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Defining and evaluating methods of using crop canopy data collected by boom-mounted sensors to adjust plant growth regulator inputs and the timings of nitrogen applications

by

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CONTENTS

1. ABSTRACT

The aim of the project was to interpret and evaluate crop canopy information for winter wheat crops collected using boom-mounted sensors that could then be used in the planning of nitrogen fertiliser timing and plant growth regulator application strategies. These strategies would aim to minimise the risk of lodging whilst also maintaining crop yield and minimising plant growth regulator (PGR) use.

Experimental plots were established over three seasons on two sites with different soil types using seed rates in the range 70 to 400 seeds/m^2 to give different crop canopy characteristics. Measurements of the crop canopy characteristics (crop height and a Normalised Vegetation Difference Index – NDVI) made at each site and on three occasions in each season using a boom-mounted sensor system showed that there was a consistent relationship between NDVI and Leaf Area Index (LAI)/Green Area Index (GAI) measured with a manually operated light attenuation instrument. There was also a relationship between the variability of the NDVI signal and the tiller/shoot number which, for a given field calibration, could provide information about plant populations on a spatially selective basis. It was therefore concluded that crop canopy sensing systems could provide input data for managing root and stem lodging risk based on existing decision rules. The sensor systems gave the steepest responses for both the NDVI/LAI (GAI) and the variability of NDVI/tiller (shoot) counts relationships at the early measurement timings and this corresponds to the times at which decisions relating to nitrogen timings and PGR inputs are most relevant.

In the first year of the project, plots were managed using variable treatments determined from a set of decision rules defined for each of three separate strategies: standard, variable nitrogen timings and variable PGR inputs. Results were found to be dominated by weather effects during the 2006/07 season and therefore for the final two years of the work a more conventional randomised plot design was used. Crop yields from plots treated with no early nitrogen and a low PGR input consistently gave lower yields than those treated with a standard nitrogen split and either a low PGR input or a robust PGR input. Crop lodging was only recorded on the heavy land site with some lodging for all strategies and seed rates in the first year of the work, for the highest seed rate plots only in the second year and no lodging in the third year. Lodging risk analyses were therefore based on previously established relationships.

2. SUMMARY

2.1. Introduction and background

Concern over crop lodging has increased as combine harvester capacity (tonnes/machine per season) has needed to increase in response to economic pressures such that a standing crop is now a critical requirement in any UK cereal production strategy. Crop lodging also incurs potential additional costs related to crop drying and increases the risk of mycotoxins in the grain. However, there are also increasing concerns about the chemical residues of plant growth regulators in the food chain. The most commonly occurring pesticide residues in grain are glyphosate and plant growth regulators. There is concern over the levels of use of some plant growth regulator formulations but current alternatives are less effective when used alone and are more expensive. Therefore, approaches that minimise the risk of lodging using well managed inputs of growth regulators based on information about the crop canopy have potentially important advantages. If plant growth regulator use is restricted then an important way of reducing lodging risk relates to the adjustment of the timings of nitrogen inputs.

This project aimed at testing the hypothesis that the risk of crop lodging can be effectively managed by applying growth regulators and adjusting the timings and splits of nitrogen inputs based on measurements of the crop canopy structure. A review of approaches to crop canopy sensing identified spectral reflectance as the principle most commonly used as a basis for determining cereal crop canopy characteristics both in research studies and commercial developments. The work described in this report builds on previous studies conducted as part of an HGCA Fellowship (HGCA Project Ref. 2265 that commenced on 01/05/2000) in which it was shown that there was the potential to obtain information about crop canopy structure from boom-mounted sensors in terms of both Green Area Index and shoot/tiller numbers and hence a basis for the management of lodging risk using established relationships.

2.2. Methods

The project was conducted over three cropping seasons and involved the establishment of winter wheat plots on two sites: a heavy land site near Biggleswade in Bedfordshire, and a light land site near Andover in Hampshire. Different crop canopies were achieved at each site by using seed rates in the range 70 to 400 seeds/m^2. A boom-mounted sensor system, developed as part of previous project work (Scotford and Miller, 2004) and including radiometers to measure spectral reflectance and ultrasonic transducers to monitor boom height, was mounted on a self-propelled lawn mower chassis that enabled the transducers to be moved across the plots at a speed of approximately 4.0 km/h with data recorded directly to a computer at a rate of 10 Hz. Measurements were made on three occasions at each site: in early March, April and May. On each measurement occasion, the Leaf Area Index/Green Area Index was measured in each plot with a manually operated light attenuation instrument ("Sun Scan" – Delta-T Devices Ltd).

In the first year of the work plots received treatments based on three strategies:

- Standard nitrogen split and standard PGR programme according to best practice for the site.
- Standard nitrogen split with a variable PGR programme based on crop canopy measurements.
- Variable nitrogen split based on crop canopy measurements and a standard PGR programme.

Decision rules were developed based on the results of the crop canopy measurements and applications of both nitrogen and plant growth regulators were made according to these rules. In the early spring of 2007, crop canopies, particularly at the heavy land site, had much greater Leaf Area Indices than expected following a relatively mild winter. There then followed a dry spring period during which crops at the heavy land site lost leaf such that the application strategies based on the developing canopy could not be implemented as initially envisaged. It was therefore decided that in the second and third years of the work a more conventional randomised plot experimental design would be used with defined treatments applied representing the three strategies. For each of the plots in each year, assessments were made of:

- Shoot counts in February/March prior to the first scan timing – counted manually;
- Final ear population (ears/m^2) at GS 80- counted manually.
- Crop height – measured manually at GS 80 and with the sensor system at the earlier timings.
- Lodging (>45^o) and leaning (<45^o) - % of crop area and date of occurrence – assessed manually.
- Grain yield at 15% moisture content – using a plot combine.
- Specific grain weight and thousand grain weight – from analysis of collected grain samples.

In addition to the measurements made with the boom-mounted sensors in the first year of the project, assessment were made of the lodging risk for each plot at the heavy land site at the March timing by an experienced agronomist enabling a direct comparison with these manual estimates and results from the sensor measurements.

2.3. Key results

Results from measurements of a vegetative index (Normalised Vegetation Difference Index – NDVI) and Leaf Area Index/Green Area Index showed a consistent form over all seasons at both sites. Because measurements with the sensors and the manually operated light attenuating instrument were made relatively early in the season, it was assumed that there would be a close relationship between the parameters of Leaf Area Index and Green Area Index such that existing rules relating to the evaluation of lodging risk that use Green Area Index as a parameter could be used in the study. Examples of the measured relationships are given in Figures I and II. It can be seen that the largest changes in the measured NDVI for a given change in the Leaf Area Index (LAI) occurred at the early sampling times when the crop was at the earlier growth stages. This is consistent with the measurement of NDVI tending to saturate as the crop canopy gets larger such that for values of LAI above 3.0, sensor resolution is relatively poor. Information relating to the management of lodging risk will therefore be generated when the reflectance sensing instrument is relatively sensitive to changes in crop canopy structure.

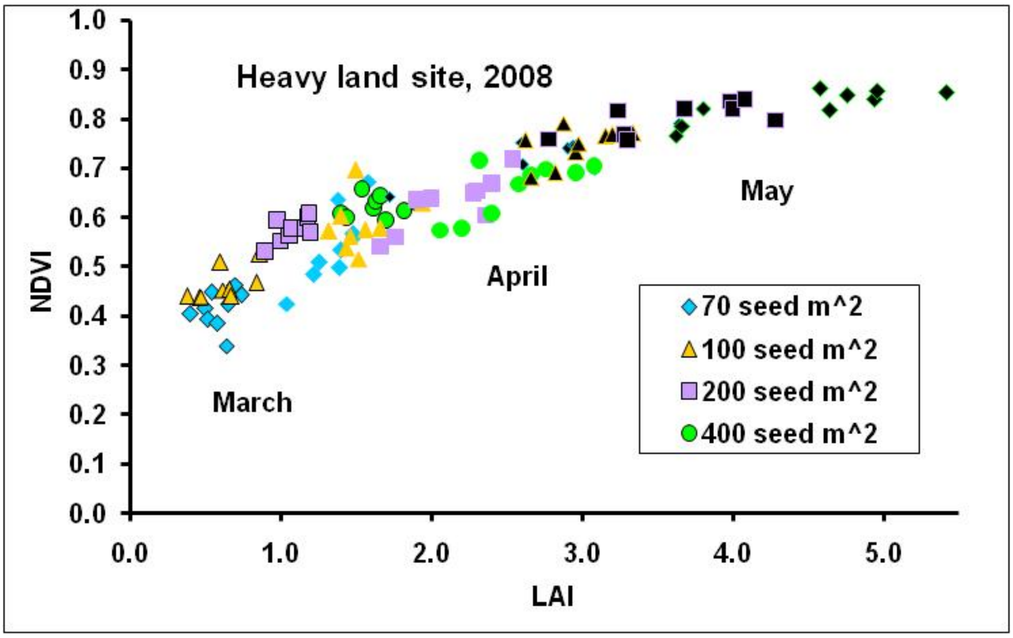

Figure I. The relationship between Leaf Area Index (LAI) and a Vegetation Index (NDVI) measured at the heavy land site on three occasions in 2008.

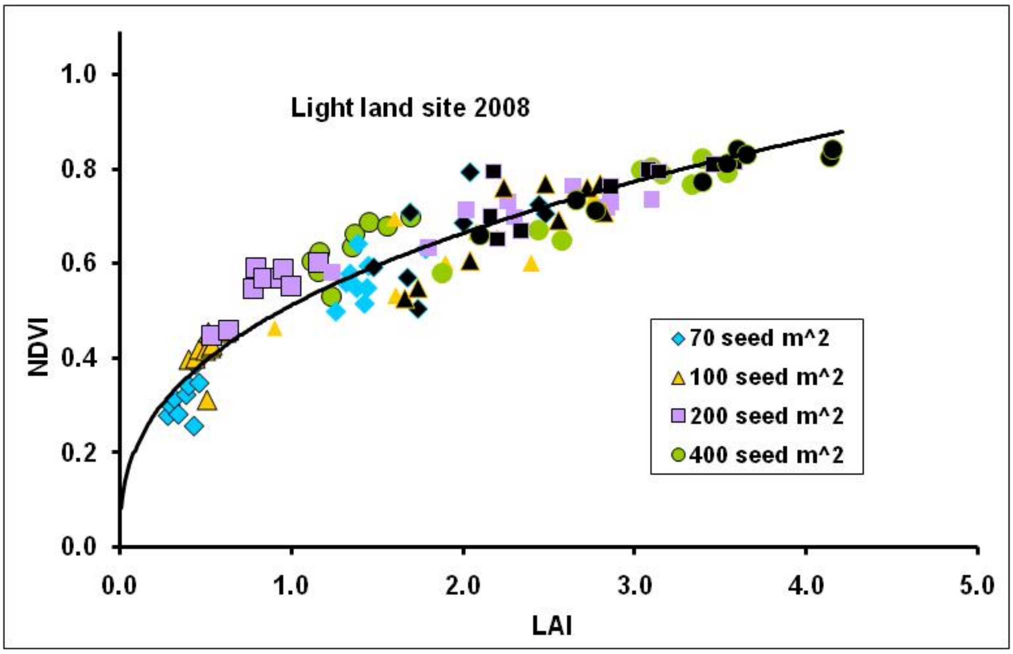

Figure II. The relationship between Leaf Area Index (LAI) and a Vegetation Index (NDVI) measured at the light land site in March (lined symbols) and April (unlined symbols) during 2008.

In the second and third years of the study the variability of the NDVI value from the sensor cluster was shown to correlate well with manual counts of tiller numbers made early in the season at both sites (see Figures III and IV) whereas no correlation was established in the first year of the project. This probably relates to the size of the "footprint" of the sensor. In the first year the boom was positioned approximately 1.0 m above the crop at the earliest sampling time giving a footprint in the order of 0.1 m^2. For years two and three, the height of the boom was reduced such that the sensors were approximately 0.5 m above the crop canopy at all sampling times giving a "footprint" area of the order of 0.02m^2.

Although the variability in sensor output decreased with increasing seed rate and growth stage as expected, there were still relationships between the coefficient of variation of the NDVI signal and manually recorded tiller counts for sensor measurements made at the May timing at both sites.

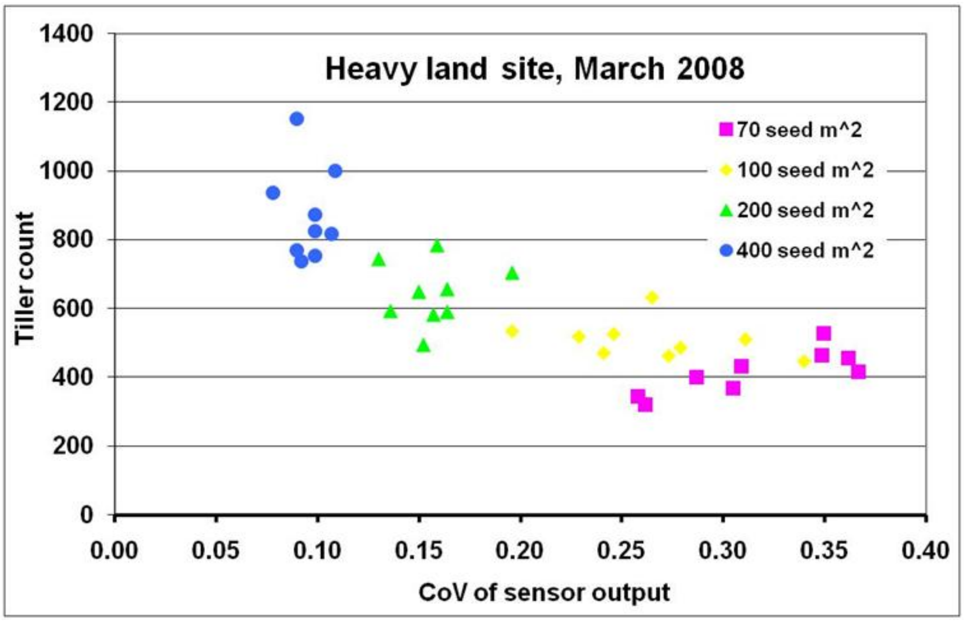

Figure III. Coefficient of Variation (CoV) of NDVI measured with the sensors plotted against manually counted tiller numbers in March 2008 at the heavy land site

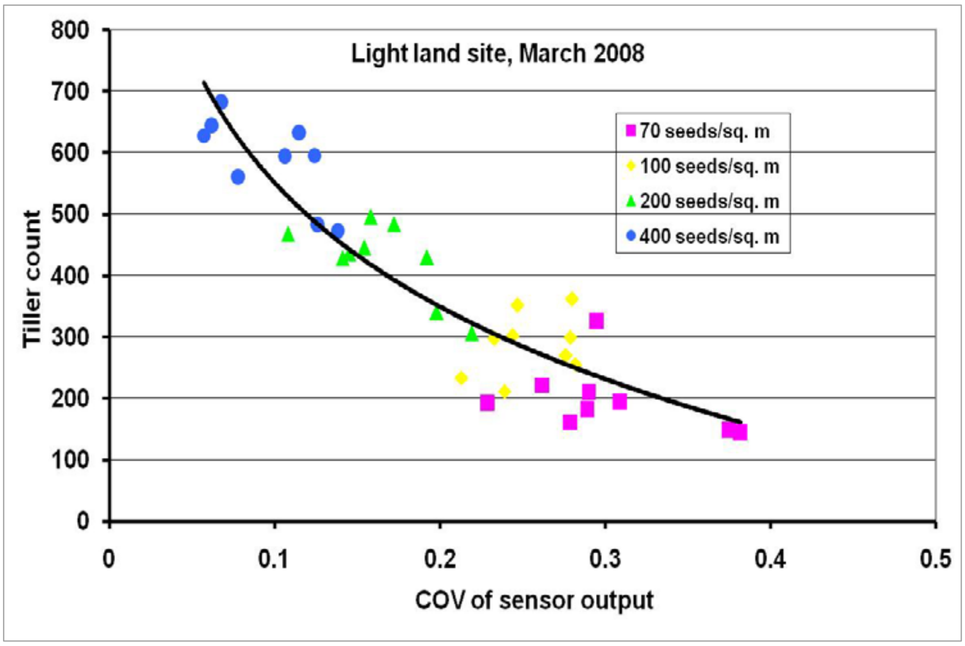

Figure IV. Coefficient of Variation (CoV) of NDVI measured with the sensors plotted against manually counted tiller numbers in March 2008 at the light land site

Assessments of the lodging risk made manually by an experienced agronomist on the heavy land site in the first year of the project showed a consistent relationship with the Leaf Area Index (LAI) measured with the light attenuation instrument. Measurements of the crop canopy on the light and heavy land sites in the spring of 2007 showed very different Leaf Area Indices for comparable tiller counts (Figure V) indicating that the tillers on the heavy land site were much larger than those on the light land.

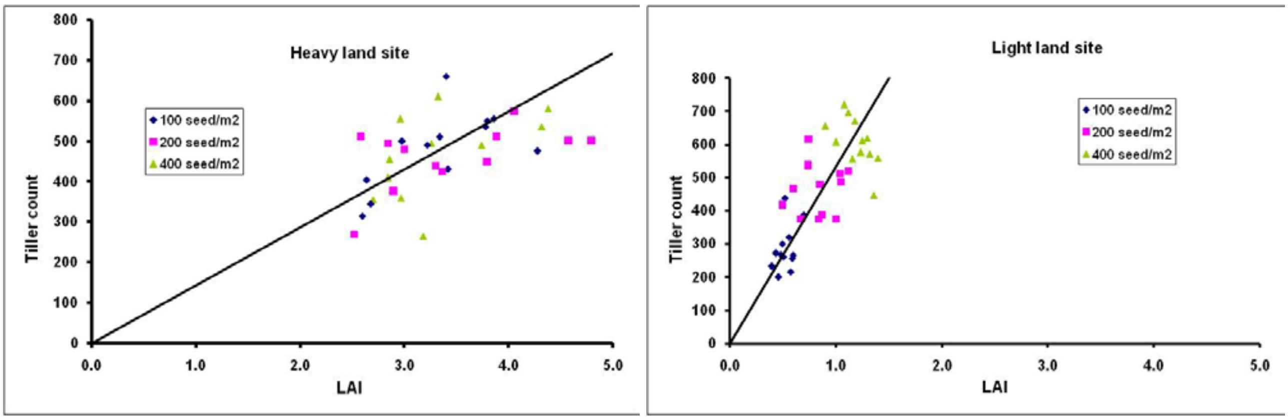

Figure V. The relationship between Leaf Area Index (LAI) and tiller counts at the two site in March 2007.

Examples of the relationships between plot yields and the applied treatments for the 2009 harvest season are shown in Figures VI and VII.

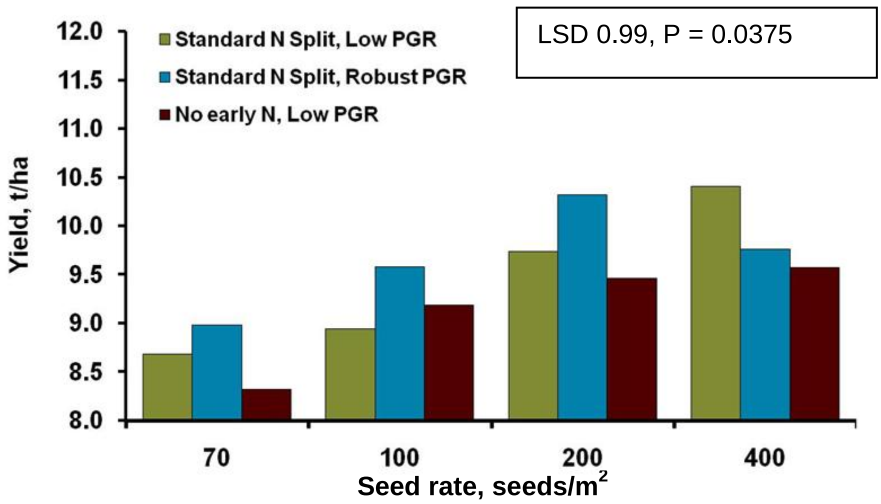

Figure VI. Plot yields recorded on the heavy land site in the 2009 harvest season

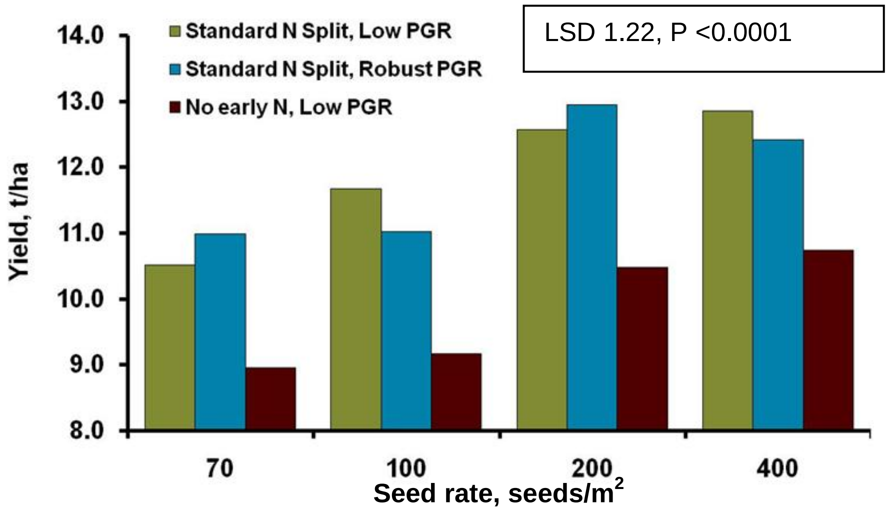

Figure VII. Plot yields recorded on the light land site in the 2009 harvest season

The agronomic assessment showed some consistent trends, namely:

- Not applying early nitrogen consistently gave lower yields although this loss of yield compared with a standard application strategy was not always statistically significant: this result emphasises the need for lodging predictions to be as accurate as possible since delays in nitrogen application for reasons other than lodging control are likely to result in a yield loss.
- Only low levels of lodging were recorded over the period during which the study was conducted: no lodging in any season was recorded on the light land site; and on the heavy land site lodging occurred mainly in the first year of the study, with only plots established at the highest seed rate showing lodging in year 2 of the study, and no lodging recorded in the last year of the work. The low levels of lodging in years 2 and 3 were mainly due to seasonal effects.
- The effect of the applied treatments on crop height was variable between both sites and seasons but where significant differences were recorded these followed the expected trends with plots having a low PGR input giving taller crops (e.g. at the light land site in the 2009 season) and those receiving a robust PGR input giving shorter crops (e.g. the heavy land site in the 2008 season).
- There were some differences in the number of ears/m^2 and the specific grain weight but these were mainly related to seed rate rather than the application strategy.
- The expected form of yield against seed rate relationship was found for both sites and soil types (Figures VI and VII) with yields generally increasing with seed rates up to 200 seeds/m^2 and then declining at the higher seed rate. This relationship was particularly pronounced on the light land site for all seasons and on the heavy land site in the 2009 season only – in the earlier seasons at the heavy land site the relationship between seed rate and yield showed less variation.

2.4. Main implications from the work

The study showed that the output from crop sensing systems has the potential to provide data relating to the canopy that would aid the assessment and management of the risk of crop lodging. The main advantage of using a sensor-based system is that information could be collected in a spatially variable manner and any treatments could then be applied on a spatially variable basis. Such an approach would minimise potential crop losses from delayed nitrogen applications where these were not needed to give control of lodging and would also enable the minimum quantity of plant growth regulator to be used.

Because of the low levels of lodging recorded in the experiments, particularly in the last two years of the work, the results obtained have been interpreted using established guidelines for managing crop lodging (HGCA, 2005). These relate to a number of factors but those relevant to the management of a wheat crop in the spring concern:

- Root lodging where the risk increases when the plant population exceeds 200 plants/m^2;
- Stem lodging where the risk increases when the canopy at GS31 is large – having a Green Area Index of 2 or more.

Results of the work described in this report indicate that measures of plant population can be obtained by monitoring the variability of the vegetation index signal from the boom-mounted sensors. It is recognised that the relationships are likely to vary with field and crop condition and therefore some form of in-field calibration would be needed to implement this approach. However, when calibrated it would then be possible to map a field and identify areas where the root lodging risk was high and implement an appropriate management strategy on a spatially variable basis. A robust relationship was found between measures of a vegetation index (NDVI) and Leaf Area/Green Area Index such that sensors could again be used to identify areas within a field where a spatially variable approach to the management of stem lodging could be implemented.

The study was conducted in close collaboration with commercial organisations concerned with crop sensing technologies. While the principles behind the measurements made are likely to relate to results obtained with commercial designs of sensing system, important differences may arise due to:

- The detailed wavelengths used and the calculation of a measure of canopy structure – not all commercial approaches use a Normalised Vegetation Difference Index as calculated in this work and the wavelengths used may influence factors such as the readings from different soil surfaces.
- The size of the sensor “footprint” and the frequency at which data is collected – this being particularly relevant to the determination of plant populations based on signal variability although other sensing systems may use other principles of operation.

The measurements of crop canopy structure in this study were made at defined dates rather than at fixed crop growth stages. Other project work is aiming to improve the prediction of crop nitrogen demand using canopy sensors as one component of a management system and this work will include considerations relating to crop development.

The good agreement between estimates of lodging risk based on visual assessment by an experienced agronomist and those derived from sensor measurements is encouraging and adds to the confidence relating to the development of lodging risk management strategies based on sensor measurements. However, the large differences in tiller size between crops established in the same season on two different sites with different soil types and the absence in any of the crop years of lodging on the light land site suggests that there continues to be scope for refining the prediction of lodging risk using sensor data.

3. TECHNICAL DETAIL

3.1. Introduction

It is now well established that crop canopy structure is a major factor influencing the performance of a cereal crop and therefore the parameters of Green Area Index (GAI) plant and shoot numbers are used within The Wheat Growth Guide (Revised edition, 2008, HGCA) as indicators to aid the management of a developing crop. Technological developments with sensor designs, as well as the collection and manipulation of data using computer based systems, have also had important implications for arable crop agronomy over the past two decades. In-field location systems based on satellite navigation technology, with improved accuracy and reliability, have enabled sensed data relating to crop canopy characteristics to be examined within a spatial framework such that areas of poorer (or better) crop growth in comparison with the average across a field can be identified.

A review of approaches to crop canopy sensing (Miller, 2009) identified spectral reflectance as the principle most commonly used as a basis for determining cereal crop canopy characteristics, although approaches based on mechanical resistance, ultrasonic reflectance and LIDAR/RADAR have also been developed. A wide range of approaches have also been taken in using spectral reflectance to obtain crop canopy information that can then be used as a component in determining fungicide, growth regulator and nitrogen inputs to a cereal crop, as reviewed by Scotford and Miller (2005b).

In concept, information relating to crop canopy characteristics can be used to determine components of a nitrogen fertiliser application strategy in three ways:

i. as one of the factors determining the rate of nitrogen that should be applied
ii. as a basis for manipulating the application of a given dose of nitrogen over a field area in a spatially variable manner – spatial management approaches
iii. to manipulate the timings and proportions of the total dose that are made at the different application timings – temporal management approaches.

Methods for determining nitrogen input rates for cereal crop production are well documented (e.g. Defra, 2000) and have recently been updated (Fertiliser Manual (RB209), 2010). It is likely that results from monitoring the crop canopy will mainly be used to make adjustments to such doses in response to local and seasonal factors (Knight *et al*., 2009).

Adjusting the spatial distribution of a given dose of nitrogen could be aimed at producing a more uniform crop with advantages relating to the management of the more uniform crop but this may not maximise yield for a given fertiliser input. The important issue is to identify parts of a field that are likely to be more or less responsive to nitrogen inputs. Work reported by Lark and Wheeler (2003) showed that there could be variability in the economic optimum nitrogen dose within a field with most of the benefit from spatially variable application.

Concern over crop lodging has increased as combine harvester capacity (tonnes/machine per season) has needed to increase in response to economic pressures such that a standing crop is now a critical requirement in any UK cereal production strategy. Crop lodging also incurs potential additional costs related to crop drying and increases the risk of mycotoxins in the grain. However, there are also increasing concerns about the chemical residues of plant growth regulators in the food chain. The most commonly occurring pesticide residues in grain are glyphosate and plant growth regulators. There is concern over the levels of use of some plant growth regulator formulations but current alternatives are less effective when used alone and are more expensive. Therefore, approaches that minimise the risk of lodging using well managed inputs of growth regulators based on information about the crop canopy have potentially important advantages. If plant growth regulator use is restricted then an important way of reducing lodging risk relates to the adjustment of the timings of nitrogen inputs.

3.2. Materials and methods

3.2.1. Treatment strategies and plot arrangements

For the first year of the project (2007 harvest season), plot inputs were determined based on a decision table and measurements of the Green Area Index (GAI) using a “Sunscan” instrument (Delta-T Devices Ltd). This approach was found to be very dependent on the over-winter weather conditions and therefore the strategy was changed for the 2008 and 2009 harvest seasons to one based on a more conventional randomised block design.

Strategies and plot arrangements – Year 1

Two field sites were established for the field experiments:

- at Edworth, near Biggleswade, Bedfordshire on a heavy clay soil
- at Sutton Scotney, near Andover on a light soil type.

At each site a randomised block plot layout was established using relatively large plots (5 m wide by 12 m long) by drilling a medium/high lodging risk variety (Ambrosia) at three different seed rates (100, 200 and 400 seeds/m^2) in September 2006. A different wheat variety (Welford) was drilled in buffer areas between the main plots. The crop was managed with standard inputs of herbicide, fungicide, insecticide, trace elements and fertiliser (except nitrogen) at each site.

Three treatment strategies were defined relating to the timing and final dose of nitrogen and the dose/timing of plant growth regulator (PGR) applications as follows:

1. Standard nitrogen split and standard PGR programme according to best practice for the site.
2. Standard nitrogen split with a variable PGR programme based on crop canopy measurements.
3. Variable nitrogen split based on crop canopy measurements and a standard PGR programme.

All treatment strategies were applied to all seed rates and replicated four times to give a total of 36 plots The trial was designed to allow husbandry treatments with a single (left or right hand) 5.0 m boom section of a 12.0 m wide tractor-mounted pneumatic fertiliser spreader or sprayer using unsown pathways as tramlines.

Standard approaches were as follows:

Nitrogen

Biggleswade	**Total:**	200 kg N/ha (assuming total SNS of 120 kg N/ha or less)
	Split:	150 kg GS31 early-mid April, 50 kg GS33 mid May
Sutton Scotney	**Total:**	240 kg N/ha (assuming total SNS of 120 kg N/ha or less)
	Split:	50 kg early-mid March, 140 kg GS31 mid April, 50 kg GS33 mid May

Plant Growth Regulator

Biggleswade	1.15 L/ha 3C chlormequat at GS30 followed by 1.25 L/ha 5C Cycocel at GS31 followed by 1.0 L/ha Terpal at GS37
Sutton Scotney	2.5 L/ha 5C Cycocel at GS31 followed by 0.5 L/ha Terpal at GS37

Terpal was applied with approved non-ionic wetter at 80 mL per 200 litres water.

Measurements of a vegetative index (Normalised Difference Vegetation Index - NDVI) and crop height were to be made on each plot with a boom-mounted instrumentation cluster (see Section 2 below) on three occasions at each site together with an indirect measure of Leaf/Green Area Index (LAI/GAI) using a "Sunscan" light attenuation instrument and decisions made regarding the variable treatments based on the information in Table 1 below.

Table 1. Basis for decisions concerning variable treatments

Scan date	Measurement	Decision – Nitrogen	Decision – PGR

Early March	Canopy size (GAI, height)	Apply early N dose, or delay until April timing.	Split main PGR, or wait until April timing.
Early April	Canopy size (GAI, height)	Increase, decrease or apply planned main N dose.	Dose of main PGR, and mixture.
Early May	Canopy size (GAI, height)	Increase, decrease or apply planned final N dose.	Apply late PGR or not, and dose if applied.

Canopy size definitions, based on the Wheat Growth Guide (HGCA, 2008) as given in Table 2, were used as the basis for decisions regarding variable inputs. It was recognised that sowing dates and growth stages could vary between sites and seasons and therefore Table 2 has two sets of values for each scan date.

Table 2. Canopy size definitions used in decision making regarding variable treatments

Scan date	Low canopy lodging risk	Medium canopy lodging risk	High canopy lodging risk
Early March (crop early GS30)	<GAI 0.8	GAI 0.8-1.2	>GAI 1.2
Early March (crop late GS30)	<GAI 1.3	GAI 1.3-1.9	>GAI 1.9
Early April (crop early GS31)	<GAI 1.6	GAI 1.6-2.2	>GAI 2.2
Early April (crop late GS31)	<GAI 2.2	GAI 2.2-3.0	>GAI 3.0
Late April/early May (crop GS32)	<GAI 2.5	GAI 2.5-3.5	>GAI 3.5
Late April/early May (crop GS33)	<GAI 3.0	GAI 3.0-4.2	>GAI 4.2

In addition to the assessments of LAI/GAI made based on the “Sunscan” measurements, each plot on the heavy land site was scored visually for lodging risk based on crop canopy density and height. This assessment was made by an agronomist with experience of the site and the effect of sowing date at the site.

Nitrogen Decision table

Only two categories of crop canopy were used to determine nitrogen inputs, “Low” and “High”. “Low” included both the low and medium canopy size definitions (Table 2) except at the March timing when the medium canopy was treated the same as the standard approach.

The nitrogen decision table was therefore as shown in Table 3 with the superscripts relating to the Biggleswade (B) and Sutton Scotney (S) sites.

Table 3. Nitrogen input decision table

Early March scan	Low (+ medium) Canopy	High (+ medium) Canopy

March Dose	50 kg/ha				0			
Early April scan	**Low (+ medium) Canopy**				**High Canopy**			
Previous dose	**(L)** 50		**(H)** 0		**(L)** 50		**(H)** 0	
GS31 April Dose	$100^B/140^S$ kg/ha		$150^B/190^S$ kg/ha		$75^B/115^S$ kg/ha		$100^B/140^S$ kg/ha	
Early May scan	**Low (+ medium) Canopy**				**High Canopy**			
Previous doses (totals to date)	**(L/L)** 150^B 190^S	**(H/L)** 150^B 190^S	**(L/H)** 125^B 165^S	**(H/H)** 100^B 140^S	**(L/L)** 150^B 190^S	**(H/L)** 150^B 190^S	**(L/H)** 125^B 165^S	**(H/H)** 100^B 140^S
GS33 May dose	50	50	75	100	50	50	50	75

Note: Six out of eight outcomes would have resulted in the same total dose being applied, with only the timings changed (LLL, HLL, LHL, HHL, LLH, HLH). Where the canopy was high in both April and May (LHH, HHH), the total dose applied would be reduced by 25 kg N/ha.

Plant Growth Regulator Decision Tables

Table 4. PGR Decision Table

Early March scan	**Low (+ medium) risk**			**High (+ medium) risk**
March (GS30) treatment	None			1.15 3C
Early April scan	**Low risk**	**Medium risk**		**High risk**
Previous treatment	n/a	none	1.15 3C	n/a
GS31 treatment	1.25 5C	2.5 5C	1.25 5C	1.25 5C + 0.2 Moddus
Early May scan	**Low risk**	**Medium risk**		**High risk**
GS37 treatment	none	Terpal $1.0^B/0.5^S$		Terpal $1.5^B/1.0^S$

3C = 3C chlormequat 5C = 5C Cycocel Doses are in L/ha

Terpal applied with approved non-ionic wetter at 80 ml per 200 litres water

Strategies and plot arrangements – Years 2 and 3

For the 2008 and 2009 harvest season experiments each plot received a pre-determined husbandry treatment, rather than a variable treatment based on decision tables. Each husbandry treatment was applied to each initial crop density (seed rate) in each replicate. Comprehensive sensing data was recorded and, from the lodging and harvest data, the most appropriate treatment strategy was determined and related to the sensing results obtained. Four seed rates were sown (70, 100, 200 and 400 seeds/m^2) to create plots of varying initial crop density. The field trials were again designed to allow husbandry treatments to be applied with a single (left or right hand) boom (5.0m) section of a 12.0 m tractor-mounted pneumatic fertiliser spreader or sprayer using the guard areas between plots to travel over.

Husbandry Treatments

Three strategies were used to allow crop canopy growth to be manipulated differentially:

1. Standard nitrogen split, low PGR input
2. Standard nitrogen split, robust PGR programme
3. No early nitrogen (added to final dose), low PGR input

Table 5. Treatments at the heavy land (Biggleswade) site for years 2 and 3.
(Total N dose 200 kg N/ha assuming SNS in Feb/Mar does not exceed 120 kg N/ha)

Strategy	early N GS29 start Mar	main N dose (GS31) early-mid Apr	final N dose (GS33) early May	T0 PGR (GS30) early-mid Mar	T1 PGR (GS31-32) mid Apr	T2 PGR (GS37) mid May
1	40	100	60	none	1.25 L/ha 5C Cycocel	none
2	40	100	60	1.15 L/ha 3C chlormequat	1.25 L/ha 5C Cycocel + 0.2 L/ha Moddus	1.0 L/ha Terpal
3	0	100	100	none	1.25 L/ha 5C Cycocel	none

Table 6. Treatments at the light land (Sutton Scotney) site for years 2 and 3
(Total N dose 240 kg N/ha assuming SNS in Feb/Mar does not exceed 100 kg N/ha)

Strategy	early N GS29 start Mar	main N dose (GS31) early-mid Apr	final N dose (GS33) early May	T0 PGR (GS30) early-mid Mar	T1 PGR (GS31-32) mid Apr	T2 PGR (GS37) mid May
1	40	140	60	none	1.25 L/ha 5C Cycocel	none
2	40	140	60	1.15 L/ha 3C chlormequat	1.25 L/ha 5C Cycocel + 0.2 L/ha Moddus	1.0 L/ha Terpal
3	0	140	100	none	1.25 L/ha 5C Cycocel	none

Terpal applied with approved non-ionic wetter at a rate of 80mL per 200 litres of water

Plots were scanned with the boom-mounted sensor cluster (see Section 2.2 below) to determine an NDVI value on three occasions during the growing season, and the recorded information from separate measurements (LAI/GAI, shoot population and height) was used to characterise the crop and canopy in relation to each husbandry treatment. The nominal scan timings were:

i. End of February or start of March, just prior to the early N dose and before the T0 PGR
ii. End of March or start of April, just prior to main N dose and before the T1 PGR

iii. End of April or start of May, just prior to final N dose and before the T2 PGR.

3.2.2. Sensing system

An arrangement of sensors on a small boom system as described by Scotford and Miller (2004) was used for the study. Two types of sensor were used, namely:

- A radiometer system that used two, 2-channel radiometers (Skye, type SKR 1800) measuring at narrow bandwidths of approximately 20 nm and centred at 660 and 730 nm: One radiometer fitted with a cosine corrected head and having an acceptance angle of 180^o was mounted pointing upwards to measure incoming radiation while two other sensors were pointed downwards with an acceptance angle of approximately 20^o;
- An ultrasonic height sensor (Pepperl + Fuchs, type UC 2000-30GM-IU-VI) operating at a frequency of 175 Hz and with a sensing range of 0.2 – 2.0 m. The sensor was fitted with temperature compensation, enabling operation from -25 ^{o}C to 70 ^{o}C.

Data from the radiometer system was used to calculate a Normalised Difference Vegetation Index (NDVI) using the approaches described in Scotford and Miller (2004), namely:

$NDVI = (R_{NIR} – R_R)/R_{NIR} + R_R)$ ....(Equation 1)

where R_{NIR} and R_R are the reflectance values at the near infrared and red wavelengths respectively.

For the experiments in the 2007 harvest season, the sensors, associated power supplies and recording equipment were mounted on a modified self-propelled lawn mower such that sensors were at a fixed height of 1.10 m – see Figure 1.

Figure 1. Mounting of the sensor cluster as used in the first season of the project

The mounting of the sensor cluster used in the 2007/8 and 2008/09 seasons was changed from that used in the 2006/07 season such that sensors were positioned circa 400 mm above the top of the crop/soil surface at all stages of growth and adjusted as the crop grew taller – see Figure 2.

Figure 2. Mounting of the sensor cluster as used in the second and third years of the project.

Output data from both spectral reflectance and height sensors was monitored at 10 Hz such that, with a travel speed of approximately 4.0 km/h, at least 25 values for each parameter are obtained per plot from which a coefficient of variation could be calculated. This coefficient of variation figure was then correlated with shoot counts made manually.

3.2.3. Agronomic assessments

In addition to the crop scanning measurements, the following agronomic assessments were also made at each site and in each of the three growing seasons:

- Shoot counts in February/March prior to the first scan timing;
- Final ear population (ears/m^2) at GS 80.
- Final crop height at GS 80.
- Lodging (>45^o) and leaning (<45^o) - % of crop area and date of occurrence.
- Grain yield at 15% moisture content.
- Specific grain weight and thousand grain weight.

3.3. Results

3.3.1. Results from the 2006/07 season –heavy land site

Plots established on the heavy land site during the autumn of 2006 developed well during the mild winter such that when the first measurements were made with the sensor cluster in March 2007 high levels of leaf area index (LAI) and vegetative index (NDVI) were recorded – see Figure 3. Plots established with the lower seed rate (100 seeds/m^2) tended to give lower canopy densities as expected, although there was some overlap between the canopy structures measured in the different seed rate plots. Weather conditions in the early season resulted in a loss of leaf area such that when measurements were made at the April timing, reduced values for both the LAI and NDVI were recorded (Figure 3). Assessments of the lodging risk for each seed rate and treatment strategy were made based on the established decision rules (see Table 7) and resulted in no early nitrogen being applied where this was an option but with plant growth regulator applied again where this was an option (see Table 8).

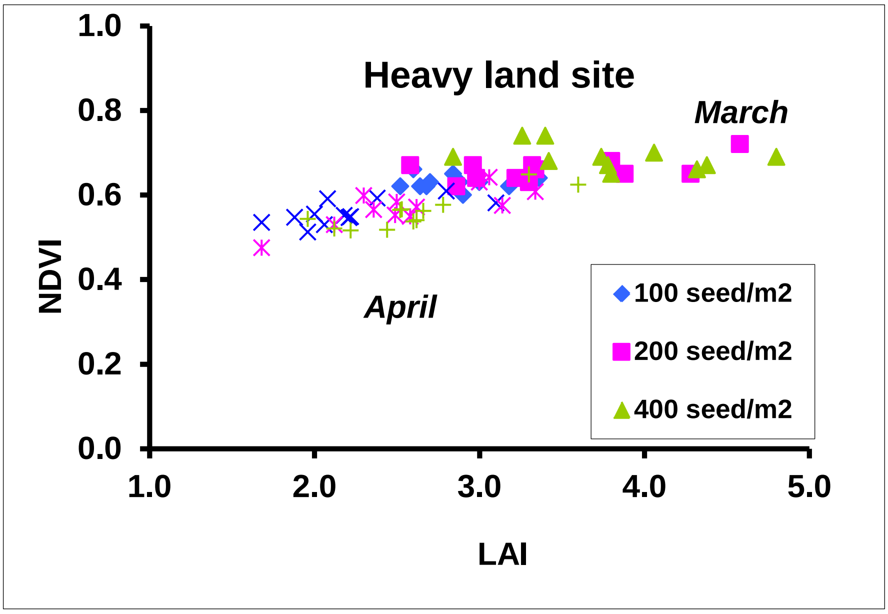

Figure 3. The measured values of Leaf Area Index (LAI) and NDVI for the heavy land site at two timings (March shown with solid symbols and April shown as crosses) in spring 2007.

Table 7. Lodging risk assessments for the heavy land site in 2007 based on measures of canopy size

Treatment	March			April			May		
100	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Strategy 1			IIII	I	II	I	IIII		
Strategy 2			IIII	IIII			II	II	
Strategy 3			IIII	II	II		IIII		
200									
Strategy 1			IIII		II	II	II	II	
Strategy 2			IIII	I	II	I	IIII		
Strategy 3			IIII	I	II	I	IIII		
400									
Strategy 1			IIII	I	II	I	III	I	
Strategy 2			IIII	I	III		IIII		
Strategy 3			IIII		III	I	IIII		

Table 7 shows the assessment of lodging risk (low, medium or high) made based on the measurements of LAI/GAI on each replicated plot using the criteria given in Table 2 with the results for each of the four replicates shown as a vertical bar in the table. Applications were made in accordance with the defined strategies based on the assessments shown in Table 7 with the mean inputs summarised in Table 8.

Table 8. Mean applications made to heavy land plots in the 2006/07 season

Treatment	First N Dose	Main N Dose	Late N Dose	1st PGR Dose	2nd PGR dose
100					
Strategy 1	**0**	**150**	**50**	**1.15**	**1.25**
Strategy 2	**0**	**150**	**50**	**1.15**	**1.25**
Strategy 3	**0**	**150**	**50**	**1.15**	**1.25**
200					
Strategy 1	**0**	**150**	**50**	**1.15**	**1.25**
Strategy 2	**0**	**150**	**50**	**1.15**	**1.25 + 0.05M**
Strategy 3	**0**	**138**	**62**	**1.15**	**1.25**
400					
Strategy 1	**0**	**150**	**50**	**1.15**	**1.25**
Strategy 2	**0**	**150**	**50**	**1.15**	**1.25**
Strategy 3	**0**	**138**	**62**	**1.15**	**1.25**

Measurements of crop canopy characteristics with both the hand-held wand to determine LAI and the boom-mounted instruments to determine NDVI showed a close correlation with assessments of lodging risk made by an experienced agronomist with knowledge of the site (Figure 4). Both measurements and assessments were made at the March timing. A fitted relationship was of the form:

$$y= 0.623x \quad \text{(Equation 2)}$$

where y is the lodging probability score and x the measured value of LAI/GAI. The relationship plotted in Figure 4 has an r^2 value of 0.46.

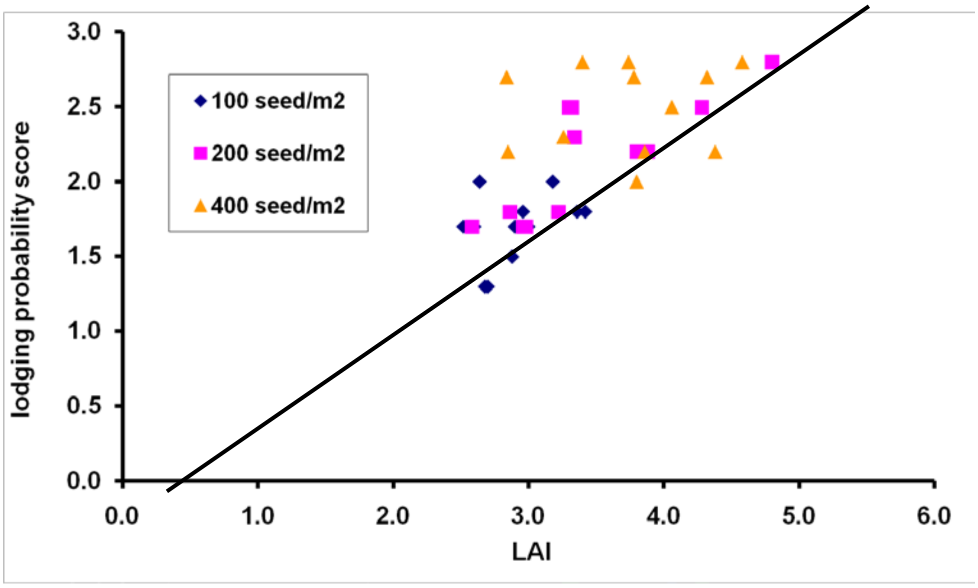

Figure 4. Lodging probability score assessed visually plotted against measured values of leaf area index (LAI)

The resulting crop yields (Figure 5) showed:

- No differences in yield between any strategies at the low and medium seed rates;
- Very similar yield for all seed rates when subjected to Strategy 2 – variable PGR applications

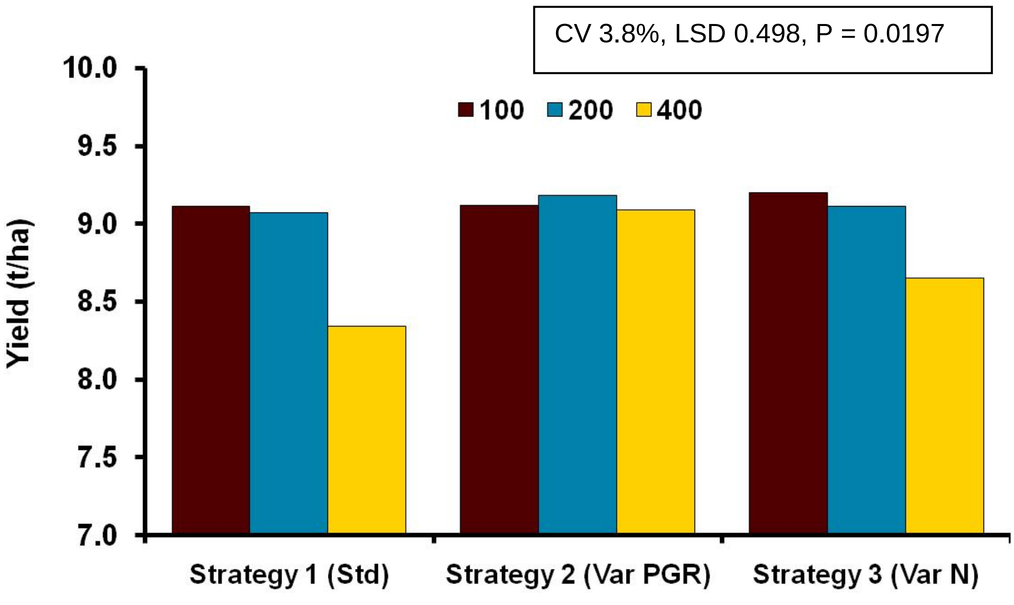

Figure 5. Crop yield at 15% moisture content measured on the heavy land site in 2007.

- Some reduction of yield at the highest seed rate, significantly so for the standard strategy but not significant in the case of the variable nitrogen strategy.

Some lodging was observed (Figure 6) with the degree of lodging increasing with seed rates for each of the application strategies. The lower lodging was recorded with both the variable strategies compared with the standard although the differences were not statistically significant. There were no significant differences in mean crop height between different treatment strategies although there was a consistent trend for taller crops at the lower seed rate with all treatment strategies and with a significant difference in height between the highest and lowest seed rates plots (data not shown).

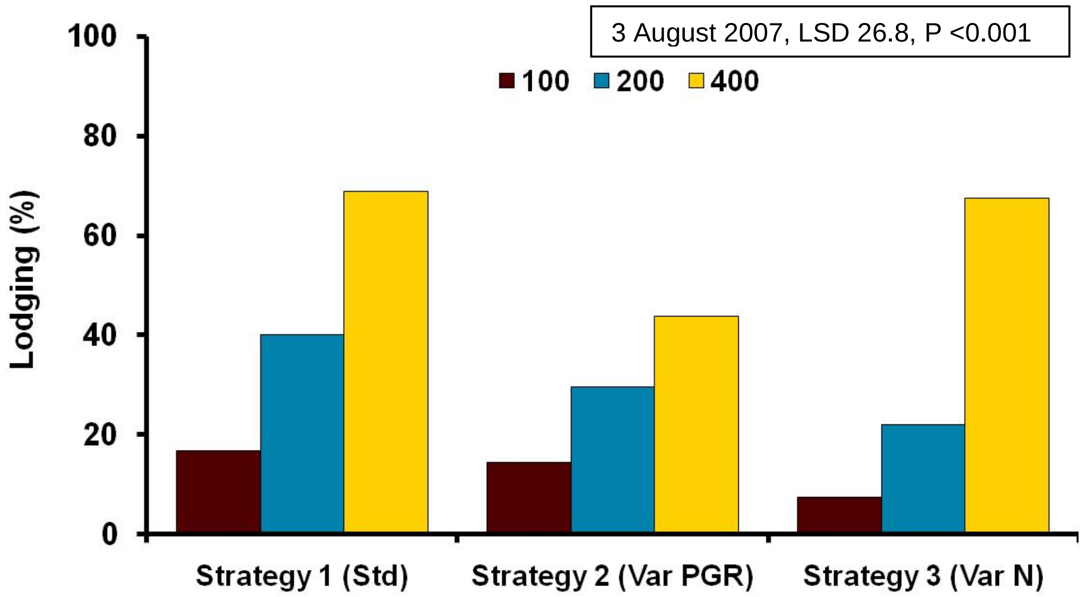

Figure 6. Crop lodging observed on the heavy land site in 2007.

Ear populations tended to follow seed rates, particularly in plots with the variable nitrogen input, with a less pronounced trend for the variable PGR plots.

3.3.2. Results from the 2006/07 season –light land site

Crop development on the light land site at Sutton Scotney followed a different pattern from that on the heavy land site with leaf area increasing over the March to May period such that measures of leaf area index (LAI) and vegetative index (NDVI) gave results of the expected form (Figure 7). Measurements at the first (March) timing gave low levels of both LAI and NDVI as expected with some differences in canopy density due to the different seed rates that remained as the crop developed. There was substantial variation in the values of NDVI obtained at the first sampling time in March, particularly with the lower seed rate plots, and this probably relates to the relatively low levels of ground cover achieved by the crop at this stage. As the crop developed, values for NDVI and LAI increased as expected and also the variability in values between plots decreased.

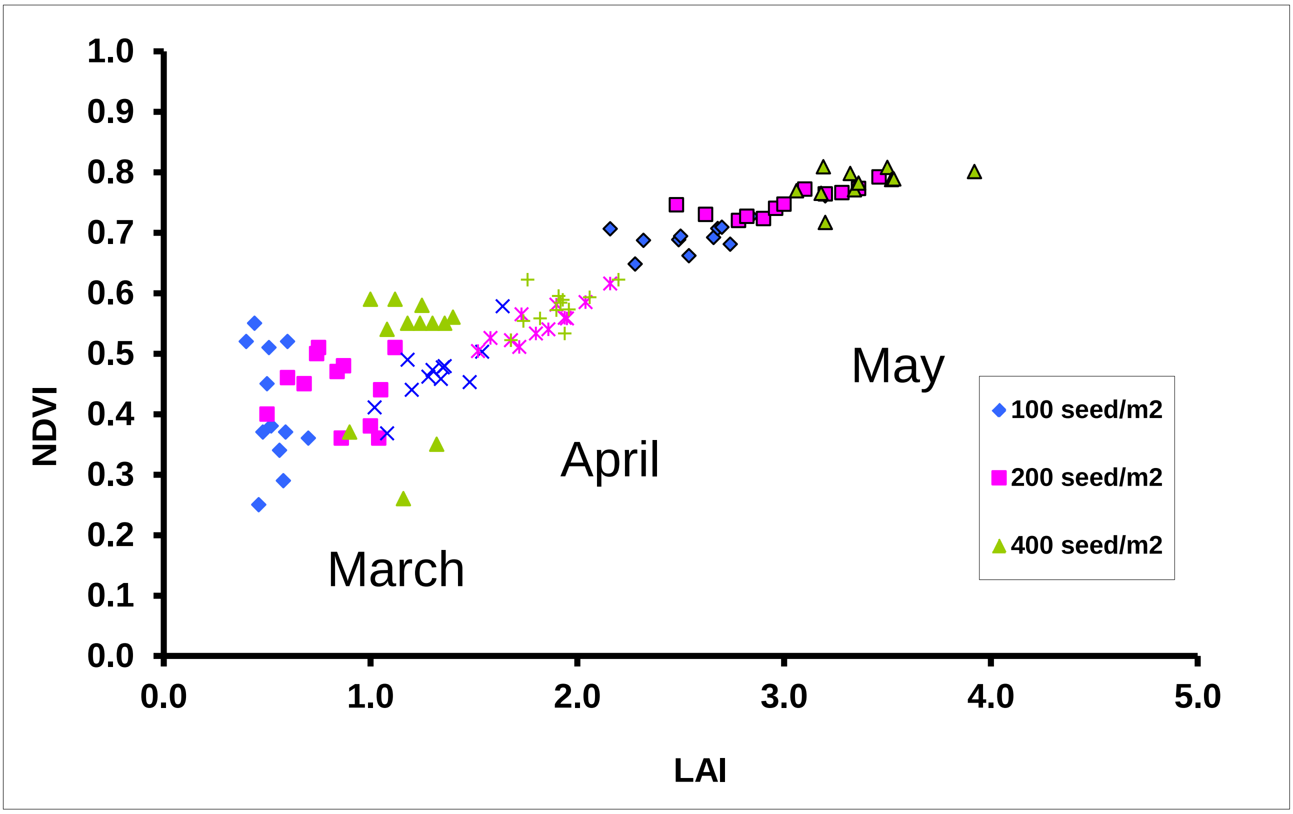

Figure 7. The measured values of Leaf Area Index (LAI) and NDVI for the light land site at three timings in spring 2007(March timing solid symbols, April timing with crosses, May timing with solid symbols and black outline).

Results of the measured crop canopy parameters were used to determine the inputs at the three key timings as for the heavy land site (see Section 3.1) and are detailed in Tables 9 and 10. There were differences in the lodging risk that corresponded to seed rate and this was reflected in the treatments applied (Table 10).

Table 9. Lodging risk assessments for the light land site in 2007 based on measures of canopy size

Treatment	March			April			May		
100	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Strategy 1	IIII			III	I			IIII	
Strategy 2	IIII			IIII			II	II	
Strategy 3	IIII			IIII			I	III	
200									
Strategy 1	II	II			IIII			IIII	
Strategy 2	II	II		II	II		I	III	
Strategy 3	I	III			IIII			IIII	
400									
Strategy 1		I	III		III	I		II	II
Strategy 2		II	II		IIII			II	II
Strategy 3		III	I		IIII			IIII	

Table 10. Mean applications made to light land plots in the 2006/07 season

Treatment	First N Dose	Main N Dose	Late N Dose	1st PGR Dose	2nd PGR dose
100					
Strategy 1	**50**	**140**	**50**	**0**	**2.5**
Strategy 2	**50**	**140**	**50**	**0**	**1.25**
Strategy 3	**50**	**140**	**50**	**0**	**2.5**
200					
Strategy 1	**50**	**140**	**50**	**0**	**2.5**
Strategy 2	**50**	**140**	**50**	**0**	**1.875**
Strategy 3	**50**	**140**	**60**	**0**	**2.5**
400					
Strategy 1	**50**	**140**	**50**	**0**	**2.5**
Strategy 2	**50**	**140**	**50**	**0.575**	**1.875**
Strategy 3	**37.5**	**152.5**	**50**	**0**	**2.5**

Crop yield showed no significant differences between the different treatment strategies (Figure 8) although there was a consistent and statistically significant trend for yield to increase with seed rate.

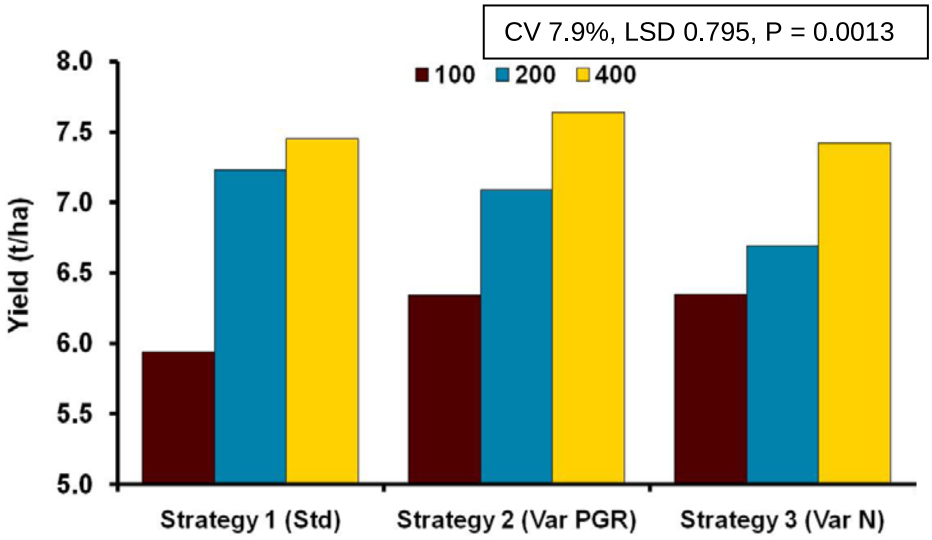

Figure 8. Crop yield at 15% moisture content measured on the light land site in 2007.

There was no crop lodging on the light land site in the 2007 harvest season and differences in crop height between the different treatment strategies were small. Differences in ear populations and specific grain weight between treatment strategies were also small.

3.3.3. Comparison between results from the sites in the 2006/07 season

Previous studies had suggested that a measure of tiller/shoot numbers could be obtained from either the height or spectral reflectance sensors by examining the variation in the output signal from such sensors (Scotford and Miller, 2005a, b). It was recognised that such an approach would need calibrating for each field condition but could potentially be used to monitor any spatial variability in plant populations within a field. The data collected from the sensor cluster at both sites and on each sampling occasion were analysed to establish any such relationships but no consistent trends in this data could be established. This was probably due to the height at which the sensors had been operated giving a relatively large sensor “footprint” which in turn would mask variability at the scale representative of differences in tiller/shoot populations.

A comparison of tiller numbers for a given leaf area index measure at both sites showed very large differences (see Figure 9) with much larger tillers on the heavy land site probably due to the interaction between weather and soil conditions.

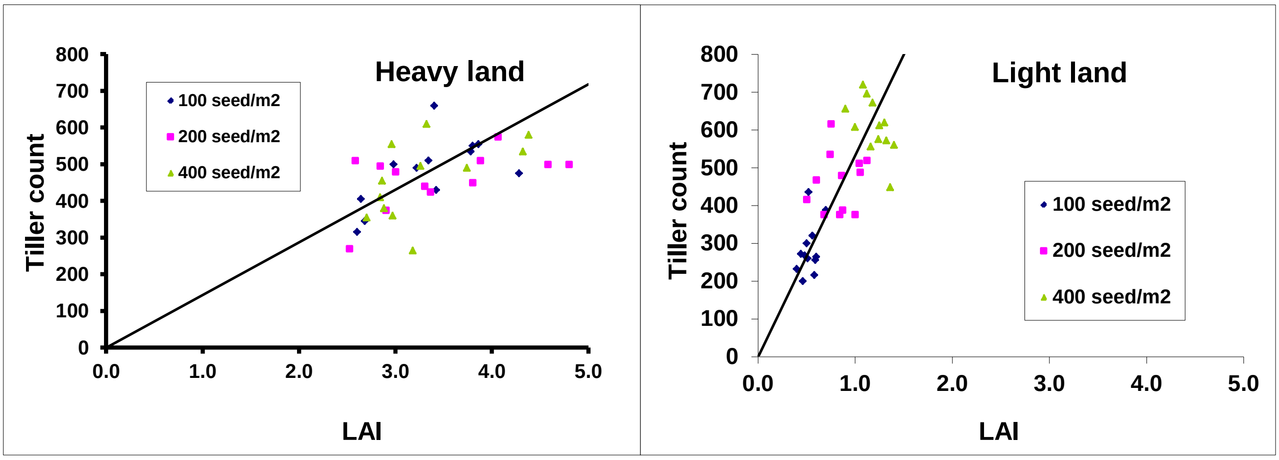

Figure 9. The relationship between leaf area index and tiller counts at the two sites – measurements made in March 2007.

The result plotted in Figure 9 indicates that any assessment of lodging risk needs to include measures of both leaf area index and the number of shoots/tillers. Weather conditions during the 2006/07 season therefore dominated the observations made and although some differences in treatment strategies were established and some savings in plant growth regulator use achieved with these strategies, the effects were small. The approach to the experimental work was therefore revised for the second and third years of the work.

3.3.4. Crop responses to treatments applied in the 2007/08 and 2008/09 seasons

Crop yield results for the 2008 and 2009 harvest seasons for the heavy and light land sites are shown in figures 10, 11, 12 and 13 respectively. It can be seen that in all cases, the strategy that involved applying no early nitrogen resulted in lower crop yields. Delaying nitrogen applications was included as a component of the strategy to minimise the risk of lodging when crop canopies were large early in the season. Lodging was monitored on all plots but only occurred on the heavy land site in the 2008 harvest and then only on the highest seed rate (400 seeds/m^2) plots. In this one condition, the delayed application of nitrogen did not reduce the percentage of crop lodging recorded.

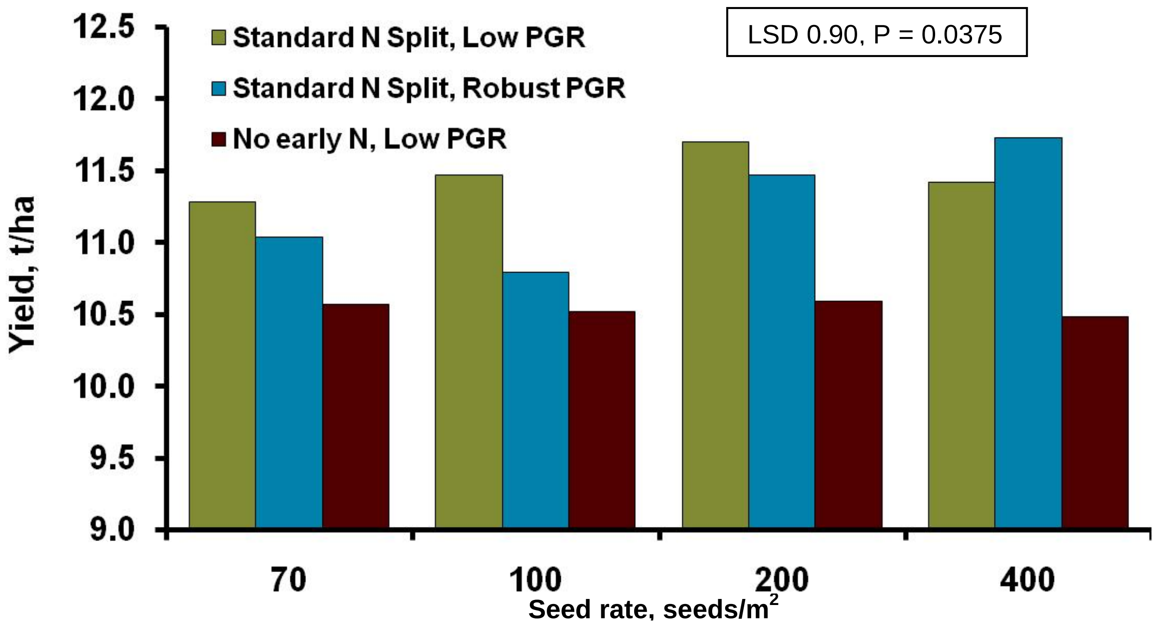

Figure 10. Yields recorded on the heavy land site in the 2008 harvest season.

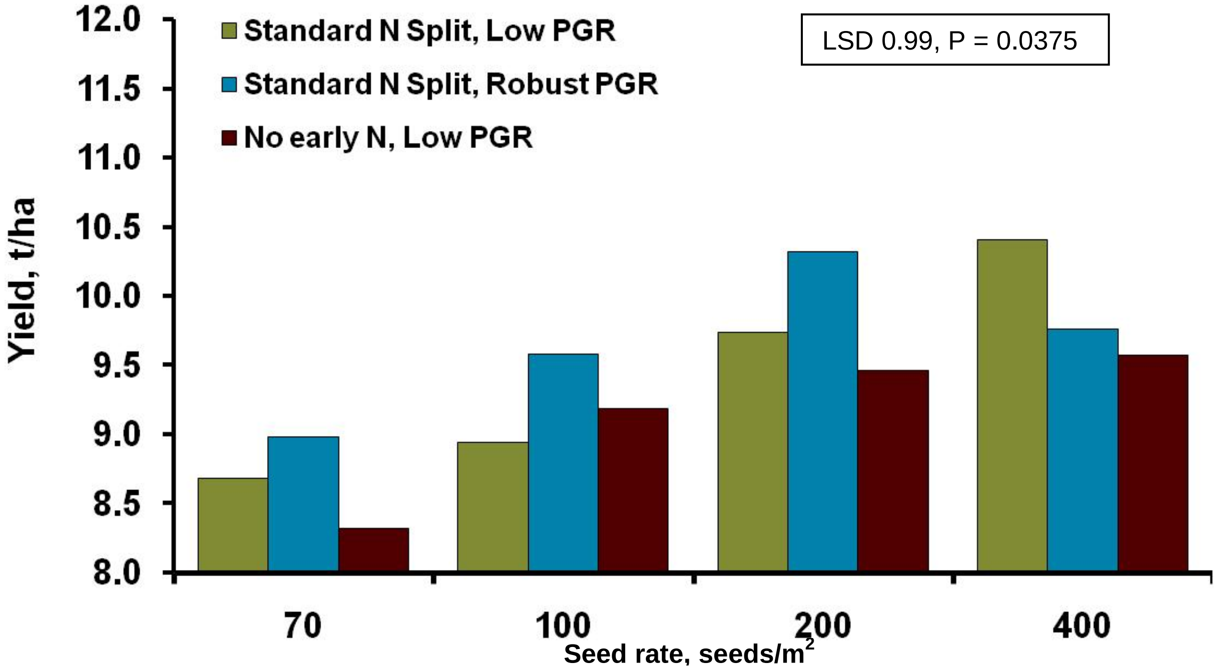

Figure 11. Yields recorded on the heavy land site in the 2009 harvest season

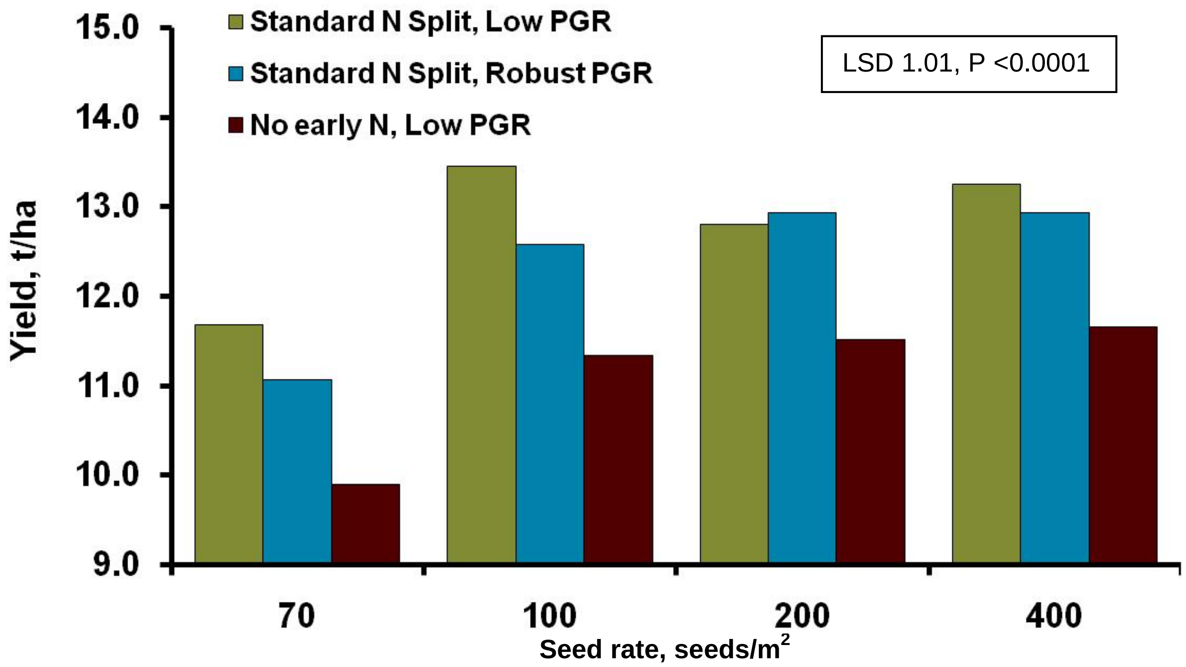

Figure 12. Yields recorded on the light land site in the 2008 harvest season.

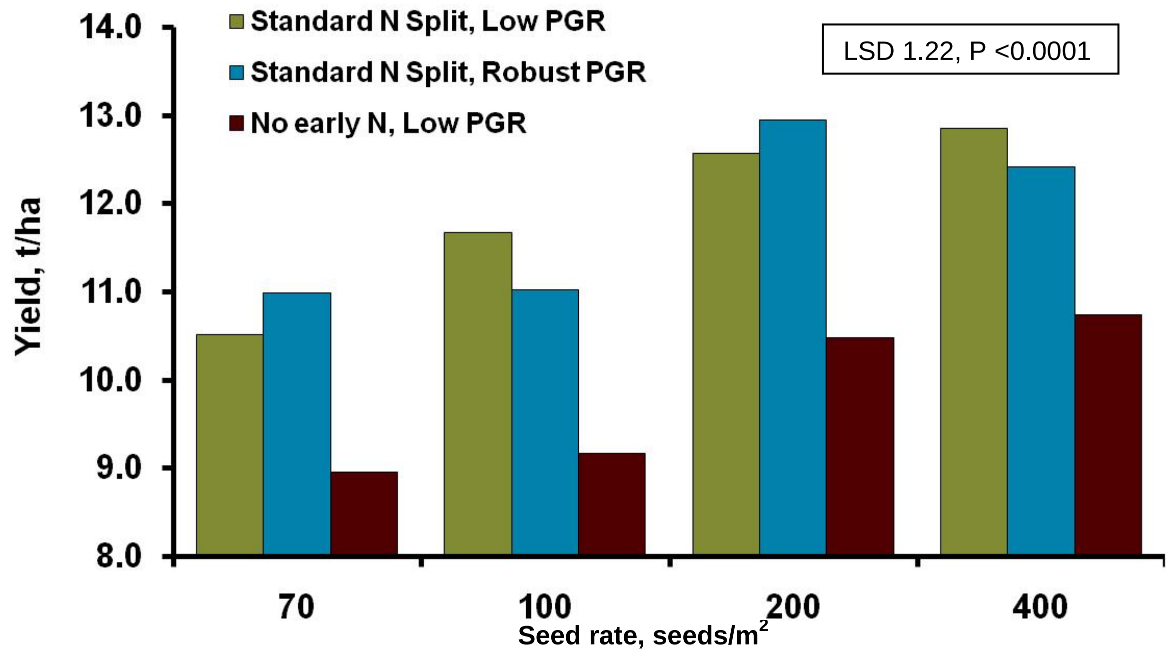

Figure 13. Yields recorded on the light land site in the 2009 harvest season.

For the heavy land site in the 2008 harvest season (Figure 10), there were no substantial differences due to seed rate and the strategy involving a standard nitrogen split and low plant growth regulators tended to give the highest yields. In the 2009 harvest season at this site (Figure 11), seed rate did influence yield and the highest yields tended to be with the strategies involving a standard nitrogen split and robust plant growth regulator use. On the light land site, seed rate effects were more consistent and in line with expectation with no differences between the strategies involving a standard split of nitrogen application.

The effects of the applied treatments on crop height was variable between both sites and seasons but where significant differences were recorded these followed the expected trends with plots having a low PGR input giving taller crops (e.g. at the light land site in the 2009 season – see Figure 14) and those receiving a robust PGR input giving shorter crops (e.g. the heavy land site in the 2008 season – see Figure 15).

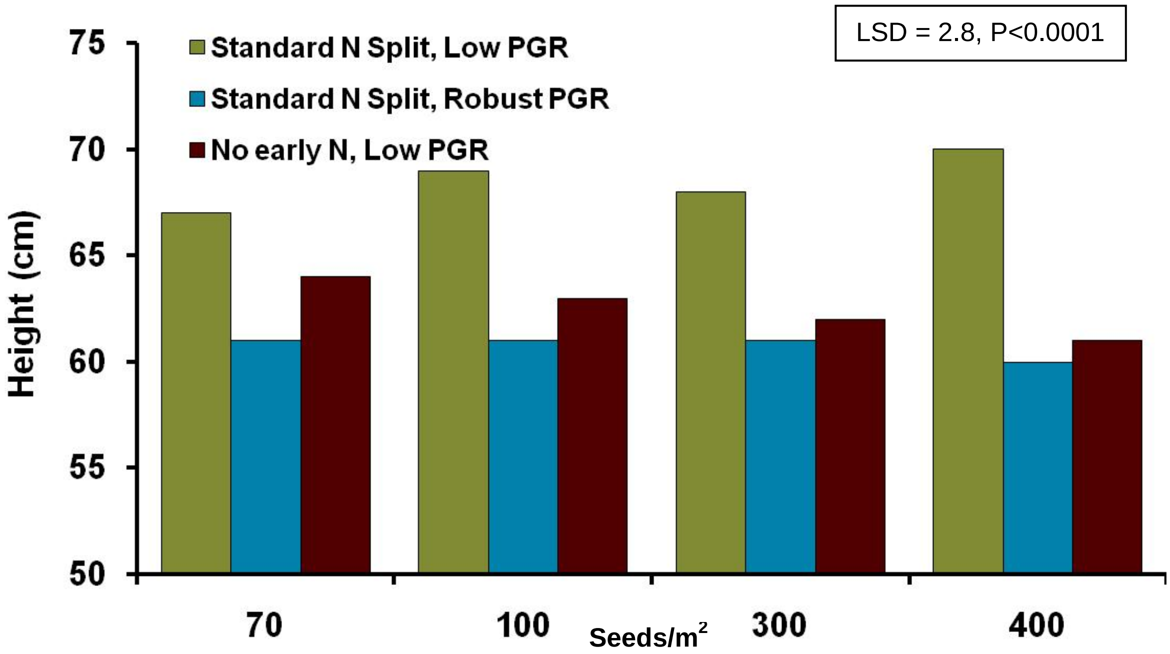

Figure 14. The effect of treatment strategy on crop height recorded on the light land site in 2009

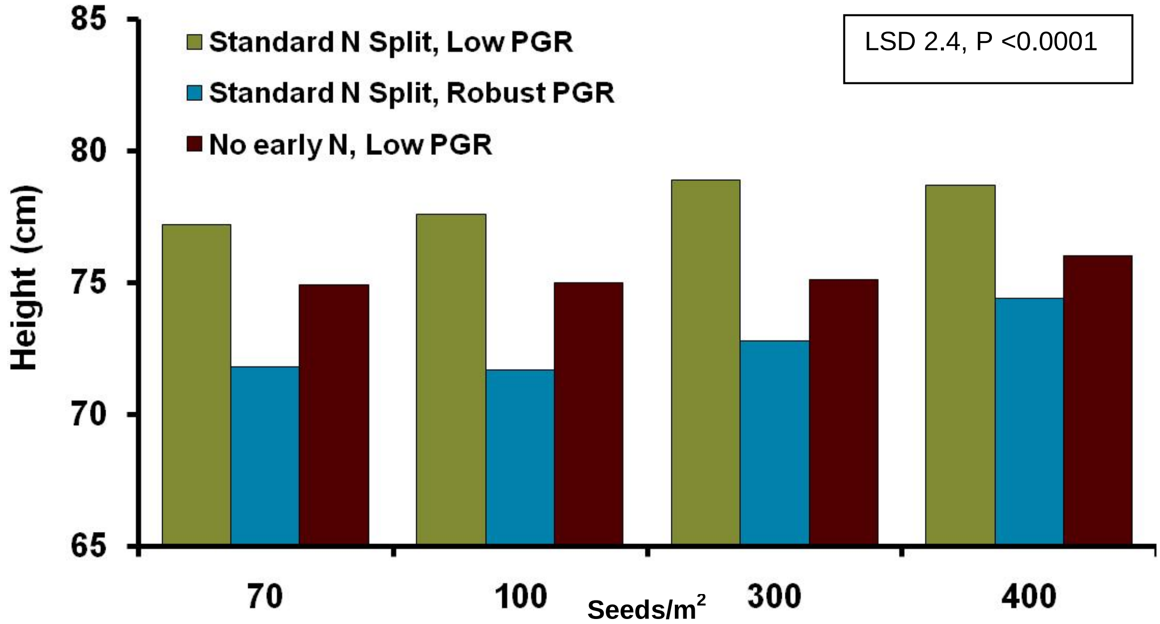

Figure 15. The effect of treatment strategy on crop height recorded on the heavy land site in 2008

There were some differences in the number of ears/m^2 and the specific grain weight but these were mainly related to seed rate rather than the application treatment.

In this series of experiments, the manipulation of seed rates was used to generate crop canopies with substantial differences particularly early in the season. High seed rates giving denser canopies would be more likely to be treated with strategies applying no early nitrogen and the results above indicate that this could incur a yield penalty providing the crop would not lodge with an early nitrogen application. There is a seasonal component to the results obtained since little crop lodging was recorded particularly in the 2009 harvest season. However, the results indicate that strategies that involve no early application of nitrogen may be too severe in terms of managing the balance between crop yields and lodging risk.

3.3.5. Crop canopy characteristics in the 2007/08 and 2008/09 seasons

Measurements of the relationship between leaf area index (LAI) and NDVI recorded with the boom sensors on the heavy land site showed the expected relationships in both the 2007/08 and 2008/09 seasons – see Figures 16 and 17 respectively. Fewer data points were recorded in 2009 at this site because it was found that electrical interference from power lines crossing the site interfered with the recorded data on some plots particularly when operating in high humidity conditions such as those experienced during March 2009. Values for the heavy land site tended to be higher earlier in the season than those measured on the light land site (Figures 18 and 19) and this is consistent with larger canopies being observed on the heavier soil early in the season.

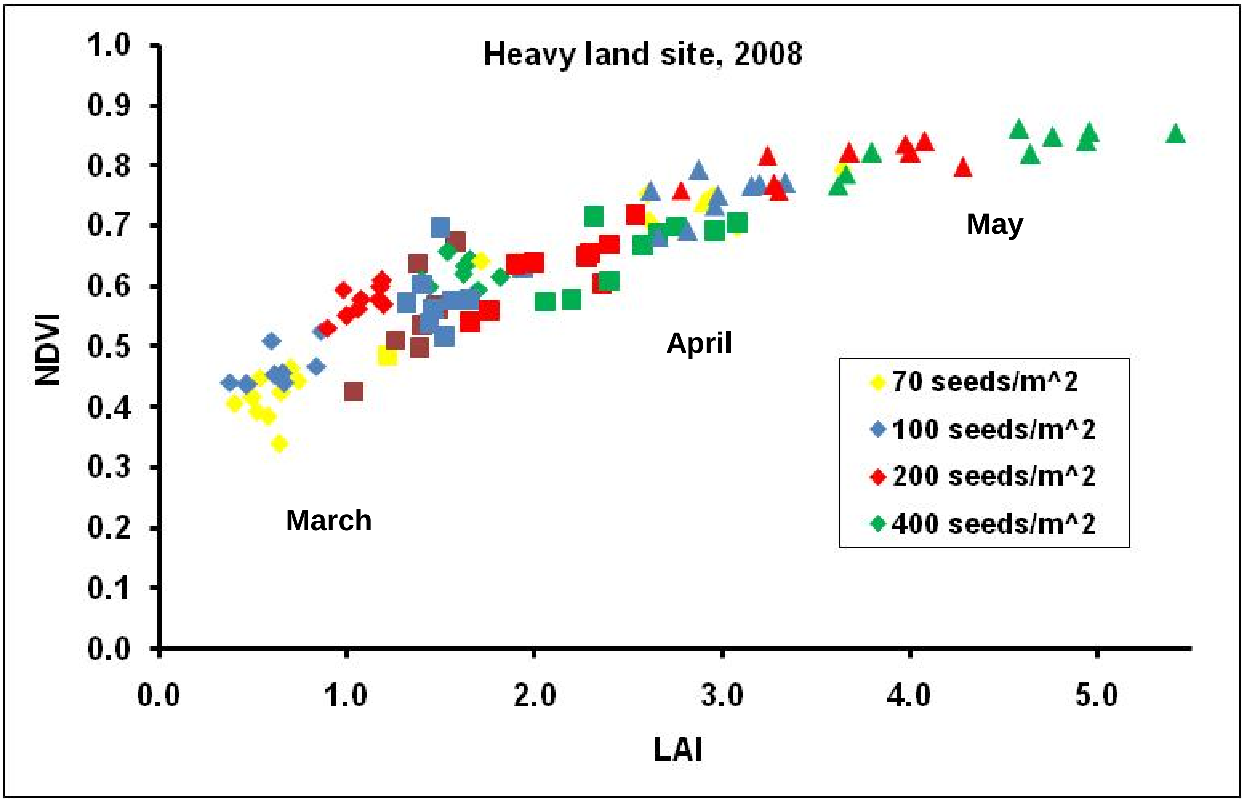

Figure 16. The relationship between LAI and NDVI measured on the heavy land site in 2008on three occasions (March – diamonds; April – squares; May – triangles)

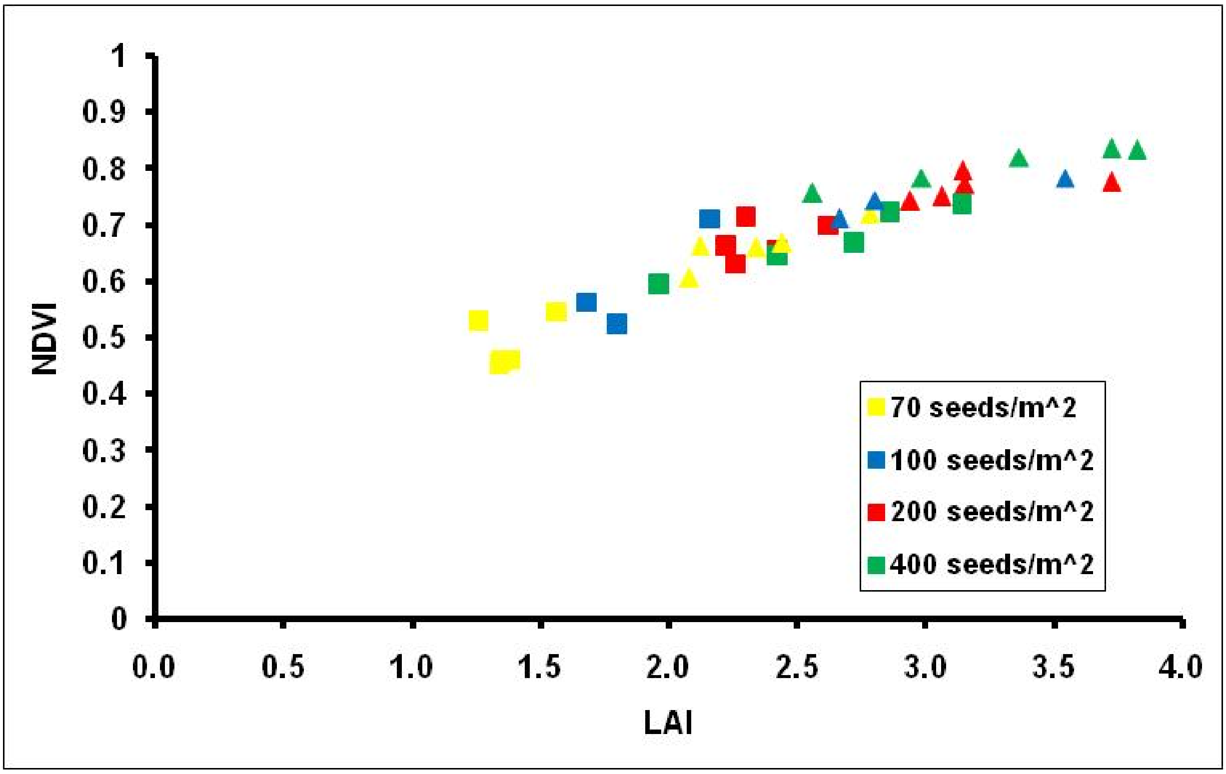

Figure 17. The relationship between LAI and NDVI measured on the heavy land site in 2009 (Key as in Figure 16).

In all cases, and particularly for the light land site, the slope of the LAI/NDVI curve is steepest in the early part of the season and it is at this time that the sensor system is able to resolve differences in canopy characteristics more effectively. At later growth stages with higher values of LAI, the reflectance signals tend to saturate.

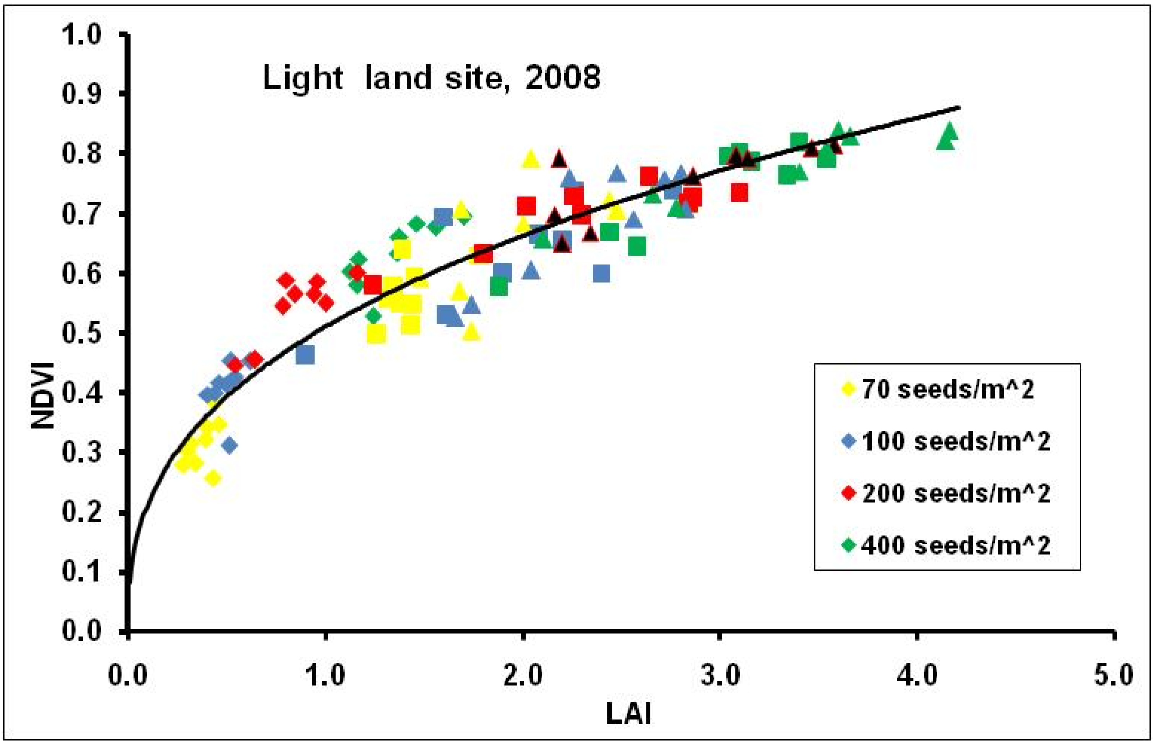

Figure 18. The relationship between LAI and NDVI measured on the light land site in 2008 (Key as for Figure 16).

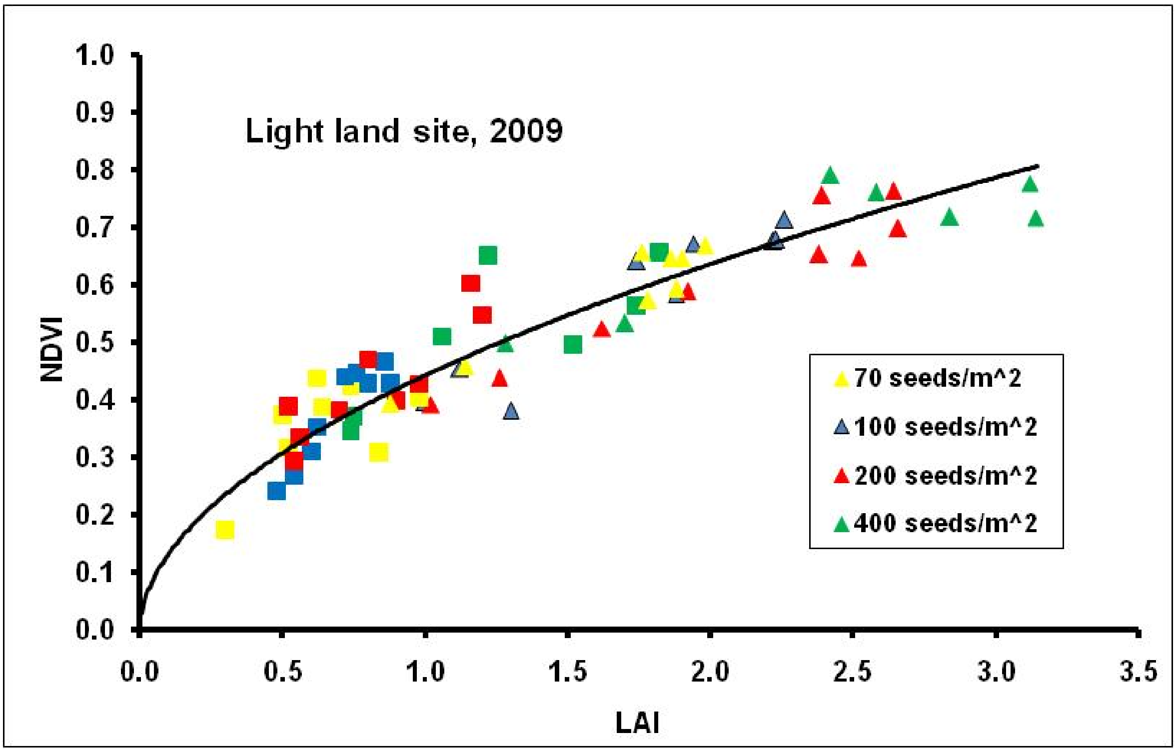

Figure 19. The relationship between LAI and NDVI measured on the light land site in 2009 (Key as for Figure 16).

Plant population is a key parameter when assessing the risk of crop lodging (HGCA 2005). Assessing plant populations in detail across a field area is time consuming and therefore methods of using the sensor outputs to assess shoot/tiller numbers have been explored. Such approaches have been based on examining the variability of sensor output as it is moved across the field area and using the result obtained as a calibration for that given field area. Data obtained in both the 2008 and 2009 harvest seasons were used to further explore such relationships and typical results recorded in the 2008 harvest season are shown in Figure 20.

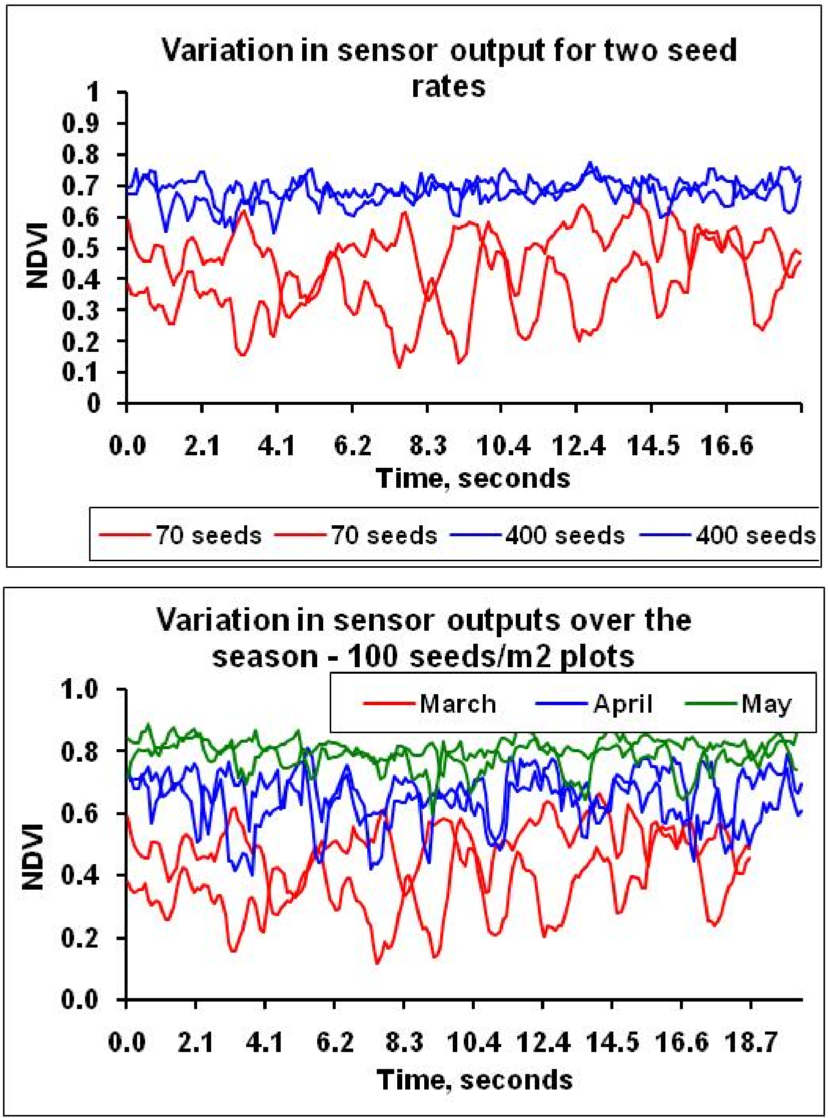

Figure 20. The measured variability in NDVI values measured on the light land site in 2008 showing the effect of seed rate (top) and time of sensing (bottom).

The two lines for each treatment occasion plotted on Figure 20 are the outputs from the two boom mounted sensors and are therefore replicate samples collected over the same time period.

At early stages of growth it was expected that there would be incomplete ground cover by the crop and therefore providing the sensor had an appropriate field of view, some variation in sensor output was expected with the degree of variation matching tiller populations. This was the case for both the heavy land site (Figure 21) and the light land site (Figure 22) where relatively consistent relationships were found between tiller counts recorded manually in March and the coefficient of variation of the spectral reflectance signal recorded at a frequency of 10 Hz and used to calculate an NDVI value.

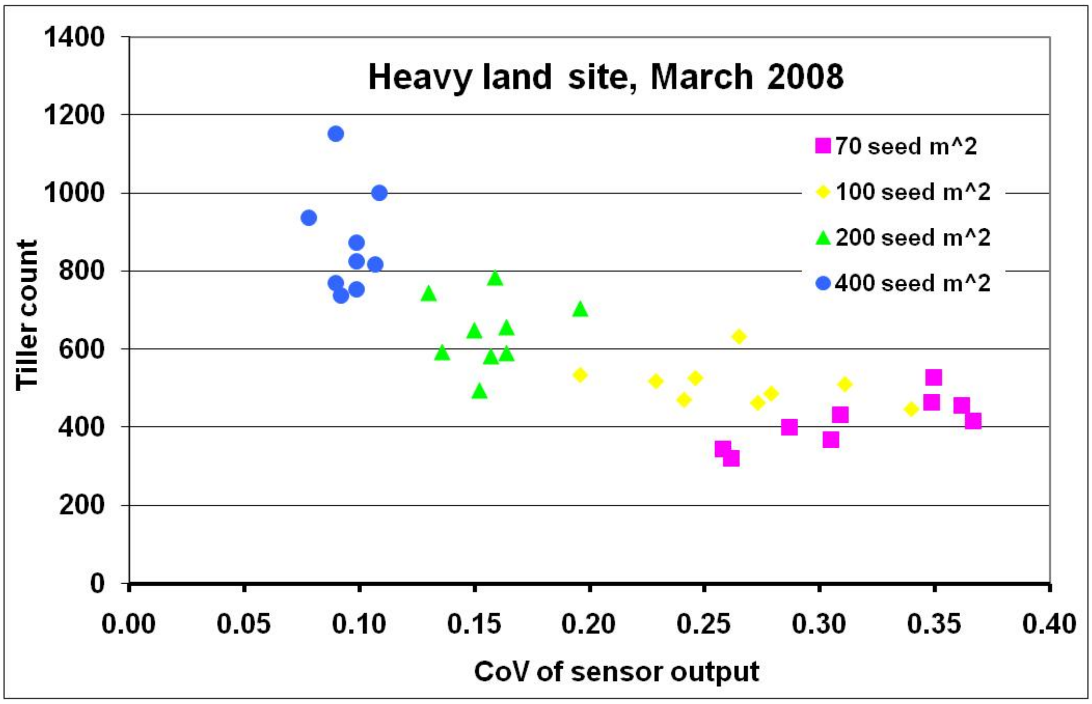

Figure 21. Coefficient of Variation (CoV) of sensor output plotted against tiller counts for the heavy land site in March 2008.

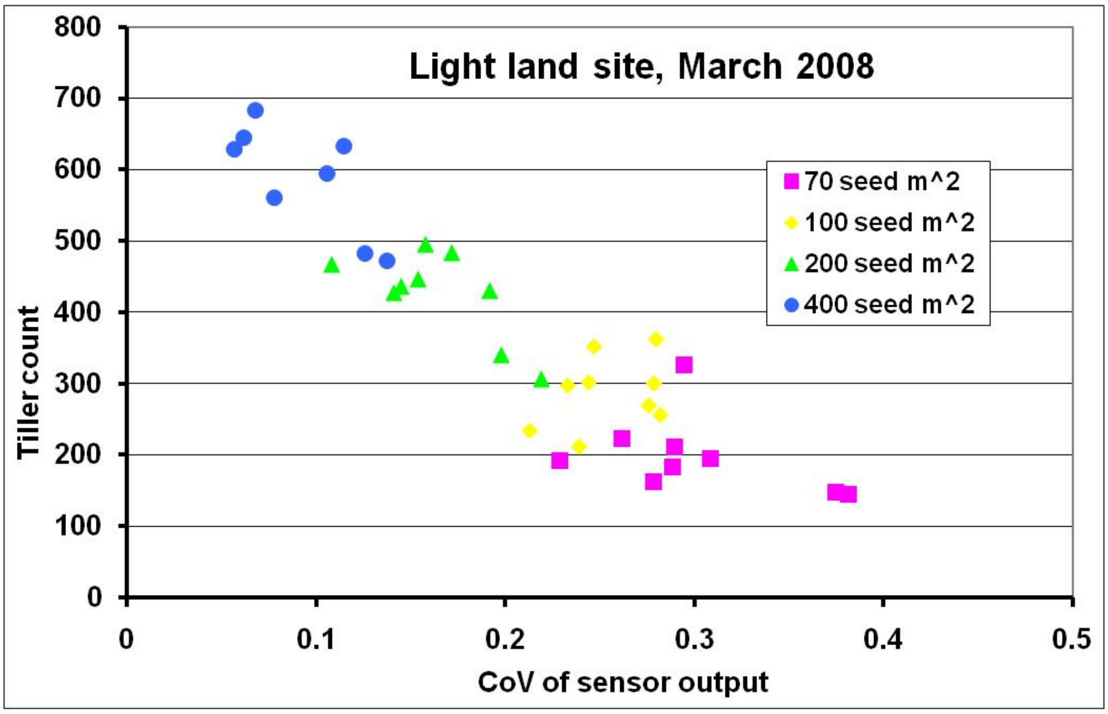

Figure 22. Coefficient of Variation (CoV) of sensor output plotted against tiller counts for the light land site in March 2008.

It was expected that as the crop canopy developed, so the variability of the spectral reflectance signal would decrease and hence the potential for monitoring tiller numbers would be reduced. However, the relationships measured at both sites showed that variability in sensor output could be detected at the May timings (Figures 23 and 24) and that this may enable information about tiller populations to be obtained at later growth stages. The result also suggests that variability in canopy structure persisted for longer than expected based on previous results reported by Scotford and Miller (2005b).

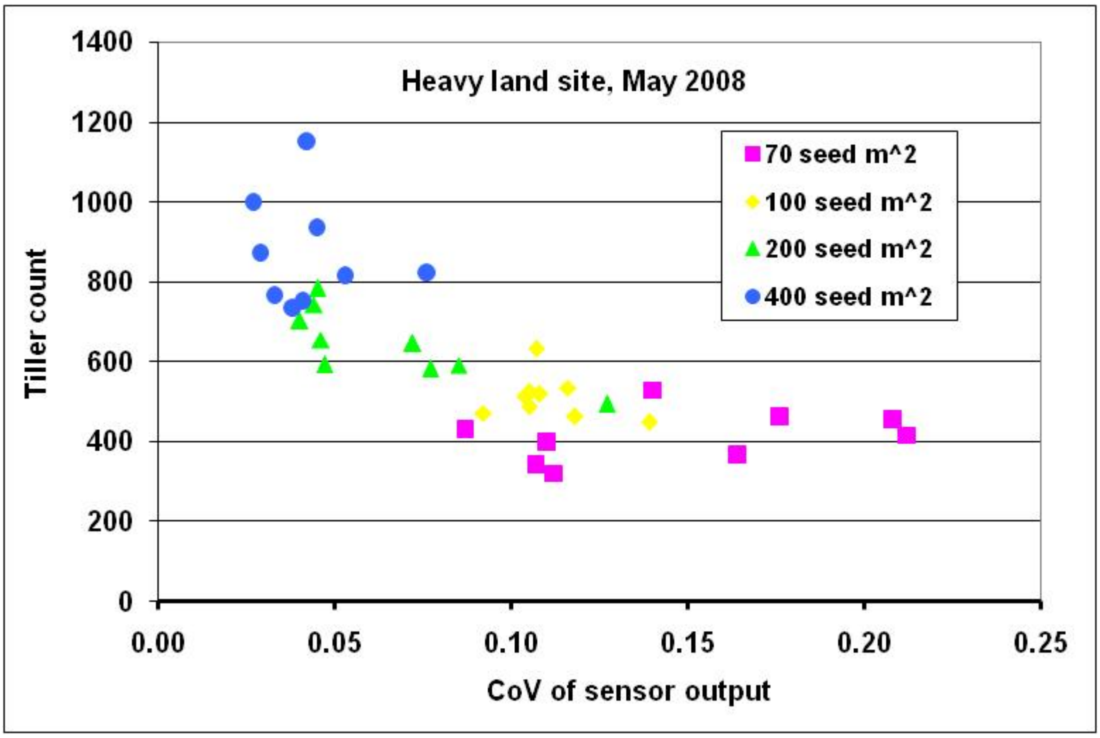

Figure 23. Coefficient of Variation (CoV) of sensor output plotted against tiller counts for the heavy land site in May 2008.

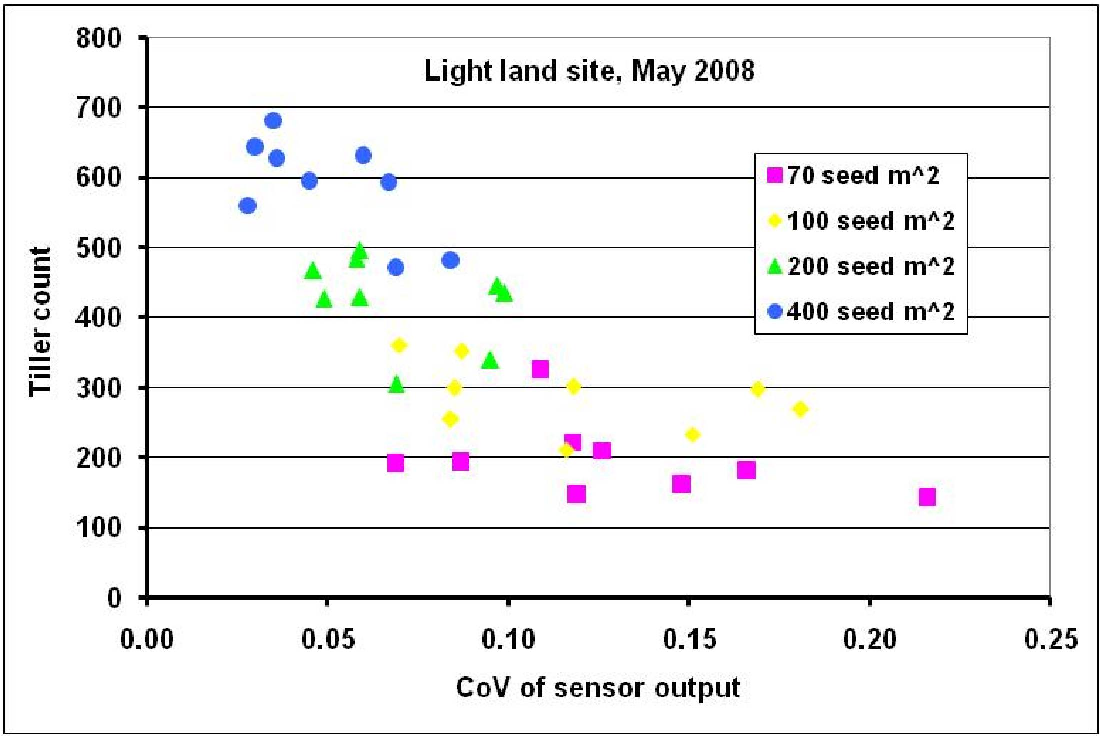

Figure 24. Coefficient of Variation (CoV) of sensor output plotted against tiller counts for the light land site in May 2008.

3.4. Discussion

Results from the study indicated that crop canopy data collected with boom-mounted sensors can play an important role in minimising the risk of crop lodging while maximising yield potential. The use of sensors is particularly relevant when strategies for minimising the risk of lodging are to be implemented in a spatially variable manner. Interpretation of the results obtained is limited because of the low levels of lodging recorded in the last two years of the study. However, existing guidelines (HGCA, 2005) provide a basis for interpreting the results obtained. It has been shown that crop condition in the spring can indicate future lodging risk (HGCA, 2005) with:

- Root lodging risk increasing when plant populations exceed 200/m^2.
- Stem lodging risk increasing when the canopy at GS31 is large (Green Area Index of 2 or more) as such crops tend to be weak-stemmed.

Given that the measures of Leaf Area Index were made with a light attenuating instrument during the early part of the growing season, it is likely that the measured values will correlate closely with Green Area Index values. Correlations between Normalised Vegetation Difference Index (NDVI) measured with the boom mounted sensors and Leaf Area Index determined with the light attenuating wand suggest that a Leaf Area Index of 2 corresponds to an NDVI value of approximately 0.6 – see Figures 3, 7, 16, 17, 18 and 19. For the light land site, this level of crop development was typically achieved around the April sampling time for crops established with 200 seeds/m^2 and this is consistent with the guidelines at GS31. On the heavy land site, values of

NDVI were generally higher at the early sampling times and hence the threshold values were reached at the March timing for a seed rate of 200 seeds/m^2 (Figure 16) but are again consistent with expectations based on the guidelines.

Care is needed when translating the NDVI values measured in this work to values that may be obtained with commercial sensor designs. This is because:

- Different sensors use different mean wavelengths either side of the “red edge” and different band widths for the sensors – the wavelengths used can be selected with some sensor designs, and values for bare soil, for example, are likely to be dependent on the wavelengths used.
- A number of commercial sensing systems do not calculate an NDVI in the same way as was done in this study – see Equation 1 in Section 2 – and may use other parameters (see Scotford and Miller, 2005b) and a larger number of wavelengths.

While results from this project work and associated studies (e.g. Scotford and Miller, 2005a) demonstrated that information relating to plant populations could be obtained by examining the variability of sensor output, it is recognised that:

- This approach is likely to require the in-field calibration of the sensor system to establish relationships representative of the given operating conditions.
- The size of the sampling “footprint” and frequency of sampling is likely to influence the results obtained and this may be important when considering the use of commercial sensor designs for the applications considered in this project.

In the first year of this project sensors were mounted more than 1.0 m above the top of the canopy at the early stages of growth such that the sensor “footprint” was in the order of 0.1 m^2. With this set up the correlation between the variability of the recorded signals and early season tiller counts was poor with no consistent relationships being established. When the sensor height was reduced in years 2 and 3 of the project, the “footprint” was in the order of 0.02 m^2 and much stronger correlations between sensor output variability and tiller numbers were established. Some preliminary measurements were made using a LIDAR system as part of the project work to establish if the small “footprint” when using a laser sampling system would improve the estimates of variability in canopy structure. Results from this work showed reasonable agreement with data from the boom-mounted sensors. Given the current costs of a LIDAR system, it is unlikely that this sensing approach will be widely adopted in cereal crops in the short term and hence the effort directed at a detailed analysis of the data collected with this system was limited.

Detailed discussions with representatives of commercial organisations as part of the project work confirmed that the results obtained would be relevant to the operation of commercially available sensing systems although some changes may be required to the set up and operation of such systems.

This study used variable seed rates to establish crop canopies with different structures. It is recognised that this approach has some limitations in that structure and plant populations are related but other approaches to varying crop canopy structure in a managed way were not considered sufficiently reliable. Care has been taken to avoid drawing conclusions from the results that may be an artefact of the way in which the study was conducted. Measurements of crop canopy structure were taken at set times rather than defined growth stages of the crop. Some variation in crop growth stage at a given date is likely and work that is now being conducted as part of a LINK project aimed at refining the prediction of crop nitrogen requirements and the timings of applications and is relating crop conditions to day degrees since drilling. This project follows an initial feasibility study (Sylvester-Bradley *et al*., 2009) that showed that measurements with crop sensors were useful in predicting soil nitrogen supplies for a range of crop conditions. This LINK project also recognises the importance of data other than that from crop canopy sensors when seeking to improve the prediction of nitrogen requirements, and future strategies for managing lodging risk on a spatially variable basis are likely to make use of other data sources.

The agreement between the lodging risk assessments made by an experienced agronomist and the results obtained from both the manually operated and boom-mounted sensing systems is encouraging in relation to the use of sensors to managing lodging risk. However, the work has also shown that weather effects can have an important effect on lodging risk and was responsible for the change in project strategy after the first year of the work. The weather in years 2 and 3 of the work was such that the risk of lodging was relatively low and the low levels of lodging recorded in these seasons influenced the ability to verify and/or extend existing relationships used to predict lodging risk. The low levels of lodging recorded on the light land site in particular suggests that there is scope for further refining the prediction and management of lodging early in the growing season.

3.5. Conclusions

It is concluded that the use of crop canopy sensors could provide data that would enable crop lodging management strategies to be implemented in a spatially variable manner across fields. Such strategies would be based on existing relationships linking plant populations in early spring to the risk of root lodging and Green Area Index at GS31 to the risk of stem lodging. The study has shown that both these parameters can be derived from sensing systems although it is likely that detailed in-field calibrations will be necessary and that care is needed in the interpretation of data from commercial sensing units.

Results from the study suggest that there is scope to refine approaches to the prediction of lodging risk using data from sensors such that the risks of reducing yield and the use of plant growth regulators can be minimised.

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