72	0.72	0.70	0.52	0.52
Heading	0.86	0.98	0.98	0.73	0.96	0.96
Milking	0.91	0.97	0.97	0.82	0.93	0.95

$\alpha = 0.05$; Data are mean of three consecutive years.

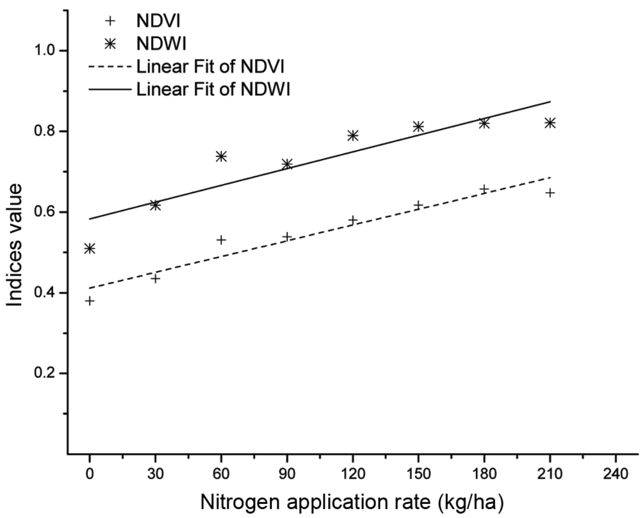

Figure 3. Relationship between different levels of nitrogen and values of NDVI and NDWI at milking stage.

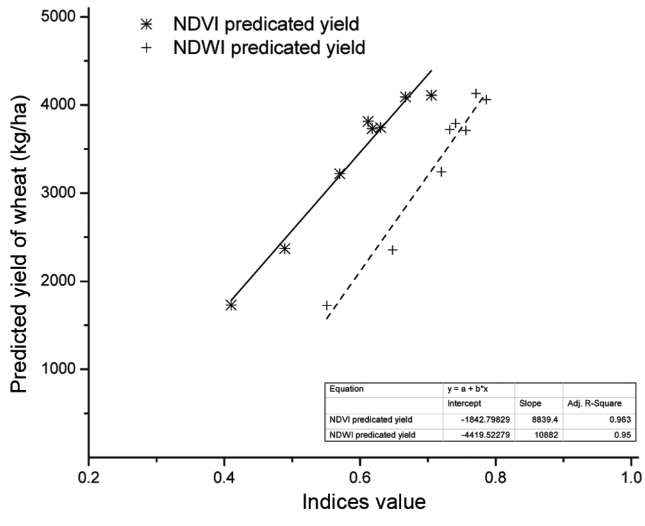

Figure 4. Relationship between grain yield and values of NDVI and NDWI at heading stage.

(R^2) for the analysis of four different phenological stages, namely tillering, booting, heading and milking (Table 5). Significantly better and positive relationships were observed among spectral vegetation indices, N level, grain yield and biomass yield at the four phenological growth stages. The variability in N level was explained at the four stages. R^2 for NDVI at tillering, booting, heading and milking stages was 0.60, 0.82, 0.89 and 0.94 and for NDWI it was 0.53, 0.70, 0.73 and 0.82 respectively. Correlation coefficient and coefficient of determination were found highest for spectral indices at the milking stage. Highest correlation for NDVI and NDWI (R^2; 0.94 and 0.82 respectively) was observed for N level at the milking stage (Figure 3). NDVI at the heading stage was observed to be a better indicator for prediction of grain and biomass yields ($r = 0.98$, $r^2 = 0.96$). However, NDVI at the milking stage was found to be the best predictor of nitrogen level ($r = 0.97$, $r^2 = 0.94$) for wheat crop.

In the regression model, grain and biomass yields showed stronger and effective significant relationship with NDVI and NDWI. The highest coefficient of determination in the heading stage was observed under NDVI and NDWI, which revealed that this stage may be the best grain yield and biomass yield indicator. Similar trend of correlation coefficient and coefficient of determination was observed in the heading stage of NDVI. The milking stage was also a good grain yield and biomass yield indicator in NDWI with highest coefficient of determination compared to NDVI. However, NDVI may be a better indicator based on the heading stage. The relationship of NDVI with grain and biomass yields was stronger at the heading stage ($r = 0.98$ and $R^2 = 0.93$). Similar relationship of grain and biomass yields was also observed for NDWI. Finally, the correlation of determination resulting in 96% and 95% variation in wheat grain yield was accounted in the heading stage for NDVI and NDWI respectively (Figure 4). Therefore, regression model-based early prediction of wheat grain and biomass yield at the heading stage can be useful. Raun *et al.*[24] suggested application of NDVI in estimating the yield of winter wheat cultivars for various levels of N application.

Conclusion

The regression models of both NDVI and NDWI positively correlated with grain yield and can be used for predicting in-season grain yield of wheat crop. Yield can be estimated well even in the heading stage using NDVI and in the milking stage using NDWI. However, a rough estimate of grain yield can be made using NDVI and NDWI after the booting stage. This model can be evaluated by analysing and validating the coefficients of SRIs at various growth stages so that yield could be estimated well in advance of harvest.

1. Li, F. *et al.*, Estimating N status of winter wheat using a handheld spectrometer in the North China Plain. *Field Crops Res.*, 2008, **106**(1), 77–85.
2. Hansen, P. M. and Schjoerring, J. K., Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least square regression. *Remote Sensing Environ.*, 2002, **86**, 542–553.
3. Clay, D. E., Kim, K. I., Chang, J., Clay, S. A. and Dalsted, K., Characterizing water and nitrogen stress in corn using remote sensing. *Agron. J.*, 2006, **98**, 579–587.
4. Zhang, J. H., Wang, K., Bailey, J. S. and Wang, R. C., Predicting nitrogen status of rice using multispectral data at canopy scale. *Pedosphere*, 2006, **16**, 108–117.
5. Scharf, P. C., Schmidt, J. P., Kitchen, N. R., Sudduth, K. A., Hong, S. Y., Lory, J. A. and Davis, J. G., Remote sensing for nitrogen management. *J. Soil Water Conserv.*, 2002, **57**(6), 518–524.
6. Jia, L. L., Buerkert, A., Chen, X. P., Romheld, V. and Zhang, F. S., Low altitude aerial photography for optimum N fertilization of winter wheat on the North China Plain. *Field Crops Res.*, 2004, **89**, 389–395.
7. Osborne, S. L., Schcpcr, J. S., Frdncis, D. D. and Schlcmmcr, M. R., Detection of phosphorous and nitrogen deficiencies in corn using spectral radiance measurement. *Agronomy J.*, 2002, **94**, 1215–1221.
8. Goel, P. K., Prasher, S. O., Landry, J. A., Patel, R. M., Bonnell, R. B., Viau, A. A. and Millerm J. R., Potential of airborne hyperspectral remote sensing to detect nitrogen deficiency and weed infestation in corn. *Comput. Electron. Agric.*, 2003, **38**(2), 99–114.
9. Lawrence, R. L. and Ripple, W. J., Comparisons among vegetation indices and bandwise regression in a highly disturbed, heterogeneous landscape: Mount St. Helens, Washington. *Remote Sensing Environ.*, 1998, **64**(1), 91–102.
10. Shibayama, M. and Akiyama, T., Estimating grain yield of maturing rice canopies using high spectral resolution reflectance measurements. *Remote Sensing Environ.*, 1991, **36**, 45–53.
11. Laudien, R., Burky, K., Doluschitz, R. and Bareth, G., Establishment of a web-based spectral database for the analysis of hyperspectral data from *Rhizoctonia solani*-inoculated sugarbeets. *Sugar Ind.*, 2006, **131**(3), 164–170.
12. Pradhan, S., Bandyopadhyaya, K. K. and Joshi, D. K., Canopy reflectance spectra of wheat as related to crop yield, grain protein under different management practices. *J. Agrometeorol.*, 2012, **14**(1), 21–25.
13. Zuzna, M., Frantisek, Z. and Kvet, J., Normalized difference vegetation index (NDVI) in the management of mountain meadows. *Boreal Environ. Res.*, 2008, **13**, 147–432.
14. Huete, A. R., A soil adjusted vegetation index (SAVI). *Remote Sensing Environ.*, 1988, **17**, 37–53.
15. Gontia, N. and Tiwari, K., Yield estimation model and water productivity of wheat crop (*Triricum aestivum*) in an irrigated command using remote sensing and GIS. *J. Indian Soc. Remote Sensing*, 2011, **39**(1), 27–37.
16. Gao, B., NDWI a normalized difference water index for remote sensing of vegetation liquid water from Space. *Remote Sensing Environ.*, 1996, **58**, 257–266.
17. Serrano, L., Penuelasa, J. and Ustin, S., Remote sensing of nitrogen and lignin in Mediterranean vegetation from AV1RIS data: decomposing biochemical from structural signals. *Remote Sensing Environ.*, 2002, **81**, 355–364.
18. Baethgen, W. E. and Alley, M. M., Optimizing soil and fertilizer nitrogen use by intensively managed winter wheat. II. Critical levels and optimum rates of nitrogen fertilizer. *Agron. J.*, 1989, **81**, 120–125.
19. Gnyp, M. L. *et al.*, Hyperspectral data analysis of nitrogen-fertilization effect on winter wheat using spectrometer in North China Plain. In *Hyperspectral Image and Signal Processing: Evolution in Remote Sensing*, First Workshop of IEEE, 2009, pp. 1–4.
20. Prasad, B., Carver, B., Stone, M. L., Babar, M. A., Raun, W. R. and Klatt and A. R., Potential use of spectral reflectance indices as a selection tool for grain yield in winter wheat under great plains conditions. *Crop Sci.*, 2007, **47**, 1426–1440.
21. Lukina, E. V. *et al.*, Effect of row spacing, growth stage, and nitrogen rate on spectral irradiance in winter wheat. *J. Plant Nutr.*, 2000, **23**, 103–122.
22. Weisz, R., Crozier, C. R. and Heiniger, R. W., Optimizing nitrogen application timing in no-till soft red winter wheat. *Agron. J.*, 2001, **93**, 435–442.
23. Arnall, D. B. *et al.*, Relationship between coefficient of variation measured by spectral reflectance and plant density at early growth stages in winter wheat. *J. Plant Nutr.*, 2006, **29**, 1983–1997.
24. Raun, W. R., Johnson, G. V., Stone, M. L., Solie, J. B., Lukina, E. V., Thomason, W. E. and Schepers, J. S., In-season prediction of potential grain yield in winter wheat using canopy reflectance. *Agron. J.*, 2001, **93**, 131–138.
25. Rouse, J. W., Haas, R. H., Schell, J. A., Deering, D. W. and Harlan, J. C., Monitoring the vernal advancements and retrogradation of natural vegetation. In NASA/GSFC Final Report, Greenbelt, MD, USA, 1974, pp. 1–37.

Received 15 December 2017; accepted 25 October 2018

doi: 10.18520/cs/v116/i2/272-278