Role of agricultural engineering in environmental and sustainable development for the valley and delta areas: 1823 -1835

THE POTENTIAL OF REMOTELY SENSED DATA TO PREDICT WHEAT YIELD UNDER MOISTURE AND NITROGEN DEFICIENCY STRESS

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ABSTRACT

Moisture and nitrogen deficiency are major limiting factors for cereal production in many regions worldwide. Detecting stress in crops at an early growth stage is important if significant reductions in yield are to be averted. In this context, remote sensing has the potential of providing a rapid and accurate tool for precision farming in cereal production. This research was undertaken to investigate the potential of broad band and hyperspectral remote sensing for predicting grain yield of wheat (Triticum aestivum L.) under moisture and nitrogen deficiency stress. A controlled greenhouse experiment was conducted to (i) investigate the influence of moisture and nitrogen induced stress on wheat and the resulting spectral reflectance characteristics at the leaf and canopy scale (ii) assess the effectiveness of different vegetation indices to predict wheat grain yield and (iii) assess the possibility of distinguishing between moisture and nitrogen deficiency stressors. Strong significant correlations between crop grain yield and some vegetation indices were observed. Ratio Vegetation Index (RVI) and Simple Ratio (SR) were found to be sensitive to wheat grain yield (r > 0.80). The correlations with grain yield were found to be strongest at the grain filling stage. Principle Component Analysis (PCA) demonstrated low ability to distinguish between moisture and nitrogen deficiency stress.

INTRODUCTION

Moisture and nitrogen deficiency stressors are major limiting factors of crop yields in many regions worldwide. The monitoring of cereal production is mainly based on point-sampling techniques, which can be laborious, costly and unrepresentative without a spatial context. Rapid and accurate techniques for detecting stress in crops are needed to advance current farming practices, particularly in developing countries

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where existing agricultural systems are struggling to cope with the demands placed upon them by rapid population growth. The concentration of photosynthetic pigments within the leaves tend to be the first parts of plants to respond to stress. Leaf pigments such as chlorophylls, xanthophylls and carotenoids strongly absorb light in the photosynthetically active portion of the electromagnetic spectrum (**Prasad *et al*., 2007**) and therefore strongly affect the spectral reflectance characteristics of plant leaves and canopies (**Araus *et al*., 2001**). Subsequently, the spectral reflectance characteristics of plant leaves and/or canopies can be used to monitor foliar pigment concentrations and thereby obtain a better understanding of crop health. Previous studies have documented the effectiveness of spectral reflectance indices derived from remotely sensed data for the detection of stress in vegetation. These include for example, the estimation of chlorophyll *a* concentration (**Ciganda et al., 2009**), the identification of pest damage (**Genc *et al*., 2008**), salinity induced stress (**Elmetwalli, 2008**), nitrogen deficiency (**Hong *et al*., 2007**) and moisture stress (**Tilling *et al*., 2007**). Remote sensing can be a potentially valuable tool for precision farming, particularly for nitrogen management. In plants the concentration of chlorophyll in leaves is strongly related to N status. **Abd-Elrahman et al. (2010)** employed in situ spectroscopy data to detect N deficiency in sugarcane and documented the effectiveness of this technique to predict sugarcane leaf nitrogen. They also reported that wave bands in the ranges 418-481, 551-608 and 697-749 nm and wave bands centered at 1266, 2142 and 2243 nm showed significant strong correlations with leaf N concentration. The ability to measure spatial variability in canopy chlorophyll concentration through remote sensing therefore allows the N status of crops to be assessed rapidly across large field systems (**Daughtry *et al*., 2000**). Other studies have demonstrated the ability to predict crop grain yield from remotely sensed data (**Prasad *et al*., 2007**). **Marti *et al*. (2007)** reported that Normalized Difference Vegetation Index (NDVI) can be used to predict wheat biomass and grain yield at early stages, and specifically that NDVI at the milk-grain stage was well correlated to final grain yield and biomass of wheat. Increased efforts are therefore needed to detect the effects of moisture and nitrogen induced stress in wheat to limit crop reduction and therefore increase productivity. Published research focused on the remote detection of moisture and nitrogen stress at the leaf scale. Measurements at the canopy scale are arguably important for evaluating the potential successful implementation of airborne or satellite remote sensing in precision agriculture. Here we present the remote detection of the combined effects of moisture and nitrogen deficiency stress on wheat health and productivity and even assess the possibility of distinguishing the two stressors at both the leaf and canopy scales. Measurements of plant reflectance were acquired under solar and artificial illumination and used to estimate wheat grain yield under moisture and nitrogen deficiency stress through the use of different vegetation indices derived from hyperspectral remotely sensed data. The specific objectives of this research were; (1) to assess the relationship between wheat grain yield and both moisture and nitrogen stressors (2) to identify the optimum vegetation index to predict wheat grain yield.

MATERIAL AND METHODS

Experimental design

A greenhouse-based experiment of wheat was undertaken at the University of Stirling, Stirling, United Kingdom during the winter season of 2008-09. Wheat was grown in pots containing ≈ 40 kg of soil. The soil was a sandy loam with low organic matter (0.09%), a pH of 4.9 and an EC of 1.2 dS m^{-1}. The particle size distribution was 58% sand, 37% silt and 5% clay. A Scottish wheat variety (gladiator) was used in this research. Wheat was sown in the second week of October 2008. Wheat seeds were sown uniformly at a seed rate of 200 seeds m^{-2} using a mesh to control the seed distribution. Phosphor and potassium were applied to the pots at levels of 60 and 60 kg ha^{-1}. The total amount of phosphorus and potassium was applied during soil preparation. eleven different treatments were used to subject plants to different levels of moisture and nitrogen deficiency stress including: one control (150 Nitrogen with 90% FC (field capacity) moisture regime, three moisture regimes at 75%, 50% and 25% FC, three nitrogen application rates of 0, 50 and 200 kg/ha and different combinations of both moisture and nitrogen levels. Nitrogen was applied in two equal doses; the first one at tillering and the other just before flowering.

Reflectance measurements

An ASD FieldSpec spectroradiometer with a 3.5° field of view (FOV) foropic was used to measure the spectral reflectance from plant canopies and leaves. The spectroradiometer was mounted at the end of a telescopic pole at a constant height of 1.7 m from the pot's soil surface to maximize the scanning area. Reflectance spectra (350 nm-1050 nm) of the plant canopies were acquired regularly under solar radiation on cloud-free days between 11:00 and 15:00 h GMT outside the greenhouses. To provide control over lighting conditions, a darkroom was constructed to collect reflectance measurements using two 300 W halogen lamps for illumination and lined with black cloth with a very low reflectance (reflectance < 5%). Spectral measurements were made at the early growth stages before applying different moisture and nitrogen deficiency treatments and were then repeated periodically over the growing season until harvest time. The instrument was calibrated to reflectance using a white spectralon reference panel. Five spectral scans were acquired from each pot, the mean spectral was derived and three pots were chosen randomly for each treatment. All records for grain yield of wheat were converted from kg m^{-2} to Mg ha^{-1}.

Spectral data analysis

The spectral reflectance data were pre-processed using the dedicated ASD software. The spectra were interpolated to a spectral resolution of 0.5 nm and then truncated between 300 and 1000 nm. Finally the data were smoothed to reduce the noise by passing a 5 nm running mean filter over the whole spectrum (Fig. 1). The spectra were then used to calculate 12 broad band and hyperspectral vegetation indices. Different formulae for calculating NDVI, RVI SAVI $GNDVI_{br}$, DVI, SR, SLAVI, OSAVI, VI1, RDVI, SI and IPVI are listed in Table 1.

Table 1 Examples of spectral vegetation indices calculated from in situ and laboratory darkroom spectroradiometery (**Le Mair et al., 2004**)

Notation	**Formulae**
NDVI	(NIR-Red)/(NIR+Red)
RVI	NIR/Red
SAVI	R+Red+L)]*(1+L)
$GNDVI_{br}$	(NIR-green)/ (NIR+green)
DVI	NIR-Red
SR	NIR/Red
SLAVI	NIR/(Red+NIR)
OSAVI	[(NIR-Red)/(NIR+Red+L)]*(1+L), L = 0.16
VI1	NIR/(green-1)
RDVI	$\sqrt{NDVI \times DVI}$
SI	Red/NIR
IPVI	NIR/(NIR+Red)

NDVI, Normalized Difference Vegetation Index; RVI, Ratio Vegetation Index; SAVI, Soil Adjusted Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; DVI, Difference Vegetation Index; SR, Simple Ratio; SLAVI, Specific Leaf Area Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; VI1, Vegetation Index One; RDVI, Renormalized Difference Vegetation Index; SI, Stress Index; IPVI, Infra-Red Percentage Vegetation Index

Principle Component Analysis (PCA) (MINITAB v.14) was performed on all spectra of different growth stages from tillering until harvesting. The mean of five scans of each treatment was calculated and three spectra for each treatment were chosen, then the overall mean was calculated. The PCA was performed to explore differences in the spectral signature of different treatments (healthy, moisture and nitrogen stressed).

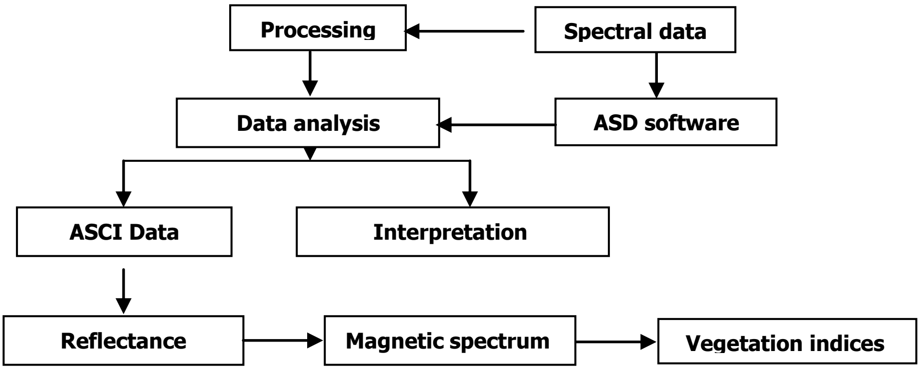

Fig.1 A flow chart detailing different processes for spectral data analysis and processing

Statistical analysis

Minitab v15 was used to perform one and two way analysis of variance (ANOVA) to establish significant differences in wheat response to moisture and nitrogen deficiency stress. Nitrogen, moisture and the interaction were used as predictor variables, and yield data as the response variable. Data were checked for normality using Anderson-Darling method with a 95% significance level. The Pearson Product Moment correlation coefficient was used to test the association between different vegetation indices and crop properties and to identify optimum vegetation indices for predicting yield. Simple linear regression analysis was used to derive regression equations to predict grain yield from reflectance spectra.

RESULTS AND DISCUSSION

Effects of moisture and nitrogen deficiency stress on wheat grain yield

ANOVA analysis was used to assess the effects of both moisture and nitrogen deficiency on wheat yield. The results are illustrated in Figure 2. The results demonstrate that both nitrogen deficiency and moisture significantly affected wheat grain yield. Moisture stress strongly reduced grain yield ($R^2 = 0.97$; $p < 0.005$). The highest grain yield of 5.86 Mg ha^{-1} of wheat was recorded with the control treatment whilst the lowest grain yield of 0.878 Mg ha^{-1} of wheat was recorded with the treatment received 25% FC moisture regime and 0 N. Nitrogen deficiency also significantly affected wheat grain yield. Significant decreases in wheat grain yield were observed with increasing nitrogen deficiency levels (Figure 2). The grain yields fell to about 15 of the maximum value for wheat when subjected to the lowest watering regime and the highest nitrogen deficiency level.

The regression analysis showed a significant linear relationship between wheat grain yield and moisture regime ($R^2 \geq 0.90$; $p<0.005$) as shown in Figure 2. This indicates that yield reductions were highest in treatments with the lowest watering regimes (25% FC). A further significant linear relationship was found between wheat grain yield and nitrogen deficiency levels ($R^2 > 0.84$; $p<0.005$) as also shown in Figure 2 indicating that grain yield reductions were greater at the highest nitrogen deficiency levels (zero nitrogen). The results therefore demonstrated that multivariate regression analysis showed significant relationships between wheat yield and both moisture and nitrogen deficiency for all trails.

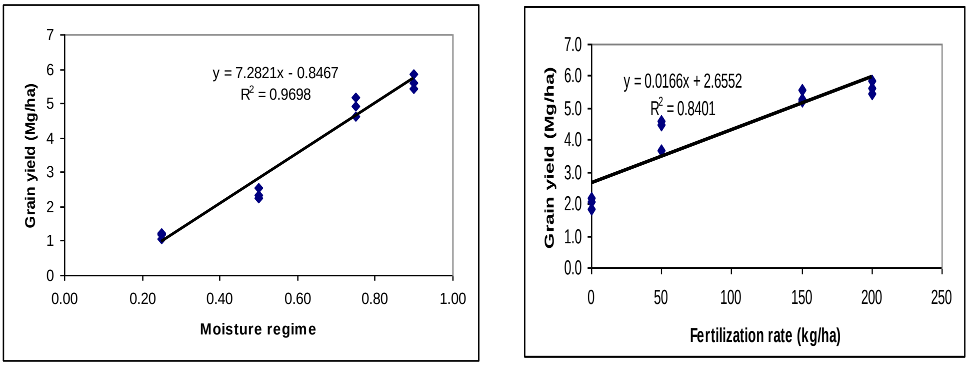

Fig. 2 The relationship between wheat yield and both moisture and nitrogen deficiency stress

Correlation between vegetation indices and wheat grain yield

The 12 calculated broad band vegetation indices demonstrated that some vegetation indices correlated strongly with the measured wheat grain yield. The data collected throughout the growing season was ranked and used to identify the optimum index for predicting wheat grain yield. The results demonstrated that the top vegetation indices to predict wheat grain yield are RVI and SR. At the tillering and jointing stages, the coefficient of correlation was non-significant ($r < 0.20$) for all the tested vegetation indices. At the booting stage, just one index demonstrated significant correlations with the measured grain yield. The coefficient of correlation increased gradually to reach a maximum at the grain filling stage. Table 2 details the coefficient of correlation between different vegetation indices and wheat grain yield at different growth stages.

Some hyperspectral vegetation indices were also calculated and evaluated to predict wheat grain yield. The results demonstrated that both hyperspectral and broad band vegetation indices provided similar correlations in most cases. RVI and SR were identified as the optimum indices to predict wheat yield (Table 3). Other indices such as NDVI, SAVI and GNDVI also produced strong significant correlations with the measured grain yield. Figure 3 shows the relationship between RVI and wheat grain yield at the grain filling stage ($R^2 = 0.70$; $p < 0.005$). These results are in broad agreement with others (Babar et al., 2006; Prasad et al., 2007) demonstrating that crop yield can be predicted before the maturation is reached. With respect to time, Babar *et al*. (2006) concluded that measuring reflectance at the heading and the grain filling stages appears to be the most suitable time for selecting different genotypes for wheat grain yield. They also found that RNDVI, GNDVI and SR showed significant correlations with grain yield at the heading and the grain filling stages. Royo *et al*. (2003) investigated the effectiveness of vegetation indices in predicting wheat grain yield and concluded that milk-grain stage was shown to be the most appropriate developmental stage for yield assessment. In contrast, other studies have demonstrated that the best time to predict wheat grain yield was recorded at maturation not at booting, heading, anthesis or milk-grain stages (Aparicio *et al*., 2000). However, the work presented here at the canopy scale has shown that the grain filling stage was shown to be the optimum stage for predicting wheat yield. The results therefore suggest that remote sensing can provide a reliable approach to predict crop properties at relatively early stages enabling appropriate management practices to be implemented to limit crop reductions and thus increase crop productivity.

Table 2 Coefficient of correlation for the relationship between vegetation indices and wheat grain yield at different growth stages in different seasons. Highlighted values are the strongest correlations

Index	**Growth stage**					
Scottish wheat 2008/2009						
	Tillering	Jointing	Booting	Flowering	Grain filling	Milking
NDVI	0.07	0.19	0.32	0.64**	0.80**	0.76**
RVI	0.11	0.09	0.28	0.61**	0.83**	0.74**
SAVI	-0.14	0.05	0.37*	0.53**	0.81**	0.64**
GNDVI	0.15	0.12	0.26	0.52**	0.80**	0.72**
DVI	-0.13	0.05	0.24	0.56**	0.81**	0.62**
SR	0.11	009	0.28	0.61**	0.83**	0.74**
SLAVI	0.07	0.05	0.32	0.50**	0.79**	0.75**
OSAVI	-0.13	0.06	0.13	0.56**	0.82**	0.68**
RDVI	0.09	-0.03	0.25	0.46*	0.81**	0.69**
SI	-0.06	0.06	0.27	0.43*	-0.77**	-0.74**
IPVI	0.07	0.05	0.28	0.48*	0.80**	0.76**
VI	0.16	0.05	0.18	0.44*	-0.69**	-0.36*

*Significant at 95%　　　　**Significant at 99%

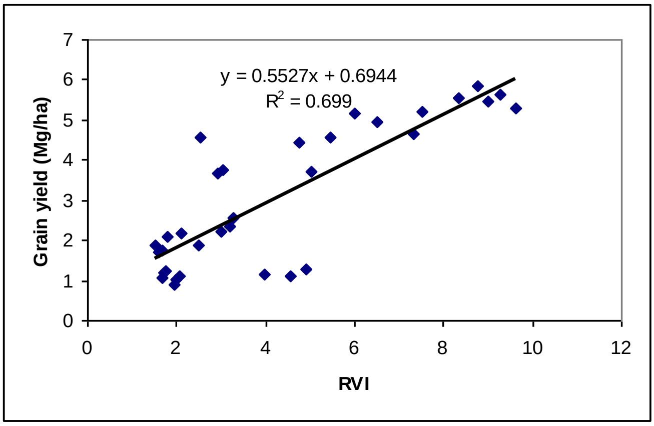

Fig. 3 The relationship between RVI derived from hyperspectral measurements obtained using solar illumination and wheat grain yield at the grain filling stage.

The spectral distinguishing between moisture and nitrogen deficiency stress

The spectral signature of different treatments of moisture and nitrogen levels collected at different growth stages shows that the reflectance increases in the visible range of the electro magnetic spectrum as illustrated in Fig. 4. The highest values of reflectance are in the red edge region. The results further showed a decrease in reflectance values in the NIR region with increasing both moisture and nitrogen stress. Nitrogen deficiency had a greater effect on the spectral signature compared with moisture stress and produced marked increases in the blue, green and red regions and decreases in the NIR region relative to the control treatment. Furthermore, at the early growth stages the spectra collected from different treatments demonstrated similar spectral response as a result of the same biophysical and biochemical properties of wheat (Fig. 4-b).

At early growth stages (e.g. tillering and jointing), PCA analysis showed difficulties to distinguish between moisture and nitrogen deficiency stressors possibly as a result of similar pigments such as chlorophyll a concentration and different biophysical properties including leaf area, plant height and aboveground biomass. From flowering stage onwards it was possible to distinguish some differences between moisture and nitrogen induced stress but the greatest differences were found at the grain filling stage. Following the application of the first dose of nitrogen, the concentration of chlorophyll a increased markedly particularly in the treatments of 150 and 200 kg ha^{-1}. Figure 5 shows the score plot of the PCA for the spectra collected at the grain filing stage. The figure clearly demonstrates that the treatments with high levels of moisture and nitrogen tend to plot in one quarter of the score plot (the lower left corner). The PCA loading plot suggest that the reflectance in the visible region of the magnetic spectrum correlated strongly with stress level for both moisture and nitrogen deficiency. Broadly, distinguishing sources of stress in wheat seems difficult which may have been a result of its thin leaves. More research is needed to investigate the potential of distinguishing sources of stress on crops with broader leaves such as sunflower, squash and maize. Additionally, some other statistical techniques such as penalized Linear Discriminant Analysis (PLDA) may give a clear distinguishing between sources of stress.

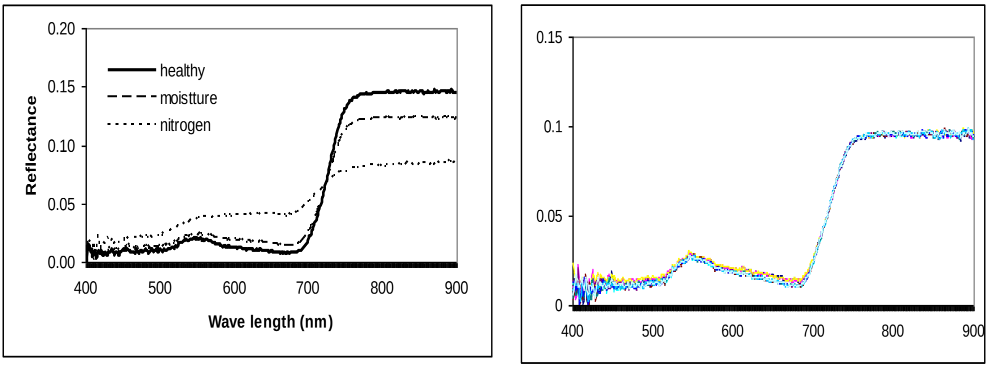

Fig. 4 The spectral signature collected from wheat canopy at (a) the grain filling stage and (b) the tillereing stage under different treatments

CONCLUSION

The effectiveness of hyperspectral and broad band remote sensing data for predicting wheat grain yield in response to moisture and nitrogen deficiency stress was investigated in this study. It can be concluded that the grain filling and milk-grain stages are the optimum growth stages of wheat to collect reflectance measurements to predict crop grain yield. The obtained results showed that the RVI and SR provided the optimum indices for predicting wheat yield.

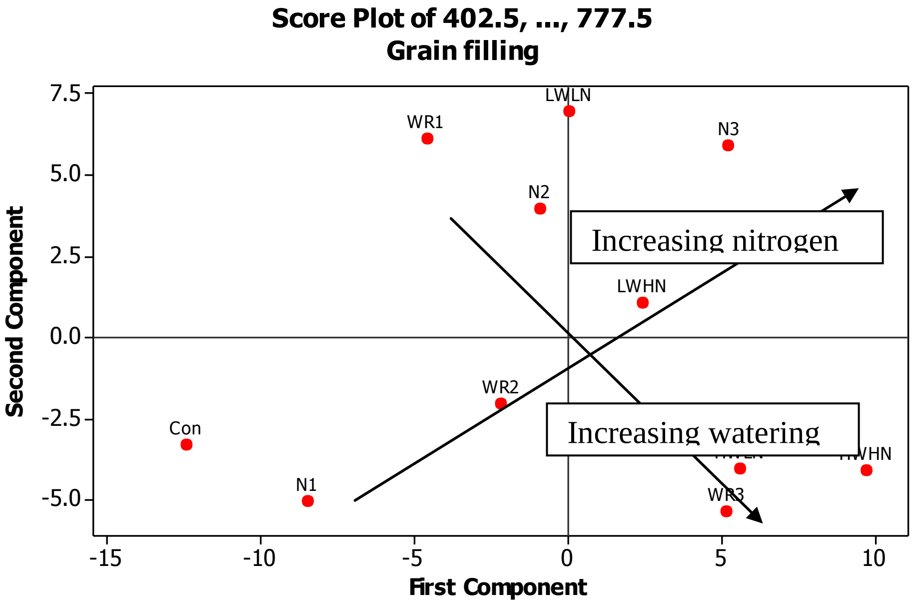

Fig. 5 The score plot of PCA for the spectra collected from health and stressed wheat canopies at the grain filling stage. Treatment label: (Con-control; WR1-75%FC; WR2-50%FC WR3-25%FC; N1-200 kg ha^{-1}; N2-50 kg ha^{-1}; N3- 0 kg ha^{-1}; HWLN-75%FC and 0 kg ha^{-1}; HWHN-75%FC and 200 kg ha^{-1}; LWLN-25%FC and 0 kg ha^{-1}; LWHN-25%FC and 200 kg ha^{-1})

Additionally, hyperspectral data provided no advantage over broad band indices in these predictions. Consequently, broad band satellite-based remote sensing platforms with high spatial resolution capabilities would be well suited to predict grain yield in semi arid and arid environments. Here we demonstrated the novel potential of using remote sensing to detect nitrogen deficiency as well as moisture induced stress at the leaf and canopy scale under both solar and artificial illumination source. The PCA analysis demonstrated low ability to distinguish moisture and nitrogen deficiency stress since no specific trend was found to plot data of each stressor in one quarter of the score plot.

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الملخص العربى

امكانية استخدام بيانات الاستشعار عن بعد للتنبؤ بانتاجية محصول القمح فى وجود اجهادى نقص المياه والتسميد النيتروجينى

عادل هلال المتولى*

أجريت هذه الدراسة على محصول القمح خلال موسم الشتاء لعام ٢٠٠٩/٢٠٠٨ بمزرعة جامعة سترلينج بالمملكة المتحدة بهدف دراسة امكانية استخدام الدلائل الخضرية المحسوبة من قياسات الانعكاس من أسطح وأوراق محصول القمح للتنبؤ بانتاجيته وكذلك دراسة امكانية التمييز بين كل من اجهاد نقص المياه واجهاد نقص التسميد النيتروجينى . ولدراسة ذلك تم تعريض محصول القمح لمستويات مختلفة من اجهاد نقص كلا من المياه والتسميد النيتروجينى والتى كانت كالتالى:

معدل اضافة المياه: ٢٥، ٥٠ ، ٧٥ ، ٩٠ % من المحتوى الرطوبى عن السعة الحقلية

معدل التسميد النيتروجينى: صفر ، ٥٠ ،١٥٠ ، ٢٠٠ كجم/هكتار

تم تجميع قياسات الانعكاس عند المراحل المختلفة لموسم النمو لكلا المحصولين مقترنة بتجميع عينات نباتية لتقدير صفاتها المختلفة وفى نهاية الموسم تم تقدير انتاجية المحصول وربط هذه الانتاجية بالدلائل الخضرية المختلفة لكل مرحلة من مراحل النمو بهدف اختيار أنسب ميعاد لتجميع بيانات الاستشعار عن بعد والتى تعطى ادق تنبؤ بانتاجية المحصول وكانت أهم النتائج المتحصل عليها كالتالى:

- نقص كلا من المياه والتسميد النيتروجينى كان له تاثير معنوى على محصول القمح حيث أن معاملة أعلى اجهاد للمياه ونقص التسميد النيتروجينى اعطت ١٥% انتاجية مقارنة بالمعاملة ذات أعلى مستوى اضافة من كمية المياه والتسميد النيتروجينى.
- وجد أن انسب مرحلة نمو لتجميع قياسات الانعكاس لكلا من القمح والذرة هى بين مرحلتى ملئ الحبوب والمرحلة اللبنية
- وجد أن تحليل PCA أظهر بعض المقدرة على التمييز بين أجهادى نقص المياه ونقص التسميد النيتروجينى ولكن عند مرحلة متأخرة من موسم النمو (ملئ الحبوب) ولكن عند المرحل المبكرة فمن الصعب التفرقة بين كلا الجهادين
- وجد أيضا أن أنسب دلائل خضرية للتنبؤ بانتاجية القمح هى RVI and SR

وتوصى الدراسة بتطبيق استخدام بيانات الاستشعار عن بعد لمتابعة محاصيل أخرى ذات أوراق أكبر فى مساحة السطح كالذرة وعباد الشمس لاعطاء نتائج أفضل فى التمييز بين مصادر الاجهاد المختلفة.

*** مدرس الهندسة الزراعية كلية الزراعة جامعة طنطا**