Advances and challenges in the spatial detection of nitrogen and water stress in wheat

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Abstract

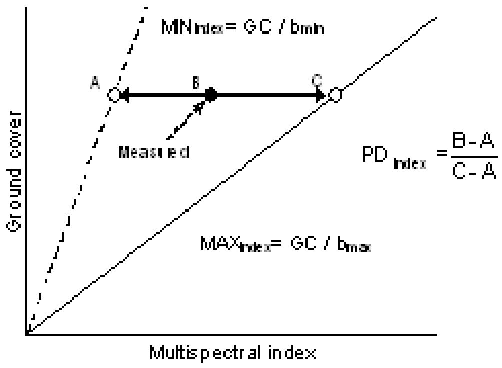
Recent advances in the capture and analysis of spatial multispectral and thermal properties of crop canopies indicate that the usefulness of the technology is proportional to our capacity to understand the linkages between those canopy properties and crop eco-physiological principles. A multidisciplinary approach that includes spectral and thermal data acquisition, a strong physiological understanding of crop and canopy function, and crop modelling techniques is required for remote sensing technologies to be useful in the spatial detection and management of nitrogen deficits in rainfed crops were complex interactions develop between nitrogen and water stress.

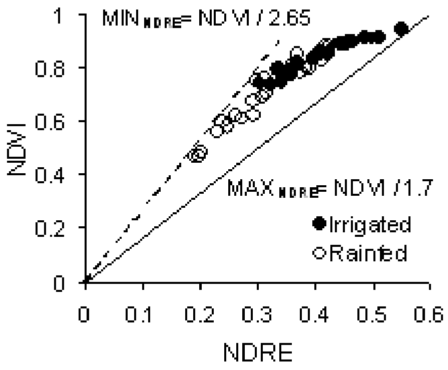
Key Words

Thermal imaging; multispectral; hyperspectral

Introduction

Advances in the identification and quantification of spatial and temporal variation in the availability and use of water and nitrogen, have reignited the debate on ways to improve their productivity with the objective of increasing farm profitability while reducing impacts on the resource base. Particularly with the widespread access to yield mapping technologies, precision agriculture, site-specific management and remote sensing techniques were expected to make a considerable mark in Australia. Though, after the recognition that season-to-season variation is at least as important as site-to-site variation, our initial over-enthusiastic mind-set has matured into one that recognises the important challenges and gaps in understanding still lying ahead. Here we aim to: (a) review recent advances in the use of remote sensing technologies for crop management; (b) identify gaps in understanding, and (c) outline a potential pathway towards the successful application of remote sensing techniques for the in-crop site-specific management of nutrients in rainfed crops. Most of the results presented in this work have already been published elsewhere (Rodriguez et al., 2005), Rodriguez et al. (2006) and Fitzgerald et al., (2006).





(a) (b)

Fig. 1 Derivation of the planar domain indices (PDindex), from the relationships between a measure of the proportion of the target (ground cover) in the field of view of the sensor (a) (represented by NDVI in b) and the signal from the target property of interest (shoot N%) represented by the spectral index normalised difference red edge (NDRE) (b).

Spatial detection of nitrogen stress in field crops

When analysing mixed spectral signals from heterogeneous crops composed of soil and vegetation elements within the field of view of the sensor, a methodology is required to derive meaningful indices representing the status of the property of interest e.g. nitrogen status, on the aimed target i.e. crop.

The target in the field of view of the sensor

We used planar domain indices (Fig. 1a) to reduce the interference from a changing proportion of bare soil in the background of the field of view of the sensor (Clarke et al., 2001; Rodriguez et al., 2006). Planar domain indices are created by measuring the proportion of the target i.e. crop, as its percentage in the whole i.e. crop plus soil elements in the field of view of the instrument. Hence, two indices are needed (Fig. 1b), one to measure the ground cover, and the other to characterise its nitrogen content. In our work we used the normalised difference vegetation index (NDVI) to represent the proportion of crop in the field of view of the spectrometer i.e. ground cover, and two other multispectral indices to evaluate its nitrogen status (only the Normalised Difference Red Edge, NDRE, is shown here).

Important multispectral indices were identified with partial least squares (PLS) regression modelling using shoot N% as the dependent variable. Most of the tested chlorophyll indices (mSR, NDRE, Chl1, NDI1, NDI2 and mND) had high and positive loading weights indicating that they all were positively related to the observed variation in shoot N%, and therefore, were potentially useful to detect changes in canopy N (not shown).

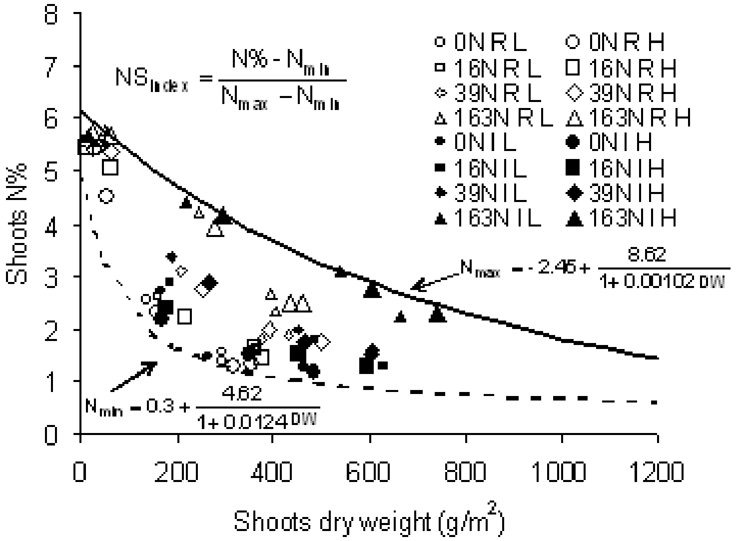


Fig. 2. Derivation of the nitrogen stress index (NSindex) from the relationship between shoot N% and shoot dry weights. The legend in the graph identifies the nitrogen levels (0, 16, 39 and 163 kg N/ha), irrigation treatments (R= rainfed, I=irrigated), and canopy density (L=low, H=high). Nmax

and Nmin are the manually-fitted upper and lower bounds of the relationship between shoot N% and shoot dry weight.

The property of the target

The rate of crop N uptake is highly variable within and between seasons, plant stands, and sites. We showed that water supply and plant density were important confounding factors when trying to derive empirical predictive relationships between the spectral indices and shoot N%. Confounding effects can originate from changes in canopy architecture, i.e., leaf rolling and leaf angle, reflectance from bare soil, and properties of leaf and soil surfaces. Dilution curves relating nitrogen content and shoot biomass allow for a nitrogen stress index (NS_{index}) useful for comparisons among water supply and plant densities (Figure 2). Despite important variations in the level of water stress and canopy density among the treatments and sampling times, the planar domain indices, CCCi and mSR_{Pi}, explained 68 and 69% of the observed variability of the area based NS_{index} as early as Zadoks 33 (Figure 3 a and b).

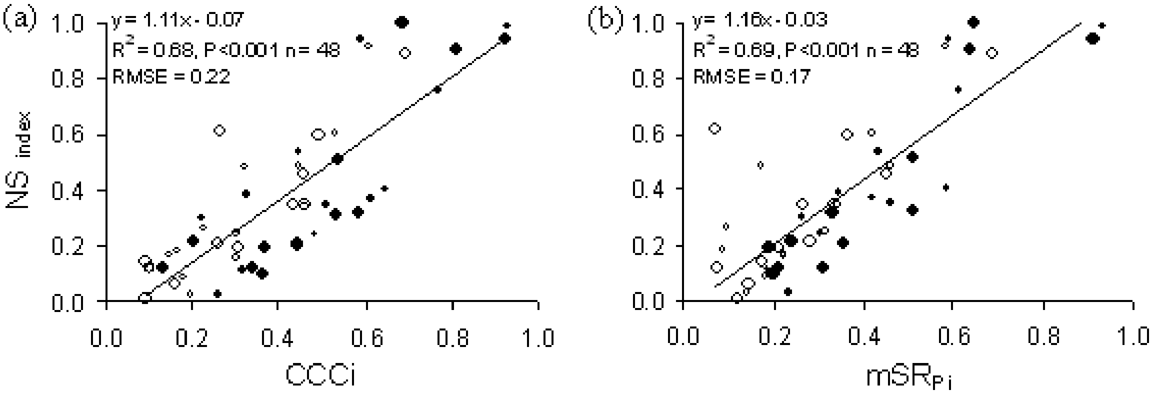


Fig. 3. Relationships between the nitrogen stress index (NS_{index}) and the planar domain (a) canopy chlorophyll content index (CCCi), and (b) modified spectral ratio (mSRPi). Open and closed symbols indicate the rainfed and irrigated treatments, and small and large symbols show the low and high canopy densities, respectively. RMSE is the root mean squared error.

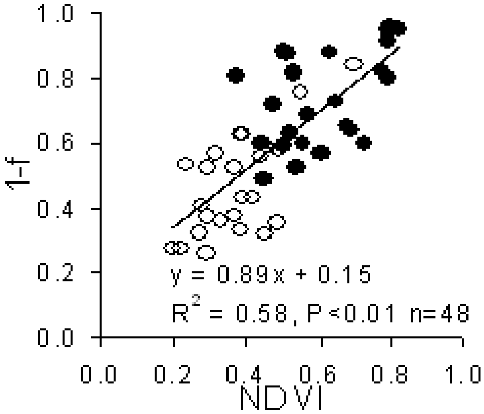


Fig. 4. Relationship between the fractional intercepted radiation (1-f) and the NDVI. Filled symbols are for irrigated plots and open symbols for rainfed plots.

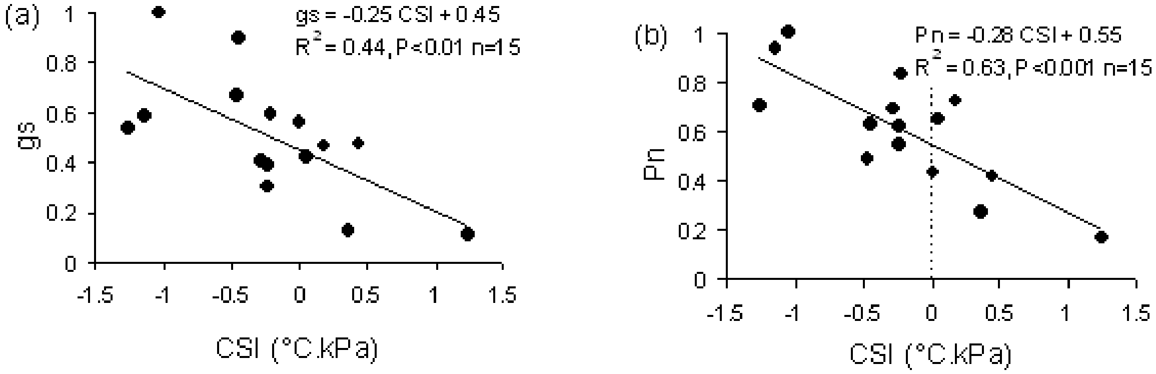


Fig. 5. Relationship between (a) leaf stomatal conductance, and (b) leaf net photosynthesis rate, and the canopy stress index (CSI). Response variables are normalised relative to maxima measured in a well-irrigated, high nitrogen control.

Spatial detection of water stress in field crops

In rainfed wheat production the margin for improving the nitrogen nutrition of the crop is small and the most likely benefit of identifying zones in the field having a differential response to N might be the avoidance of losses from non-responsive areas. In principle the capacity of the crop to respond to in-crop nutrient management depends on its physiological condition i.e. the absence of imbalances between water supply and demand, as caused by changes in soil type, sub-soil constraints, root diseases, etc. In our work we proposed that the physiological condition of the canopy can be derived from the air canopy temperature differential, which is based upon the assumption that, as water becomes limiting, transpiration is reduced and the canopy temperature increases. However the difficulty of measuring foliage temperature from partially vegetated fields, with hand-held infrared thermometers and most airborne and satellite-based infrared sensors, limited its application. The reason is that before a crop achieves full cover the temperature of the soil generally dominates the composite i.e. soil-crop, temperature measurements. Recent advances and availability of equipment for digital thermal imaging provides a unique opportunity to develop instantaneous spatial canopy stress indices for use in precision agriculture. In our work we used digital thermal imaging technology (Rodriguez et al., 2005) to: (a) develop a simple canopy physiological stress index with spatial resolution commensurate with the needs of site-specific management, and (b) test the physiological meaning of this index by exploring its association with key processes and variables at leaf and canopy levels.

The target in the field of view of the sensor

Particularly before full ground cover, digital thermal images are complex combinations of crop and soil thermal emissions. In our work we devised a simple method to retrieve the temperature of the crop from digital thermal images and ground cover measurement of wheat canopies. This was based on the fact that absorbed PAR has been well related to spectral reflectance measurements (Fig. 4), and that the relation between the fractional intercepted PAR and spectral indices derived from reflectance measurements is little affected by solar zenith angle or time of the day.

The property of the target

Based on the work of Idso et al. (1981), we defined a canopy stress index (CSI) as the difference between canopy (Tc, ?C), and air temperature (Ta, ?C) normalised by vapour pressure deficit (VPD, kPa):

CSI = (Tc – Ta)/VPD (?C /kPa) eq 1

CSI is expected to be positive and high if the capacity of the canopy to dissipate heat is reduced as when stomata close. A range of environmental factors could cause stomatal closure, including drought and pests and diseases affecting vascular tissue, roots or foliage. Stomatal closure can also be induced by shortage of nutrients, and by hormonal signals. Consequently, CSI is an index of the general physiological status of a canopy. Normalising the canopy temperature depression using VPD, the resulting CSI was able to capture physiological responses at both the leaf and crop levels. At leaf level, CSI explained a significant proportion of the variation in net photosynthesis, stomatal conductance and transpiration rate (Fig. 5).

At the crop level, CSI was related to both shoot growth rate before anthesis and grain yield (Fig. 6). As CSI was not only linearly related to the final grain yield, but also, to the growth rate around anthesis, we concluded that CSI was a meaningful variable capable of describing the physiological status of the crop at anthesis. Canopy temperature alone, particularly if it is not instantly determined from a digital thermal image of the whole area under study, cannot be used as an absolute estimator of the physiological status of the crop. This is because leaf temperature depends on its energy budget resulting from incoming solar radiation, outgoing long wave radiation, and latent and sensitive heat fluxes, which are affected by rapidly changing micrometeorological and crop conditions. Therefore, spatial temperature information becomes meaningful when adjusted by micrometeorological conditions, or incorporated into a stress index.

Spatialisation of crop models

CSI also provides a simple and elegant link with crop models to spatially simulate key physiological traits of wheat canopies i.e. “spatialise” crop models. This is the application of a crop model over areas larger than that for which it has been originally developed. The final decision on whether to top-dress N or not needs to be based on the likelihood of the economic response to the practice, which can be estimated from the assimilation of remote sensing information into crop simulation models. Early results (Fig. 7) indicate that the NS_{index} might be a good starting point to link spatial remotely sensed information into a dynamic model like the Agricultural Production Systems Simulator (APSIM).

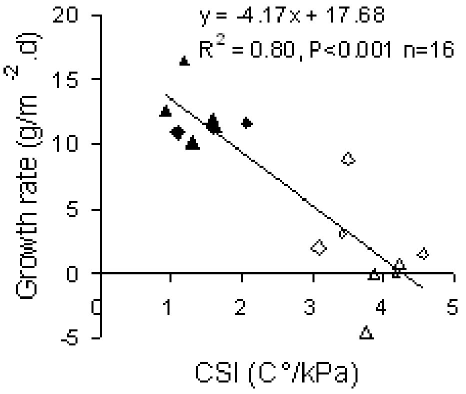


Fig. 6. Wheat growth rate around anthesis (g/m^2.d) as a function of the crop stress index (CSI, C?/kPa) calculated at anthesis, for irrigated (filled symbols) and rainfed (open symbols) plots, high (diamonds) and low (triangles) plant densities, and four levels of

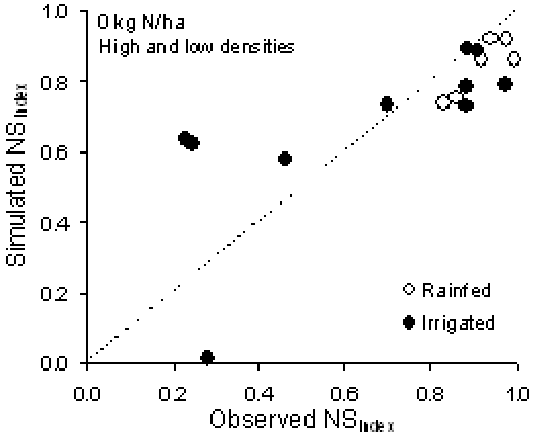


Fig. 7. Simulated versus observed nitrogen stress index for 0 kg N/ha, high and low plant density treatments at Horsham. Simulated results were obtained with APSIM 5.0.

nitrogen (0, 16, 39 and 163 kg N/ha) represented by the increasing size of the symbols.

These results can be applied by customising airborne image acquisition systems using the derived indices and methods. The relationships developed in Fig 3, can be used for variable-rate applications of top-dressed fertilisers in wheat crops as early as Zadoks 33. In SE Australia, this corresponds to July-August, a time of the year farmers consider top dressing wheat crops, and when existing seasonal climate forecasting tools, start to show good skill and value for in-season crop nitrogen management.

Conclusion

To assist farmers with in-crop N management, we propose that we should not aim to predict N%, but to derive indices of potential for response to additional N. The results in this paper highlight the importance of taking into consideration basic eco-physiological understanding when analysing remotely sensed spectral data from field-grown wheat canopies.

Acknowledgements

The experimental work was fully funded by PIRVic, this work was written while Daniel Rodriguez was working for the Queensland Department of Primary Industries & Fisheries, and Victor Sadras was funded by SARDI. We greatly appreciate the field work by Russel Argall and the contributions by Tom Clarke from USA-WCL.

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