PROJECT REPORT No. 331

ASSESSMENT OF SENSOR-BASED TECHNOLOGIES FOR MONITORING CROP GROWTH AND DEVELOPMENT IN CEREALS

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ASSESSMENT OF SENSOR-BASED TECHNOLOGIES FOR MONITORING CROP GROWTH AND DEVELOPMENT IN CEREALS

by

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ABSTRACT

A three year study was undertaken to identify sensor-based technologies that may enable the characteristics of a growing cereal crop to be monitored, inputs determined, and to establish ways in which such technologies could effectively be implemented.

Working with agronomists, a review of the current methods used to monitor soil, crop and weed factors was undertaken. The roles that these factors have in determining the required field and crop inputs for crop establishment, weed control, crop protection and crop nutrition were established. Canopy characteristics can have some influence on inputs of both crop protection chemicals and fertiliser which account for approximately 60% of the variable costs of winter wheat. Previous research has commonly used spectral reflectance techniques to measure crop canopy characteristics. However, the information from this approach has been limited because of the complex nature of the crop canopy that has many interrelated properties.

Use of a number of sensing techniques working in combination could provide a better characterisation of the crop canopy. A canopy measurement system incorporating both spectral reflectance and ultrasonic height sensing techniques was designed, built and tested over two growing seasons on a range of winter wheat varieties planted at different seed rates on different soil types.

Results from the canopy measurement system indicated:

- Normalised difference vegetation index (NDVI) values were useful up to growth stage 31 and beyond growth stage 59 whereas ultrasonic sensors proved useful for monitoring the canopy beyond growth stage 30 and up to growth stage 59. Combining these two measurements enabled the crop to be monitored over the complete growing season.
- By using a combination of normalised difference vegetation index and ultrasonic crop height measurements
  - Crop height was estimated to an accuracy of ± 0.09 m,
  - Tiller numbers were estimated to an accuracy of ± 125 tiller m^{-2} and
  - Leaf Area Index was estimated to an accuracy of ± 0.47 without the need for direct calibration using destructive sampling methods.

These values can be used directly with canopy management principles to aid the agronomic decision making process to determine the optimum level of inputs of fertilisers, fungicides and growth regulators based on the recommendations of the agronomist. The findings held true for all the variety, seed rate and soil type combinations used in this study.

SUMMARY

A three year study was undertaken to identify sensor-based technologies that may enable the characteristics of a growing cereal crop to be monitored, inputs determined, and to establish ways in which such technologies could effectively be implemented.

Working with agronomists, a review of the current methods used to monitor soil, crop and weed factors was undertaken. The roles that these factors have in determining the required field and crop inputs for establishment, weed control, crop protection and crop nutrition were established. The review indicated it is unlikely that sensing systems will completely substitute for the manual assessment and judgement of the agronomist or farmer. However, the use of sensing systems may enable the agronomist to cover a wider area by adjusting their input decisions to account for in-field conditions and variability. For example, sensors that could reliably determine weed location and densities or crop canopy characteristics could be used as a basis from which to produce treatment maps for pesticide and fertiliser applications incorporating field agronomic decisions or recommendations. However, sensing systems will only be implemented if end users have confidence in them. Evidence from research and farm demonstration projects must indicate that sensing systems are reliable, robust and cost effective.

Crop canopy characteristics, particularly tiller density and leaf area index, influence inputs of both crop protection chemicals and fertiliser. These account for approximately 60% of the variable costs of growing winter cereals. If sensing systems can be developed to characterise the variation in the canopy, savings of these inputs could potentially be made. Previous work has concentrated on using individual sensors to measure particular parameters of the crop canopy. However, the information from a single sensor is often limited because agronomic features are not sensed directly and the nature of the crop canopy is complex. The output of a single sensor can be influenced by a number of factors. For example, one of the most commonly measured parameters is the Normalised Differential Vegetation Index (NDVI) which is the ratio between visual red and infrared reflectance of the crop canopy. The problem with using this measurement technique in isolation is that it is not obvious, without other field measurements, whether the sensor is looking at a small quantity of very green material or a larger quantity of less green material. Possibly a number of sensing devices working in parallel could provide better characterisation of crop canopy, in particular tiller numbers and leaf area index over the complete growing season.

To test the hypothesis, a crop canopy measurement system which incorporated radiometers, a spectrometer and ultrasonic sensors was designed and constructed. The system used two, 2-channel radiometers measuring at narrow bandwidths, approximately 20 nm, centred at 660 and 730 nm. One radiometer, fitted with a cosine corrected head having an acceptance angle of 180º, was mounted pointing upwards to measure incoming radiation while the other pointed downwards, with an acceptance angle of approximately 20º, to measure the reflected light from the crop canopy. The upwards pointing radiometer had three levels of

automatic gain within the signal conditioning to account for large differences in incoming radiation. The system automatically selected the most suitable level of gain allowing the system to be used in most daylight conditions. The spectrometer had 3 individual spectrometer channels and 3 corresponding sets of signal conditioning, each channel measuring wavelengths ranging from 350 to 1000 nm with an optical resolution of 2 nm. One radiometer channel was fitted with a cosine corrected head having a 180º field of view, and was mounted pointing upwards to measure incoming radiation. The other two radiometers pointed downwards, having an acceptance angle of approximately 25º, to measure the reflected light from the crop canopy. Two ultrasonic sensors were used, both commercially available, one with a sensing range of 0.2 to 2.0 m and the other with a sensing range of 0.25 to 5.0 m. The different measuring devices were mounted on a 3.75 m boom attached to the rear of a tractor so that they could be traversed over the crop canopy (Fig. 1).

Figure 1 The crop canopy measurement system in operation

The system was tested over two growing seasons on plots of winter wheat each measuring 4 x 20 m. During the first growing season (2001/2002), plots were established with three varieties of winter wheat, Claire, Consort and Riband, at low, medium and high seed rates 50, 150 and 250 kg ha^{-1} respectively (approximately 100, 300 and 500 seeds m^{-2}), giving a total of six treatments, each being replicated three times across the plot area. The 18 plots were randomised and were drilled on 19 October 2001 on a field with a heavy clay soil, typical of that used commercially for growing winter wheat in the United Kingdom. In the second season (2002/2003), a plot trial was drilled on the 12-13 October 2002. This trial involved two wheat varieties (Claire and Soissons) drilled at three seed rates (50, 150 and 250 kg ha^{-1}) on two soil types (sandy and heavy clay). The 12 treatments were each replicated three times in a block design similar to that used in the previous trial resulting in a total of 36 plots. During both growing seasons the whole plot areas were treated uniformly in line with good agricultural practice in terms of weed control, fungicides and fertilisers - the aim being to minimise the variability associated with weeds, disease and fertiliser deficiencies within the plots.

Using the measurement system, crop height and spectral characteristics were measured at approximately weekly intervals. For all experiments the downward pointing radiometer, spectrometer and ultrasonic sensor were mounted 1 m above the ground, the sampling frequency was 2 Hz and the run time was 10 s; therefore approximately 20 data values per plot were obtained. For these experiments the forward speed of the tractor was set at 0.22 m s^{-1}; therefore during a typical 10 s scan, a linear distance just over 2 m was covered resulting in sensor readings being recorded every 0.11 m travelled assuming a sampling frequency of 2 Hz. During the first growing season (2001/2002), the plots were sampled between 25 March and 2 August 2002, representing crop growth stages (GS) between mid tillering (GS 25) and grain ripening (GS 91). In the second growing season (2002/2003) the plots were monitored at weekly intervals from 14 March to 11 June 2003 between mid-tillering (GS 25) and early milk (GS 73). In addition the plots were monitored periodically for plant numbers, tiller numbers, GS, crop height and leaf area index.

The results from this work indicated:

- No one vegetation index was better than any other when assessing different sizes of canopies.
- Normalised difference vegetation index (NDVI) measurements provided a representation of a canopy expansion and senescence curve for winter wheat. NDVI values were most useful for monitoring the growth of winter wheat up to growth stage 31 and beyond growth stage 59.
- Ultrasonic sensors were useful for monitoring the growth of winter wheat beyond growth stage 30 and up to growth stage 59 when the crop reaches maximum height.
- Combining Normalised Difference Vegetation Index (NDVI) measurements and ultrasonic measurements enabled the crop to be monitored over the complete growing season.
- The ultrasonic sensor was able to estimate the height of the crop over two growing seasons to an accuracy ranging from ± 0.04 to ± 0.09 m when compared with the manually measured height values of all varieties, seed rates and soil types used in this study.
- Analysis of the data indicated that the coefficient of variation (CV) of the Normalised Difference Vegetation Index data could be used throughout the growing season to estimate tiller numbers. Using a relationship identified in the 2001/2002 growing season, the tiller numbers in the 2002/2003 growing season were estimated, without using any other direct field measurements, to an accuracy of ± 125 tiller m^{-2} when compared with manually counted tillers.
- Using a relationship identified in the 2001/2002 growing season for estimating tiller, and crop height, the leaf area index in the 2002/2003 growing season was estimated accuracy of ± 0.47 when compared to leaf area index measurements obtained using a commercially available light interception instrument.

- These findings hold true for all the variety, seed rate and soil type combinations used in this study over two growing seasons.
- These combined sensing approaches enable winter wheat to be monitored throughout the growing season, beyond growth stage 31 which has generally been the limit of traditional spectral reflectance techniques.

This study has shown that a tractor-mounted sensing system can be used to assess crop height, tiller numbers and leaf area index. These values offer the potential to be used directly with canopy management principles to aid the agronomic decision making process. They can be used to help determine the optimum level of inputs of fertilisers, fungicides and growth regulators to account for variations within a field based on the field-scale recommendations of the agronomist or farmer.

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1. INTRODUCTION

All industries require some form of management or decision making process and cereal crop production is no exception to this. Traditionally, this management process is normally conducted by agronomists, advisors or farmers on a field by field basis. However, over the last few decades, field sizes have been increasing (Stafford, 2000) making it more difficult to select one management option, due to in-field variations, that provides the optimal input for the whole field. Precision farming can help to address this issue by taking the in-field variation into consideration when making management decisions allowing inputs to be varied to account for localised conditions.

Existing technologies, particularly positioning systems (e.g. the Global Positioning System, GPS), geographical information systems (GIS), computer and microprocessor controlled equipment make it possible to vary inputs depending on the spatial variation of the crop or soil. However, one of the main factors preventing the uptake of precision farming is the inability to produce rapid, reliable and low cost field treatment maps, which define the in-field variation and the associated input strategy. To specify a required input, the location must be known and an assessment of the local conditions undertaken. These data can then be interpreted, using some form of decision making process so that the correct input can be determined for the given location. Currently inputs on a large unit or field scale are determined by the agronomist, advisor or farmer using their historic field knowledge and current field observations combined with their expert knowledge. Using this approach, recommendations for the whole farm can be produced with the field as the smallest unit area. Precision farming enables operation at a much higher resolution, the in-field variations can be assessed and the recommendations varied accordingly. The farmer or agronomist could apply their expert knowledge to sub areas within the field and generate a treatment map for a particular field. However, this would be a time consuming exercise and unlikely to be practical or cost effective.

In recently published reviews, Stafford (2000) suggests 'there is a need for further developments in the area of sensing and mapping crop and soil variability' and concludes development of rapid sensing systems must take place before precision agriculture will be widely adopted. Dampney *et al*. (1998) also concluded that 'cheap but quantitative methods of measuring important crop and soil properties during the growing season are urgently required to provide objective and unambiguous data as the basis for decision making at the field level'. If such systems were available the production of treatment maps would become a less laborious task. It seems clear therefore that any future research aimed at the implementation of precision agriculture must be directed at achieving this goal. The overall aim of this study was to identify sensor-based technologies that may enable the characteristics of a field area and/or growing cereal crop to be monitored, inputs determined and adjusted; and to establish ways in which such technologies can effectively be implemented. The work had three main components:

- reviewing methods currently used by agronomists and advisors to determine the appropriate inputs for growing cereal crops and to identify opportunities for remote sensing in cereal crop production
- analysing available sensing technologies to identify which of these alone or in combination are most likely to provide information that can be used to aid input decisions.
- using the findings of the previous two components to
  - define a specification for, and the development of a prototype sensing system to demonstrate the feasibility of the proposed approaches;
  - field-scale evaluation of the prototype sensing system; and
  - establishing methods of processing the data to give information on which input decisions can be based.

2. OPPORTUNITIES FOR REMOTE SENSING IN CEREAL CROP PRODUCTION

2.1 Introduction

The overall aim of agronomists or advisor is to provide practical cost effective advice which helps to maintain and increase the profitability of their customers' crop production whilst ensuring production is sustainable and environmentally friendly. This is achieved by using a standard approach detailing the required inputs, which is modified to account for weather conditions; and localised factors which are identified during field visits. Weather conditions obviously cannot be changed, however they heavily influence the agronomic decisions, and therefore must be accounted for in any decision making process.

The aim of this review was to identify the localised factors (e.g. soil condition, crop characteristics, weeds, disease, pests, etc.) that the agronomist uses to determine the required inputs (e.g. seed rates, herbicides, fungicides and fertilisers) and to establish if these factors could be remotely sensed. The approach taken was to shadow three agronomists, two independent agronomists who are paid per hectare for their advice, one based in Hampshire and the other in Norfolk. The third agronomist, based in Bedfordshire, works for an agricultural merchant and provides service agronomy. The study was conducted by having regular field visits with the agronomists between autumn 2000 and spring 2002.

For the purpose of this review the overall management of a crop was split into four main areas; crop establishment, weed control, crop protection and crop nutrition (Table 2.1.1). The following sections identifies the aims of the agronomist in each of these areas and indicates potential opportunities for remote sensing that may enable the production of treatment maps for use in precision agriculture. However it should be noted that precision agriculture will only be adopted if it can provide benefits to the farmer. This review therefore not only identifies potential opportunities for remote sensing, but also indicates whether they provide an agronomic, economic and/or environmental benefit.

Table 2.1.1 Typical breakdown of variable costs in 2000 for winter wheat

Variable	Range of costs (£ ha^{-1})	Typical % of total cost
Crop establishment		
Seed	25 - 40	14
Weed control		
Herbicide	30 - 55	18
Crop protection		
Fungicide	40 - 50	19
Insecticide	0 – 5	1
Growth regulator	0 – 5	1
Crop nutrition		
Fertiliser	80 - 120	41
Other (e.g. slug pellets)	5 - 30	6
Total	180 - 300 (typical £240)	100

2.2 Crop establishment

The requirement is to establish an even crop at the correct time with the required population (plants m^2). Depending which crop wheat, barley or rape, and time of sowing, there are standard figures (HGCA, 1998a; HGCA, 2000a; HGCA, 2002a; Primrose McConnell's, 1995) of sowing dates, seed rates (kg ha^{-1}) and target plant populations (plants m^2). However in practice the following local factors are generally used to determine seed rates:

- time of sowing - early sowing low seed rate, later sowing higher seed rate
- soil type and seed bed quality - good seed bed low seed rate, poor seed bed higher seed rate
- slug risk - no slug risk low seed rate, slug risk higher seed rate.

Using this information, seed rates (seeds m^2) for particular crops are established and using the thousand grain weight (g) of the seed, provided by the seed supplier, the seed rate in terms of kg ha^{-1} can be determined. The drilling date is generally set by the prevailing weather conditions and availability of labour, but quantification of a good or poor seed bed is very subjective and given terms like loose, compact, fine, cloddy and shallow. The agronomist or farmer must visually assess the condition of the seed bed and specify a seed rate for the whole field based on their knowledge and experience. If sensors were available to determine the variability of the seed bed or clod size within the field this could be used vary the seed rate accordingly. The feasibility of this approach is promising, commercial seed drills already exist that can adjust the seed rate on the move.

Sensing seed bed condition and varying seed rate could provide agronomic benefits by achieving a more even crop establishment, which may result in higher yields. However, economically it is unlikely that savings will be made on seed input costs. Assuming the agronomist or farmer uses the average seed bed conditions to determine the seed rate for the whole field, such a sensing system would only proportionally redistribute the seeds to take account of in-field variability. However, the higher yield associated with a more even crop establishment is likely to represent an economic gain. Environmentally, sensing seed bed condition is unlikely to represent either a gain or loss over current practices.

It is less likely that sensors for direct slug detection would be used at crop establishment. Generally the heavier the soil the greater the slug risk, the risk increasing if the seed bed is poor, indicated by a large clod size. If a seed bed sensing system can be established, a slug factor could be applied if a known slug problem existed simply by increasing seed rates for heavier soils compared with lighter ones.

2.3 Weed control

The requirement is to control weed populations to an acceptable level, usually described as the threshold value (plants m^2). Where the economic threshold means the cost of applying the herbicide does not exceed the value of yield lost, if the herbicide had not been applied. Weeds vary in their competitiveness and therefore the economic threshold value for each weed and crop combination differs. The most competitive weeds in cereals are black-grass, wild oats and cleavers and their threshold value tends to be the limit of detection (Swallow, 2000), whereas other weeds have a much higher economic threshold value. For example it is reported (SAC, 2001) that low populations (10 plants m^2) of volunteer barley in oilseed rape can reduce yields by 5%, whereas populations of broadleaved weeds (excluding cleavers) can be up to 200 plants m^{-2} without significantly effecting crop yield. Similarly it is reported (HGCA, 2000b) that providing crops are grown at sufficient density (80 to 100 plants m^{-2} for oilseed rape) weeds may have relatively little effect on yield. However, with the move towards canopy management (Sylvester-Bradley *et al*., 2000), resulting in lower planting densities, it is likely that weed threshold values may reduce increasing the requirements for herbicide. Irrespective of differing thresholds it is clear that cereal crops can suffer severe yield reduction if weeds are not controlled. It is reported as being quite common for certain weed competition, if left unchecked, to reduce winter wheat yields by 50% (Clarke *et al*., 2000). Assuming a potential yield for wheat of 9 t ha^{-1} the resulting financial loss would be £270 ha^{-1} based on a feed wheat price of £60 t^{-1}. Using Table 2.1.1, even if maximum levels of herbicide were applied it is clear that applying herbicides is worthwhile from a financial point of view if half the yield is at risk.

The agronomist must therefore plan for or identify the type of weed, its density (plants m^{-2}) and it size (growth stage) in order to select the required type and dose of herbicide to use. In addition weeds are not uniform distributed in the field, but often occur in patches; therefore in order to control weeds the agronomist must select a herbicide at a sufficient dose to control the weeds within the most infested patches. To make this decision they must walk the field to identify weed type, growth stage, density and location. If this procedure could be achieved by remote sensing at a suitable spatial resolution the in-field variability of the weeds could be mapped providing a basis for variable herbicide applications.

If reliable and robust weed sensing systems can be developed they may offer major savings on herbicide use. Biller (1998) reports herbicide reduction rates from 30 to 70% for a weed targeted system for delivery of herbicide compared with conventional blanket spraying and still reported 100% weed control. Other studies have also shown weeds to be patchy (HGCA, 1998b; Nordmeyer *et al*., 1997) typically indicating only 50% of the field has a weed presence thus also representing a potential 50% saving on herbicide usage. Whereas research by Lutman *et al*. (2002a; 2002b) indicated that patch spraying herbicide is likely to save between £6 and £20 ha^{-1}, concurring with the findings of other workers (HGCA, 2002b) suggesting that herbicide savings of up to £18 ha^{-1} can be achieved. These savings on herbicide not only represents a large economic saving it will also result in a reduced amount of herbicide in the environment.

2.4 Crop protection

To ensure an acceptable yield, the requirement is to protect the crop against pests, diseases and lodging. For winter cereals, particularly wheat and barley, variety selection and seed dressing are normally all that is required to protect the crop over the winter period. However, under certain weather conditions it may be necessary to check and spray for aphids to prevent Barley Yellow Dwarf Virus (BYDV), gout fly and frit fly especially for early sown crops. In addition it may be necessary to spray for various types of midge and other insects during crop flowering. However, insecticides only represents about 1% of the variable costs (Table 2.1.1), hence remote sensing of insects is not considered further in this study. Nevertheless late insecticides in any crop can have harmful environmental effects and further research may be justified on this basis alone.

During the spring winter cereal crops require fungicide applications, generally depending on feed or milling varieties, they either require two or three applications, typically being timed at growth stage (GS) 31, GS 39 and if required at GS 59 (Zadocks *et al*., 1974). The type and dose rate of fungicide selected is based on many factors, the main ones being drilling date, crop variety, growth stage, canopy characteristics and disease pressure. During field walking the agronomist is assessing the last three factors. In practical terms it is the crop variety that has a major influence on fungicide selection, whereas growth stage determines timing and; canopy characteristics and disease pressure help to determine dose. Therefore if the canopy characteristics can be remotely sensed, the dose of fungicide could be varied accordingly. Indeed it has been suggested (Sylvester-Bradley *et al*., 2000) that penetration of fungicide into thinner crops is improved as compared with penetration into thicker crops. Miller *et al*., (2000) also implies this is the case. In addition, Miller *et al*., (2000) reports much higher spray deposition at GS 32 compared with GS 39 concluding there is potential to optimise fungicide application by adjusting spray volume to match crop canopy characteristics.

Similarly Bjerre (1999) suggests that disease pressure increases with increasing crop density and adjusting fungicide dose accordingly could optimise their use. This evidence suggests that both canopy characteristics and growth stage affect the spray deposition of fungicide and by sensing these factors there is potential to adjust fungicide application rates without loss of efficacy.

During the spring growth regulators are normally applied to the crop to prevent it from lodging. It is reported (HGCA, 1999) that large canopies and high plant populations increase the risk of lodging and these canopy characteristics are assessed by the agronomist to determine if growth regulator is required.

It is likely therefore, that if sensing systems could reliably measure crop canopy characteristics, ideally without the need for ground truthing, fungicide applications and growth regulator inputs could be tailored to suit differing areas of growth in the field. It is unlikely that this would have any agronomic benefits, since the current practice already provides a robust method of crop protection. However matching fungicide and growth regulator use to canopy variation within fields should mean reduced rates of pesticide applied for the same efficacy resulting in economic benefits and reduced amounts of pesticide in the environment.

2.5 Crop nutrition

The requirement is to ensure the crop is supplied with sufficient nutrients (nitrogen, phosphorus, potassium, sulphur and other trace elements) to maintain healthy crop growth. The most significant nutrient, and also most difficult to measure is nitrogen (N). Typically a soil index (MAFF, 2000) is used for soil nitrogen levels, these indices being based on the previous crop grown and soil type. The total amount of nitrogen a cereal crop requires is dependant on crop variety, soil type, soil nitrogen index and expected yield. Tables are used to determine the amount of nitrogen required for a particular crop soil combination at differing indexes (MAFF, 2000). These recommendations are given based on the average yield for a particular crop type soil type combination, ideally for crops with higher or lower expected yields than average, the amount of nitrogen is adjusted accordingly. This nitrogen is usually applied in three splits for wheat during the spring. Research by Sylvester-Bradley *et al*. (2000) on Canopy Management also suggests that these nitrogen rates are further adjusted based on the visual inspection of the crop, in particular crop density and leaf area index, these factors also determining the timing of nitrogen application.

If sensing systems could be used to remotely measure soil type and nitrogen content, crop density and leaf area index to assess in-field variability this would offer both agronomic and environmental benefits by matching specific crop requirements to nitrogen supply. On the basis that the nitrogen levels currently applied are the average of the field it seems unlikely that major economic benefits would arise, since the nitrogen will simply redistributed, more to areas of the field with higher requirement and less to areas with lower requirements. However research based on canopy management principles (HGCA, 2002b) has indicated that savings up to £22 ha^{-1} can be obtained by matching nitrogen inputs to tiller numbers.

The amount of phosphorus (P) and potassium (K) a cereal crop requires is dependant on the level of reserves in the soil, expected yield and whether the straw is to be removed. As with nitrogen standard tables are available (MAFF, 2000) that detail the amount of phosphorus and potassium that is required by a particular crop. If the index is 0 or 1 then the phosphate and potash must be applied to the seed bed. When the index is 2 or higher the phosphate and potash can be applied at any convenient time during the growing season, since it is required for the subsequent crop and is for maintenance purposes only. Through good management, P and K levels should not generally be allowed to fall below index 2 and in most situations only maintenance levels of P and K are required. Wheat, barley and rape are now also showing a response to sulphur, especially on light land and is often now applied as a matter of course.

The levels of P, K and Mg in the soil are monitored every three to four years. This is usually achieved by walking, or driving, a ‘W’ across the field and taking 15 to 20 soil samples from the top 15 cm of soil. These samples are bulked together and a single sample is sent to the laboratory for analysis. The result of this one sample is then said to represent the complete field. This is usually a confirming exercise, since by knowing the starting point and monitoring the off-take from the field the agronomist can derive the maintenance level required hence the soil index should remain unchanged.

2.6 Discussion and conclusions

Agronomists, advisors or farmers base their decisions on field information (gained from field walking), previous field history and their expert knowledge. The factors identified in this study, that the agronomist uses to determine inputs are those which can generally be assessed by visual inspection, usually during field walking. Table 2.6.1 summarises the results of this study and offers a subjective assessment of the benefits that are likely to arise from being able to remotely sense the various factors. However it is not only these factors that the agronomist is observing. Each time a field is visited the agronomist must multitask observing many things such as population, disease, weeds, puffiness, deficiencies, check that things have been done, wet areas, etc. Therefore even if these factors (Table 2.6.1) could be remotely sensed this would not negate the requirement of agronomy field visits. Nevertheless, research (Clarke *et al*., 2000; Sylvester-Bradley *et al*., 2000; Miller *et al*., 2000; HGCA, 1998a; HGCA 1998b; HGCA, 1999; HGCA 2000a; HGCA 2000b; HGCA 2000c; HGCA, 2002a; HGCA 2002b) has indicated that if these factors could be sensed remotely, they could be used to spatially apply inputs such as seed, crop protection chemicals and fertilisers based on the whole field recommendations of the agronomist.

It seems clear from Table 2.6.1 that if any of these factors were remotely sensed and used to spatially apply the inputs to cereal production, they could bring a combination of agronomic, economic and/or environmental benefits. Although deciding which one would be most beneficial is difficult to determine since absolute benefits are not easily quantifiable.

The main driver for uptake of precision farming approaches is likely to be economic, from this point of view crop canopy characteristics affect both the inputs of crop protection chemicals and fertilisers which account for about 60% of the variable costs (Table 2.1.1) and hence offer the largest potential savings. Each of the other factors affects less than 20% of the variable costs and therefore offer less potential for savings to be made. In addition, research (Scarlett *et al*., 1997; Stafford and Ambler, 1990; Day, 1992 and Germain *et al*., 1998) has already identified systems for determining seed bed condition and tilth but as yet there has been little development of commercial systems. Also weed patch detection has been the subject of recent research and commercial development (HGCA, 1998b; Lutman *et al*., 2002a; Lutman *et al*., 2002b). Therefore based on the potential benefits, particularly from an economic point of view it was decided that this work should concentrate on improved methods for sensing crop canopy characteristics to provide a basis for aiding input decisions.

Table 2.6.1 Visual factors which agronomists use to assist their input decisions and the potential benefits assuming they could be remotely sensed

Visual factors which agronomists use to assist their input decisions	**Potential benefits over conventional practice. 1 – little or no benefit, 2- moderate benefit, 3 – major benefit**		
	Agronomic	**Economic**	**Environmental**
Crop establishment			
seed bed condition	❁ ❁	£	☼
slug risk	❁ ❁	£ £	☼ ☼
Weed control			
weed species	❁	£ £	☼ ☼ ☼
weed growth stage	❁	£	☼ ☼
weed density	❁	£ £	☼ ☼
weed location	❁	£ £ £	☼ ☼ ☼
Crop protection			
growth stage	❁	£ £	☼ ☼
crop canopy characteristics	❁	£ £ £	☼ ☼ ☼
Crop nutrition			
crop canopy characteristics	❁ ❁	£ £ £	☼ ☼

During the last decade, spectral reflectance in the visible and near infrared region (400 - 2500 nm) has been identified as a popular method to sense parameters relating to agricultural crops. Results from spectral reflectance measurements have been widely used in arable research to evaluate such factors as: crop density (Basso *et al*., 2001; Miller *et al*., 2000; Wood *et al*., 2000); crop nitrogen (Oberti and De Baerdemaeker, 2000; Dumont *et al*., 2000); weed detection (Biller *et al*., 1997; Vrindts *et al*., 1999; Borregaard *et al*., 2000) and soil properties (O'Mahony *et al*., 1998; Barnes and Baker, 2000). However, despite considerable research activity, spectral reflectance is not widely used for commercial applications. The following review details spectral reflectance techniques and summaries the research identifying its use, limitations and future potential particularly in respect to measuring canopy characteristics.

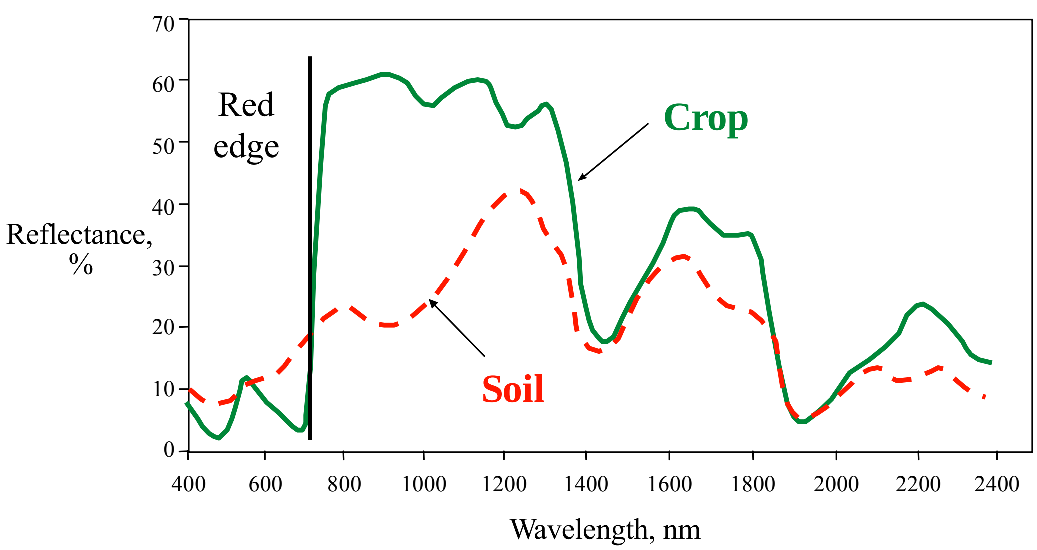
3. REVIEW OF SPECTRAL REFLECTANCE TECHNIQUES

3.1 Spectral reflectance techniques

3.1.1 *Theory*

The basis of most spectral reflectance studies in arable research is the large differences in the reflectance characteristics between soil and crop, especially at the 'red edge' the point where the electromagnetic spectrum changes from visual to near infra red at a wavelength of approximately 700 nm (Figure 3.1.1.1). However, different soils and different crops can also have different spectral reflectance characteristics and this has also been exploited in some research. Many studies have used measurements in the visible (400 - 700 nm wavelength) and near infra red (700 - 2500 nm wavelength) region of the electromagnetic spectrum. Indeed, recent scientific reviews (Dampney *et al*., 1998; Zwiggelaar, 1998) and a paper by Moran (2000) concluded that wavelengths in this region can potentially detect many physiological and biological functions of crops and therefore offer potential for applications in agriculture, including measurements of crop green area, crop density, crop chlorophyll, weed detection and soil properties.

Figure 3.1.1.1 Typical reflectance spectral signatures of soil and crop



The principle behind these measurements is that the energy (E) of the electromagnetic waves is related to their wavelength (λ) (Grounds and Kirby, 1990):

$$E = \frac{h\,c}{\lambda}$$

where h is Plank's constant (6.6×10^{-34} J s) and c is the speed of light (3×108 m s^{-1}). From this equation it can be seen that the smaller the wavelength (λ), the more energy (E) a particular wave exhibits. As this energy hits the surface of a body (crop or soil) it is either reflected from, absorbed by, or transmitted by it, the degree of each being determined by the specific wavelength and the physical and chemical properties of the contacted body. Measuring the amount of energy reflected at known wavelengths enables some information to be obtained about the contacted bodies characteristics.

For most agricultural studies, the spectral reflectance of at least two wavelength bands, usually either side of the 'red edge' (Figure 3.1.1.1) are measured enabling a ratio to be calculated. Many forms of ratio, usually termed vegetation indexes have been used, examples of which are detailed in Table 3.1.1.1 and correlated against a property relating to agricultural studies e.g. canopy characteristics, weed properties.

When only a small number of wavelength bands are measured data analysis is relatively simple. However, limiting the number of wavelengths can limit the information gained from the measurements. Spectrometers, capable of quickly measuring many wavelengths, produce large amounts of data from a single measurement and can potentially provide more information relevant to the canopy. The interpretation of this hyperspectral data is complicated by the interrelationships between wavelength variables (Riding and Bryson, 2000) and many statistical techniques have been utilised to analyse such data. For example, neural networks (Moshou *et al*., 1998; Bennedsen *et al*., 2000; Jayas *et al*., 2000); Partial Least Squares analysis (Dumont *et al*., 2000); fuzzy logic (Hemming and Rath, 2001); Principle Component Analysis (Nielsen *et al*., 2000) and stepwise multiple linear regression (Hummel *et al*., 2001) have all been used. This review does not aim to provide the detail or merit of these approaches, only to indicate that many statistical techniques are available and have been used for agricultural studies.

Index	Equation	Wavelengths used, nm	Reference
Normalised difference vegetation index, *NDVI*	$NDVI = \frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red}}$	NIR = 730, red = 660 NIR = 830, red = 660 NIR = 840, red = 640 NIR = 800, red = 600	Stafford and Bolam, 1998 Oberti and de Baerdemaeker, 2000 Wood *et al.*, 2000 Basso *et al.*, 2001
Ratio vegetation index, *RVI*	$RVI = \frac{R_{NIR}}{R_{red}}$	NIR = 850, red = 650 NIR = 830, red = 660	Biller, 1998 Oberti and de Baerdemaeker, 2000
Green ratio vegetation index, RVI_G	$RVI_G = \frac{R_{NIR}}{R_{green}}$	NIR = 830, green = 560	Oberti and de Baerdemaeker, 2000
Chlorophyll estimation, *CE*	$CE = \frac{R_{NIR}}{R_{700}}$	NIR = not given	Gitelson *et al.*, 2001
Soil adjusted vegetation index, *SAVI*	$SAVI = \frac{1.5\left(R_{NIR} - R_{red}\right)}{R_{NIR} + R_{red} + 0.5}$	NIR = 760, red = 660	Bennedsen and Guiot, 2001
Weighted vegetation index, *WDVI*	$WDVI = R^c_{NIR} - \left(\left(\frac{R^s_{NIR}}{R^s_{red}}\right) \times R^c_{red}\right)$	NIR = 730, red = 660	Stafford and Bolam, 1998
Photochemical vegetation index, *PRI*	$PRI = \frac{R_{531} - R_{570}}{R_{531} + R_{570}}$		Méthy, 2000
Vegetation fraction and density estimation, $VARI_{green}$	$VARI_{green} = \frac{R_{green} - R_{red}}{R_{green} + R_{red} - R_{blue}}$	red = 670, green = 550, blue = 460	Gitelson *et al.,* 2001
Visible atmospherically resistant index, $VARI_{700}$	$VARI_{700} = \frac{R_{700} - (1.7 \times R_{red}) + (0.7 \times R_{blue})}{R_{700} + (2.3 \times R_{red}) - (1.3 \times R_{blue})}$	red = 670, blue = 460	Rundquist *et al.,* 2001
Infrared on green index, *NirGR*	$NirGR = \frac{R^2_{830}}{R_{660} \times R_{550}}$		Oberti and de Baerdemaeker, 2000

Table 3.1.1.1 Vegetation indexes used in previous research

3.1.2 *Measurement methods*

Radiometers are typically used for taking spectral reflectance measurements, using either natural (sunlight) or artificial light as the illumination source. A Charge Coupled Device (CCD) detector within the radiometer measures the total amount of radiant energy. The light sensitive surface of the CCD detector produces an electrical current which is proportional to the light energy hitting its surface. A number of different CCD detectors are available, each being suitable for measuring particular wavelength ranges and therefore the selection of detector is mainly determined by the wavelength region of interest. For example, silicon photodiode detectors are suitable for measuring wavelengths from approximately 200 to 1100 nm, whereas if measurement of longer wavelengths (up to 2500 nm) are required, then indium gallium arsenide (InGaAs), or lead sulfide (PbS) detectors are more commonly used (Ryer, 1997).

The light exposed to the CCD detector is normally filtered by an optical band pass filter so that only the specific wavelengths of interest are measured. For example, a radiometer designed to measure at a wavelength of 630 nm would typically have a band width of 20 nm and measure the total radiant energy of wavelengths from 620 to 640 nm. For crop canopy studies, radiometers typically used are designed to measure at two specific wavelength bands, usually either side of the 'red edge' (Miller *et al*., 2000), having a CCD detector and optical band pass filter for each wavelength band.

More complex radiometers referred to as spectrometers or spectroradiometers, can quickly measure the reflected energy over a range of wavelengths. These devices use either a fixed grating and a CCD array detector or a scanning grating and a single element CCD detector. In the former, the fixed grating separates the collected spectrum into many small wavelength bands and the CCD array measures the light energy from each of the wavelength bands simultaneously. The width of the bands depends on the type of grating used and the number of elements on the CCD detector, but such spectrometers usually have a range of about 600 nm with a spectral resolution of approximately 2 nm. In the later type the grating is automatically adjusted allowing specific wavelengths in turn to be exposed to the detector, thus the wavelengths are not measured simultaneously, but one after the other until a complete spectrum is measured.

Although not strictly spectral reflectance measurements, several workers (Scarr *et al*., 1997; Paice *et al*., 1999; Taylor *et al*., 2000; Wood *et al*., 2000) have used digital cameras fitted with optical band pass filters as an alternative to radiometers so that the captured image represents specific wavelength bands reflected from the crop / soil surface. Alternatively, unfiltered colour camera output can be decoded to represent the red, green and blue components of the full image (Tillet, 1991). The resulting images of either of these approach represents the energy of the particular wavelength bands being measured and can be used to calculate the various indexes as detailed in Table 3.1.1.1.

Radiometers, spectrometers or digital cameras can be mounted on a variety of platforms either space, aerial or ground. The advantages and disadvantages of each platform are summarised in Table 3.1.2.1, with the choice of platform being heavily influenced by the end use of the image. In terms of precision agriculture, Dampney (2002) described two levels of complexity: (i) simple applications - to help target crop inspections and to prioritise fields for management inputs by comparing crop growth and development; and (ii) complex applications - to provide quantitative crop or soil information to aid crop input decisions and to provide an objective record of crop status. For the simple applications, scanning large areas quickly is beneficial and the timing of image capture is not too critical. Satellite or aerial images are therefore generally suitable for these applications. However, complex applications may require a higher spatial resolution and the timing of image capture is critical. In these situations ground based or aerial images are better suited. The final choice of platform will depend on availability but specific operations are likely to require different levels of spatial resolution and timing of image capture. For example, Stafford (1998) suggests a spatial resolution of 30 m being adequate for variable fertiliser application, whereas a spatial resolution of 1 m would be better suited for variable application of herbicide.

Table 3.1.2.1 Summary of the main advantages and disadvantages of different sensing platforms

	Space	Aerial	Ground
Area covered per scan	Area scanned increases with height of platform		
	typically km^2	typically m^2	typically cm^2
Spatial resolution (pixel size)	As platform height increases resolution coarseness increases		
	15 to 900 m^2	0.05 to 2 m^2	mm^2 to cm^2
Temporal resolution	weeks	days	hours
Affect of cloud cover	Influence of cloud increases with platform height		
	Heavily influenced	Moderately affected	Not affected
Affect of light conditions	Influence of light conditions decreases with platform height		
	Not affected	Moderately	Heavily
Availability of data to end user	Long delays	Some delays	No delays
Control of end user	Limited control	Some control	Full control

3.2 Uses of spectral reflectance measurements

3.2.1 *Canopy characteristics*

It is well documented that there is temporal and spatial variation of crop canopy characteristics within field particularly in terms of density and colour (Godwin, 2000; Miller, 2000). Spectral reflectance techniques have been widely used to assess this variability; in particular a ratio of reflectance between the visible red and near infra-region is used. For such studies, wavelengths within the respective ranges of 620-680 nm and 730-890 nm are commonly used (Paice *et al*., 1999; Miller *et al*., 2000; Danson and Rowland, 2000). The principle behind these studies is that the majority of the red light is absorbed by the chlorophyll in the canopy and therefore little is reflected, whereas the opposite is the case for near infra-red light, where a high proportion is reflected. As canopy green area increases, either due to increasing crop density or chlorophyll content, the percentage of red reflectance decreases whilst the near-infra-red reflectance increases (Figure 3.2.1.1). Consequently if these reflectance values were used to calculate NDVI, it would increase with increasing green area index (Figure 3.2.1.2). However this only holds true until canopy closure when the crop has a green or leaf area index (LAI) of up to three (Dampney *et al*., 1998; Danson and Rowland, 2000), depending on the cereal type and variety this generally occurs between growth stages GS 30 to GS 40 (HGCA, 1998). Therefore any ratio or vegetation index based on these two reflectance measurements has the greatest sensitivity when measuring crop canopy variation up to a LAI of 3; once canopy closure occurs the response of the vegetation index tends to be relatively flat and any differences in the canopy are not easily measured. This can cause problems since many inputs (*e.g*. fungicides) are not applied until the crop has reached GS 31 when the spectral reflectance type measurements are reaching saturation.

Figure 3.2.1.1 Typical relationship of red and infra-red reflectance against Green Area Index (after Dampney *et al*., 1998)

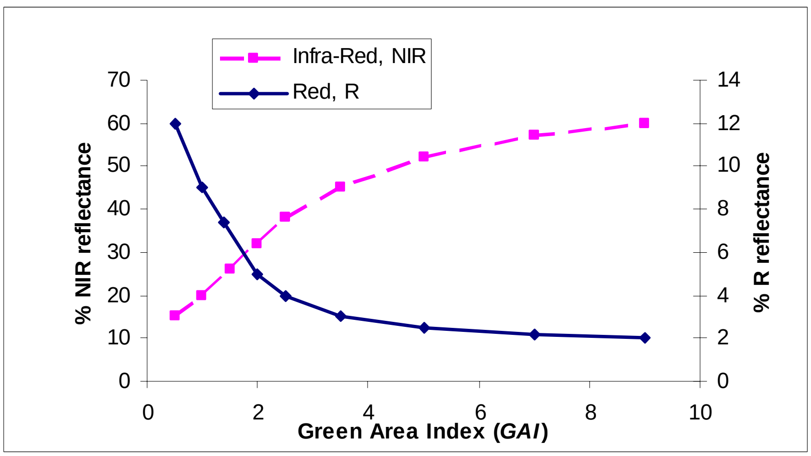
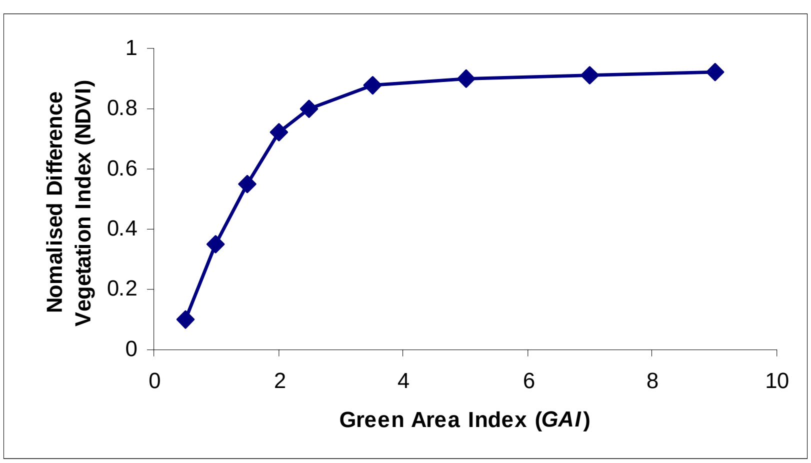


Figure 3.2.1.2 Typical relationship of NDVI against Green Area Index (after Dampney *et al*., 1998)



3.2.2 *Nitrogen application*

Experiments by Godwin (2000), Wood *et al*. (2000) and Taylor *et al*. (2000) used aerial digital photography (ADP) in the Red and NIR region to calculate NDVI and demonstrated a good correlation against plant numbers or tiller density. However, to obtain absolute values of plant and tiller numbers, ground truthing was conducted by detailed quadrant assessment. Based on these measurements, the nitrogen input was varied according to tiller density, with higher levels of nitrogen applied to low tiller densities and low levels of nitrogen to higher densities (HGCA, 2002). The objective was to manipulate the variable canopy with nitrogen to achieve an optimum GAI. These experiments concluded this was a useful method to estimate crop density and provided a basis for variable nitrogen application, allowing a nitrogen application strategy to be implemented based on previously derived canopy management principles (HGCA, 1998). The research discussed above clearly indicates the potential that the ratio of reflectance between Red and NIR reflectance can be used to estimate the density of the crop canopy and subsequently be used to determine nitrogen applications.

An alternative approach reported by Oberti and De Baerdemaeker (2000) hypothesised that the chlorophyll content in plants is highly correlated to the nitrogen uptake from the soil and the optical properties of leaves, in the visible range, is affected by their chlorophyll content. Using this assumption and a simple ratio vegetation index (NIR/G and NIR/R), these authors were able to predict the crop nitrogen content within ± 17% of the average content of a wheat crop canopy. Similarly Dumont *et al*. (2000) measured the reflectance at 5 wavelengths (480, 550, 660, 830 and 1650 nm) of a wheat crop at three different growth stages. Using partial least squares analysis, the plant nitrogen content was predicted to ± 17%, 12% and 11% of the mean at the three different growth stages, although different predictive models were required for each growth stage of the crop. In a separate study, Nielsen *et al*. (2000) made preliminary measurements using a spectrometer in the range 400 to 760 nm and found good correlation between a soil adjusted vegetation index (SAVI) and the nitrogen content of winter wheat.

The research above clearly indicates the potential to estimate the nitrogen status of crops using spectral reflectance, thus offering the possibility to derive a variable nitrogen application strategy based on these measurements. Indeed, using colour as an indicator of chlorophyll content, Wollring *et al*. (1998) used a tractor mounted spectrometer (Hydro, 2000) to estimate the nitrogen content in growing cereal crops and subsequently used this information to variably apply nitrogen by increasing the amounts of nitrogen to areas of the crop identified as having low chlorophyll content and decreasing nitrogen to areas of the crop where high chlorophyll content was observed.

3.2.3 *Fungicide and growth regulator application*

Researchers have also used spectral reflectance to characterise canopy and subsequently use the information to adjust fungicide application. For example, Bjerre (1999) measured the ratio vegetation index (RVI) using ground based radiometers and adjusted fungicide dose depending on density, increasing volume application rate with high crop densities and lowering it for less dense areas, the assumption being this would achieve a uniform rate of active ingredient per unit of leaf area. The results indicated a higher efficacy for mildew control but little difference for Septoria control compared with conventional uniform application. However, Bjerre (1999) also reported that generally mildew levels increase with increasing density; whereas Septoria generally decreases with increasing density, hence the findings of this study are not surprising based this assumption. Therefore, for some diseases adjusting fungicide dose according to crop density offers potential to optimise the use of fungicides resulting in both economic and environmental benefits. For example, Secher (1997) compared blanket application of fungicide (0.84 units ha^{-1}) to variable rate application (0.67 - 1.02 units ha^{-1}) with higher rates being applied to thicker areas of the crop. It was reported that the variable application rate strategy achieved significantly higher yields than the blanket application, 7.39 t ha^{-1} compared with 7.09 t ha^{-1}. In this case powdery mildew was the dominating disease and thus these findings concur with those of Bjerre (1999). However, the assumption that simply increasing the volume application rate to increase the dose will automatically increase the deposit level of active ingredient needs to be further investigated. Experiments by Miller *et al*. (2000) reported that sprayer operation at volumes of 100 and 200 l ha^{-1} designed to apply the same dose rate achieved higher deposits of active ingredient (ml g^{-1} of leaf) at the low volume application compared against the higher rate by 63 and 14% at growth stages 32 and 39 respectively. In addition these authors used two radiometers, one in the 640-660 nm wavelength band and the other in 790-810 nm wavelength band to classify at an early stage of growth, the crop into high and low densities, with values of NDVI above 0.77 representing high canopy densities and values below 0.77 low densities. At growth stage 32 it was reported that the mean deposit levels (ml g^{-1} of leaf) were higher in the low density areas than the high density areas. Although these findings were not statistically significant, probably resulting from small differences in the canopy structure being insufficiently different between areas of high and low density to significantly influence the spray deposition patterns. However this work and that of Bjerre (1999) does indicate the importance of matching application methods to canopy characteristics and simply applying higher volumes to thicker areas of the crop may not be the way forward.

3.2.4 *Weed detection*

A review by Lamb and Brown (2001) suggest that differences in spectral reflectance between weeds and their background, either soil or plant canopy can be used to remotely sense weeds. The simplest form of this discrimination is the detection of weeds against a soil background, either on fallow ground or between crop rows. The two materials, plants and soil, have significantly different spectral reflectance characteristics particularly in the red and near infra red wavelength bands (Figure 3.1.1.1). The ratio of these wavelength bands being identified by Zwiggelaar (1998) and Marchant *et al*. (2001) as useful to detect weeds against soil background. Using this principle, a prototype hand held patch sprayer activated by spectral differences was developed (Haggar *et al*., 1983) and was reported to have killed approximately 90% of grass weeds. Although no figures were given, it was suggested this method offered the potential for large economic savings over blanket application. Whereas Biller *et al*. (1997) and Biller (1998) measured the percentage of radiant energy reflected at 645 nm (Red) and 850 nm (NIR) from a fallow field and by using a simple RVI ratio was able to reliably identify the presence of green plant material against a soil background under field conditions, values of RVI ranging from 1 - 1.5 representing soil and values 6 - 15 green plant material. When used to control the output of a sprayer applying herbicide on a conventionally tilled field, herbicide savings of between 30 and 70% were achieved compared with conventional blanket application. Similarly, Felton (1995) tested a commercial spot spraying system and reported herbicide savings up to 90% compared with blanket application.

Although useful to detect weeds against a soil background, this situation is not common in Northern European agriculture, and also the herbicides used for this application tend to be inexpensive, therefore any potential economic savings are small. A more useful system would be able to detect weeds in a growing crop. In this situation herbicides are generally more expensive and greater savings would be achieved. Stafford and Benlloch (1997) used two CCD cameras fitted with interference filters at 680 and 800 nm. Using image analysis techniques, the weeds in between the rows when the cereal crop was at an early growth stage could be identified by implying if a plant was not in a row it was a weed. However, weeds within the rows could not be reliably sensed due to the similar spectral reflectance characteristics of the weeds and the cereal crop, at the wavelengths being measured.

To overcome the limitations of only scanning at two wavelengths bands, Rew *et al*. (1999) collected multispectral images at four wavelength bands, namely 440 nm, 550 nm, 650 nm and 770 nm under field conditions from a triticale crop at an average plant density of 36 plants m^{-2} inter planted with patches of wild oats. The images were processed to produce NDVI values and the technique was able to detect densely infested areas with wild oat densities above 30 plants m^{-2}. However, the approach could not discriminate between areas with a population of less than 20 wild oats m^{-2} and weed free areas of crop. A similar study by Lamb *et al*. (1999) also concluded that by using NDVI weed populations of less than 28 weeds m^{-2} could not be discriminated from weed free regions, although by using a SDVI this reduced to 17 weeds m^{-2}. From this evidence it seems unlikely that using the measured reflectance of a limited number of wavelength bands, under field conditions, that it will be possible to detect weeds in a growing crop, especially at low weed densities. However the approach may be useful in aiding manual weed patch detection (Perry *et al*., 2001; Lutman *et al*., 2002a).

In an attempt to improve weed detection using spectral reflectance measurements, Vrindts and De Baerdemaeker (1997) measured the reflectance spectra from 200 to 2000 nm of young weed and crop plants using an integrating sphere under laboratory conditions. Using between three and seven 10 nm wavelength bands, the spectra could be reliably classified into weeds or crop. Vrindts *et al*. (1999) also conducted further work measuring the reflectance spectra of weed and crop plants illuminated by an artificial light source, rather than an integrating sphere, from 400 to 2000 nm. Similarly they concluded that the spectra could be classified using three wavelength ratios (*i.e.* 6 wavelengths bands). Borregaard *et al*. (2000) also measured the spectral reflectance between 660 and 1060 nm of weed and crop species under artificial light conditions in the laboratory and achieved reliable weed crop classifications using only two or three wavelengths. These studies seem to contradict the findings of the field studies, showing that weeds can be identified using only a limited number of spectral reflectance bands. However it must be remembered this was only possible under ideal laboratory conditions, using constant artificial light sources. In field experiments, the light conditions are variable and this is likely to be the cause of some of the weed classification errors. Indeed, Vrindts *et al*. (1999) concluded that the laboratory measurements were influenced by experimental set up: the variable positions of the light source as well as the relative position of the leaves to the sensor. For field applications any sensing system would have to operate on the move, further increasing the level of complexity that would be required.

Some weed detection studies have been conducted at field scale based on measurement of spectral reflectance at a range of wavelengths. A study by Bennedsen *et al*. (2000) measured hyperspectral reflectance from 380 to 760 nm from a wheat crop under field conditions, with the illumination (sunlight) levels changing as the measurements were made. The subsequent data were analysed using neural networks and achieved classification rates between 87.8 and 99.3% for six objects namely: soil, soil in shade, wheat leaf, rape leaf, rape leaf nervation and leaf in shade. Although this technique provided good classification results, it was concluded that as conditions change with time, the neural network would also require retraining. Similarly, Vrindts and De Baerdemaeker (2000) measured the spectral reflectance of sugar beet, maize and weeds between 480 and 820 nm wavelengths under field conditions. In the case of sugar beet leaves, 90% were classified correctly when compared with weed leaves during experiments in which the ambient light conditions remained fairly constant. In contrast only 15% of the maize leaves were classified correctly when compared to the weed leaves, during these experiments the ambient light conditions were changeable.

To overcome the problem of changing light condition under field conditions, Hemming and Rath (2001) conducted field experiments, eliminating the variability of sunlight illumination by using an artificial light source. A covered steel frame mounted on the three point linkage was used to block out sunlight and cameras collecting green, blue and red images plus metal halogen lights were located under the cover. The system was used identify weeds in vegetable crops, namely cabbage and carrots, depending on the growth stage of the crop between 51 and 95 % of the plants were classified correctly. Although this system eliminates the light variability it is unlikely to be acceptable for practical applications. Marchant and Onyango (2002) have developed a mathematical model for calculating invariant spectra of light reflected from surfaces under changing daylight illumination conditions. The model proved successful in reducing most of the variation of the reflected spectra of 21 coloured surfaces with the range 350 to 830 nm and offers a solution to the problem of changing sunlight conditions in field measurements. However, as yet this method has only been tested on artificial coloured surfaces under controlled conditions where the targets were static. Further work is required to determine if the principles also holds true for leaf surfaces in practical applications when sensing is conducted on the move.

3.2.5 *Soil moisture and type*

Spectral reflectance techniques, albeit at different wavelengths to those used for canopy characterisation and weed detection, have also been used to estimate soil type and moisture content. Water molecules have absorption bands at 2093, 1940 and 1450 nm; also to a lesser degree at 970 and 760 nm (Stafford, 1988; Whalley and Stafford, 1992; O'Mahony *et al*., 1998; Zwigelaar, 1998). Studies by O'Mahony *et al*. (1998) used a simple ratio of the reflectance at two wavelengths under artificial light, namely 1928 nm, a water absorbing band; and 1800 nm, a reference band and were able to predict the moisture content of processed peat samples to an accuracy of ± 7.5% for high moisture content peat (approximately 340 kg m^{-3}) and to ± 3.5% for medium and low density peat (approximately 240 and 180 kg m^{-3} respectively). Hummel *et al*. (2001) measured the spectral reflectance, from 1600 to 2600 nm of undisturbed soil samples and was able to predict the soil moisture content within a standard error of 5.31% in a range from 4 to 57%, using multiple linear regression on only 4 wavelengths (1837 nm, 2035 nm, 2114 nm and 2233 nm). However this study only used silty clay and silty clay loam soils and it was concluded that more work would be required to extend the applicability beyond these soil types.

Both of these studies were conducted under carefully controlled laboratory conditions, using either processed peat or undisturbed soil samples. The main variable was therefore the moisture content and under these conditions the technique is generally reliable. A review by Stafford (1988) concluded that NIR reflectance has potential for sensing soil moisture content, but reported that the reflectance properties of the soil also depends on its type. This agreed with the findings of Hummel *et al*. (2001), that the reflectance properties of soil and other materials, in the water absorbing region of the spectrum, are not solely related to its moisture content. Furthermore, a study by Barnes and Baker (2000) used space borne and aerial multi-spectral images (blue, green, red and NIR wavelength bands) to classify soil types into textural classes and achieved a classification accuracy of about 50% across the entire study area of 350 ha. However, when the classification was conducted on a field by field basis, the accuracy increased to around 80%. It was reported that many factors impinge on the soils apparent reflectance properties which are not related to physical characteristics such as crop residue, tillage practices and surface moisture. Therefore it was concluded that this technique was best suited to farms whose fields have uniform tillage and moisture conditions at the time the images are obtained. In practical situations this is unlikely to be the case, indicating the limitations of this technique.

3.3 Discussion

The instruments that are used for spectral reflectance measurements, radiometers, spectrometers or digital cameras, are suitably robust for agricultural use and can be mounted on space, aerial or land based platforms. Space borne sensors have problems with providing sufficient spatial and temporal resolution; and there can also be problems with delivery of the information to the end user (Dampney *et al*., 1998). Despite this, it has been suggested (Stafford, 1998) that they do provide sufficient spatial and temporal resolution for fertiliser planning. Whereas Lamb and Brown (2001) indicate that images from space borne platforms do not provide sufficient spectral resolution for mapping weeds at field scale, this activity requiring aerial or land based sensing systems. Nevertheless, by selection of a suitable sensing platform sufficient resolution can be obtained for most applications associated with sensing variability in agricultural crops.

When used for sensing canopy characteristics, spectral reflectance techniques are only suitable until the crop reaches canopy closure at approximately GAI 3, beyond this stage little difference in reflectance properties are observed. Nevertheless some inputs are applied to the crop before this growth stage and therefore the technique can be used to aid some input decisions. Research in this area clearly indicates that the spectral reflectance properties of the crop canopy in the visible red and near infra-red region is affected by its density and chlorophyll concentration (colour). Using this assumption, it seems reasonable to suggest that the workers measuring crop chlorophyll or nitrogen content assumed an even crop canopy density. Conversely those workers measuring the differences in crop density assumed and even canopy chlorophyll content.

There is no doubt that spectral reflectance measurement provides a basis for variable nitrogen, fungicide and growth regulator strategies. However to improve these strategies a better characterisation of the canopy is required. Ideally the two main factors that influence the spectral reflectance of the crop canopy, crop density and chlorophyll content (colour), need to be measured independently. This is likely to necessitate using additional sensors in tandem with spectral reflectance measurements. Indeed, Dampney *et al*. (1998) and Miller (2000) concluded that the future direction of precision agriculture would involve multiple sensors linked together. For canopy measurement, there is a need to separate out the plant or tiller density measurement from the chlorophyll content or colour of the crop. This could involve sensors that can measure the physical structure of the crop, such as ultrasonic sensors (Stafford *et al*., 1997; O'Sullivan, 1986) and LIDAR (Dampney *et al*., 1998).

When used for weed detection, spectral reflectance is suitable for detecting weeds against a soil background and can be used for selective application of herbicide. However this technique is not reliable enough to detect weeds in a growing crop. For practical applications, especially for competitive weeds such as wild oats and blackgrass, weeds need detecting down to densities of 1 plant m^{-2}, whereas in practice the best that has been achieved is about 17 plants m^{-2} (Lamb *et al*., 1999). Under controlled laboratory conditions there are sufficient differences between the spectral characteristics of weed and plant tissue to separate the two. However in field conditions this is not the case, changeable light conditions (Andersen and Granum, 1998) and to a lesser degree the orientation of the leaves to the sensor (Vrindts *et al*., 1999) increases the level of noise in the data preventing reliable weed identification. Work has been conducted using controlled light in field conditions for the purpose of weed detection, and a limited amount of success achieved (Hemming and Rath, 2001), however such a system is unlikely to be suitable for most practical applications. However, invariant models (Marchant and Onyango, 2002) have the potential to alleviate illumination variability in the future. It is unlikely that existing spectral reflectance techniques, without complex mathematical manipulation, will be able to detect weeds in a growing crop and new techniques are required to achieve this goal.

Using spectral reflectance as a technique for soil moisture is reliable if the soil type is relatively constant. However, in most practical situations this is not the case and therefore this technique is not generally suitable for this application. Other techniques such as electro magnetic induction (EMI) scanning offer a much better solution to soil moisture and type detection and have been shown to be robust and reliable by several workers (King & Dampney, 2000; Waine *et al*., 2000; James *et al*., 2000).

3.4 Conclusions

It is clear from this review that spectral reflectance is a useful management tool for cereal crop production and it can be concluded that:

- Instruments for measuring spectral reflectance are sufficiently robust and can provide adequate resolution for many precision agriculture applications if mounted at an appropriate distance from the target.
- Spectral reflectance can provide a measure of green crop area, either associated with crop density or crop chlorophyll content (colour), which can subsequently be used to derive variable nitrogen, fungicide and growth regulator strategies.
- Spectral reflectance can be used for practical applications to identify weeds against a soil background, but not against a crop background.

However it is recognised that this technique does have its limitations:

- Spectral reflectance cannot differentiate between crop density and crop chlorophyll content (colour) without some form of ground truthing.
- Spectral reflectance is suitable until the crop reaches canopy closure when it has reached a leaf area index of about three.
- Differing levels of natural illumination affect the spectral reflectance properties of plant materials and are the main source of noise in field collected data making weed identification against a crop background very difficult in field conditions.
- Spectral reflectance is not suitable for soil moisture or soil type measurement; other techniques such as EMI scanning are more suitable for this application.

4. EXPERIMENTAL WORK

4.1 Introduction

In section 2.6 it was concluded that the rates and timings of inputs (e.g. fertilisers, fungicides, growth regulators) for winter wheat are influenced by crop growth stage (GS); as defined by Zadoks *et al*., 1974; and assessment of canopy condition, in particular its density in terms of tiller numbers and leaf area index. Traditionally this is achieved by crop dissection (for GS) and visual inspection (for canopy condition). However, these approaches are both labour intensive and subjective, therefore constraining the number of hectares that can be covered by a single observer, and the repeatability of the measurement. This results in the agronomist having to take the average condition of the whole field in order to determine field inputs. To overcome these limitations, systems are required to assess crop condition in terms of tiller density and leaf area index so that the in-field variability can be assessed quickly, thus automating the process allowing more hectares to be covered and eliminating the subjective nature of the measurements.

In section 3.5 it was shown that spectral reflectance measurements in the visible and near infrared region of the electromagnetic spectrum and subsequent calculation of a vegetation index have been widely used to assess canopy condition (Wollring *et al*., 1998; Miller *et al*., 2000; Wood *et al*., 2000). However, it was also suggested (Dampney *et al*., 1998; Danson & Rowland, 2000) that this method is only suitable until canopy closure when the crop has a leaf area index; defined as the ratio between the total leaf area, one side only, per unit area of ground; of about three which for winter wheat crops in European conditions typically occurs at about GS 31/32 (HGCA, 1998a). In addition, vegetation index measurements provide an estimation of crop green area but are unable to differentiate between crop chlorophyll content (crop cover) and crop structure (Miller, 2002). Nevertheless, inputs have been based on these measurements, although improvements in the agronomic decisions are considered possible if the objective of measuring crop cover and structure independently could be achieved. Indeed both Dampney *et al*. (1998) and Miller (2002) reached a similar conclusion and suggested that the combined output of multiple sensors would be required to measure both crop cover and structure.

If sensors were available to measure crop structure their output could be combined with vegetation index measurements to achieve this goal. It has been suggested (O'Sullivan, 1986; Miller, 2000) that ultrasonic sensors are potentially suitable for this purpose. Indeed, recent work by Kataoka *et al*. (2002) in Japan showed that ultrasonic sensors are suitable for measuring the height of soyabean and corn crops. However, in European conditions ultrasonic sensors have not been used for crop height measurements, although they have been used in other agricultural studies. For example Scarlett *et al*. (1997) used a single ultrasonic sensor to measure seedbed condition whereas Stafford *et al*. (1997) used two ultrasonic sensors to monitor the cut width of a cereal combine harvester. This limited evidence suggests that ultrasonic sensors are suitable for agricultural use and that a cereal canopy should provide a sufficient target for ultrasound reflectance.

The objective of this experiment was to investigate the practicalities, limitations and usefulness of a tractor mounted radiometer and spectrometer system in parallel with an ultrasonic sensor to establish if these combined sensing approaches can provide useful information about crop cover and the structure of the crop canopy. In particular to investigate sensing systems that can provide information about the cereal canopy beyond growth stages at which the leaf area index has a value of three. Therefore, offering tools which offer the potential to monitor the growth of cereal crops; assess tiller numbers and measure leaf area index all of which can be used for controlling chemical inputs throughout the growing season.

4.2 Sensing theory

The theory of spectral reflectance has been previously described in section 3.1.1. The ultrasound sensors work by sending out a pulse of sound and waiting to hear the echo. The sound leaves the transmitter and bounces off the first surface it comes into contact with, the returning echo being recorded by the receiver. If the speed of sound is known, the distance between the sensor and the object can be calculated from the time delay between the emitted and reflected sound. While in principle calculating distance from time of travel is simple it should be noted that temperature of the air will alter the speed of sound (Nelkon and Detheridge, 1987) by

$$v=\sqrt{\frac{\gamma R T}{M}}$$

where v is the velocity of sound in m s^{-1}, γ is the ratio of the molar heat capacities of the gas, R is the universal gas constant in kJ mol^{-1} K^{-1}, T is the absolute temperature in K and M is the mass of 1 mole of the gas in kg $kmol^{-1}$. However since R is the universal gas constant; γ and M are constant for a given gas such as air, it follows that

$$v \propto \sqrt{T}$$

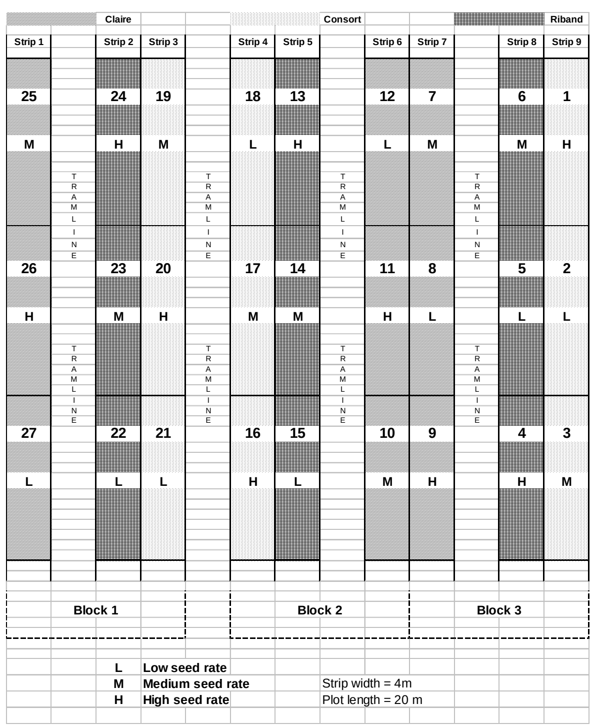
Ultrasonic sensors typically have an operating range of 90ºC which would result in measurement errors of greater than 30%, therefore ultrasonic sensors usually incorporate temperature measurement and compensation. In addition the humidity of the air alters the attenuation of the sound, higher frequencies improve the sampling interval and response times of the senor, but attenuate more thus reducing its range. Therefore the frequency of ultrasonic sensors is related to the distance the sensor is designed to measure. High frequencies (typically 400 kHz) are used for measuring short distances (approximately 0.5 m) whereas longer distances (5 m) require a lower frequency (typically 50 kHz).

4.3 Materials and Methods

4.3.1 *Field experiments*

Field experiments were conducted over two consecutive growing seasons 2001/2002 and 2002/2003. In each season a range of crop canopies were obtained by manipulating variety and seed rate. In the 2001/2002 growing season a plot trial was established on the 19th October in a field with heavy clay soil typical of that used for commercial winter wheat production in the UK. Three varieties of winter wheat each sown at three different seed rates, making a total of nine treatments were used which were replicated three times across the plot area making a total of 27 plots. The varieties were Claire, Consort and Riband (HGCA, 2000d), these varieties being the most commonly grown varieties of class 3 winter wheat in the UK (Dalgety, 2000). The three seed rates used were 50, 150 and 250 kg ha^{-1} being selected as low, typical and high seed rates respectively for mid October sowing of winter wheat (Primrose McConnell's, 1995). Due to the logistics of drill operation at field scale the plot experiment was designed in blocks and strips these were randomised using a statistical software package (Genstat®). Three blocks were used each one containing the nine treatments (3 varieties by 3 seed rates). A block contained three strips each representing a wheat variety and within each strip the three seed rates, for ease of identification the plots were numbered 1 to 27 (Figure 4.3.1.1). Each plot was 4 m wide (the drill width) by approximately 20 m to ensure the required seed rate was achieved for each plot following the seed rate being adjusted on the drill.

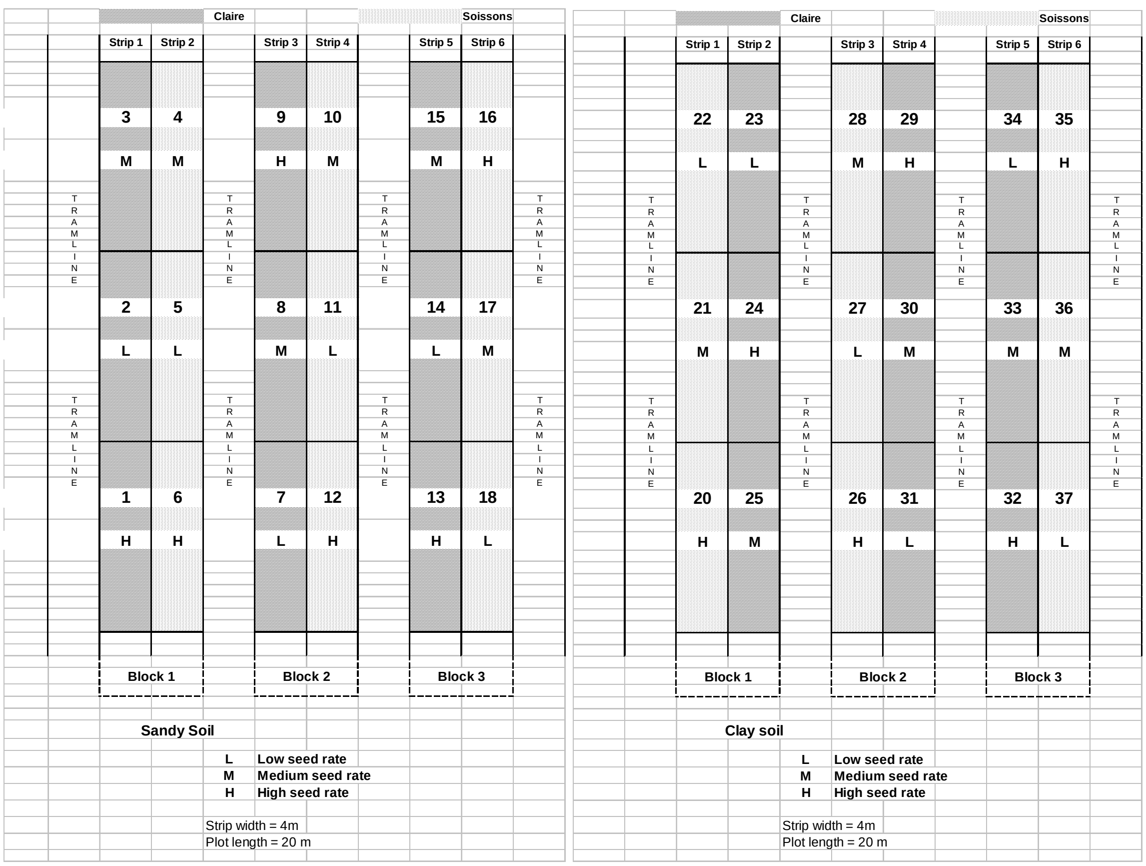
Figure 4.3.1.1 Layout of plot experiment for growing season 2001/2002



In the 2002/2003 season a plot trial was established on the 12-13th October. This trial involved two wheat varieties (Claire and Soissons) drilled at three seed rates (50, 150 and 250 kg ha^{-1}) on two soil types (sandy and heavy clay). Hence making a total of 12 treatments each replicated three times in a block design similar to that used in the previous trail resulting in a total of 36 plots. For ease of identification the plots were numbered 1 to 18 on the sandy soil and 20 to 37 on the clay soil (Figure 4.3.1.2).

In both years the whole plot area was treated uniformly in line with good agricultural practice in terms of weed control, fertilisers' inputs, fungicides and growth regulators. The aim was to minimise any variability associated with weeds, disease and fertiliser deficiencies.

Figure 4.3.1.2 Layout of plot experiment for growing season 2002/2003



4.3.2 *Design of experimental equipment*

A crop canopy measurement system which incorporated radiometers, a spectrometer and ultrasonic sensors was designed and constructed. A brief description of the system is given below and a full specification together with information on operating the system is provided in Appendix A

The canopy measurement system used two, 2-channel radiometers (Skye, type SKR 1800) measuring at narrow bandwidths, approximately 20 nm, centred at 660 and 730 nm. One radiometer, fitted with a cosine corrected head having an acceptance angle of 180º, was mounted pointing upwards to measure incoming radiation (sunlight) while the other pointed downwards, with an acceptance angle of approximately 20º, to measure the reflected light from the crop canopy. The upwards pointing radiometer had three levels of automatic gain within the signal conditioning to account for large differences in incident radiation (sunlight). The system automatically selected the most suitable gain thus preventing the radiometer from over-ranging in bright sunlight conditions, allowing the system to be used in most daylight conditions.

The spectrometer had 3 individual spectrometer channels and 3 corresponding sets of signal conditioning each channel measuring wavelengths ranging from 350 to 1000 nm with an optical resolution of 2 nm. One channel, fitted with a cosine corrected head having a 180º field of view (FOV), was mounted pointing upwards to measure incoming radiation (sunlight). The other two pointed downwards, having a FOV of approximately 25º, to measure the reflected light from the crop canopy. The spectrometer was factory optimised for operation within the range 400 to 850 nm and only data within this range was used for subsequent data analysis. Six metre optical fibres, of 200 μm diameter, were used to transmit light to each spectrometer channel each containing a fixed grating (600 lines mm^{-1}) and a charge coupled device (CCD) array detector with 2048 detecting elements. The fixed grating separated the collected spectrum into many small wavelength bands and the CCD array measures the light energy in each of the wavelength bands simultaneously. Signal conditioning converts the light energy into a digital signal and outputs all 3 channels via a universal serial bus (USB) link to a laptop computer, the USB link also supplies power to the spectrometer from the laptop computer. The software on the computer allowed the operator to select the integration time - the time the CCD arrays are exposed to the light source. Each channel of the spectrometer outputs a string of 2048 digital values from 0 to 4095 the value representing the illumination level on the individual detecting elements of the CCD array. The system was factory calibrated to ensure the illumination level on each of the detecting elements corresponds to the wavelength being measured.

Two ultrasonic sensors were used, both commercially available a Pepperl + Fuchs, type UC 2000-30GM-IU-V1 with a sensing range of 0.2 to 2 m and a Milltronics probe, type 1 with a sensing range of 0.25 to 5 m. Both sensors were fitted with temperature compensation allowing operation in all temperatures likely to be encountered in the UK.

The different measuring devices were mounted on a 3.75 m boom attached to the rear of a tractor so that they could be traversed over the crop canopy (Fig. 4.3.2.1). The output from each of the sensors was signal conditioned using an analogue to digital converter and transferred, via a universal serial bus (USB) link, to a laptop computer. Using the purpose written software on the laptop computer the radiometers and spectrometers were calibrated to give an output of light level and the ultrasonic sensors calibrated to give an output of distance. The radiometer values were further processed to give values of NDVI (Table 3.1.1.1) and the ultrasonic values were used to calculate a measure of crop height H in m using:

$$H = H_G - E$$

where, H_G is the height of the sensor above the ground (for all experiments this was set at 1 m) and E is the distance measured by the ultrasonic sensor in m. The purpose written software installed on the computer also allowed the operator to select the sampling interval, *i.e.* the frequency the samples were collected and duration of a sampling run.

Figure 4.3.2.1 The crop canopy measurement system in operation

Following the first growing season and prior to the second season improvements were carried out to the canopy measurement system which included:

- Installing a dedicated power supply rather than using power supplied off the tractor electrics.
- Replacing the Milltronics probe, type 1 ultrasonic sensor with another Pepperl + Fuchs, type UC 2000-30GM-IU-V1 ultrasonic sensor.
- Adding another downward pointing two-channel radiometer (Skye, type SKR 1800).

4.3.3 *Experimental procedure*

Using the canopy measurement system the plots were measured at approximately weekly intervals. For all experiments the downward pointing radiometer, spectrometer and ultrasonic sensor were mounted 1 m above the ground, the sampling frequency was 2 Hz and the run time was 10 s, therefore approximately 20 data values per plot were obtained. For these experiments the forward speed of the tractor was set at 0.22 m s^{-1}

therefore during a typical 10 s scan, a linear distance just over 2 m was covered resulting in sensor readings being recorded every 0.11 m travelled assuming a sampling frequency of 2 Hz.

During the first growing season (2001/2002) the plots were sampled between 25 March and 2 August 2002, representing crop growth stages (GS) between mid tillering (GS 25) and grain ripening (GS 91). In addition on several occasions between 11 April and 2 August 2002, the crop height of the plots was also measured using the ultrasonic sensor at a sampling frequency of 18 Hz, the fastest achievable with the system. For these experiments the run time was 10 s, so that approximately 180 crop height measurements were recorded on each of these sampling occasions. In the second growing season (2002/2003) all 36 plots were monitored at weekly intervals from 14 March to 11 June 2003, representing crop growth stages (GS) between mid tillering (GS 25) and early milk (GS 73).

During both growing seasons the plots were monitored periodically for plant numbers, tiller numbers, GS, crop height and leaf area index (LAI). Table 4.3.3.1 details the measurement methods used to monitor these parameters in each of the growing seasons.

Table 4.3.3.1 Measurement methods used to measure crop characteristics

	Methods used to measure parameter	
Measured parameter	Growing season 2001/2002	Growing season 2002/2003
Plant numbers (plant m^{-2})	The number of plants in three 1 m rows were counted on each plot and plants m^{-2} calculated in accordance to HGCA (1998a)	The number of plants in five 0.5 m rows were counted on each plot and plants m^{-2} calculated in accordance to HGCA (1998a)
Tiller numbers (tillers m^{-2})	The number of tillers in three 1 m rows were counted on each plot and plants m^{-2} calculated in accordance to HGCA (1998a)	The number of tillers in five 0.5 m rows were counted on each plot and plants m^{-2} calculated in accordance to HGCA (1998a)
Growth stage (Zadoks *et al*., 1974)	Assessed by visual inspection of the crop	Assessed by visual inspection of the crop
Crop height (cm)	Assessed using a metre rule at three locations within each plot, the average of these being recorded as the crop height.	The highest point of the crop was measured using a metre rule and recorded at five locations within each plot, the average of these measurements being taken as the crop height for each plot
Leaf area index (LAI)	LAI was assessed using destructive sampling. 20 tillers per plot were selected and their area measured using a Optimax image analysis system	LAI assessments were based on light transmittance measurements through the canopy using a commercially available instrument (SunScan – Delta T Devices)

4.4 Results and discussion

4.4.1 *Plot establishment*

The wet weather in October 2001, at the start of the 2001/2002 growing season resulted in the plots being drilled into a less than ideal seedbed. This, coupled with continuing rain, resulted in lower than expected establishment. As a result the low seed rate plots, 50 kg ha^{-1}, for all three varieties were not monitored during the experiment due to insufficient plant numbers. Therefore the results reported for the 2001/2002 growing season are for all three varieties at the two higher seed rates, namely 150 and 250 kg ha^{-1}. No problems were encountered with establishment during the 2002/2003 growing season and all 36 plots were monitored. However early spring 2003 was particularly dry resulting in slower than normal development of the canopies.

For the duration of the experiment, only low levels of weeds and disease were observed on any of the plots in either growing season. In addition, none of the plots indicated any signs of nutrient deficiencies. Hence, the uniform treatment was successful and it is considered that any variability associated with weeds, disease and fertiliser deficiencies were negligible between any of the plots.

4.4.2 *Comparison of vegetation indexes*

Measuring reflectance of a crop at specific wavelengths and calculating vegetation indexes enables information about the character of the crop to be determined. Many studies have been undertaken and a number of vegetation indexes described (Table 3.1.1.1), however most of these authors only use one index making it difficult to make comparisons between different indexes. Therefore from the literature it is often unclear which wavelengths or index is the most suitable for a given application; or indeed if there are benefits in using a particular wavelength index combination over another. The aim of this comparison was to use the measured spectral reflectance values (400 to 850 nm) of the three varieties of winter wheat grown in the 2001/2002 growing season and to assess the degree to which the described vegetation indexes, as listed in Table 3.1.1.1, differ from each other.

During the 2001/2002 growing season six of the high seed rates plots were used for the comparison (Claire plots 26 & 9; Consort plots 1 & 16 and Riband plots 4 & 24). These plots were scanned on 17 occasions between 25 March and 2 August 2002, representing growth stages (HGCA, 1998a) between mid tillering (GS25 and ripening (GS 91) using the spectrometer. For these experiments only two of the three spectrometer channels were used; one was pointing upwards measuring incoming radiation (sunlight) and the other pointing downwards measuring the crop reflectance. At the beginning of each sampling occasion the integration time was set so that the spectrometer channel measuring incoming radiation (sunlight) was approximately three quarters of full scale. During the term of the experiment the integration time ranged from 20 ms (sunny days) to 60 ms (cloudy days).

The output readings from the two channels of the spectrometer were averaged into 10 nm bands, each averaged reading representing a 10 nm band for example band 400 was the average of readings from 395 to 405; band 410 from 405 to 415...................band 850 from 845 to 855. The percentage crop reflectance R, % for each 10 nm band was calculated using:

$$R = \frac{S_c^{10}}{S_s^{10}} \times 100\,(for\ each\ 10nm\ band)$$

where S_c^{10} and S_s^{10} represent the 10 nm bands for spectrometer channel pointing downwards towards the crop and upwards towards the sky respectively.

For each of the 6 plots (2 of each variety) on each of the 17 sampling occasion a value of R for each 10 nm band, from 400 to 850 inclusive, was obtained by taking the average of the 20 readings taken during a typical scanning run. These average values of R representing the reflectance value for an area approximately 1 m^2, *i.e.* the total area scanned during a typical scanning run of 10 s.

For all 17 sampling occasions the vegetation indexes, as detailed in Table 3.1.1.1, were calculated for each of the six plots using the appropriate R values. It should be noted that 4 values of NDVI were calculated using the different wavelengths specified by the authors listed in Table 3.1.1.1 making a total of 13 different vegetation indexes. To enable one index to be compared directly with another each set of 17 calculated index values were normalised.

Index and variety combination were plotted against time, forming profile response curves which followed the general pattern of increasing to a maximum, as the canopy increased in size, and then decline as the crop senesced. Over the observed period the curves for set of plots exhibited the same patterns for each vegetation index. With no mechanistic model to underpin an analysis, the approach adopted to compare these curves followed Verbyla *et.al*. (1999) in which a spline model is fitted to the overall data and then 'discrepancy functions' (*i.e.* the offset of the individual data points from the spline model) are applied to the overall spline model representing the effects of indices and varieties. When these discrepancy functions are plotted (Figures 4.4.2.1 and 4.4.2.2) various trends can be observed. All four values of NDVI and SAVI for all variety and plot combinations have very similar 'M' shape discrepancy values. Similarly RVI, RVI_G, CE, PRI and NirGR have very similar 'W' shape discrepancy values. WDVI also has a 'W' shape curve but the values are higher than those observed with the other 'W' shape curves. Whereas neither the $VARI_{green}$ nor the $VARI_{700}$ have a well defined pattern. On closer inspection of these discrepancy values we can further group the 'M' and 'W' shape curves since one is simply the inverse of the other. On investigation of the wavelengths used to calculate these indexes it is observed that they all use a combination of wavelengths either side of the red edge, *i.e.* one in the NIR region and one or more from the visible range. In contrast to this the two vegetation indexes that were different from all the others only uses wavelengths in the visible range.

Figure 4.4.2.1 Discrepancy plots for different vegetation indexes over time for plots 26 (Claire), 1 (Consort) and 4 (Riband).

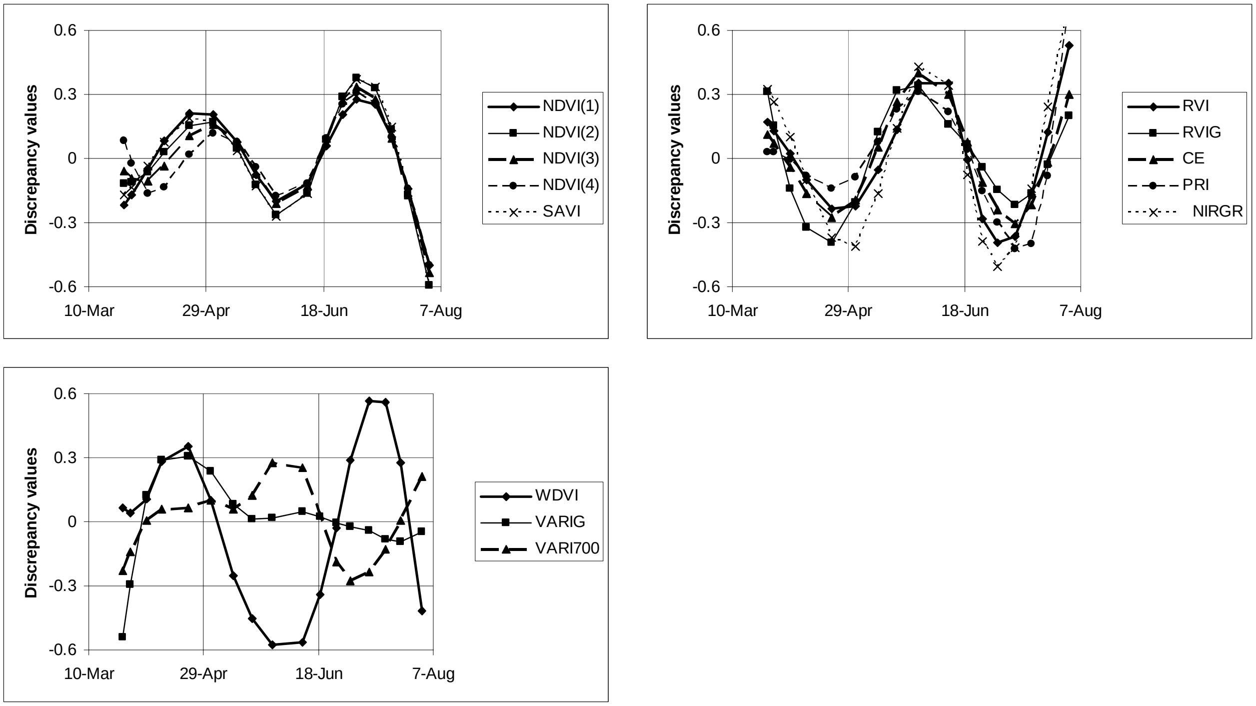
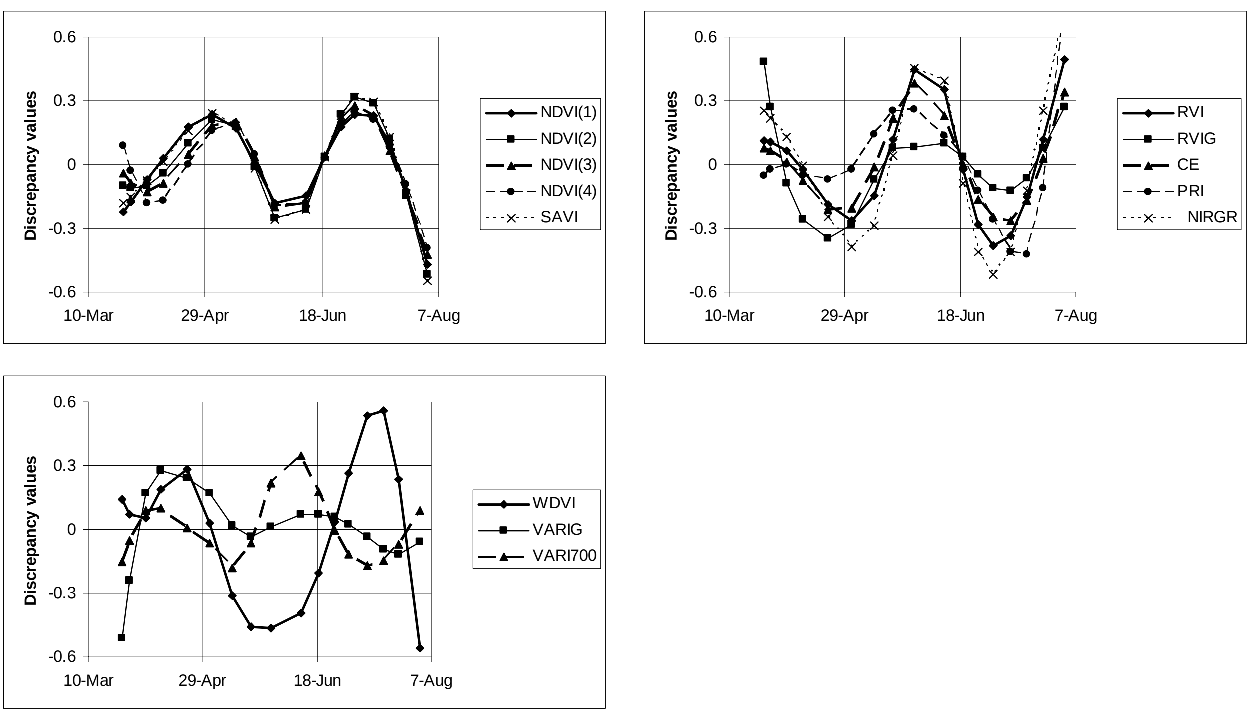


Figure 4.4.2.2 Discrepancy plots for different vegetation indexes over time for plots 9 (Claire), 16 (Consort) and 24 (Riband).

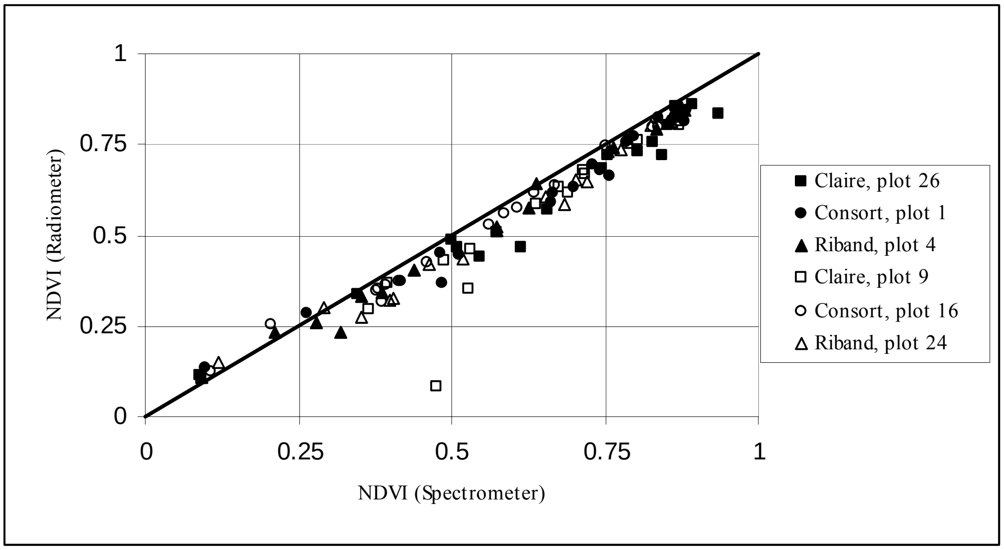


The evidence suggests that when using vegetation indexes to look at different canopy sizes then any vegetation index using wavelengths from the either side of the red edge will give similar results. Even though the discrepancy plots indicate that the $VARI_{green}$ and $VARI_{700}$ have a different shape of discrepancy curve they still seem to exhibit a similar trend to the other vegetation indexes for this application. It should be remembered that this comparison was conducted on plots that differed in variety and plant density only and that the varieties chosen were similar in colour. If experiments were conducted on different soil types or different nitrogen levels for example it might be expected that certain vegetation indexes may be more useful than others, but further work is required to verify this.

It seems clear that there is no particular benefit from using one vegetation index over another when assessing the different size of canopies, especially when the wavelengths used to calculate the index are from either side of the red edge. The most popular and widely used vegetation index for crop studies is the NDVI (Basso *et al*., 2001; Godwin, 2000; Oberti & De Baerdemaeker, 2000). It was therefore decided to only use the NDVI values for the remainder of the data analysis conducted in this study, there being no obvious benefit in using other vegetation indexes. Obviously calculating different vegetation indexes is not the only way to analyse hyperspectral data. However a comprehensive project on the subject (Wiltshire *et al*., 2002) funded by HGCA has recently been completed and therefore did not justify further analysis in this project.

As well as being able to measure the NDVI using the spectrometer the canopy measurement system was also fitted with radiometers for the purpose of specifically measuring NDVI values. To ensure that these two sets of NDVI values gave similar values, values of NDVI were obtained from the same six plots on each of the measuring occasions using the radiometers allowing the two to be compared. Figure 4.4.2.3 shows a comparison between the two sets of NDVI values. From this graph it can be seen that the NDVI values calculated using the spectrometer gave slightly higher absolute values than those obtained from the radiometers, nevertheless there is a good linear relationship between the two sets of data indicating that either would provide a similar measure of canopy size. For the remainder of the data analysis conducted in this study all NDVI values are those obtained from the radiometers.

Figure 4.4.2.3 Comparison of NDVI values measured using the spectrometer and radiometers for Claire, Consort and Riband plots during the 2001/2002 growing season

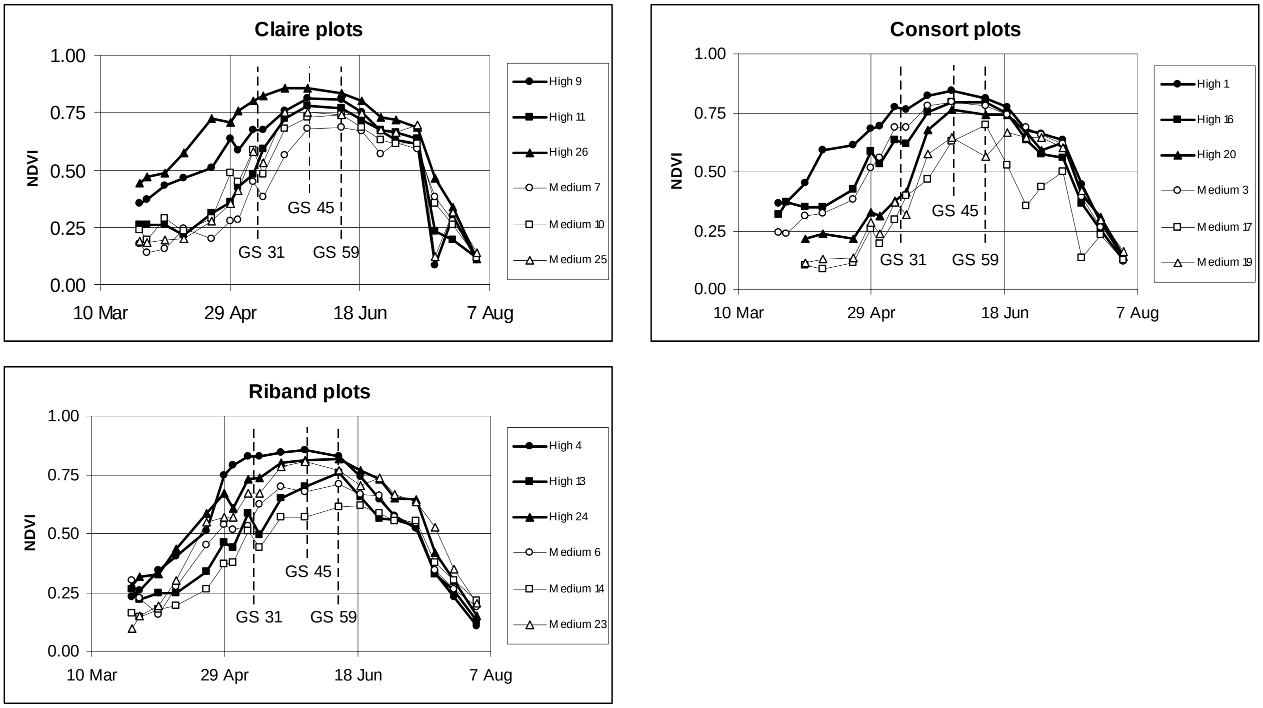


4.4.3 *Measuring crop growth using normalised difference vegetation index*

For each plot a single value of NDVI was calculated by taking the average of the 20 readings taken during the 10 s scanning period. For the three varieties assessed during the 2001/2002 growing season, the average NDVI values for each plot were plotted against time (Figure 4.4.3.1). As expected NDVI values gradually increased with time until a maximum was reached before starting to decrease. For the majority of plots, especially the high seed rate plots, the most rapid gain in NDVI occurred up until early to mid May, when the crop was at about GS 31/32 (early stem elongation). Following this period NDVI values increased more slowly peaking in late May, corresponding to about GS 45 (mid booting), before starting to decrease. Although generally this represents a typical canopy expansion and senescence curve of winter wheat (HGCA, 1998), it should be noted that maximum LAI usually occurs at or just after GS 59 (ear completely emerged) whereas the measured NDVI values peak at about GS 45 (mid booting). In addition it is reported (HGCA, 1998) that the greatest increase in LAI occurs between GS 31 (first node detectable) and GS 39 (flag leaf all visible), during this period the NDVI values increase gradually, whereas LAI values typically increase from about 2 to 6. This evidence illustrates the limitations of using NDVI measurements to estimate LAI beyond GS 31 (first node detectable) and concurs with the findings of Dampney *et al*., 1998 and Danson and Rowland, 2000.

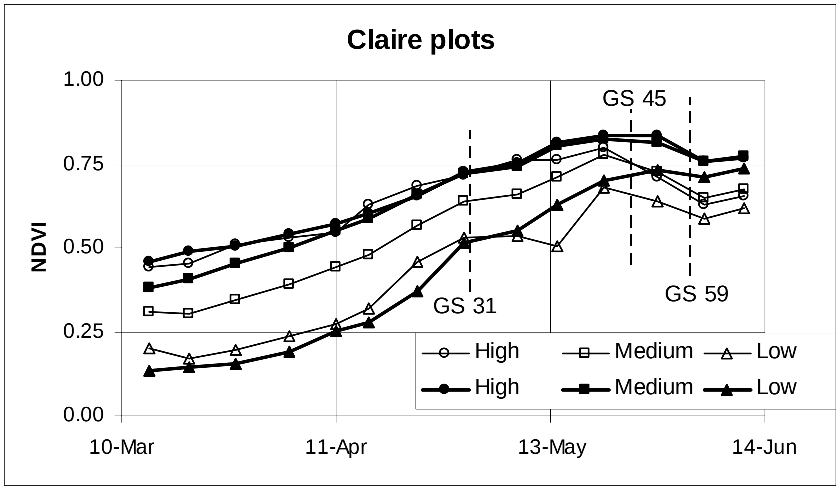
Although all of the plots illustrate the typical expansion and senescence curve of a winter wheat canopy it can be seen that the high seed rate plots (250 kg ha^{-1}) generally have a higher value of NDVI throughout the growing season than the lower rate plots (150 kg ha^{-1}) as expected. This is particularly true in the case of the plots established with the variety Claire. For these plots the tiller counts for the high seed rate plots were all higher than lower seed rate plots. In the case of the plots established with the variety Consort, it can be seen in particular that the medium seed rate plot (3) has a high value of NDVI, comparable with that of the high seed rate plots (1) and (16). However, this corresponds to a higher tiller count compared with either of the other two medium seed rate plots. For plots established with the variety Riband, the NDVI values for all of the plots are much closer, nevertheless higher NDVI values tend to correspond to increasing tiller numbers.

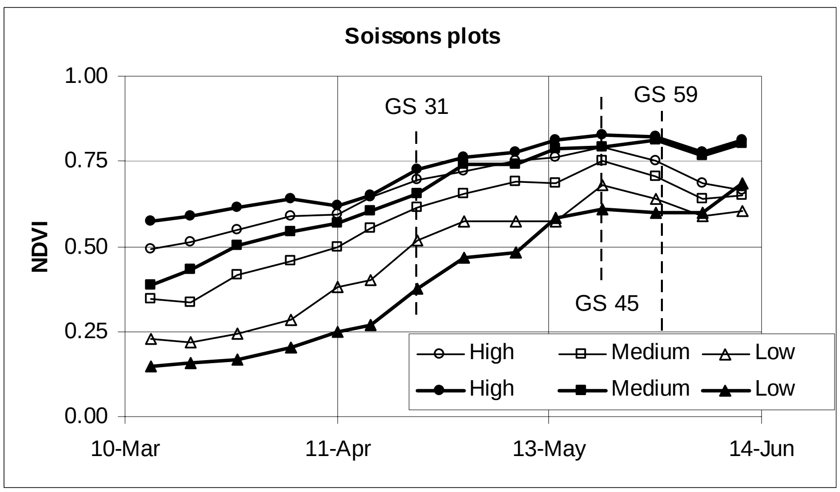
Figure 4.4.3.1 relationship between NDVI and time for the high and medium wheat plots during the 2001/2002 growing season



For the 2002/2003 growing season data a single value of NDVI was obtained for each of the 12 treatments (two varieties, three seed rates and two soil types) by taking the average of each set of the three plots representing a particular treatment, these values were plotted against time (Figure 4.4.3.2). During this season we do not see the early rapid gain in NDVI values that was observed in the previous year. However this is considered to be caused by a lack of rain resulting in generally smaller and slower developing canopies that would have been anticipated. Nevertheless once again we saw that the higher seed rate plots in the majority of cases did have a higher NDVI value throughout the season compared to the lower rate seed rates. The exception to this being that the medium rate Claire and Soissons plots on the clay soil which tend to have similar values of NDVI to the high seed rate plots, despite having a lower number of tillers. Suggesting that the tillers on the medium rate plots were larger than those on the high seed rate plots thus indicating that NDVI cannot be directly used for estimating tiller numbers.

Figure 4.4.3.2 Relationship between NDVI and time for high, medium and low seed rate plots for the 2002/2003 growing season (thin & thick lines represent sandy & clay soil respectively)





4.4.4 *Measuring crop growth using ultrasonic measurements*

For each plot a single value of crop height was obtained by taking the average of the 20 readings obtained during the 10 s scanning period. For all 3 varieties assessed during the 2001/2002 growing season the average values were plotted against time (Figure 4.4.4.1). From this figure it can be seen that the most rapid gain in crop height for all of the plots occurred from early May, when the crop was at about GS 30 (early stem elongation) to mid June, when the crop was at GS 59 (ear completely emerged). Prior to this period, pre GS 30, the height of the crop increased only steadily. This evidence suggests that ultrasonic sensors are most useful in monitoring the growth of winter wheat from GS 30 up to GS 59 when the crop gains no further height. This is trend is repeated during the 2002/2003 growing season (Figure 4.4.4.2) when a single value of ultrasonic crop height was obtained for each of the 12 treatments (two varieties, three seed rates and two soil types) by taking the average of each set of the three plots representing a particular treatment, these values were plotted against time.

Figure 4.4.4.1 relationship between ultrasonic crop height and time for the high and medium wheat plots during the 2001/2002 growing season

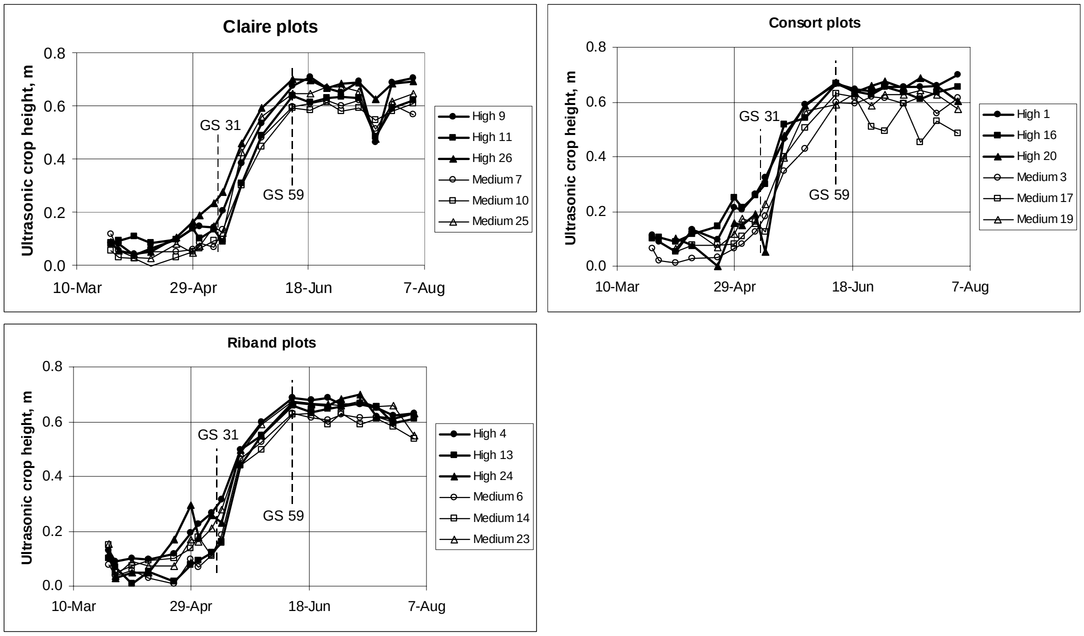
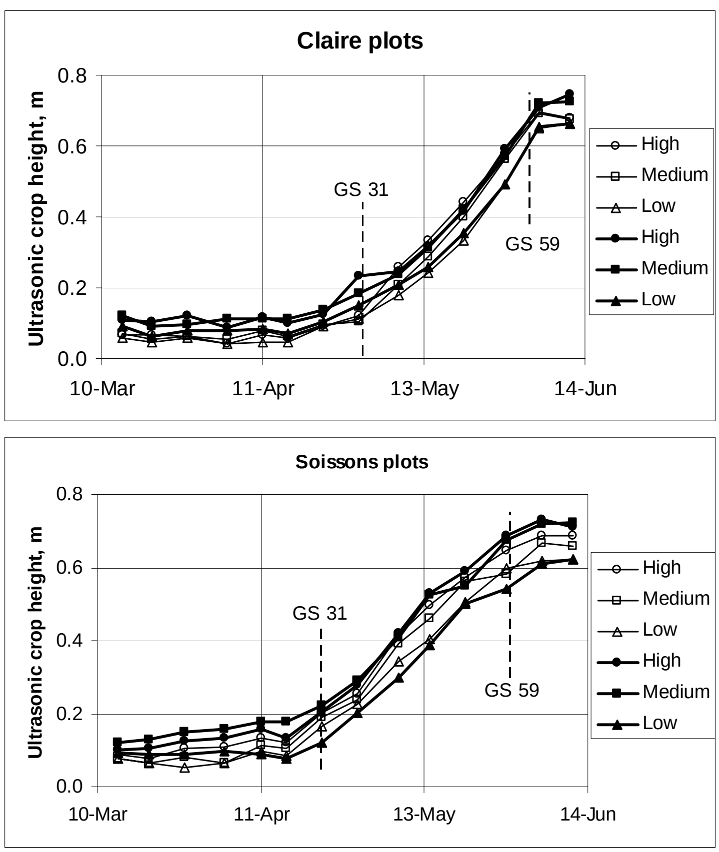


Figure 4.4.4.2 Relationship between ultrasonic crop height and time for high, medium and low seed rate plots for the 2002/2003 growing season (thin & thick lines represent sandy & clay soil respectively)



4.4.5 *Combination of sensing approaches to monitor crop growth*

When using these type of sensing approaches to monitor the growth of winter wheat the evidence presented above suggests that the NDVI measurements are most useful up to GS 31 and less useful after this stage whereas the ultrasonic crop measurements are most useful from GS 31. It therefore seems sensible to suggest that, by combining these two measurements, the growth of winter wheat can be monitored throughout the growing season. Pre GS 30 the crop is tillering and increasing in biomass, which is illustrated by the gain NDVI values, but not growing vertically indicated by the results of the ultrasonic sensor. It then starts to grow vertically until the ear is fully emerged at which point the crop gains no further height. During this period the NDVI values only increases slowly, especially when the crop is not water limited as it was in the 2002/2003 growing season, before starting to decrease. In contrast the ultrasonic sensor measurements increase rapidly from GS 31 to 59 which correspond to increasing LAI. The crop then starts to senesce following GS 59 at this point the NDVI values decrease rapidly whereas the ultrasonic crop height remains relatively constant.

This evidence illustrates that combining these measurements enables the crop can be monitored over the complete growing season which cannot be achieved using either sensing approach in isolation. In addition the sensors have proved reliable indicating their robustness and suitability for agricultural use. However to make practical use of such sensing systems information about the canopy that can be linked directly to agronomic decisions is required, *e.g*. crop height, crop density (tiller numbers) and leaf area index (LAI).

4.4.6 *Estimation of crop height*

The ultrasonic sensor records the distance to the first object the sound pulse comes into contact with, for a crop such as winter wheat, the sound pulse may bounce off the ground, *i.e.* missing the plants completely, or a lower part of the plant and not necessarily off the top of the canopy. This is especially true before canopy closure at about GS 31/32 or where the crop is open and has a low plant or tiller density. Therefore simply taking the average value (as used in Section 4.4.4) will not give a true representation of crop height.

On several occasions during the 2001/2002 growing season the ultrasonic sensor was used to measure the crop height at a sampling frequency of 18 Hz (Section 4.3.3). It should be noted that only the data from the Pepperl + Fuchs ultrasonic sensor was used, the other ultrasonic sensor did not produce reliable data and was subsequently replaced with a Pepperl + Fuchs sensor (see Section 4.3.2). Using these data sets to estimated the crop height H_E; 50%, 75%, 90%, 95% and 100% percentile values were calculated and compared with the manually measured value of the crop height H_M (as described in Table 4.3.3.1). Sums of squares S_S defined as:

$$S_S = \sum (H_M - H_P)^2$$

where H_P is the percentile value of the crop height, were used to identify which percentile value gave the best indication of H_E (Table 4.4.6.1). From this table it can be seen that the 75% to 95% percentiles generally provided the best estimate of crop height for each of the plots *i.e.* they have the lowest sums of squares.

However, when all the plots are considered together, the 90% percentile provides the best overall estimate of crop height and therefore this value was considered to be the most useful for estimating the crop height when compared against the value for H_M.

Table 4.4.6.1 Results of the sums of squares analysis for the 50%, 75%, 90%, 95% and 100% percentiles for the 18 plots of winter wheat grown during the 2001/2002 growing season; values in bold represent the lowest calculated value of sums of squares for each of the plots

Wheat variety and seed rate	Plot	Sums of squares for different percentiles 50%	75%	90%	95%	100%
Claire high	9	0.043	**0.022**	0.022	0.027	0.048
	11	0.074	0.031	0.020	**0.013**	0.026
	26	0.134	0.067	0.036	0.029	**0.016**
Claire medium	7	0.071	0.044	0.033	**0.029**	0.039
	10	0.073	0.035	0.018	**0.013**	0.015
	25	0.054	0.031	**0.030**	0.033	0.065
Consort high	1	0.043	0.020	**0.015**	0.018	0.059
	16	0.054	**0.044**	0.047	0.052	0.090
	20	**0.033**	0.049	0.079	0.100	0.141
Consort medium	3	0.035	**0.022**	0.023	0.033	0.089
	17	0.107	0.051	**0.046**	0.060	0.078
	19	0.045	**0.036**	0.049	0.058	0.129
Riband high	4	0.022	**0.009**	0.010	0.018	0.042
	13	0.083	0.045	**0.029**	0.040	0.068
	24	0.083	0.035	0.019	0.012	**0.006**
Riband medium	6	0.127	0.053	0.028	0.015	**0.009**
	14	0.109	0.056	0.038	**0.036**	0.061
	23	0.066	0.031	**0.024**	0.028	0.032
Total		1.255	0.682	**0.565**	0.614	1.013

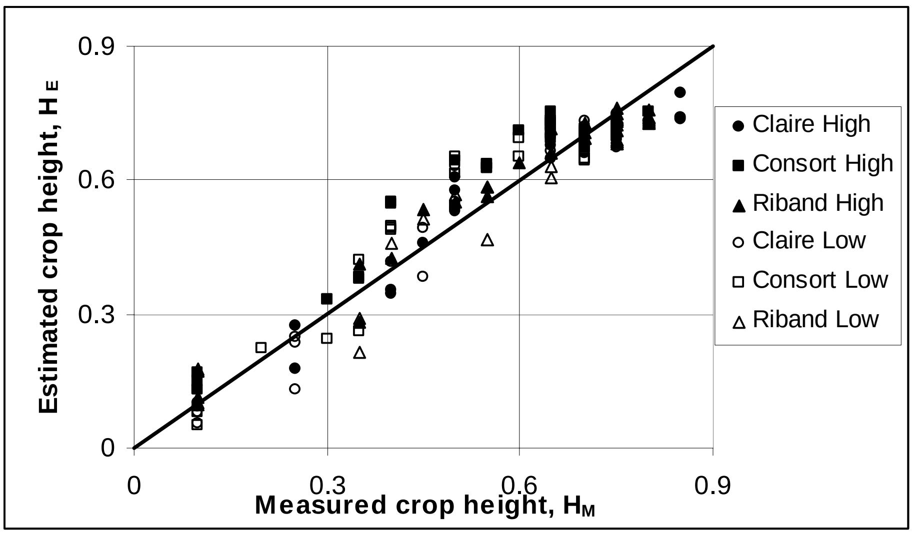
The estimated crop height values H_E (the 90% percentile values) were plotted against the measured crop height values for H_M (Fig. 4.4.6.1). Values of standard error per observation (se) were calculated for each data set representing a variety at medium and high seed rates using:

$$se = \sqrt{\frac{\sum (H_E - H_M)^2}{N}}$$

where N is the number of observations. When considering the yaw associated with the ultrasonic sensor being mounted on a 3.75 m boom attached to the rear of a tractor travelling at 0.22 m s^{-1} and the subjective nature of the manually measured crop height, the standard error per observations are small, ranging from

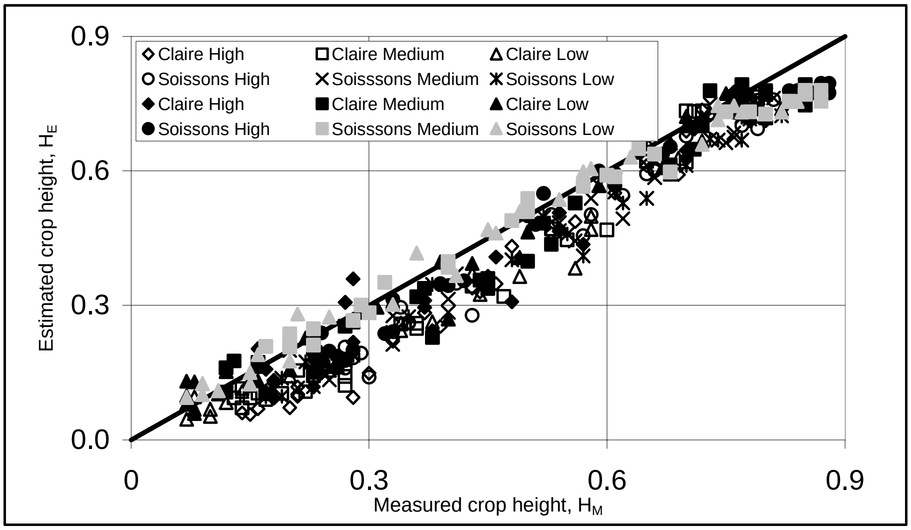
±0.046 m for plots established with Riband at the high seed rate to ±0.072 m for the plots established with Consort also at the high seed rate. These results compares favourably with the work of Kataoka *et al*. (2002) where an ultrasonic sensor was used to measure the height of soyabeans and maize achieving accuracies of ± 0.03 m and ± 0.10 m respectively. These authors concluded that better accuracies were achieved with the soyabeans since this is a broad leafed crop and the leaf surfaces are horizontal, *i.e*. perpendicular to the ultrasonic sensor, whereas the leaves of maize grow in a vertical direction providing a smaller target for the ultrasonic pulse, this also tends to be the case with winter wheat.

Figure 4.4.6.1 Estimated crop height values H_E (the 90% percentile values) compared with the measured crop height values H_M for the 2001/2002 growing season. Values of standard error (se) per observation high seed rate plots Claire ± 0.054, Consort ± 0.072, Riband ± 0.046 and medium seed rate plots Claire ± 0.055, Consort ± 0.066, Riband ± 0.058



The ultrasonic data analysed above was collected at a frequency of 18 Hz, a measurement being taken every 0.012 m travelled as the sensor was traversed across the plot. However for an ultrasonic sensor to be used commercially it would be desirable if this sampling resolution could be reduced, limiting the amount of data that would need to be collected and processed. The ultrasonic data from the 2002/2003 growing season was collected at a sampling frequency of 2 Hz, this data was analysed to establish the accuracy of the height estimation at this sampling frequency. In this case the 90% percentile values are calculated from both the ultrasonic sensors used in the second growing season and the average of these taken. Once again there is a good correlation of the output of the ultrasonic sensors compared to the manually measured crop height (Figure 4.4.6.2). The ultrasonic sensor does tend to under estimate the crop height, however the standard error per observation is still small and comparable with those obtained by Kataoka *et al*. (2002). This under estimation may be a result of the different sampling frequencies used or the different methods used to measure the crop height in each of the growing seasons, nevertheless despite these differences between seasons this work does illustrate the usefulness of such an approach to measure the height of a winter wheat crop.

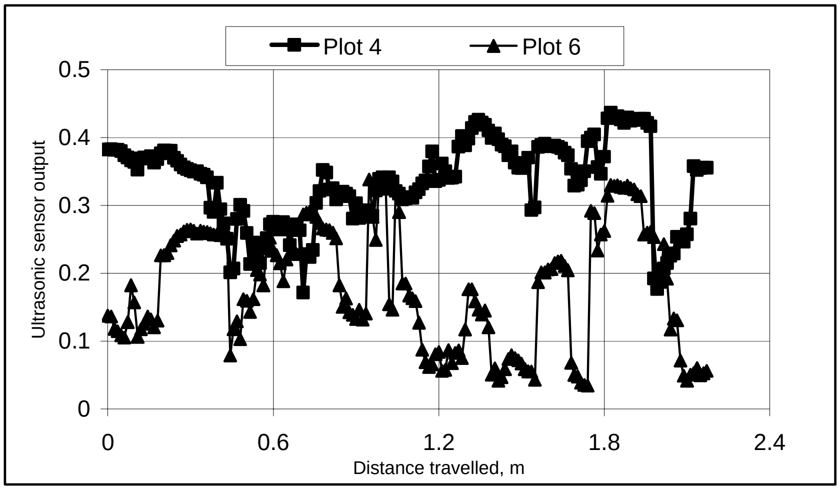
Figure 4.4.6.2 Estimated crop height values H_E (the 90% percentile values) compared with the measured crop height values H_M for the 2002/2003 growing season. (open symbols = sandy soil and filled in symbols = clay soil). Values of standard error (se) per observation ranging from ± 0.041 to ± 0.090



4.4.7 *Estimating crop density using the ultrasonic senor*

To estimate crop density it was hypothesised that there would be less variation in the ultrasonic sensor output as it traversed over the canopy for a dense crop compared with one of lower density. Figure 4.4.7.1 illustrates a typical example of the data obtained from a high and medium seed rate plots during the 2001/2002 growing season, on examination of this example this seems to be the case. To test this hypothesis, the coefficient of variation (CV) of the ultrasonic sensor output was calculated for each treatment (seed rate, variety, soil type combination) on each of the measuring occasions. The CV values are given in Table 4.4.7.1 where the CV for each treatment is the average CV for the three plots of the same treatment and the standard deviation is that between the three plots. From this table it can be seen that the CV calculated for the 2001/2002 growing season is generally higher for the medium seed rate plots compared with those plots of higher seed rate. This tends to be the case until the end of May when the crop was at about GS 45 (flag leaf sheath swollen). During this period the difference in the CV for the high and medium seed rate plots generally decreases. Subsequently there are smaller differences in CV for any of the plots as they all tend to level off at less than 20% CV before starting to increase slightly after early July as the crop starts to senesce. This pattern is largely expected: pre GS 31 (first node detectable) the thicker crops have more leaf area for the ultrasonic sensor pulses to reflect off, whereas on the thinner crops the pulses are more likely to miss the crop and be reflected from the ground. As the crop starts to grow vertically between GS 31 (first node detectable) and GS 59 (ear completely emerged), the leaves of the wheat tend to increase in size providing a larger target for the ultrasonic sensor pulses and are therefore more likely to offer a reflective surface even on the thinner plots. As the crop senesces the leaves die, reducing in size and opening up the canopy, so more ground is visible to the ultrasonic sensor pulses and therefore the CV tends to increase.

Figure 4.4.7.1 Typical example of ultrasonic sensor measurements versus distance travelled. Both examples are for Riband plots where Plot 4 is high seed rate and Plot 6 a medium seed rate, measurements taken on 12 May 2002



A similar trend is observed during the 2002/2003 growing season. Although during this season there are only small differences between the high and medium seed rate plots but the CV does increase for the majority of the low seed rate plots. These two seasons of results seem to indicate the potential of this technique to distinguish between different canopy densities, particularly up to GS 45 (mid booting), suggesting that the hypothesis is true and that tiller numbers can be linked directly to the CV of the ultrasonic height measurements. During the 2001/2002 growing season tillers were only counted on two occasions (12 April 2002 and 10 May 2002) whereas during the 2002/2003 growing season tillers were counted on a weekly basis. For the occasions when tillers were counted they were plotted against the CV of the ultrasonic height measurement (Figure 4.4.7.2). It can be seen from this graph that as expected the CV does tend to increase with decreasing tiller numbers. However there is a lot of noise in this data, indicating that for practical purposes it is unlikely that this technique can be used directly to determine tiller numbers without ground truthing.

Figure 4.4.7.2 Comparison of ultrasonic CV against tiller numbers

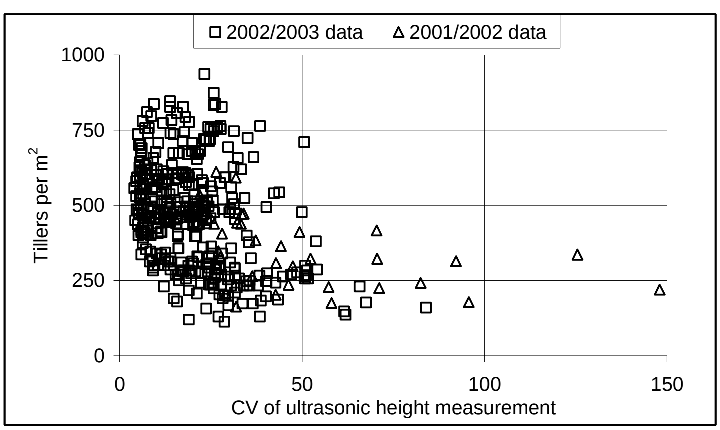


Table 4.4.7.1 Mean values of coefficient of variation (CV) of the ultrasonic signal (standard deviation in parenthesis)

Date and (GS)	Mean values of coefficient of variation (CoV)					
	Claire high	Consort high	Riband high	Claire low	Consort low	Riband low
2001/2002 growing season						
11 April (22-29)	52 (19)	60 (57)	33 (12)	96 (47)	75 (19)	56 (32)
02 May (30-31)	33 (4)	20 (2)	31 (18)	53 (22)	34 (0)	43 (25)
12 May (31-32)	32 (5)	23 (6)	33 (15)	48 (22)	31 (5)	42 (8)
20 May (37-39)	19 (7)	9 (4)	11 (5)	21 (6)	22 (4)	16 (7)
29 May (43-47)	8 (1)	9 (0)	9 (3)	14 (3)	14 (6)	9 (3)
11 June (55-59)	6 (1)	7 (1)	10 (2)	11 (6)	12 (7)	15 (6)
19 June (65-69)	6 (1)	8 (1)	10 (8)	9 (1)	18 (10)	13 (4)
26 June (69-73)	6 (1)	9 (3)	8 (2)	8 (2)	13 (7)	12 (8)
10 July (77-83)	9 (2)	10 (2)	10 (2)	9 (3)	19 (16)	12 (2)
24 July (83-87)	10 (2)	15 (4)	13 (2)	12 (6)	22 (15)	26 (3)

2002/2003 growing season (Claire)	Clay high	Clay medium	Clay low	Sandy high	Sandy medium	Sandy low
14 March (22-29)	16 (2)	16 (5)	18 (5)	19 (6)	17 (4)	16 (4)
20 March (22-29)	18 (3)	17 (4)	27 (6)	21 (10)	28 (16)	31 (14)
27 March (22-29)	18 (1)	25 (5)	23 (8)	18 (9)	24 (17)	22 (11)
4 April (22-29)	20 (8)	21 (8)	22 (6)	52 (32)	26 (10)	36 (11)
11 April (22-29)	21 (1)	22 (7)	17 (5)	32 (13)	23 (8)	44 (21)
16 April (22-29)	22 (7)	24 (10)	28 (14)	32 (17)	37 (13)	48 (12)
23 April (30)	19 (3)	25 (1)	22 (7)	24 (8)	25 (5)	26 (5)
30 April (31-32)	19 (3)	21 (1)	26 (10)	26 (10)	24 (5)	33 (16)
8 May (32–37)	17 (2)	20 (3)	24 (6)	13 (5)	20 (4)	35 (14)
14 May (37-39)	14 (3)	15 (4)	30 (9)	11 (4)	18 (2)	35 (14)
21 May (39-43)	13 (4)	15 (6)	28 (16)	13 (8)	15 (6)	34 (16)
29 May (51-59)	9 (3)	14 (3)	22 (8)	10 (5)	12 (4)	30 (22)
5 June (59-65)	6 (1)	6 (1)	14 (6)	7 (5)	7 (1)	11 (6)
11 June (65-71)	6 (1)	9 (7)	14 (4)	6 (1)	6 (1)	9 (3)

2002/2003 growing season (Soissons)	Clay high	Clay medium	Clay low	Sandy high	Sandy medium	Sandy low
14 March (22-29)	22 (4)	17 (2)	22 (8)	20 (6)	21 (5)	26 (5)
20 March (22-29)	20 (8)	18 (7)	28 (4)	27 (9)	25 (6)	34 (16)
27 March (22-29)	18 (3)	17 (5)	27 (24)	22 (9)	23 (3)	56 (29)
4 April (22-29)	21 (2)	20 (8)	26 (6)	30 (2)	62 (46)	57 (36)
11 April (22-30)	26 (1)	19 (1)	29 (11)	28 (3)	30 (10)	42 (19)
16 April (30)	29 (6)	18 (3)	33 (13)	33 (5)	43 (12)	56 (34)
23 April (31)	24 (6)	20 (5)	36 (13)	24 (1)	26 (7)	26 (11)
30 April (37)	21 (3)	23 (1)	34 (4)	24 (2)	25 (7)	30 (9)
8 May (39-41)	17 (4)	22 (3)	38 (10)	14 (0)	17 (5)	31 (7)
14 May (43-47)	9 (2)	10 (1)	33 (9)	9 (2)	15 (5)	24 (7)
21 May (45-59)	7 (1)	13 (3)	26 (12)	8 (1)	10 (3)	20 (8)
29 May (59-65)	6 (1)	8 (4)	33 (22)	9 (2)	15 (6)	15 (8)
5 June (65-71)	6 (0)	6 (1)	26 (13)	8 (2)	9 (1)	19 (8)
11 June (71-73)	6 (1)	7 (1)	22 (13)	9 (3)	9 (1)	18 (7)

4.4.8 *Estimating crop density using normalised difference vegetation index*

Similar to the hypothesis used for measuring crop density using the CV of the ultrasonic height measurements it was also noted that the CV of the NDVI measurement varied as it traversed across the plot and that it too was expected to be less variable on more dense plots (Figure 4.4.8.1). To test this hypothesis, the coefficient of variation (CV) of the NDVI measurements were calculated for each treatment (seed rate, variety, soil type combination) on each of the measuring occasions (Table 4.4.8.1). The CV values are the average CV for the three plots of the same treatment and the standard deviation is that between them. On examination of these values it can be seen that in all cases the CV of the NDVI measurements increased with decreasing seed rates, once again suggesting that tiller numbers can be linked directly to the CV of the NDVI measurements. Figure 4.4.8.2 shows the comparison between the CV of the NDVI and tiller numbers for the two growing seasons.

Figure 4.4.8.1 Typical example of NDVI versus distance travelled. Examples are for Soissons plots where Plot 20 is high seed rate, Plot 21 a medium seed rate and Plot 22 low seed rate on a clay soil, measurements taken on 27 March 2003

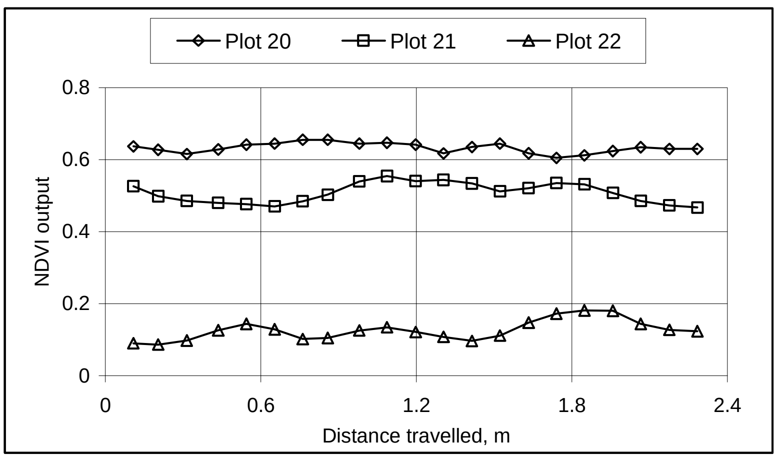


Figure 4.4.8.2 Comparison of NDVI CV against tiller numbers

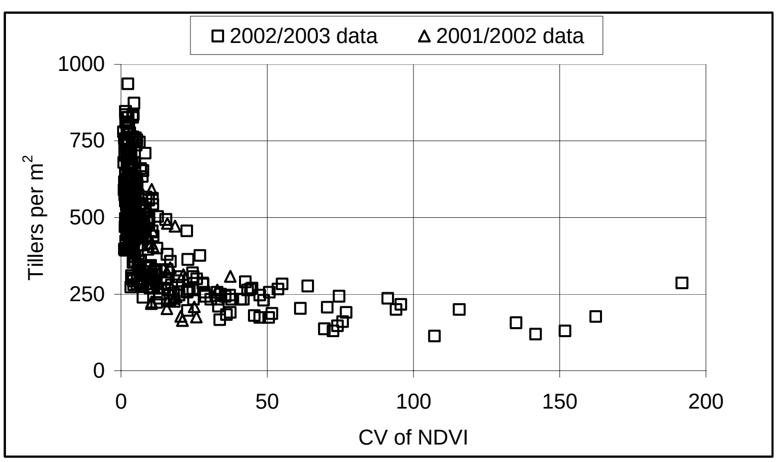


Table 4.4.8.1 Mean values of coefficient of variation (CV) for values of NDVI (standard deviation in parenthesis)

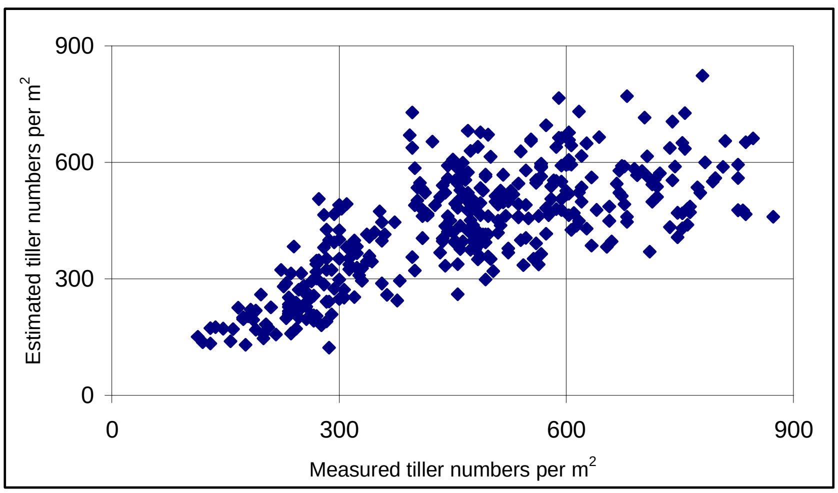
Date and (GS)	Mean values of coefficient of variation (CoV)					
	Claire high	Consort high	Riband high	Claire low	Consort low	Riband low
2001/2002 growing season						
11 April (22-29)	12 (3)	14 (6)	15 (4)	15 (4)	20 (6)	27 (9)
02 May (30-31)	8 (4)	9 (4)	8 (7)	15 (6)	22 (12)	17 (7)
12 May (31-32)	5 (3)	11 (1)	6 (6)	10 (2)	21 (14)	11 (5)
20 May (37-39)	4 (2)	4 (2)	6 (5)	10 (8)	13 (10)	10 (6)
29 May (43-47)	4 (2)	3 (1)	4 (5)	7 (1)	14 (10)	9 (6)
11 June (55-59)	3 (1)	5 (4)	2 (1)	8 (3)	17 (15)	10 (6)
19 June (65-69)	4 (1)	4 (1)	6 (4)	8 (4)	17 (14)	16 (5)
26 June (69-73)	8 (3)	9 (1)	9 (2)	12 (9)	21 (22)	9 (4)
10 July (77-83)	8 (1)	19 (2)	10 (4)	7 (3)	13 (7)	14 (3)
24 July (83-87)	23 (7)	19 (4)	19 (1)	19 (5)	22 (6)	25 (10)
2002/2003 growing season (Claire)						
	Clay high	Clay medium	Clay low	Sandy high	Sandy medium	Sandy low
14 March (22-29)	5 (2)	6 (1)	15 (4)	3 (1)	6 (1)	14 (1)
20 March (22-29)	6 (1)	6 (2)	16 (6)	6 (2)	10 (5)	18 (8)
27 March (22-29)	5 (0)	5 (0)	17 (7)	3 (2)	11 (6)	16 (4)
4 April (22-29)	4 (1)	5 (1)	22 (5)	3 (1)	5 (1)	14 (3)
11 April (22-29)	3 (0)	3 (0)	18 (5)	3 (1)	7 (3)	17 (8)
16 April (22-29)	3 (1)	4 (1)	17 (5)	3 (1)	5 (2)	14 (1)
23 April (30)	2 (1)	4 (2)	22 (4)	3 (1)	4 (2)	12 (8)
30 April (31-32)	2 (0)	3 (0)	12 (4)	2 (0)	4 (1)	11 (8)
8 May (32–37)	2 (0)	3 (0)	14 (5)	2 (0)	5 (2)	12 (9)
14 May (37-39)	2 (0)	2 (0)	13 (5)	2 (2)	3 (1)	36 (39)
21 May (39-43)	1 (0)	2 (1)	8 (2)	1 (0)	2 (0)	6 (6)
29 May (51-59)	1 (0)	2 (1)	10 (6)	2 (0)	3 (0)	7 (6)
5 June (59-65)	2 (1)	2 (1)	9 (4)	3 (2)	3 (1)	7 (6)
11 June (65-71)	2 (1)	2 (0)	6 (2)	2 (1)	2 (0)	7 (5)
2002/2003 growing season (Soissons)						
	Clay high	Clay medium	Clay low	Sandy high	Sandy medium	Sandy low
14 March (22-29)	4 (2)	13 (3)	15 (6)	5 (1)	6 (2)	8 (2)
20 March (22-29)	3 (1)	8 (2)	23 (4)	3 (0)	6 (1)	19 (9)
27 March (22-29)	3 (1)	7 (2)	23 (2)	4 (2)	7 (3)	14 (5)
4 April (22-29)	3 (0)	7 (2)	19 (6)	3 (1)	5 (0)	10 (2)
11 April (22-30)	3 (0)	4 (1)	20 (4)	3 (1)	5 (2)	10 (8)
16 April (30)	2 (1)	3 (1)	24 (3)	3 (1)	6 (2)	13 (7)
23 April (31)	2 (1)	5 (2)	16 (13)	2 (1)	4 (1)	8 (3)
30 April (37)	2 (0)	3 (0)	18 (5)	2 (1)	4 (1)	6 (4)
8 May (39-41)	2 (1)	3 (1)	19 (7)	2 (0)	4 (2)	9 (7)
14 May (43-47)	1 (0)	2 (0)	19 (11)	2 (0)	4 (1)	8 (9)
21 May (45-59)	1 (0)	2 (0)	15 (6)	2 (1)	3 (1)	6 (3)
29 May (59-65)	2 (1)	2 (1)	13 (6)	2 (0)	3 (1)	8 (5)
5 June (65-71)	2 (0)	3 (0)	12 (6)	3 (1)	3 (1)	7 (1)
11 June (71-73)	1 (0)	2 (1)	8 (4)	3 (1)	2 (1)	7 (5)

On examination of this graph it can be seen that there is a much better relationship between the CV of the NDVI and the tiller numbers than observed between the CV of the ultrasonic signal, indicating once again that this may be a useful technique to estimate tiller numbers. The usefulness of this technique was further investigated by determining the relationship between CV of the NDVI and tiller numbers during the 2001/2002 growing season and using this relationship to estimate the tiller numbers in the 2002/2003 growing season. It was found that the best fit relationship for the 2001/2002 growing season was power law fit of the form:

$$Tillers = 775 \times CV\ of\ NDVI^{-0.35}$$

Using this relationship the tiller numbers (m^{-2}) were estimated for all the treatments used in the 2002/2003 growing season and compared against the measured values (Figure 4.4.8.3). Although there is some degree of scatter in the data this technique offers potential to estimate a value of tiller density throughout the growing season that could be used to aid agronomic decisions without the need for ground truthing.

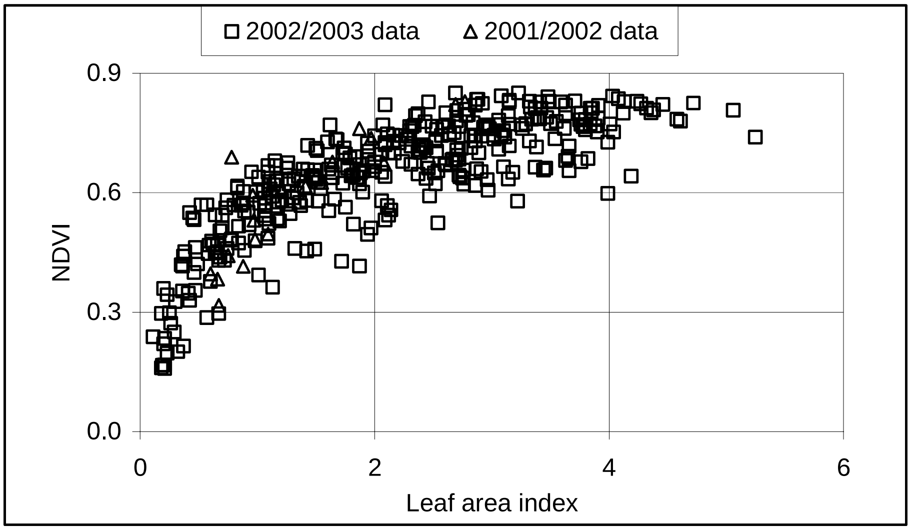
Figure 4.4.8.3 Comparison of estimated and measured tiller numbers for the 2002/2003 growing season (standard error per observation = ± 125 tiller m^{-2})



4.4.9 *Estimating leaf area index (LAI)*

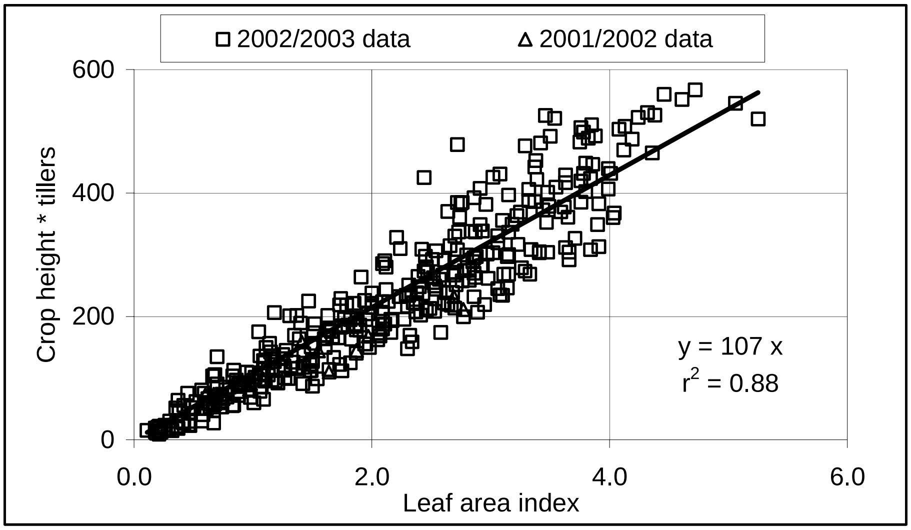
In section 4.1 it was suggested that NDVI was only suitable for estimating the leaf area index of the crop until canopy closure or until the crop has a leaf area of three or more. To illustrate this fact the LAI is plotted against the NDVI (Figure 4.4.9.1). As predicted NDVI is only useful up to about LAI 2 to 3 and then remains fairly constant after this point irrespective of the increasing LAI values. It should be remembered that the 2001/2002 LAI data was obtained using destructive sampling whereas the 2002/2003 LAI data was obtained using the SunScan instrument that uses light interception at the base of the canopy. Nevertheless both of these data sets follow this trend indicating that the two methods used for LAI measurement are comparable.

Figure 4.4.9.1 Comparison of normalised difference vegetation index (NDVI) and leaf area index (LAI)



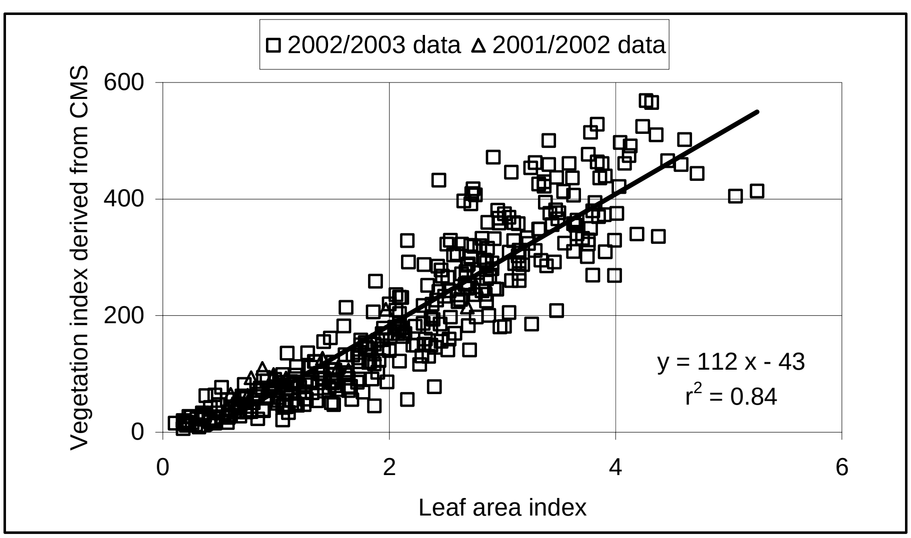
The fact that NDVI cannot be used to estimate LAI beyond about three is not unsurprising, since the reflectance values that are used to calculate NDVI are reflected mainly off the surface of the crop, whereas LAI is related to the volume of the crop and not the area as measured by NDVI. For example a tall plant is likely to have a larger LAI than a shorter plant due to the fact that as it grows taller it produces more leaves; and also that the leaves get bigger. It then follows that having more plants or tillers per unit area will also increase the LAI. To illustrate this point a volume measurement of the crop was calculated by multiplying the crop height by the number of tillers per unit area and compared against the leaf area index (Figure 4.4.9.2). It can be seen from this graph that there is a good relationship between the two with an r^2 value of 0.88, illustrating this is a much better method of estimating leaf area index than using NDVI. However crop height and tiller numbers used in this example were respectively measured and counted manually and therefore are time consuming to conduct and do not offer advantages over using destructive sampling or the SunScan instrument to measure LAI.

Figure 4.4.9.2 Comparison of leaf area index against a crop volume measurement (crop height * number of tillers)



It was previously shown in section 4.4.6 and section 4.4.8 that the crop height and tiller numbers respectively could be estimated from the output of the canopy measurement system, using a combination of the outputs from the ultrasonic sensor and radiometers. Therefore simply by substituting the manually measured values of crop height and tiller numbers with values estimated by the sensors used in the canopy measurement system it should be possibly to obtain a vegetation index that is related to the LAI (Figure 4.4.9.3). Thus illustrating by using a combination of simple measurement techniques that the leaf area index of a wheat crop can be monitored throughout the growing season.

Figure 4.4.9.3 Comparison of canopy measurement system vegetation index to LAI (standard error per observation ± 0.47)



4.5 Conclusions

- The tractor mounted canopy measurement systems worked enabling hyperspectral, normalised difference vegetation index (NDVI) and ultrasonic crop height measurements to be conducted over two growing seasons.
- Comparison of vegetation indexes indicated no clear benefit of using a particular index over another when assessing different sizes of canopies, especially when the wavelengths used to calculate the vegetation index are from either side of the red edge.
- Normalised difference vegetation index (NDVI) measurements provide a representation of a canopy expansion and senescence curve for winter wheat. However the information gained from this is limited; NDVI values are useful up to growth stage 31 and beyond growth stage 59 as the crop starts to senesce.
- Ultrasonic sensors proved useful for monitoring winter wheat beyond growth stage 30 and up to growth stage 59 when the crop reaches maximum height.
- Combining normalised difference vegetation index measurements and ultrasonic measurements enables the crop to be monitored over the complete growing season.
- The ultrasonic sensor was able to estimate the height of the crop over two growing seasons to an accuracy ranging from ± 0.04 to ± 0.09 m when compared against the manually measured height values of all varieties and soil types used in this study.
- Analysis of the ultrasonic data indicated that the coefficient of variation (CV) of the height measurements gave an indication of the crop density, but there was a lot of noise in the data. As a result the CV of the height measurements cannot be used to estimate tiller numbers.
- Analysis of the data indicated that the coefficient of variation (CV) of the normalised difference vegetation index data could be used throughout the growing season to estimate tiller numbers. Using a relationship identified in the 2001/2002 growing season the tiller numbers in the 2002/2003 growing season were estimated, without using ground truthing, to an accuracy of ± 125 tiller m^{-2} when compared with manually counted tillers.
- Leaf area index of winter wheat was found to correlate well with a volume measurement derived from manually measured values of crop height and manually counted values tillers.
- Using a relationship identified in the 2001/2002 growing season for estimating tillers, and crop height from data obtained from the canopy measurement system the leaf area index in the 2002/2003 growing season was estimated accuracy of ± 0.47 when compared to leaf area index measurements obtained using a commercially available light interception instrument.

5. DISCUSSION AND CONCLUSIONS

5.1 General findings

The findings of the agronomic review identified several sensing opportunities including seed bed condition, weed identification and crop canopy characteristics, which could potentially provide agronomic, economic and/or environmental benefits. Currently all of these parameters are assessed using visual inspection conducted during field walking and therefore these measurements are both subjective and time consuming to undertake. From an economic aspect it was identified that crop canopy characteristics had most scope for savings to be made by varying inputs, particularly fertilisers, fungicides and growth regulators. It has been suggested (HGCA, 2002b) that savings of up to £44 ha^{-1} can be obtained by varying these inputs which is nearly 20% of the typical variable costs of winter wheat production.

The most popular method used to assess crop canopy characteristics is spectral reflectance whether measured using radiometers, spectrometers or digital cameras. A review of this subject found that current spectral reflectance measurement techniques are sufficiently robust for agricultural use and provide a measure of green crop area. However they cannot distinguish between crop density and crop chlorophyll content; and once the crop has reached canopy closure when the crop is at about growth stage 31 spectral reflectance measurements tend to reach saturation and are less able to discriminate between differences in canopies. Nevertheless agronomic inputs have been based on these inputs with varying degrees of success (HGCA, 2002a; Miller *et al*., 2002). This review concluded that improvements in determining agronomic inputs would be made if crop cover or green area and crop structure could be measured independently especially if such measurements could be made once the crop had grown past growth stage 31 when the canopy reaches closure. This is particularly important for fungicide applications which are generally applied after growth stage 31 and for the second and third nitrogen applications which are also applied after the crop has reached growth stage 30, particularly when following canopy management principles (HGCA, 2000b; HGCA, 2002b).

Spectral reflectance is obviously a useful technique to assess canopy characteristics, but it does have its limitations. This study identified that ultrasonic sensing techniques may be able to provide a measure of canopy structure and be used in conjunction with spectral reflectance measurements to enable a better characterisation of the crop canopy. As a result a tractor mounted canopy measurement system was developed that incorporated spectrometers, radiometers and ultrasonic sensors. During two seasons of testing with the canopy measurement system it was found that:-

- Comparison of vegetation indexes indicated no clear benefit of using a particular index over another when assessing different sizes of canopies, especially when the wavelengths used to calculate the vegetation index are from either side of the red edge as a consequence of this normalised difference vegetation index (NDVI) measurements were used for all the data analysis.

- Combining normalised difference vegetation index measurements and ultrasonic measurements enables the crop to be monitored over the complete growing season.
- The ultrasonic sensor was able to estimate the height of the crop over two growing seasons to an accuracy of ± 0.09 m.
- Analysis of the ultrasonic data indicated that the coefficient of variation (CV) of the height measurements indicated the density of a wheat crop, but the data was noisy and it was unlikely that this technique could be used for this purpose. Whereas analysis of the data indicated that the coefficient of variation (CV) of the normalised difference vegetation index data could be used throughout the growing season to estimate tiller numbers to an accuracy of ± 125 tiller m^{-2}.
- Using the output from the canopy measurement system the leaf area index of winter wheat was estimated to an accuracy of ± 0.47 when compared to leaf area index measurements obtained using a commercially available light interception instrument.

These findings hold true for all the variety, seed rate and soil type combinations used in this study over two growing seasons. These combined sensing approaches enable winter wheat to be monitored throughout the growing season, beyond growth stage 31 which has generally been the limit of traditional spectral reflectance techniques. Using a combination of the coefficient of variation of the normalised difference vegetation index combined with the ultrasonic measurements enables estimates of crop height, tiller numbers and leaf area index to be made without the need for ground truthing. These values can then be used directly to aid the agronomic decision making process to determine the optimum level of inputs.

5.2 Practical implications from the work

This study has shown that a tractor mounted sensing system can be used to assess crop height, tiller numbers and leaf area index without the need for ground truthing over the complete growing season. These values can be used directly with canopy management principles to aid the agronomic decision making process to help determine the optimum level of inputs of fertilisers, fungicides and growth regulators based on the recommendations of the agronomist. It is important to recognise that

- a combination of sensing systems (spectral reflectance and ultrasonic sensors) mounted on a ground based vehicle offers the potential for the automated monitoring of crop condition, such systems can be used to provide estimates of crop height, tiller numbers and leaf area index throughout the growing season.
- these estimates can be linked directly to agronomic decision making process to help achieve the optimum level of inputs, in particular for fertiliser, fungicide and growth regulators.

- the aim of these sensing systems is to compliment agronomy not to replace it – more hectares per person.
- further developments of this prototype system are required to provide a system suitable for farm use.

Making full use of information from sensor systems such as those developed as part of this project is likely to require some further research and, initially at least, involve third parties to work with farmers/advisors to interpret such data and make recommendations relating to crop inputs.

As indicated in the review part of this report, information defining aspects of canopy structure is likely to be relevant to the application of surface acting chemicals (e.g. some fungicides), to matching application variables to target specific parts of the crop canopy or as inputs to crop development predictions in terms of nutrient and/or growth regulator inputs. These are areas of previous and ongoing commercial developments involving for example:

- The tractor mounted sensors of the Hydro Precise system for determining nitrogen inputs to cereal crops; and
- Aerial imagery as being used on a large scale experimental basis by Syngenta Crop Protection (UK) Ltd and Velcourt Ltd again varying nitrogen and growth regulator inputs.

Canopy management approaches to winter cereal production in the UK require assessments of crop condition particularly coming out of the winter period. This is currently done visually. It is expected that the further development of the sensor system used as part of this project work will enable such assessments to be automated.

In summary, the main direct practical implications of the work are dependent on other developments but there is now strong evidence that these will take place.

5.3 Further research

The findings of this research offer a way forward for remote sensing of crop canopies but it is recognised that the canopy measurement system used in this study could not be used at field scale. A full scale system needs developing and further assessment conducted. Aspects that require particular attention include:

- Assessing the ultrasonic sensors accuracy when mounted on a 24 m boom and operated at spraying speeds of up to 15 km h^{-1}.
- Assessing the optimum sampling distance required for the normalised difference vegetation index measurements and subsequent calculation of coefficient of variation and tiller numbers.

Agronomic trials are required to establish the usefulness of these combined sensing approaches, such trials may include:

- Assessing to what extent fungicide use could be reduced by matching it to the canopy characteristics while maintaining adequate levels of disease control.
- Assessing the economic benefits of using these sensing techniques to determine inputs compared with conventional practice.

6. TECHNOLOGY TRANSFER ACTIVITIES

This work has resulted in the production of the following:

- Scotford I M, Miller P C H (2002). Poster for HGCA R & D Conference, Coventry 15-16 January 2002

- Scotford I M, Miller P C H (2002). Abstract for HGCA R & D Conference, Coventry 15-16 January 2002

- Scotford I M, Miller P C H (2002). Spectral reflectance as a management tool for cereal crop protection : A review. Paper submitted to Crop Protection

- Scotford I M, Miller P C H (2002). Combination of spectral reflectance and ultrasonic sensing to monitor the growth of winter wheat. Paper accepted for publication in Biosystems Engineering: published in 2004, Volume 87 (1), pages 27-38

- Scotford I M, Miller P C H (2002). Intermediate Results from HGCA Fellowship Project. Precision Farming Alliance News Letter.

- Miller P C H, Scotford I M (2002). Agronomic Intelligence: the basis for profitable production, HGCA project 2265: Senior fellowship - advanced technology sensors. HGCA R&D Conference Coventry, 15-16 January 2002, London UK; HGCA.

- Miller P C H (2002). Spray behaviour associated with boom and air assisted application systems. ASAE meeting presentation, paper No. 021004. 2002 ASAE International Meeting, Chicago, USA, 28-31 July.

- Scotford I M, Miller P C H (2003). Monitoring the growth of winter wheat using measurements of normalised difference vegetation index (NDVI) and crop height. Paper No. 086 presented at the European Conference on Precision Agriculture (ECPA), Germany, Berlin, June 2003.

- Scotford I M, Miller P C H (2003). Characterisation of winter wheat using measurements of normalised difference vegetation index and crop height. Paper No. 087 presented at the European Conference on Precision Agriculture (ECPA), Germany, Berlin, June 2003

- Miller P C H, Scotford I M, Walklate P J (2003). Characterising crop canopies to provide a basis for improved pesticide application. ASAE meeting presentation, paper No. 031094. 2003 ASAE International Meeting, Las Vegas, USA, 27-30 July.

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APPENDIX A

Crop Canopy Measurement System (CMS):
Specification and User Guide

by

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Crop Canopy Measurement System (CMS) : Specification and User Guide

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July 2002

Crop Canopy Measurement System (CMS) : Specification and User Guide

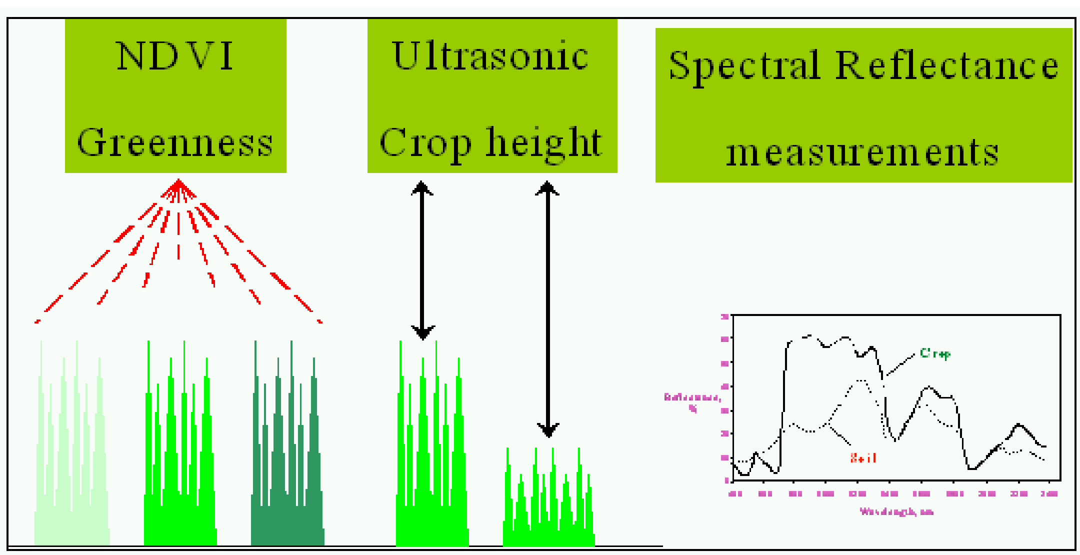
I M Scotford; P A Richards; P F Inskip

SUMMARY

Crop canopy characteristics influence inputs of both crop protection chemicals and fertiliser which account for approximately 60% of the variable costs of winter cereals. If sensing systems can be developed to characterise the canopy, savings of these inputs could potentially be made.

A Crop Canopy Measurement Sensing System (CMS) has been designed and assembled to meet this goal. The CMS contains radiometers measuring at 660 nm (Red) and 730 nm (NIR) wavelengths to calculate the normalised differential vegetation index (NDVI), two ultrasonic sensors to measure the height of crop canopy and a 3 channel spectrometer measuring wavelengths within the range of 350 - 1000 nm. It is hypothesised that the combined output of all three sensors will provide a better characterisation of the crop canopy than a single sensor.

This report details the specification of the CMS and details it use.



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Crop Canopy Measurement System (CMS): Specification and User Guide

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1. Introduction

Crop production requires a series of inputs herbicides, fungicides, growth regulators, fertilisers, *etc*. to be applied to the crop at the right time, in the right place and at the correct dose rate. Agronomists must consider a number of agronomic factors such as weather conditions, crop variety, weed type, crop growth stage, crop canopy characteristics *etc*. to determine the most suitable inputs. Their overall aim being to optimise crop production, ideally achieving high yields whilst minimising inputs hence maximising profit. Agronomic decisions are heavily influenced by weather conditions, but the agronomist cannot change these only account for them in the decision making process. From the other parameters it is crop variety, crop growth stage (GS) and canopy characteristics that mainly influence the input of fungicides, growth regulators and fertiliser inputs, which in combination typically account for 60% of the variable costs (Nix, 2000). This point is further emphasised by Bryson *et al.* (2000) who indicated that crop canopy affects agronomic decisions on fertilisers, fungicides, pesticides, herbicides and growth regulators. In addition, crop protection chemicals are surface acting and research by Miller *et al.* (2000) indicates that there is potential to optimise fungicide use by tailoring the delivered spray to match crop canopy characteristics. Based on these assumptions, there would be obvious benefits if the canopy characteristics could be sensed remotely and linked back to the agronomic decision making process.

Previously research concerned with measuring particular parameters of the crop canopy have concentrated on using individual sensors. However the information from this approach is often limited because the nature of the crop canopy is complex, having many interrelated properties, and the output of a single sensor can be influenced by a variety of factors (Scotford and Miller, 2002). For example, one of the most commonly used measurement techniques, the Normalised Differential Vegetation Index (NDVI), is the ratio between visual red and infrared reflectance of the crop canopy. The drawback of using this measurement technique in isolation, is that it is not obvious whether the sensor is looking at a small quantity of very green material or a larger quantity of less green material. In addition NDVI is also affected by differing levels of illumination, sensor geometry, soil background as well as other crop physiological properties. In the future it is likely that a better characterisation of the canopy will be required and ideally the two main factors that influence spectral reflectance of a particular crop, namely crop density and chlorophyll content (colour) need to be measured independently. This is likely to necessitate using additional sensors in parallel with spectral reflectance measurements. Indeed both Dampney *et al.* (1998) and Miller (2000) concluded that the future direction of precision agriculture would involve the use of multiple sensors.

To help address these problems, a crop canopy measurement system (CMS) has been designed to use multiple sensors working in parallel to establish if the combined output of these sensors can provide a better characterisation of crop canopy.

2. Measured properties

The CMS uses NDVI measurements since several workers (Paice *et al.*, 1999; Miller *et al.*, 2000; Wood *et al.*, 2000) have shown that NDVI does provide a useful element to characterise the crop canopy. However, to improve this characterisation it is also useful to measure a physical property of the crop. Ultrasonic sensors have been identified for this purpose, since they have been shown to be reliable in field conditions (Stafford *et al.*, 1997) and evidence suggests (O=Sullivan, 1986) that they can be used to measure the height of surfaces such as cereal crops. It is hypothesised that by using NDVI in conjunction with ultrasonic measurements it will be possible to determine if NDVI is measuring a small quantity of very green material or a larger quantity of less green material.

The sensors used for NDVI measurement typically use wavelengths of 660 and 730 nm (Stafford and Bolam, 1998). However evidence suggests (Scotford *et al.*, 2001) that other wavelengths within the range of 350 - 1000 nm also provide useful information about the crop canopy. Hence in addition to NDVI, a three channel spectrometer is included in the CMS each channel capable of measuring from 350 to 1000 nm. Table 1 lists the sensors which are included in the CMS.

Table 1. Individual sensors used for the CMS

Channel	Sensor type	Comments	Symbol
1 - 2	Skye (2001) Radiometer measuring at 660 and 730 nm	Radiometer measuring ambient light, channel 1 measuring at 730 nm (NIR) and channel 2 measuring at 660 nm (Red). Fitted with cosine correction filter	Red_1 NIR_1
3 - 4	Skye Radiometer measuring at 660 and 730 nm	Radiometer measuring crop reflectance, channel 3 measuring at 730 nm (NIR) and channel 4 measuring at 660 nm (Red)	Red_2 NIR_2
5 - 6	Skye Radiometer measuring at 660 and 730 nm	Not currently used, but set so that channel 5 is measuring at 730 nm (NIR) and channel 6 measuring at 660 nm (Red)	Red_3 NIR_3
7 - 8	Skye Radiometer measuring at 660 and 730 nm	Not currently used, but set so that channel 7 is measuring at 730 nm (NIR) and channel 8 measuring at 660 nm (Red)	Red_4 NIR_4
9	Milltronics (2001) ultrasonic proximity sensor	4 - 20 mA output, converted to linear distance (m), range 0 - 5 m, requires 24 VDC power supply,	H_1
10	Pepperl + Fuchs (2001) Ultrasonic proximity sensor	0 - 10 V output, converted to linear distance (m), range 0 - 2 m, requires 12 VDC power supply	H_2
11 - 12	Spare	0 - 5 V, not currently used	S_1 & S_2
13 -14	Spare	4 - 20 mA, not currently used	S_3 & S_4
15 - 16	not connected		

Channel	Sensor type	Comments	Symbol
USB	Ocean Optics (2001) Spectrometer master channel	measuring ambient light from 350 - 1000 nm, CCD array has 2048 pixels, therefore each pixel represents 0.32 nm, fitted with cosine correction filter	O_M
USB	Ocean Optics Spectrometer slave 1 channel	measuring crop reflectance from 350 - 1000 nm, CCD array has 2048 pixels, therefore each pixel represents 0.32 nm	O_1
USB	Ocean Optics Spectrometer slave 2 channel	measuring crop reflectance from 350 - 1000 nm, CCD array has 2048 pixels, therefore each pixel represents 0.32 nm	O_2
RS 232	Global Positioning System (GPS)	Not currently used	G

3. Mechanical installation

The CMS is designed to fit onto a standard tractor 3-point linkage, allowing ease of transport and use. A framework constructed from 40 x 40 mm and 40 x 60 mm aluminium box section (Figure 1) fits onto the 3-point linkage. Attached to this framework, via anti vibration mounts, is a instrumentation box (50 x 50 x 25 cm) which houses the signal conditioning units. A folding boom constructed from 40 x 60 mm aluminium box section to which all the individual sensors (Figure 2) are fitted is also attached to the frame. It is designed so the boom can be fitted to extend from either side of the tractor so that the end of the boom is 3.75 m from the centre line of the tractor. When fitted onto a Ford 7000 tractor the boom height is designed to be adjusted by raising or lowering the 3-point linkage, from 0.8 to 1.4 m above the ground (Figure 3). Full details and dimensions of the CMS framework are available from SRI Drawing No. 3986.

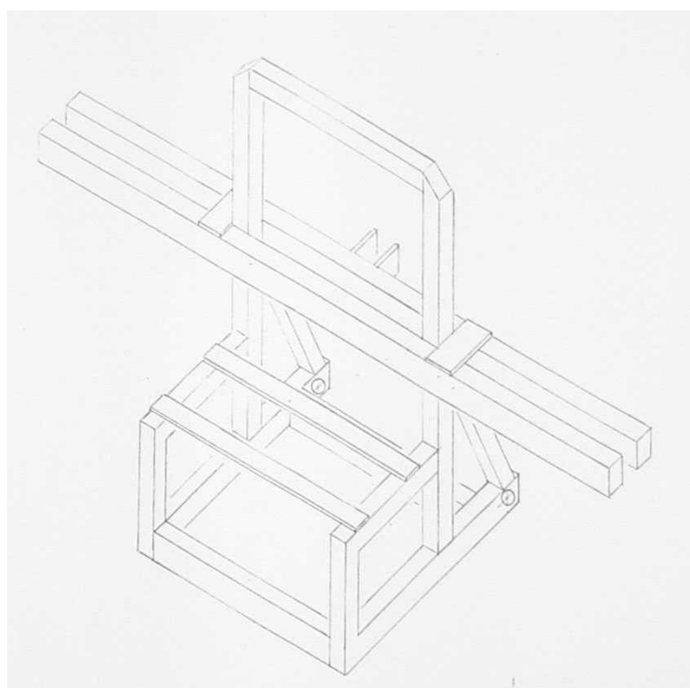


Figure 1. CMS Framework (SRI Drawing No. 3986)

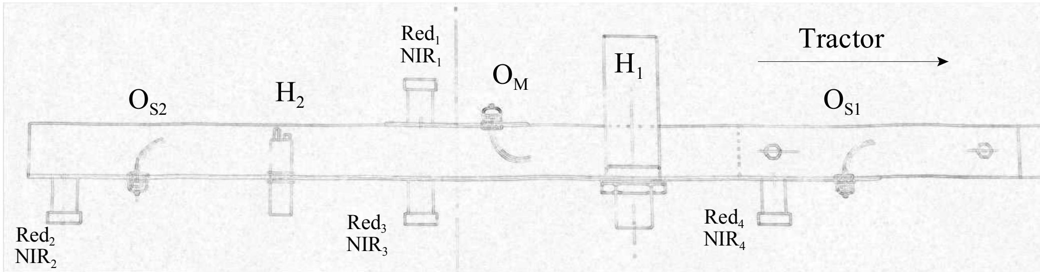


Figure 2. Position of sensors used for CMS

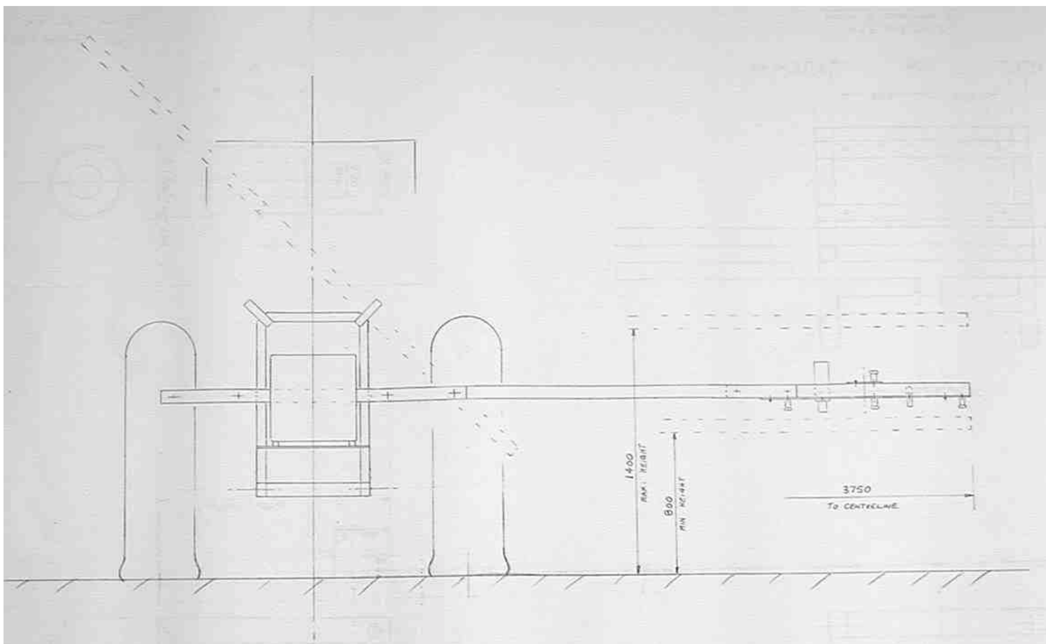


Figure 3. CMS fitted to rear of Ford 7000 tractor (SRI drawing No. 3986)

4. <u>Instrumentation hardware</u>

The CMS consists of 3 main signal conditioning units (SRI signal conditioning for sensors channels 1 to 16, signal conditioning for 3 channel Ocean Optics (2001) Spectrometer, Global Positioning System (GPS)) which are housed in the instrumentation box fitted to the CMS framework. The output signal of the SRI signal conditioning unit and Ocean Optics spectrometer is sent via a 4 port USB hub to a laptop PC, fitted in the tractor cab, where the data can be displayed and stored. The general wiring layout of the CMS is shown in Figure 4. Note - the GPS system is not currently fitted to the CMS.

The SRI signal conditioning unit contains the signal conditioning for channels 1 - 14 (note - no signal conditioning is currently set up for channels 15 - 16) and all relevant isolated power supplies (Appendix a). It also incorporates a DT 9800 series USB data acquisition module (Amplicon, 2001) into which the output, following signal conditioning, of the Skye (2001) radiometers and ultrasonic sensors are input. The module converts the analogue signals to digital before outputting to the laptop PC via the USB link. The module can accept up to 16 input channels:-

Channel	1 - 8	4 Skye radiometers (only 2 currently installed)
	9 - 10	2 ultrasonic height sensors
	11 - 12	set to accept 0 - 5 V input (currently not used)
	13 - 14	set to accept 4 - 20 mA input (currently not used)
	15 - 16	not set up

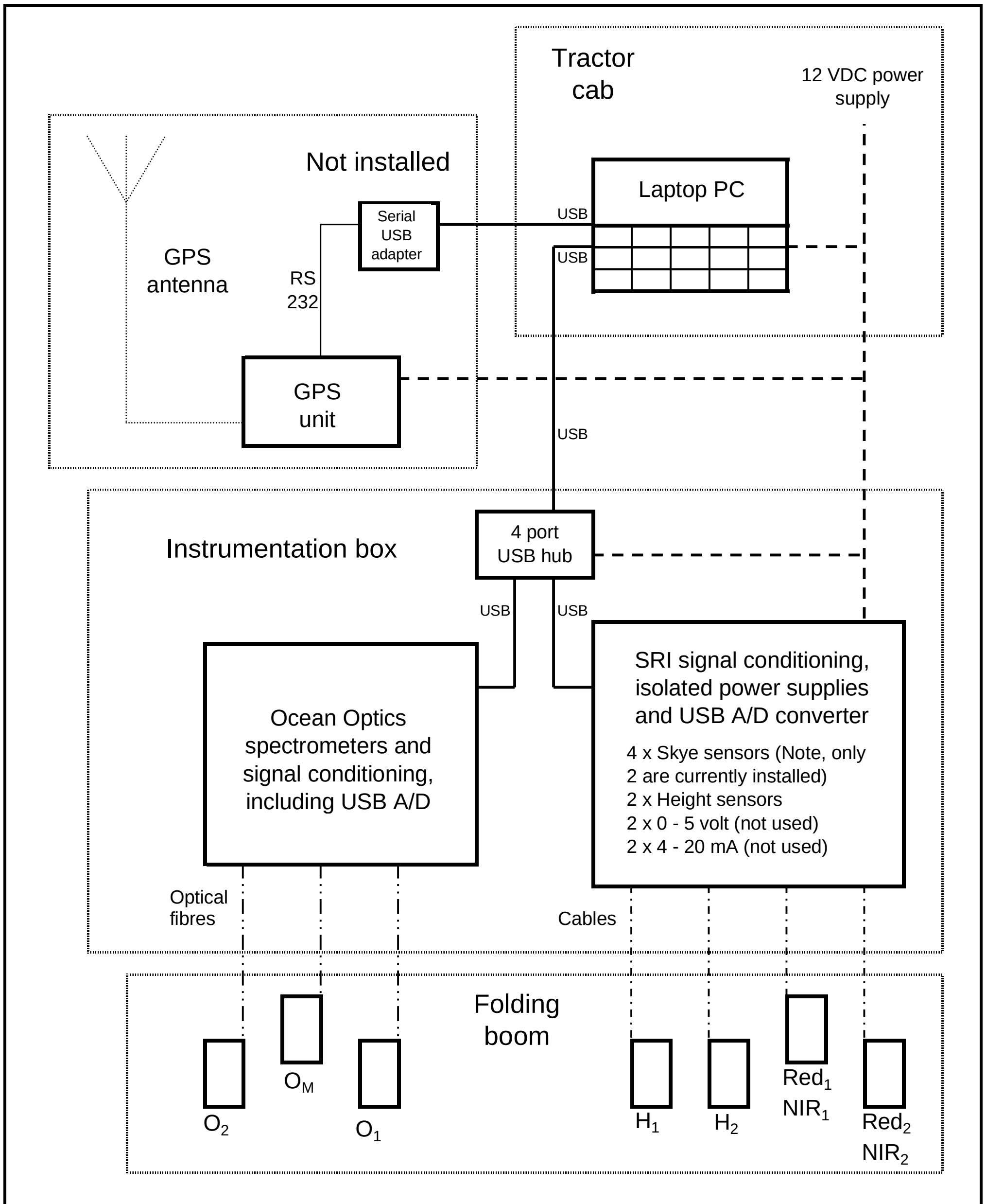


Figure 4. General wiring layout of the CMS

Each of the individual sensors (2 Skye radiometers and 2 ultrasonic sensors) are fitted at the end of the boom (Figure 2) and connected to the SRI signal conditioning unit via cables running the length of the boom. The unit requires a 12 VDC power supply which is supplied from the tractor.

The Ocean Optics signal conditioning unit comprises 3 individual spectrometers and 3 corresponding sets of signal conditioning. 3 Optical fibres from the end of the boom are used to transmit light along the length of the boom to each spectrometers which contain a fixed grating and a Charge Coupled Device (CCD) array detector with 2048 detecting elements. The fixed grating separates the collected spectrum into many small wavelength bands and the CCD array measures the light energy in each of the wavelength bands simultaneously. Signal conditioning converts the light energy into a digital signal and outputs all 3 channels via a USB link. The unit requires very little power this being supplied via the USB link.

The GPS unit output is an RS232 this connect to the laptop USB port via a serial to USB adapter.

5. Instrumentation software

The CMS is operated via a laptop computer running the CMS software. The software is written in Visual Basic and has a Windows user interface. The software converts the input from the individual sensors to engineering units, conducts data analysis and stores the data in Excel files. It is designed to be operated in either timed or continuous mode. In the timed run mode the operator selects the sampling interval and the number of samples to be collected per run. In the continuous mode the operator selects number of samples collected before and average is taken and stored.

5.1 Sensor calibration

Channels 1 to 16 are converted from ADC to engineering units using linear conversion $E = M\,x + C$, where E = engineering value; M is the slope of line; x is the ADC reading from sensor and C is the zero offset. For each channel a calibration routine allows the operator to view the ADC value against a known value in engineering units. These values are used to calculate M and C for each channel, which are manually entered into the software. Channels 1 and 2 (Red_1 and NIR_1) have 3 levels of gain to account for differing levels of illumination or sunlight. These channels therefore require a M and C to be calculated and input for each level of gain. In addition channels 1 - 8 have a correction factor (sensor constant) to account for the slight variability in the sensitivity of the radiometers.

Each channel of the Ocean Optics spectrometer outputs a pixel number (0 - 2047) and corresponding digital value (0 - 4095) representing the illumination level on that pixel. To convert the pixel number to a corresponding wavelength the software uses a third order polynomial as follows:

$$\lambda_p = I + C_1\,P + C_2 P^2 + C_3\,P^3$$

where λ is the wavelength of pixel p, I is the wavelength of pixel 0 or intercept value, C_1 is the first coefficient (nm/pixel), C_2 is the second coefficient (nm/pixel) and C_3 is the second coefficient (nm/pixel). The system was calibrated at the factory and the following calibration factors given.

Ocean Optics Serial No.	MC2J246		
Channel	Master	Slave 1	Slave 2
Intercept	342.6714604	347.9639278	348.7683966
First coefficient	0.36363645	0.363093931	0.361077035
Second coefficient	-1.81032 E-05	-1.94315 E-05	-1.69881 E-05
Third coefficient	-1.21908 E-09	-7.74614 E-10	-1.69629 E-09
Regression fit	0.999999704	0.999999604	0.999999703

These values are used are pre set in software and used to calculate the wavelength number from each pixel number for each channel.

Global positioning system (GPS) outputs position (northing and easting), time and quality of signal where 0 = no fix, 1 = GPS fix and 2 = GPS and differential fix

5.2. Data conversion

Channels 1 to 8 are used to calculate normalised differential vegetation index *NDVI* values using the following formulae:

$$NDVI_1 = \frac{(NIR_2 / NIR_1) - (\mathrm{Re}\,d_2 / \mathrm{Re}\,d_1)}{(NIR_2 / NIR_1) + (\mathrm{Re}\,d_2 / \mathrm{Re}\,d_1)}$$

$$NDVI_2 = \frac{(NIR_3 / NIR_1) - (\mathrm{Re}\,d_3 / \mathrm{Re}\,d_1)}{(NIR_3 / NIR_1) + (\mathrm{Re}\,d_3 / \mathrm{Re}\,d_1)}$$

$$NDVI_3 = \frac{(NIR_4 / NIR_1) - (\mathrm{Re}\,d_4 / \mathrm{Re}\,d_1)}{(NIR_4 / NIR_1) + (\mathrm{Re}\,d_4 / \mathrm{Re}\,d_1)}$$

The height sensors are set a distance *HS* from the ground predetermined by the operator, to calculate the crop height (*CH*), the following formulae is used:

$$CH_1 = HS_1 - H_1$$

$$CH_2 = HS_2 - H_2$$

where *H* is the distance measured using the ultrasonic sensors and subscript *1* and *2* refer to the Milltronics and Pepperl + Fuchs sensors respectively.

Ocean Optics channels (O_M, O_1, O_2) are all corrected for dark readings. Even when no light enters the spectrometer the CCD array outputs a signal, this signal tends to drift with time. Hence to obtain a reliable signal the dark readings for each channel are subtracted from the light readings for the corresponding channel. A dark reading is obtained by blocking the light to all 3 channels and recording the dark output from each channel (OD_M, OD_1, OD_2). The corrected values are calculated as follows:

$O_M - OD_M = OC_M$ (Corrected reading for master channel)
$O_1 - OD_1 = OC_1$ (Corrected reading for slave 1 channel)
$O_2 - OD_2 = OC_2$ (Corrected reading for slave 2 channel)

For each of the spectrometer readings (OC_M, OC_1, OC_2) the data are averaged into 10 nm bins, hence giving a reading representing a 10 nm bin for example 350 - 359, 360 - 369, 370 - 379..................970 - 979, 980 - 989, 990 - 999 and given the symbols OC_M^{10},OC_1^{10}, OC_2^{10}. The percentage reflectance R for channels slave 1 and 2 for each 10 nm are calculated as follows

$$R_1 = \frac{OC_1^{10}}{OC_M^{10}} \times 100 \; (for\ each\ 10\ nmbin)$$

$$R_2 = \frac{OC_2^{10}}{OC_M^{10}} \times 100 \; (for\ each\ 10\ nmbin)$$

For values of $NDVI_{1,\,2,\,3,\,p}$, CH_1, CH_2, OC_M^{10},OC_1^{10}, OC_2^{10} (for each 10 nm bin) R_1 *and* R_2 the average (ave), standard deviation (std), minimum (min) and maximum (max) values of the samples collected during a timed run are calculated.

5.3. Data storage

The CMS has two modes of operation either timed run for collecting data over a set period of time or continuous mode. Note the continuous mode is not currently commissioned.

In the timed run mode the operator selects the sampling interval and the number of samples to be collected per run. The CMS stores the data in two Excel files, the raw and the processed data. The file names consists of the date and a plot or run number. The format of the data saved is given in Table 2.

Although not currently commissioned, in the continuous mode the operator selects the sampling interval and number of samples to be averaged. The file name consists of date and plot or run number. The CMS stores the data in two files, the raw and the processed data. The file names consist of the date and a plot or run number. The format of the data saved is given in Table 3.

Table 2. Format of data saved in timed run mode

Raw data	Processed data
$Red_{1, 2, 3, 4}$ for each sample	$NDVI_{1, 2, 3}$ for each sample, plus ave, std, min, max $NDVI_{1, 2, 3}$ of all samples
$NIR_{1, 2, 3, 4}$ for each sample	ave, std, min, max NDVI for plot ($NDVI_P$) note channels 5 to 8 are not currently being used, hence $NDVI_P$ is the same as average $NDVI_1$
H_1 and H_2 for each sample	CH_1 and CH_2 for each sample, plus ave, std, min, max CH_1 and CH_2 of all samples
$S_{1, 2, 3, 4}$ for each sample (currently not being used)	No data currently stored for $S_{1, 2, 3, 4}$
Values of linear coefficients *M, C* for channels 1 - 14 and sensor constants for channels 1 - 8	
Values of OD_M, OD_1 and OD_2	OC_M^{10}, OC_1^{10}, OC_2^{10} for each sample and 10 nm bin, plus ave, std, min, max OC_M^{10}, OC_1^{10}, OC_2^{10} of all samples for each 10 nm bin
All values of OC_M, OC_1 and OC_2 of each CCD pixel for each sample	R_1 and R_2 for each sample, plus ave, std, min, max R_1 and R_2 of all samples
All GPS data (not currently used)	Average GPS readings (not currently used)

Table 3. Format of data saved in the continuous mode

Raw data	Processed data
$Red_{1, 2, 3, 4}$ for each averaged sample	$NDVI_{1, 2, 3}$ for each averaged sample
$NIR_{1, 2, 3, 4}$ for each averaged sample	Average of $NDVI_{1, 2, 3}$ for each averaged sample
H_1 and H_2 for each averaged sample	CH_1 and CH_2 for each averaged sample
$S_{1, 2, 3, 4}$ for each sample (currently not being used)	No data currently stored for $S_{1, 2, 3, 4}$
Values of linear coefficients *M, C* for channels 1 - 14 and sensor constants for channels 1 - 8	
Current values of OD_M, OD_1 *and* OD_2	OC_M^{10}, OC_1^{10}, OC_2^{10} for each averaged sample
Values of OC_M, OC_1 and OC_2 for each averaged sample	R_1 and R_2 for each averaged sample
All GPS data	GPS readings for each averaged sample

6. System operation

The operation of the CMS is divided between hardware and software.

6.1. Hardware operation

To lower the boom from it transports position remove pins A and B (Figure 5) and rotating the boom clockwise around pin C. Lock boom in position by replacing pin B. For safe keeping replace pin A Set the desired height of the boom using the 3-point linkage on the tractor. Using the adjustments on the off-side bottom link and top link of the 3-point linkage ensure the boom is level and the sensor faces are parallel to the ground or target being scanned.

After use the boom is placed back in the transport position by removal of pins A and B (Figure 5) and rotating the boom anticlockwise around pin C. Secure boom in transport position by replacing pin A. For safe keeping replace pin B.

Figure 5. Pin position for lowering the boom

6.2. Software operation

The software allows the operator to select the mode of operation (either timed or continuous), calibrate the individual sensors, set up the data collection routine and collect data from the CMS. The CMS programme is started by double clicking the CropCanopy icon on the laptop screen. On starting the program the menu on top of the screen (Figure 6), from right to left shows the following options:

About	shows program information such as current version
Sensors	allows sensors 1 - 16 to be tested and calibrated (see 6.2.1)

Ocean Optics — enables the parameters of the Ocean Optics spectrometer to be set (see 6.2.2)
Configure — enables the data collection parameters to be set (see 6.2.3)
Data Collection — enables data collection (see 6.2.4)
Program — exits the program

Each of the options is selected either with the mouse or by holding down the ALT key and pressing the underlined letter.

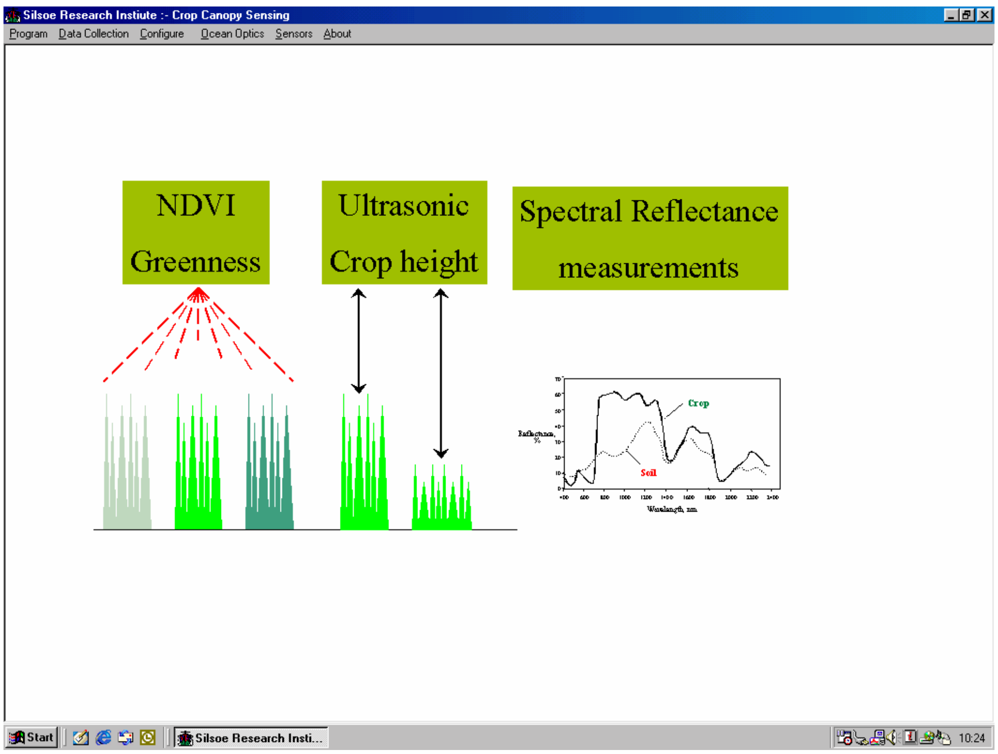
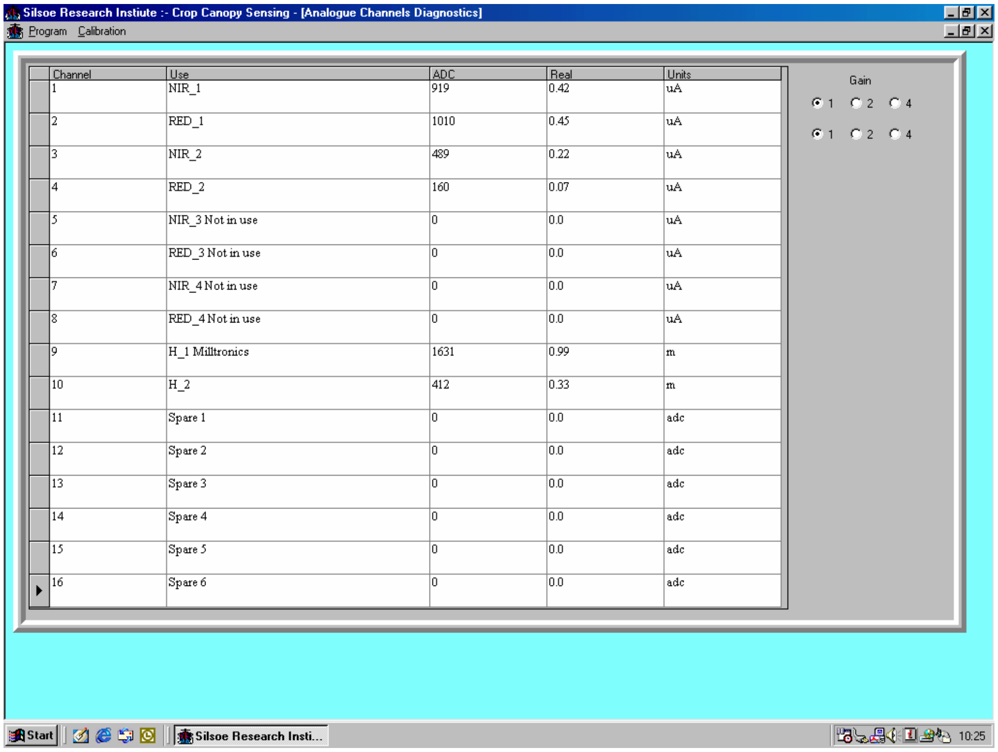


Figure 6. Main menu of CMS software

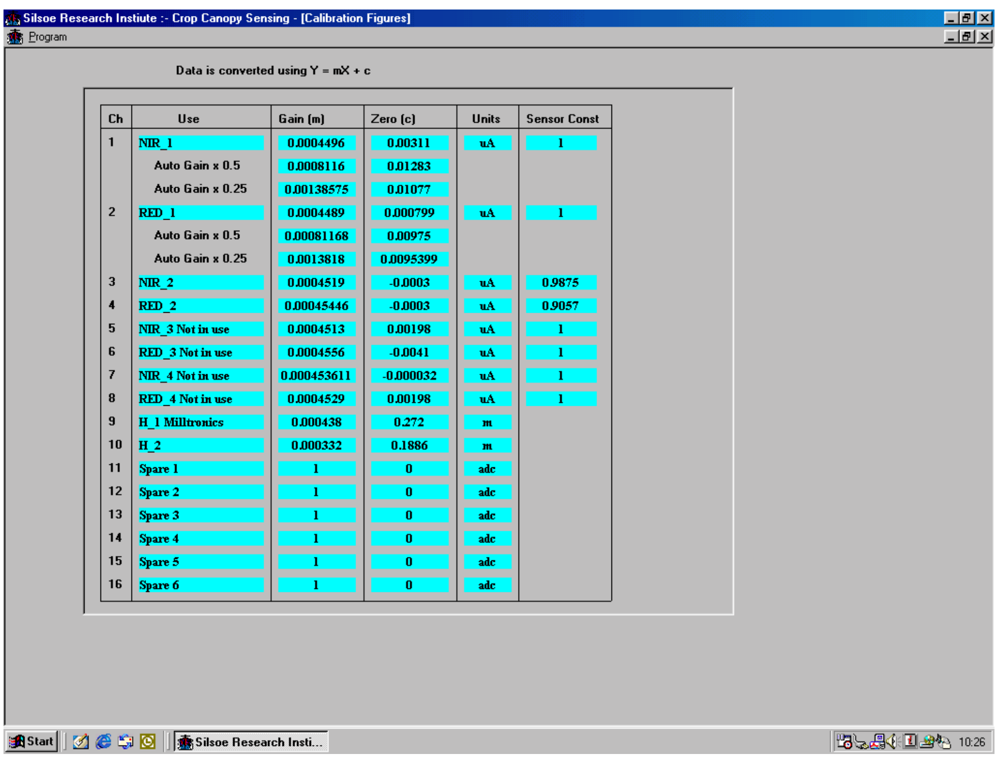
6.2.1 Sensor calibration

Selecting Sensors from the main menu displays the analogue channels diagnostics screen showing all sixteen channels (Figure 7), this screen is used for calibration purposes. A known engineering value is input via the sensor into the CMS and the corresponding ADC value displayed on the screen. This process is repeated several times, at least 3 readings are required for each channel. These values are subsequently used to calculate M and C for each channel. On channels 1 and 2 the gain can be manually set allowing calibration for each gain setting. Selecting the Calibration page (Figure 8) allows the operator to input the names and units for each of the 16 channels and to input the previously calculated M and C values. The sensor constant for channels 1 - 8 (see section 5.1) are also input on this page. Appendix b details the calibration report and associated calibration figures used in the current set up of the CMS software.



Channel	Use	ADC	Real	Units
1	NIR_1	919	0.42	uA
2	RED_1	1010	0.45	uA
3	NIR_2	489	0.22	uA
4	RED_2	160	0.07	uA
5	NIR_3 Not in use	0	0.0	uA
6	RED_3 Not in use	0	0.0	uA
7	NIR_4 Not in use	0	0.0	uA
8	RED_4 Not in use	0	0.0	uA
9	H_1 Milltronics	1631	0.99	m
10	H_2	412	0.33	m
11	Spare 1	0	0.0	adc
12	Spare 2	0	0.0	adc
13	Spare 3	0	0.0	adc
14	Spare 4	0	0.0	adc
15	Spare 5	0	0.0	adc
16	Spare 6	0	0.0	adc

Figure 7. Analogue channel diagnostics screen



Ch	Use	Gain (m)	Zero (c)	Units	Sensor Const
1	NIR_1	0.0004496	0.00311	uA	1
	Auto Gain x 0.5	0.0008116	0.01283		
	Auto Gain x 0.25	0.00138575	0.01077		
2	RED_1	0.0004489	0.000799	uA	1
	Auto Gain x 0.5	0.00081168	0.00975		
	Auto Gain x 0.25	0.0013818	0.0095399		
3	NIR_2	0.0004519	-0.0003	uA	0.9875
4	RED_2	0.00045446	-0.0003	uA	0.9057
5	NIR_3 Not in use	0.0004513	0.00198	uA	1
6	RED_3 Not in use	0.0004556	-0.0041	uA	1
7	NIR_4 Not in use	0.000453611	-0.000032	uA	1
8	RED_4 Not in use	0.0004529	0.00198	uA	1
9	H_1 Milltronics	0.000438	0.272	m	
10	H_2	0.000332	0.1886	m	
11	Spare 1	1	0	adc	
12	Spare 2	1	0	adc	
13	Spare 3	1	0	adc	
14	Spare 4	1	0	adc	
15	Spare 5	1	0	adc	
16	Spare 6	1	0	adc	

Figure 8. Calibration page

6.2.2. Ocean optics set up

Selecting Ocean Optics from the main menu displays the spectrometer set up page (Figure 9), the operator has the following options:

Number of spectra to average - the number of spectra that are collected before a value is stored. The larger the value the better the signal to noise ratio but this results in increasing the sampling time.

Integration time - the time the CCD arrays of the spectrometer are exposed to the source, this is analogous to the shutter speed of a camera. This function allows the operator to set the most suitable integration time for a given light condition. The integration time is adjusted so that a signal of about 3500 is achieved when the greatest amount of light for a particular application is entering the spectrometer.

Boxcar width - this sets the number of pixels on the CCD array that the CMS averages over. A value of 5 for example averages each data point with 5 points to its left and 5 points to its right. Increasing the boxcar width improves the signal to noise ratio but results in loss of spectral resolution.

Start / Stop - starts and stops the spectrometer scanning. Note in this page the 3 spectrometer channels are displayed on the screen but the data is not saved.

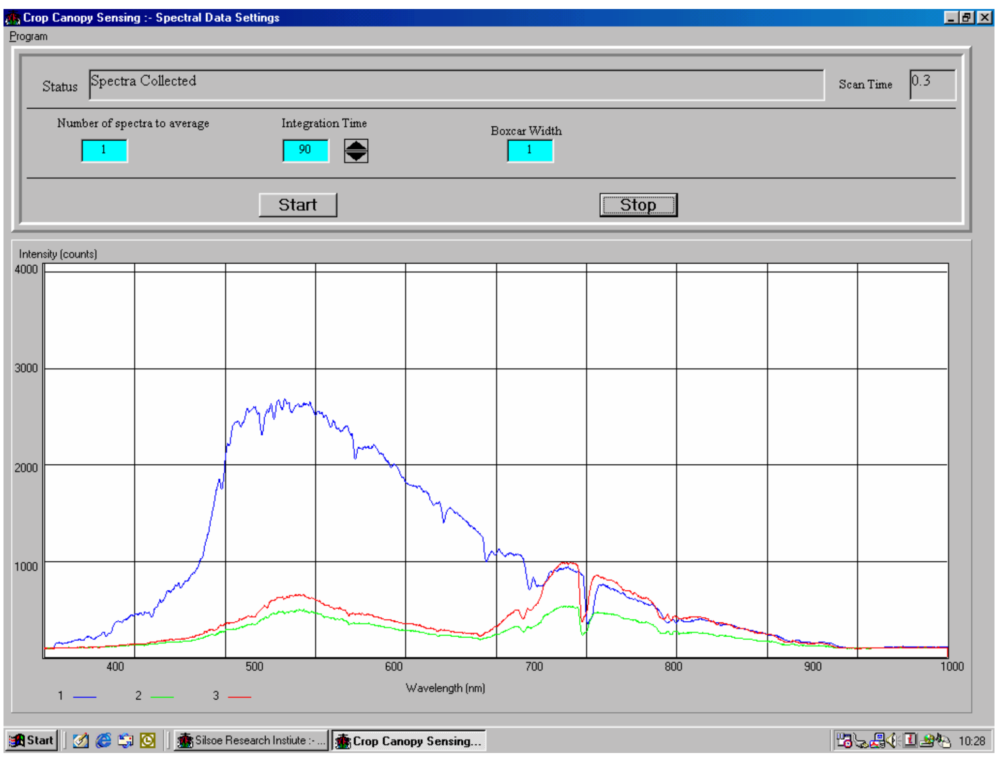


Figure 9. Spectrometer set up page

6.2.3. System configure

Selecting Configure from the main menu displays the data collection parameters page (Figure 10) which allows the operator to select the parameters and set up the plot or field information. The following options are available:

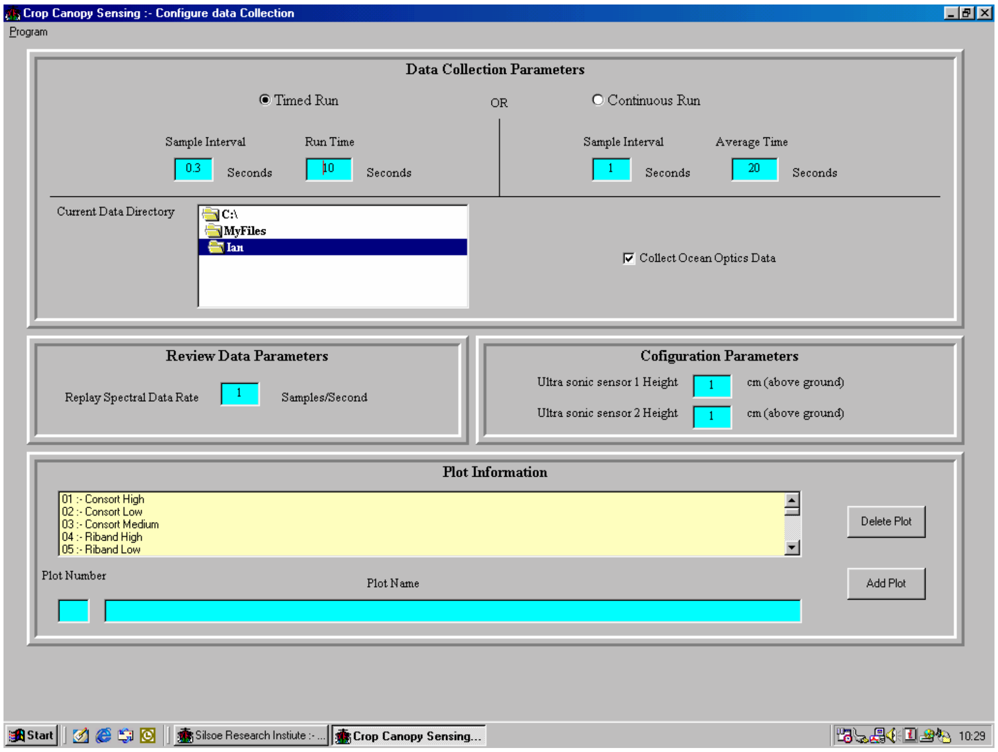


Figure 10. Configure data collection page

Timed or continuous run - the operator can select either timed run or continuous, currently only timed run is operational.

Sample interval - the frequency at which samples are taken i.e. a sampling interval of 0.5 s would achieve a sampling rate of 2 Hz.

Run time - the duration of the timed run

Average time - the duration at which the scans are averaged and stored. Note this function is not currently working.

Current data directory - the default directory where all of the data is stored.

Collect Ocean Optics data - if this box is ticked the spectrometer data is saved, if not ticked no spectrometer data is saved.

Configuration parameters - allows the operator to input values for HS_1 and HS_2 i.e. the height of the height sensors above the ground (see section 5.2).

Review data parameters - in the data collection routine there is a playback function (see section 6.2.4) for the collected spectral data, this box allows the operator to select the playback speed.

Add plot / Delete plot - allows the operator to input or delete a plot or file number and a description. Note the plot number is used when the data are stored (see section 5.3).

6.2.4. Data collection

Selecting Data Collection from the main menu displays the main data collection page (Figure 11) and allows the operator to collect data using the CMS. The options, as detailed below, are displayed at the top of the screen. The majority of these functions can be operated by either a mouse point and right click, holding down the >ALT= key and pressing the underlined letter or by the function keys as detailed on the screen.

Configure - allows the operator to return to the system configure page (see section 6.2.3).

Plot - the operator can select which plot, from the plots set up in system configure page (see section 6.2.3) they wish to use. F8 = next plot, F9 = previous plot.

Spectrometer - allows the operator to take dark reading (OD_M, OD_1, OD_2). Note the light to each spectrometer channel should be blocked before the dark readings are taken. >Shift= F7 also takes a dark reading. Note the dark readings are used in the data conversion (see section 5.2) and the data collection routine will not work until a dark reading has been taken.

Collect - start and stops data collection. F11 = start data collection and F12 stops data collection. When the CMS is operating in the timed run mode the data collection routine stops automatically when the pre-set run time has been reached.

Replay - when a data collection run has been conducted the operator can look at the data to check if it is correct. Various options are available:

Sensor data (F1) - the output of the individual sensors can be viewed graphically, the operator can select, by use of check boxes, which channels are viewed.

Spectral data (F2) - the average values of OC_M, OC_1 and OC_2 are displayed graphically.

Statistical data (F3) - the average, maximum, minimum and standard deviation for channels 1 - 16, $NDVI_{1,2,3,plot}$ and heights $CH_{1,2}$ are displayed in a table.

Replay spectra (F4) - the data for each channel of the spectrometer is displayed graphically and replays each scan taken during the timed run at a pre-determined playback rate (see section 6.2.3).

NDVI + height (F5) - the calculated values of $NDVI_{1,2,3,plot}$ and heights $CH_{1,2}$ can be displayed graphically, the operator can select, by use of check boxes, which channels are viewed.

Reflectance (F6) - the calculated values of R_1 and R_2 are displayed graphically.

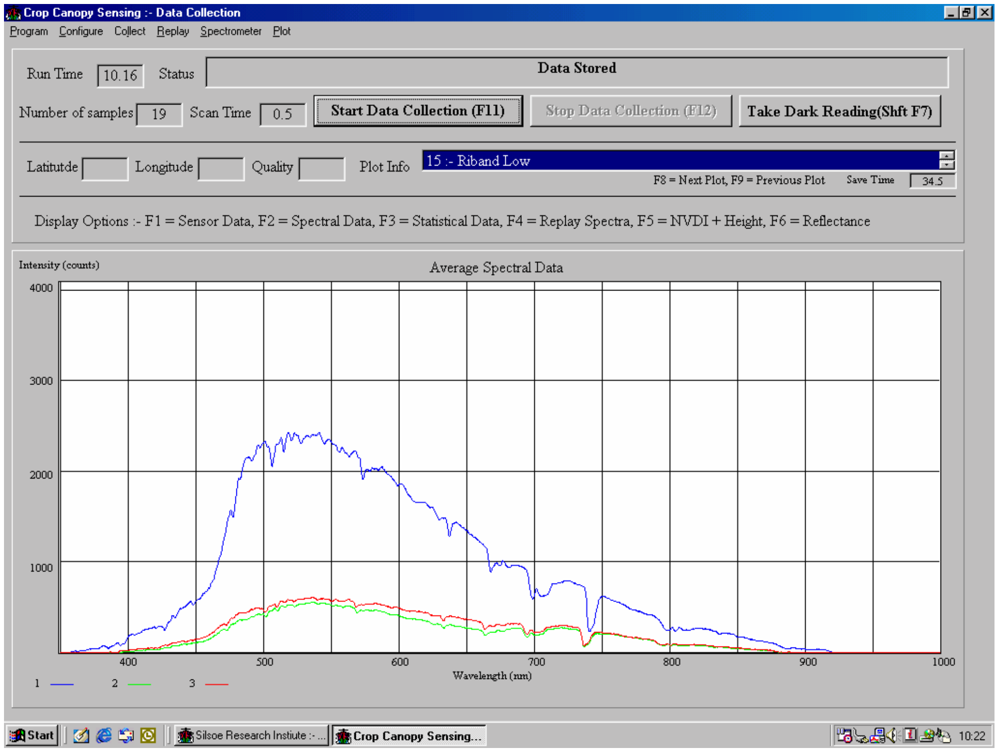


Figure 11. Data collection screen

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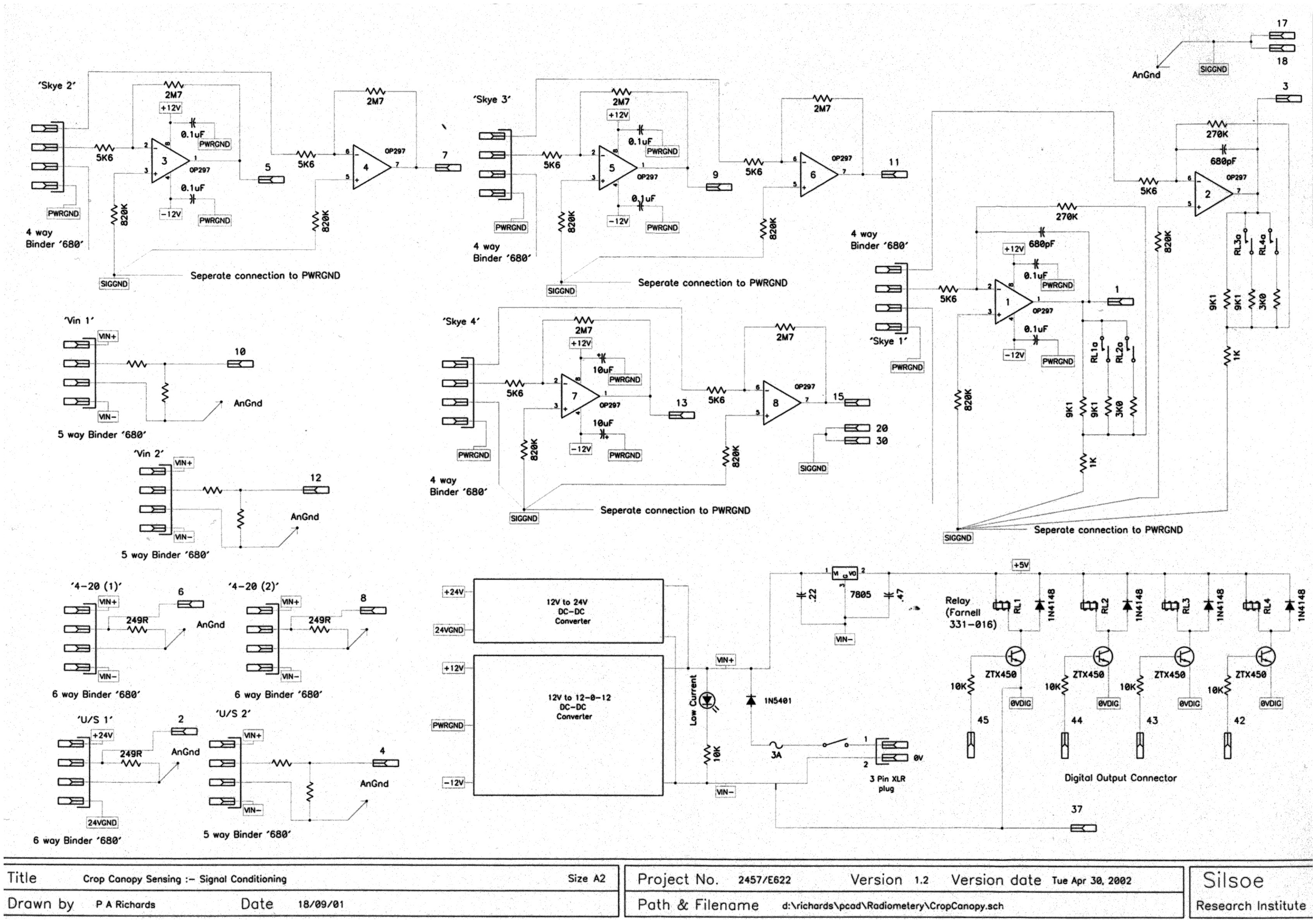
Appendix a, SRI Signal Conditioning Unit 1



Appendix b

Calibration Report

Channel No.	Property	Comments	Symbol
1	light (730 nm)	2 channel Skye Radiometer used for measuring ambient light	NIR_1
2	light (660 nm)		Red_1
3	light (730 nm)	2 channel Skye Radiometer used for measuring crop reflectance	NIR_2
4	light (660 nm)		Red_2
5	light (730 nm)	2 channel Skye Radiometer used for measuring crop reflectance (not currently fitted)	NIR_3
6	light (660 nm)		Red_3
7	light (730 nm)	2 channel Skye Radiometer used for measuring crop reflectance (not currently fitted)	NIR_4
8	light (660 nm)		Red_4
9	height	Milltronics ultrasonic distance transducer	H_1
10	height	Pepperl + Fuchs ultrasonic distance transducer	H_2
11 - 12	spares, set to accept 0 - 5 V input		S_1, S_2
13 - 14	spares, set to accept 4 - 20 mA input		S_3, S_4
15 - 16	not connected		

Channels 1 - 8 Skye Radiometers

The signal conditioning for each radiometer although similar requires calibrating to account for any variability in the circuits caused by the A/D convertor, component values and amplifier gains. The signal conditioning for each channel was calibrated by inputting a known µA value and noting the ADC value. Channels 1 and 2 have three levels of gain each one requiring separate calibration. The input values µA and corresponding ADC values are given in Table 1. Using these values a straight line of the form

$$E = Mx + C$$

where E = engineering value; M is the slope of line; x is the ADC reading and C is the zero offset was fitted. The resulting values of M and C for each channel are provided in Table 2. These values are input to the CMS software via the Sensor calibration page (see section 6.2.1).

Table 1. μA and corresponding ADC values for Skye Radiometers (channels 1 - 8)

	ADC values					
	Channel 1 (NIR_1)			Channel 2 (Red_1)		
input (μA)	Gain = 1	Gain = 0.5	Gain = 0.25	Gain = 1	Gain = 0.5	Gain = 0.25
0.1	217			223		
1	2213	1218	716	2220	1223	716
1.5	3332	1830	1074	3343	1832	1079
3		3681	2154		3685	2165
5			3602			3611
	Channel 3 (NIR_2)	Channel 4 (Red_2)	Channel 5 (NIR_3)	Channel 6 (Red_3)	Channel 7 (NIR_4)	Channel 8 (Red_4)
0.1	221	220	217	229	224	216
1	2216	2203	2212	2202	2195	2205
1.5	3318	3300	3319	3302	3313	3307

Table 2. Constants M and C for channels 1 - 8 (in all cases r^2 = 0.999)

Channel No. and Symbol		*M*	*C*
	Gain = 1	0.0004496	0.00311
	Gain = 0.5	0.0008116	0.01283
1 (NIR_1)	Gain = 0.25	0.00138575	0.01077
	Gain = 1	0.0004489	0.000799
	Gain = 0.5	0.00081168	0.00975
2 (Red_1)	Gain = 0.25	0.001318	0.0095399
	3 (NIR_2)	0.0004519	-0.0003
	4 (Red_2)	0.00045446	-0.0003
	5 (NIR_3)	0.0004513	0.00198
	6 (Red_3)	0.0004556	-0.0041
	7 (NIR_4)	0.000453611	-0.000032
	8 (Red_4)	0.0004529	0.00198

In addition to the calibration of the signal conditioning, the Skye Radiometers output needs to be standardised so that for a given amount of light input the output of all the radiometers is equal i.e. their sensitivity is the same. The radiometers are factory calibrated and supplied with a calibration certificate, indicating their sensitivity to light. The calibrations for the two radiometers currently used are given in Table 3. Using these figures the sensor constant is calculated as follows. It is assumed that channels NIR_1 and Red_1 are the reference channels.

Calculating for NIR (730 nm) channels 1, 3, 5 and 7

Average sensitivity $SNIR_A$ is calculated

$$SNIR_A = \frac{\sum SNIR_{1,2,3,4}}{4}$$

where $SNIR_{1,\ 2,\ 3,\ 4}$ are the factory calibrated sensitivities provided by the manufacturer

Reference sensitivity $SNIR_R$ is calculated

$$SNIR_R = \frac{SNIR_1}{SNIR_A}$$

Each sensor constant (SC) can then be calculated

$$SCNIR_1 = \frac{SNIR_1}{SNIR_A\ x\ SNIR_R} = (1\ reference\ channel)$$

and

$$SCNIR_2 = \frac{SNIR_2}{SNIR_A\ x\ SNIR_R}$$

Similarly calculating for Red (660 nm) channels 2, 4, 6 and 8

Average sensitivity $SRed_A$ is calculated

$$SRed_A = \frac{\sum SRed_{1,2,3,4}}{4}$$

where $SRed_{1,\ 2,\ 3,\ 4}$ are the factory calibrated sensitivities provided by the manufacturer.

Reference sensitivity $SRed_R$ is calculated

$$SRed_R = \frac{SRed_1}{SRed_A}$$

Each sensor constant (SC) can then be calculated

$$SCRed_1 = \frac{SRed_1}{SRed_A\ x\, Red_R} = 1\,(\,the\ reference\ channel\,)$$

and

$$SCRed_2 = \frac{SRed_2}{SRed_A\ x\ SRed_R}$$

To check the calibration the radiometers were pointed at similar targets (i.e. sky and uniform grass cover) to check that their signals were similar.

Table 3. Skye Radiometer calibration figures and calculated sensor constants					
Channel No.	Symbol	Serial No.	Wavelength	Sensitivity (S) (μmol μA^{-1})	Sensor constant (SC)
1	NIR_1	1800 0901 23044	730	69.42	1
2	Red_1		660	64.34	1
3	NIR_2	1800 0901 23043	730	68.55	0.9875
4	Red_2		660	58.27	0.9057
5	NIR_3	not currently fitted	730		
6	Red_3		660		
7	NIR_4	not currently fitted	730		
8	Red_4		660		

Channels 9 and 10 Ultrasonic distance transducers

The ultrasonic distance (height) sensors were calibrated by positioning a board at know distances from the sensors and recording the corresponding ADC readings for each of the sensors. The calibration results are reported in Table 4. Using these figures the M and C for each channel was calculated and input into the CMS software.

Table 4. Calibration results for Channel 9 and 10, ultrasonic distance transducers

Channel 9 (Milltronics)		Channel 10 (Pepperl + Fuchs)	
Distance	ADC	Distance	ADC
0.65	865	0.63	1340
1.16	2025	1.10	2750
1.61	3055	1.45	3800
1.14	1975	0.51	960
M	C	M	C
0.000438	0.272	0.000332	0.1886