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Relating satellite imagery with grain protein content

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ABSTRACT

Satellite images, captured during the growing seasons of barley, sorghum and wheat were analysed to establish a relationship between the spectral response and the harvested grain protein content. This study was conducted near Jimbour (approx. 151°10'E and 27°05'S) in southern Queensland. Grain protein contents of the geo-referenced samples, collected manually during the harvest, were determined using a laboratory-based near-infrared spectrophotometer. Grain protein contents in grain varied between 7.4–15.2% in barley, 6.2–10.6% in sorghum and 13.1–15.6% in wheat. The Landsat images of 18 September 1999 (a week after barley flowering), 5 March 2000 (three weeks before sorghum harvest), and 15 August 2001 (two weeks before wheat flowering) were analysed. Additionally, an ASTER image of 24 September 2001 (three weeks after wheat flowering) was also examined. Digital numbers, extracted from raw image bands and derived indices, were correlated with grain protein contents. The grain protein content in barley was correlated strongly ($r>0.80$) with bands 2, 4 and 5 of the Landsat scene, first principal component, and the tasselled cap brightness and greenness indices. Similarly, wheat protein content was well correlated ($r>0.75$) with the near infrared band (band 4) of the Landsat scene, first principal component, and the tasselled cap brightness, greenness and wetness indices. The band 3 (near infrared band) of the ASTER image, captured well after flowering, was moderately correlated ($r<0.5$) with the protein content of the wheat. However, the grain protein content in sorghum was found poorly correlated ($r<0.20$) with Landsat image bands and indices. Results indicate that it may be possible to use certain bands and indices of the satellite images, captured around the time of flowering, to predict grain protein content of barley and wheat crops.

KEYWORDS: Satellite image bands, remote sensing, Landsat, ASTER, grain protein content, barley, wheat, sorghum, flowering date

Introduction

Reflected electromagnetic radiation, captured in multi-spectral remote sensing images, is routinely interpreted to understand and forecast crop performances. In recent years, many researchers have used multi-spectral images to predict quantitative performances of crops such as grain yield (eg. Yang and Everitt 2002, Lobell et al 2001, Raun et al 1993) and biomass production (eg Yang et al 2000). However, there are no reports in the literature of any attempt to relate crop quality, such as grain protein content, with the electromagnetic reflectance.

Grain protein content is an important qualitative parameter for cereal crops with premiums being paid to meet niche markets. For example, good malting quality barley requires 9–12% protein content on a dry weight basis (Hector et al. 1996). Similarly, protein contents above 12.5% in wheat provide sufficient gluten to form good dough for bread making. Grain yield and protein content in cereal crops is strongly and inversely correlated (Simmonds 1996). Variation in grain yield is common due to ground-, climate- and input-related factors and their interactions (Duke et al. 2001, Yang et al 1998). Since grain yield and protein content are related, the grain protein contents also vary considerably within a paddock (Strong et al. 2003, Stewart et al. 2002). This relationship has been investigated in the Grains Research and Development Corporation (GRDC) funded project DAQ434 and is detailed in the final report (QDPI 2002).

Advanced site-specific knowledge of grain protein contents on a paddock-scale, is useful information that would provide opportunities to manage grain harvest differently. Areas of paddock with higher grain protein contents could be separated from the rest to take advantage of the price-premium. Advance knowledge of grain protein content of a standing crop may also provide opportunities to manipulate inputs to optimise outputs. Currently, there are limited opportunities to determine grain protein content before the maturity of the crop as traditional laboratory methods of protein determination require collection of matured grain samples, preparation of samples and extensive analyses. The recent development in remote sensing and image processing technologies has provided opportunity to forecast crop performance (eg grain yield, biomass production) using electromagnetic radiation. Since plant biomass, yield, nitrogen content and protein content are interrelated (Simmonds 1996), it should in theory, be possible to use electromagnetic radiation to predict grain protein content, yield, nitrogen content and biomass.

Considering these relationships the objective of this study was to link the spectral information captured in the satellite images with grain protein content retrospectively. Successful linking of this information would allow prediction of grain protein content in advance which could lead to new management strategies such as zone farming (Fridgen et al. 2000).

Materials and methods

The grain protein contents of barley, sorghum and wheat crops were retrospectively correlated with spectral responses captured in the satellite images. The study was conducted as follows:

The study area

The study was conducted near Jimbour (approx. 151°10'E and 27°05'S) in southern Queensland. The study area included three separate fields (Figure 1). The *Bon Accord–8* paddock (151°12'E and 27°06'S) of approximately 75 hectare was cropped to barley in winter 1999. A sorghum crop was sown in the 40 ha *Bon Accord-2* paddock (151°13'E and 27°06'S) in the summer of 2000. The *Lindenow* paddock (151°10'E and 27°00'S) with an area of 47 ha was cropped to wheat in the winter of 2001.

Protein content data

Geo-referenced grain samples were collected manually using apparatus described by Jensen et al. (2001) for protein content determination during the harvest of each crop. Depending on the operating speed of the harvester, the sampling points were located every 20 to 30 m along the path of the harvester. Protein contents of the samples were determined in the laboratory using a near-infrared spectrophotometer. Standard sample preparation and analysis procedure was followed. Protein measurements obtained from the laboratory based near infrared analyses were transferred into a vector file format using the corresponding sample coordinates.

Satellite images

Satellite images captured around the flowering time of the cropping season were acquired from various sources. Flowering time was considered critical for protein content determination after consultations with experts in this area (eg. personal communication—Strong, W 1999). A Landsat-5 scene of 18 September 1999 (a week after barley flowering) was acquired. Landsat-7 scenes of 5 March 2000 (three weeks before sorghum harvest) and 15 August 2001 (two weeks before wheat flowering) were also acquired. An ASTER image of 24 September 2001 (three weeks after wheat flowering) was obtained. The Landsat images, captured initially at 30 m resolution, were already re-sampled to 25 m pixel size when purchased. The first three bands of the ASTER image used in this analysis were captured at 15 m resolution.

Data pre-processing

The projection compatibility and spatial accuracy of satellite images and protein data were examined thoroughly. Whenever necessary, the image and protein data were reprojected in the matching coordinate system. Images, not properly aligned with the protein data, were re-registered using standard geo-referencing procedure available in the ERDAS Imagine 8.6. Suitable pre-registered images and cadastral boundaries were used as a reference for geo-referencing. The image for each paddock was subset into an area of interest for further analysis (Figure 1). One row of mixed pixels around the edges of the paddock was excluded in the subset image to avoid any undesirable effects of mixed pixels.

THE STUDY AREA

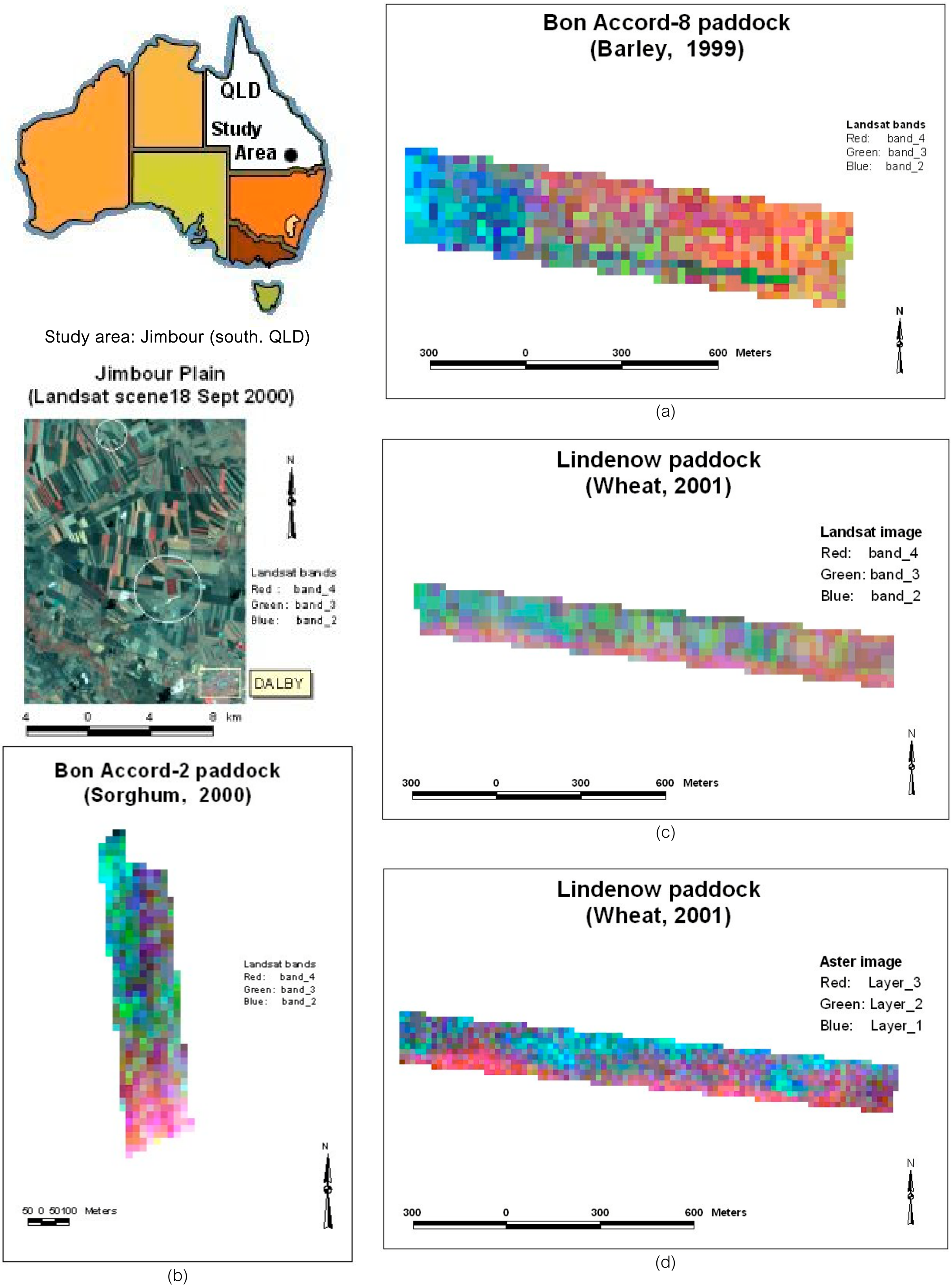

Figure 1 **Study areas and their approximate locations in southern Queensland, Australia**

The protein data, stored initially in vector file format, was spatially interpolated using a local variogram model within Vesper kriging program (Minasny et al. 1999). Spatial interpolation of protein data was necessary to; (a) aggregate excessive protein data points, (b) match protein data with image resolution, (c) bring protein and image data into a common grid, (d) smooth any unusual data points, and (e) compensate for any missing data. To ensure perfect match between kriged protein output and image data, a grid file extracted from the image data was used.

Vegetation indices

Normalised difference vegetation index (NDVI) and orthogonal transformations such as principal component analysis (PCA) and tasselled cap transformation were calculated. NDVI is a popular vegetation index related to some biophysical properties, such as leaf area index, percent green cover, green biomass, and amount of photo-synthetically active radiation absorbed by the canopy (e.g. Tucker, 1979; Tucker, et al., 1985). The PCA produced three components that are uncorrelated to one another in terms of image variation. The tasselled cap transformation calculated brightness, greenness and wetness indices (Christ, 1985). Brightness is a weighted average of six TM (thematic mapper) bands while greenness is a visible/near infrared contrast and wetness is a contrast between mid infrared and the red/infrared bands.

Statistical analysis

Image to ASCII conversion function within ERDAS Imagine 8.6 was used to extract the grid file as well as pixel values (ie. digital numbers) for each image band. The output of the Vesper kriging program was an ASCII grid file with corresponding protein data. This output was then merged with corresponding pixel values extracted from the image. This process created a spreadsheet that contained easting, nothing, pixel values for each image band and index and protein data (eg Table 1). The tabulated spreadsheet was read into the JMP statistical program to make a pair-wise correlation between bands, indices and grain protein contents. The output of the JMP program included a correlation matrix and a scatter plot matrix for visualisation of correlations between each variable pair.

Table 1 Sample spreadsheet showing geo-referenced digital numbers extracted from individual image bands and indices together with kriged protein output

Easting	Northing	B-1	B-2	B-3	B-4	B-5	B-7	NDVI	PC-1	PC-2	PC-3	BI	GI	WI	Protein %
320744	7000916	59	54	32	189	69	31	106	–178.64	124.33	99.01	198	90	34	8.541
320769	7000916	59	54	32	189	70	31	106	–179.37	118.60	95.17	198	90	33	8.351
320794	7000916	59	51	34	190	70	33	72	–180.78	117.53	97.40	199	90	33	8.800
320819	7000916	63	53	34	191	71	31	76	–181.52	117.75	94.99	201	90	34	8.892
320744	7000891	61	53	35	182	69	31	26	–171.74	124.12	101.69	195	83	32	8.372
320769	7000891	59	50	35	182	69	34	26	–173.28	113.34	97.25	195	84	30	8.303

B = band, PC = principal component, BI, GI, WI = brightness, greenness and wetness indices

Results and discussions

The within paddock variation of harvested grain protein contents was considerable for each crop. The protein content of the barley crop at *Bon Accord–8* paddock ranged between 7.4 and 15.2% in 1999. For sorghum crop at *Bon Accord-2* paddock it ranged between 6.2 and 10.6% in 2000. In comparison, the wheat crop at *Lindenow* paddock had 13.1 to 15.6% protein content in 2001. The within paddock variations in grain protein contents reflected a cumulative effect of ground-, climate- and input-related factors. As such, no attempts have been made to offer any explanation to these variations since it is beyond the scope of this study.

Barley 1999

It was found that the grain protein content in barley crop grown in *Bon Accord-8* paddock in 1999 was strongly correlated with selected individual bands (band 2: r=0.80), band 4: r=0.82), band 5: r=0.84) of the Landsat scene, as well as derived indices (Table 2 and Figure 2) such as first principal component (r=–0.84), green vegetation index (r=0.84) and soil brightness index (r=0.83).

Table 2 Correlations between Landsat image bands, derived indices and harvested grain protein content for barley crop grown in *Bon Accord-8* paddock in 1999

Variable	B-1	B-2	B-3	B-4	B-5	B-7	NDVI	PC-1	PC-2	PC-3	GVI	SBI	YVI	Protein
Band 1	1.00	0.17	0.05	–0.17	–0.14	–0.11	–0.12	0.17	0.02	–0.11	–0.10	–0.21	0.01	–0.14
Band 2	0.17	1.00	0.29	–0.72	–0.74	–0.43	–0.56	0.75	0.26	–0.20	–0.70	–0.74	–0.12	–0.80
Band 3	0.05	0.29	1.00	–0.36	–0.31	–0.10	–0.38	0.37	0.04	0.24	–0.24	–0.45	0.02	–0.31
Band 4	–0.17	–0.72	–0.36	1.00	0.80	0.43	0.75	–1.00	0.05	–0.02	0.98	0.99	0.56	0.82
Band 5	–0.14	–0.74	–0.31	0.80	1.00	0.45	0.63	–0.83	–0.34	0.20	0.85	0.81	0.04	0.84
Band 7	–0.11	–0.43	–0.10	0.43	0.45	1.00	0.29	–0.45	–0.40	0.59	0.48	0.40	–0.20	0.47
NDVI	–0.12	–0.56	–0.38	0.75	0.63	0.29	1.00	–0.75	–0.04	–0.10	0.73	0.76	0.38	0.65
PC-1	0.17	0.75	0.37	–1.00	–0.83	–0.45	–0.75	1.00	0.00	0.00	–0.98	–0.99	–0.51	–0.84
PC-2	0.02	0.26	0.04	0.05	–0.34	–0.40	–0.04	0.00	1.00	0.00	–0.02	0.03	0.61	–0.18
PC-3	–0.11	–0.20	0.24	–0.02	0.20	0.59	–0.10	0.00	0.00	1.00	0.06	–0.05	–0.44	0.19
BI	–0.10	–0.70	–0.24	0.98	0.85	0.48	0.73	–0.98	–0.02	0.06	1.00	0.96	0.50	0.84
GI	–0.21	–0.74	–0.45	0.99	0.81	0.40	0.76	–0.99	0.03	–0.05	0.96	1.00	0.52	0.83
WI	0.01	–0.12	0.02	0.56	0.04	–0.20	0.38	–0.51	0.61	–0.44	0.50	0.52	1.00	0.20
Protein	–0.14	–0.80	–0.31	0.82	0.84	0.47	0.65	–0.84	–0.18	0.19	0.84	0.83	0.20	1.00

The image of the *Bon Accord-8* paddock was captured one week after flowering of the barley crop. This stage of crop development is marked with high level of nitrogen content (close to peak) and greenness. High reflectance on green band is a typical response of actively photosynthesising healthy green leaves (Jensen 2000) while green leaves are a function of nitrogen content. Since grain protein is related to nitrogen content in the plant (Holford et al. 1992), a strong correlation between green band (band 2) and protein content seems logical.

A strong correlation between grain protein content and the near infrared (band 4) has been the most important finding in this study. For a typical healthy green leaf, the electromagnetic reflectance increases dramatically in the near-infrared region which immediately next to the visible red band with high-energy absorption. This dramatic change from high-energy absorption (red band) to high-energy reflectance (near-infrared band) is due to the natural protection mechanism of the plant to avoid overheating. Overheating of the plant is known to irreversibly denature the protein (Jensen 2000). Therefore, high reflectance in the near-infrared band and grain protein content are logically related. On the other hand, many researchers have been successful in establishing a strong correlation between crop yield and plant nitrogen content with near-infrared band and derived indices such as NDVI (eg. Chenghai and Everitt 2002, Yang et al 2000, Raun et al. 1984). It is also well established that the crop yield and nitrogen content are related to grain protein content (eg. Simmonds 1996). Therefore, the relationship between the near-infrared band and protein content is coherent. After all, the laboratory based protein analyser also uses near infrared radiation to determine grain protein content.

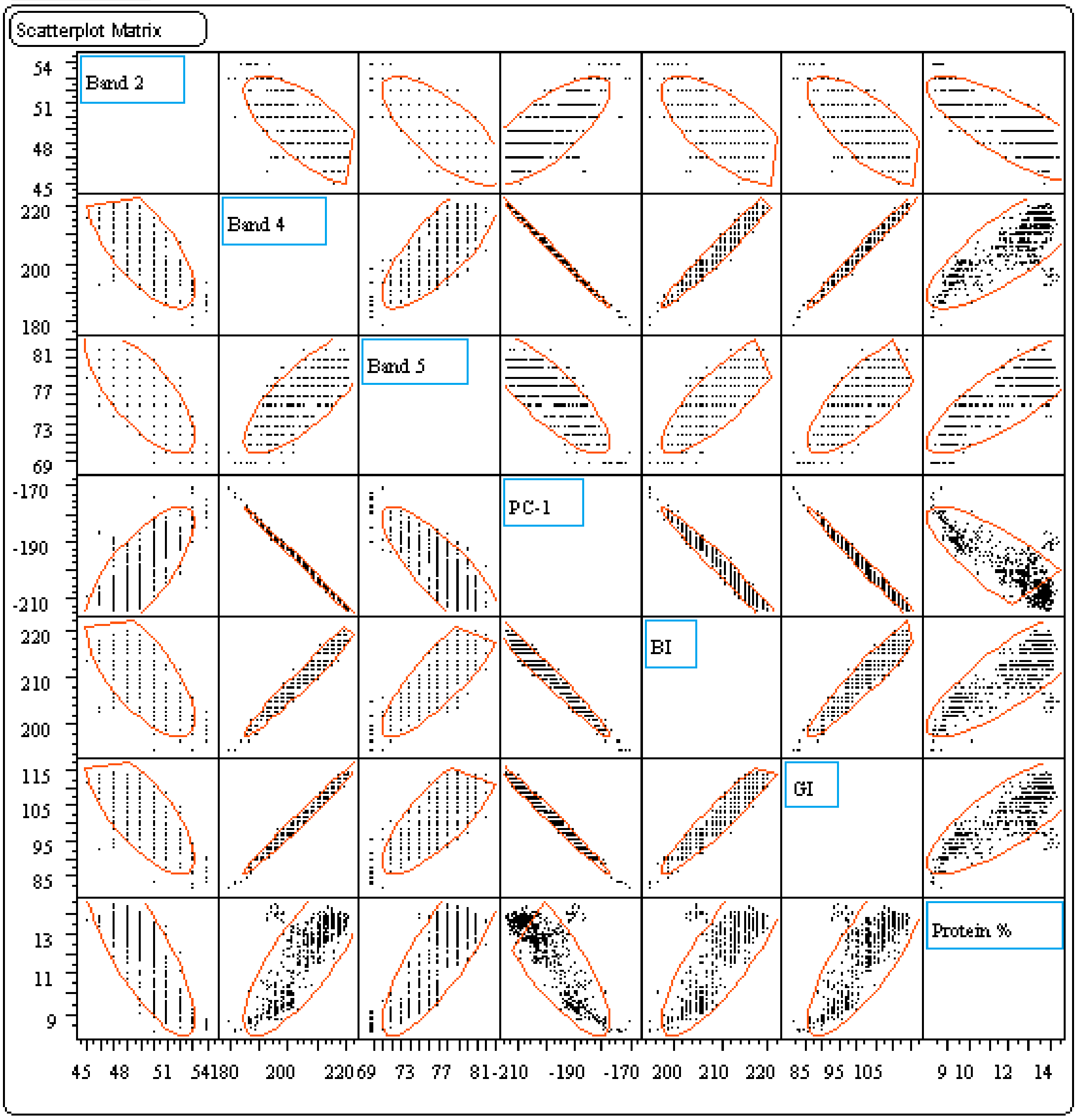

Figure 2 **Scatter plot of the selected bands, indices and protein content for barley crop—1999**

A strong correlation between mid-infrared band (band 5) and protein content is an interesting finding requiring more in-depth study. This is because the reflectance in the mid-infrared band is strongly correlated with the amount of water present in the leaves of a plant canopy (Jensen 2000). As the moisture content of leaves decreases, reflectance in the mid-infrared region increase. Therefore, the positive correlation between mid-infrared reflectance and grain protein content clearly indicates a higher grain protein content at the time of harvest due to lower moisture content in the leaves at the time of flowering. This finding clearly supports the relationship established by Dalal et al. (1987) between moisture content, grain yield and grain protein content.

The first principal component and the tasselled cap green vegetation and soil brightness indices were also correlated strongly with grain protein content in barley. However, these indices were mostly derived from the near infrared band 4 (refer to correlation coefficient in Table 2) and therefore they did not reveal any additional information. The scatter plot between band 4 and protein content (Figure 2) revealed a substantial number of outlying data points, which could possibly be the mixed pixels. Correct identification and exclusion of such mixed pixels from the analysis could possibly further improve the relationship between near-infrared band and grain protein content.

Sorghum 2000

The protein content in sorghum crop was poorly correlated with the reflectance measurements captured in individual image bands (Table 3). The near-infrared band indicated some relationship (r=0.18) with protein content but none of the bands were reliable predictor. A number of factors could have contributed to this result.

Table 3 Correlations between Landsat image bands and harvested grain protein content for sorghum crop grown in *Bon Accord-2* paddock in 2000

Variable	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7	Protein
Band 1	1.00	0.22	0.23	0.04	0.25	0.21	–0.03
Band 2	0.22	1.00	0.31	0.39	0.53	0.25	0.09
Band 3	0.23	0.31	1.00	–0.06	0.47	0.50	0.06
Band 4	0.04	0.39	–0.06	1.00	0.54	–0.22	0.18
Band 5	0.25	0.53	0.47	0.54	1.00	0.49	0.02
Band 7	0.21	0.25	0.50	–0.22	0.49	1.00	–0.13
Protein	–0.03	0.09	0.06	0.18	0.02	–0.13	1.00

Firstly, the timing of the capture of image for sorghum crop was three weeks before harvest, which is well after flowering. It could have been simply too late to detect grain protein content since the reflectance of the sorghum head is likely to dominate the composite reflectance measurements towards the final stage of crop development. Earlier images were unavailable due to satellite downtime. Secondly, sorghum crop has a different canopy structure and appearance when compared to barley and wheat. A greater canopy influence on the reflectance measurements could possibly conceal the effect of grain protein content. Thirdly, the spatial alignment of protein data and satellite image is extremely important in accurately correlating grain protein content with electromagnetic reflectance. Misalignment of these data by a pixel width could make a significant difference since 25 m is a considerable distance as far as field variation is concerned. Although, extra attempts have been made to correctly align sorghum protein content data with the images it is still possible that the alignment problem was not fully rectified. Given that other researchers (eg. Yang and Everitt 2002, Yang et al. 2000) have been successful in finding a significant correlation between satellite imagery bands and sorghum grain yield, a good relationship between Landsat image bands and grain protein content is highly likely. Therefore, more work is required to find a better correlation between sorghum protein content and satellite image bands.

Wheat 2001

The protein content at the time of harvest of wheat crop was found well correlated with near-infrared band (band 4) of the Landsat scene (r=0.80), first principal component (r=–0.80) and brightness and greenness (r>0.77) indices (Table 4 and Figure 3).

The relationship between near-infrared band and wheat grain protein is similar to the barley crop, and can be explained in a similar fashion as the barley 1999 results. The major difference between barley and wheat was however the timing of the capture of images. The Landsat-7 image was captured on 15 August 2001, which was well before flowering of wheat. It was probably too early as far as protein estimation is concerned because the results were quite different as compared to barley 1999. There was no apparent relationship between green band (band2) and grain protein content and there was only a moderate relationship between mid-infrared band (band 5) and grain protein content.

The first principal component, brightness and greenness indices did not add much to the relationship between near-infrared band and protein content because these indices were mostly derived from band 4 (Table 4).

Table 4 Correlations between Landsat image bands, derived indices and harvested grain protein content for wheat crop grown in *Lindenow* paddock in 2001

Variable	B-1	B-2	B-3	B-4	B-5	B-7	NDVI	PC-1	PC-2	PC-3	GVI	SBI	YVI	Protein
Band 1	1.00	0.18	0.06	–0.18	–0.02	0.16	–0.14	0.19	–0.86	0.45	–0.07	–0.25	–0.12	–0.21
Band 2	0.18	1.00	0.08	–0.08	0.08	0.14	–0.08	0.08	–0.31	–0.10	0.01	–0.12	–0.06	–0.14
Band 3	0.06	0.08	1.00	–0.50	–0.24	0.20	–0.84	0.50	–0.04	–0.17	–0.39	–0.56	–0.37	–0.36
Band 4	–0.18	–0.08	–0.50	1.00	0.59	–0.19	0.87	–1.00	0.00	0.02	0.97	0.99	0.89	0.80
Band 5	–0.02	0.08	–0.24	0.59	1.00	–0.02	0.49	–0.61	–0.43	–0.65	0.70	0.59	0.23	0.42
Band 7	0.16	0.14	0.20	–0.19	–0.02	1.00	–0.22	0.19	–0.29	–0.11	–0.11	–0.23	–0.35	–0.12
NDVI	–0.14	–0.08	–0.84	0.87	0.49	–0.22	1.00	–0.87	0.01	0.11	0.80	0.90	0.74	0.67
PC-1	0.19	0.08	0.50	–1.00	–0.61	0.19	–0.87	1.00	0.00	0.00	–0.98	–0.99	–0.89	–0.80
PC-2	–0.86	–0.31	–0.04	0.00	–0.43	–0.29	0.01	0.00	1.00	0.00	–0.17	0.07	0.14	0.08
PC-3	0.45	–0.10	–0.17	0.02	–0.65	–0.11	0.11	0.00	0.00	1.00	–0.07	–0.01	0.36	0.03
BI	–0.07	0.01	–0.39	0.97	0.70	–0.11	0.80	–0.98	–0.17	–0.07	1.00	0.95	0.83	0.77
GI	–0.25	–0.12	–0.56	0.99	0.59	–0.23	0.90	–0.99	0.07	–0.01	0.95	1.00	0.88	0.79
WI	–0.12	–0.06	–0.37	0.89	0.23	–0.35	0.74	–0.89	0.14	0.36	0.83	0.88	1.00	0.73
Protein	–0.21	–0.14	–0.36	0.80	0.42	–0.12	0.67	–0.80	0.08	0.03	0.77	0.79	0.73	1.00

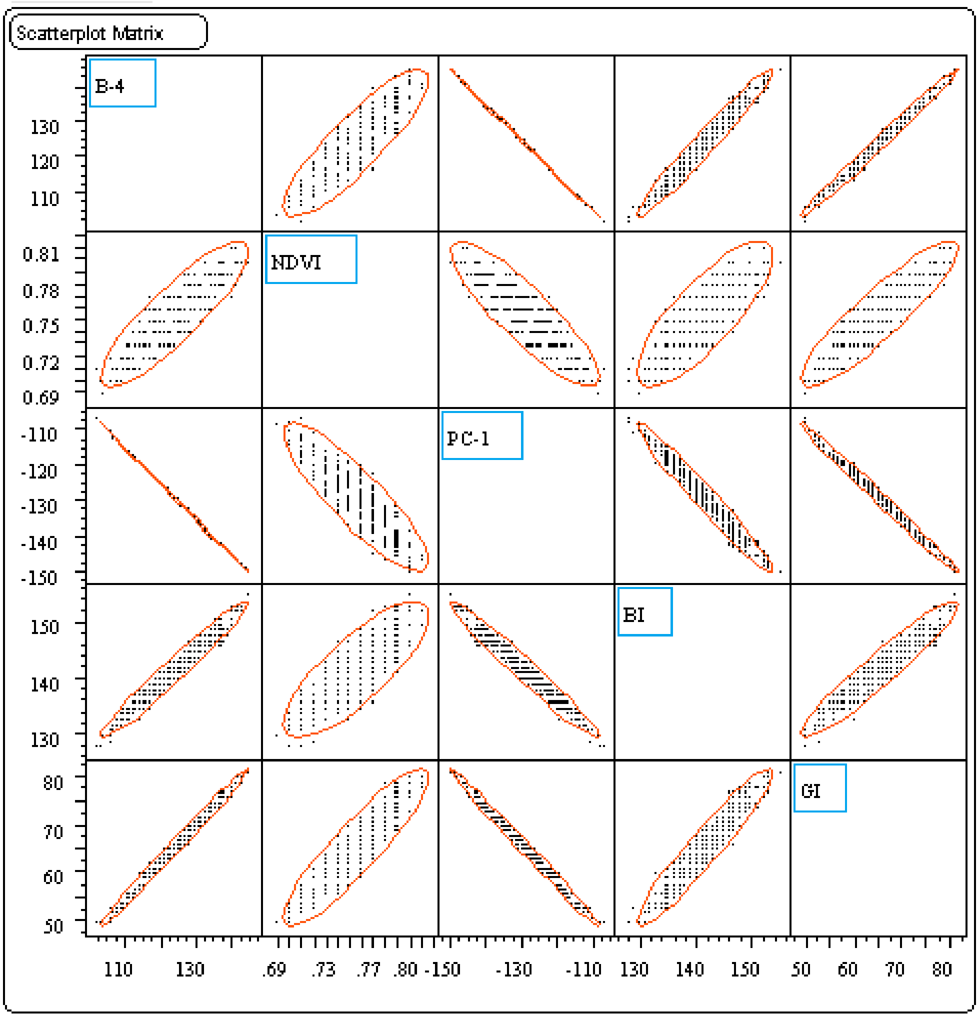

Figure 3 Scatter plot of the selected bands, indices and protein content for wheat crop—2001

The protein content at the time of harvest of wheat was only moderately correlated (r=0.47) with the infrared band (band 3) of the ASTER image (Table 5) despite its better spatial resolution than Landsat. The near-infrared band of the Landsat image, captured two weeks before flowering was found better correlated with harvested grain protein content than the infrared band (band 3) of the ASTER image that was captured three weeks after wheat flowering.

Table 5 Correlations between Aster image bands and harvested grain protein content for wheat crop grown in *Lindenow* paddock in 2001

Variable	Aster B1	Aster B2	Aster B3	Protein
Aster 1	1.00	0.50	–0.47	–0.15
Aster 2	0.50	1.00	–0.69	–0.23
Aster 3	–0.47	–0.69	1.00	0.47
Protein	–0.15	–0.23	0.47	1.00

The result once again indicated the criticality of the timing of the capture of image in linking grain protein content with the reflectance measurement. Most probably neither Landsat nor ASTER images were captured at the right time when compared to the result of the barley crop. [Indications are that that the best timing may be within one week before or after the flowering date.too speculative?] It also appears that the timing of the capture of the image is even more critical than the image resolution when compared to 15m and 30m resolutions of ASTER and Landsat scenes respectively. However, these hypotheses need to be tested using appropriately designed experiment.

The narrow range of grain protein content in wheat (13.1–15.6%) indicates less within paddock variation in the *Lindenow* paddock. Given the narrow range of protein content and the ability of the image to capture such information, the result obtained through this study is very encouraging.

Conclusions

Results indicate that it may be possible to use certain bands and indices of the satellite images to predict harvested grain protein content in barley and wheat crops. The timing of the capture of image appears to be critical. Near-infrared bands of the images captured around the time of flowering were best correlated with harvested grain protein content in barley and wheat. The mid-infrared band may provide additional information on moisture-protein relationship if the image is captured at the right time. Better image resolution would not prove to be beneficial unless the timing of the image acquisition is right.

The harvested grain protein content in sorghum could not be adequately linked with electromagnetic reflectance captured in the satellite images at this stage. A number of factors including the spatial misalignment of protein content data with satellite image could have contributed to this effect in sorghum. Correct spatial alignment of the data was found to be extremely critical throughout the investigation. More work is necessary to better understand the timing of the capture of images as well as the relationship of satellite images with harvested grain protein content in sorghum.

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