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ASSESSMENT OF CROP PERFORMANCE POTENTIAL USING REMOTE SENSING

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FOR THE DEGREE IN DOCTOR OF PHILOSOPHY

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ABSTRACT

This report demonstrates the potential use of optical remote sensing for monitoring the growth and development of winter sown wheat at the field scale. Spectral vegetation indices have been shown to be correlated to important agronomic variables i.e. Leaf Area Index, per cent cover, intercepted solar radiation and grain yield. For winter sown cereals, relationships to grain yield at harvest have been proposed at various times during the growth of the crop. However the precise timing of the remotely sensed input to such models has not received investigation in relation to sowing date, variety and development stage. Further the effect of fungal diseases on such models is not well understood. To address these problems, commercial agronomy trials were used to monitor the reflectance patterns of winter wheat over two growing seasons. During growth and development of the crop, the wheat was destructively sampled and the apex development stage was recorded. Key stages of apex development were found in which spectral data was correlated to grain yield. The relationships were found to be complex in relation to sowing date, variety and fungicide treatment and may therefore not be applicable on a year to year basis.

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CHAPTER 1 INTRODUCTION

1.1 Current Techniques for Crop Performance Monitoring.

1.1.1 The Use of Meteorological Data and Trend Lines.

In the member countries of the European community, there is a requirement for accurate and timely information on agricultural production. However, there are differences in agricultural production between member state countries.

This has resulted in a complex arrangement of regulations and subsidies known as the Common Agricultural Policy (CAP). The CAP relies in turn on the accuracy of the agricultural statistics. Since the member states of the European Community do not collect information that is uniform, it is difficult to compare data from country to country.

Currently models are being developed to estimate production forecasts for the main crops on the basis of meteorological data. A model is first constructed to forecast the various crop yields in each of the member states. The forecast yields are then multiplied by the agricultural areas determined by the various member states. Forecasts are prepared at the beginning of the crop year for each crop and for each country and are refined as the year proceeds, De Bast and Palm (1990). Inputs to the models are long term averages of yield data and weather variables such as precipitation and long term averages of temperature.

Examination of the annual yield series reveals rising trends in yields. These trends can be linked to advances in crop husbandry and to new and improved varieties. A trend model accounts for fluctuations in yields. In the construction of a forecast model, the effect of general trend is separated from the effect of meteorological conditions. To achieve this, the yield is broken down into three components:

$$\text{Yield} = f1(t) + f2(m) + ei \quad \text{eq. 1.1}$$

f1 is the trend component
f2 is the meteorological component
ei is the random component

The trend in yield is considered as a function of time, independently of meteorological conditions. Then the deviations in the residuals is explained by the use of meteorological variables. Separation of the trend effect from meteorological conditions has the advantage of simplifying model construction and enabling the part played by each component to be evaluated, De Bast and Palm (1990).

At present, the modelling is applied to the main annual crops, e.g. cereals, root crops, dried pulses and oilseeds. Until recently the model has been used at the country level but it has also been studied for regional application. Further inputs to these models would be in the form of agronomic variables such as accumulated temperature or evapotranspiration calculated from the Meteorological Office Rainfall and Evaporation System, (MORECS).

1.1.2 Simulation Models Based on Agro - Meteorological Data.

These models rely on a number of driving variables, for example average temperature, day length, daily wet and dry bulb temperatures and daily net short-wave solar radiation. Photosynthesis is calculated according to the amount of radiation intercepted by the canopy and a photosynthetic light response curve. Respiration is subtracted to give the daily increase in carbohydrate. This is then partitioned between roots, leaves, stems and later, ears in proportions which vary with the stage of development. Such a model has been produced for wheat, e.g. AFRC WHEAT. The model receives detailed description by Weir et al. (1984), Porter (1984) and Weir et al. (1985). The performance of the model has been tested by monitoring the cultivar Avalon sown simultaneously at ten sites throughout the UK, Porter et al. (1987); Kirby et al. (1987). Tests on the cultivar Hustler at Rothamsted Experimental station have revealed that there is good correspondence between the components of grain yield and the simulated components of yield using the model, Weir et al. (1984).

1.1.3 Crop Simulation Models Based on Dry Matter Partitioning.

Greenwood et al. (1985) developed a simulation model to interpret nitrogen fertilizer experiments on potatoes. The model calculates the total growth of dry matter, the nitrogen uptake, the partition of dry matter and of nitrogen between tuber and foliage and the distribution of inorganic nitrogen down the profile for each day during the growing season. Greenwood et al. (1985) tested the validity of the model on experimental plots on three different soil types. They found reasonably good agreement for their model which required only 9 inputs.

1.2 The Present Role of Remote Sensing in Crop Performance Monitoring.

1.2.1 Regional Scale.

The community interested in the remote sensing of agricultural production is diverse. It includes scientists, national and international agencies (e.g. USAID, ODA and international agencies, FAO and the World Bank), Allan (1990). Remote sensing provides timely information over large areas of economic importance. For example, wheat production has been monitored by the Large Area Crop Inventory Experiment (LACIE), MacDonald and Hall (1980). This experiment established that remotely

sensed data could be used as a model parameter for national and regional estimation of crop production. It was found that satellite coverage provided an improved estimate of the crop area and therefore production. Another example of regional monitoring using remote sensing is the Automated Real Time Environmental Monitoring Information System or ARTEMIS at the FAO in Rome. Using Meteosat and AVHRR data, it provides rainfall prediction based on cloud top temperatures and greenness / vegetation index maps which are useful in identifying locust breeding grounds. Such information is regularly used in Sahel countries, Allen (1990).

Other projects have sought to provide warnings of crop condition assessment. For example one of the eight programmes in Agricultural Resource Inventory Surveys Through Aerospace Remote Sensing (AGRISTARS) was directly aimed at providing early warning of crop condition. The project developed crop stress indicator models that provide data filter and alert capabilities for monitoring global agricultural conditions. The project developed a technique for using NOAA satellite Advanced Very-High-Resolution Radiometer (AVHRR) data for operational crop condition assessments. It developed procedures for using remotely acquired thermal data for crop water stress indicator modelling, Boatwright and Whitehead (1986). Other studies have combined meteorological data and remotely sensed data to provide estimates of dry matter production based on the efficiency of conversion of light energy into carbohydrate, Prince (1990).

1.2.2 Local Scale.

For crop performance monitoring at the regional and local scales, the Commission of the European Communities has initiated a pilot project to assess the use of remote sensing in crop inventory. This project is called the 'Agriculture Project'. The aim of this project is to improve and standardise the collection of statistical information and Agricultural forecasts over Europe. It consists of a number of actions, which started in the course of 1988. The four main actions are: Regional Inventories, Crop Monitoring and Yield Indicators, Yield Forecast models and Rapid Estimates of Areas and Potential yield. The project depends on the analysis of data from most of the available earth-resources satellites (NOAA AVHRR, LANDSAT TM and SPOT) and extensive ground observations, Klersy (1990). The initial findings are contained in 'The application of remote sensing to agricultural statistics', Toselli and Meyer-Roux (1990). This research effort has led to the incorporation of remote sensing into real time monitoring projects at the farm scale, e.g. the 'setaside' scheme. However, cloud conditions over the UK for example, can limit the acquisition of useable data. A new generation of radar systems are now being developed which are able to acquire data day or night and can penetrate the cloud layer (e.g. The European Remote Sensing Satellite, ERS-1). The potential use of such systems for agricultural monitoring is now being investigated, RSAC (1992).

Apart from space borne sensors, the use of photographic media in crop monitoring has been realised for some time. Aerial photographs play an important role in crop advisory information offered to farmers and land managers at the local and field scales. For example, Brenchley (1966) pioneered the use of aerial photographs for the discrimination of potato blight (Phytopthoa infestans) in the Fens of East Anglia. Although aerial photography cannot provide the same synoptic view as satellite data, it has advantages in terms of resolution, timeliness of acquisition, completeness of cover and cost, Blakeman (1990). The Agricultural Development and Advisory Service (ADAS) now provides information on the development of Potato Blight, Sugar Beet Yellows Virus, Yellow Rust, Barley Yellow Dwarf Virus, Take all, Barley Yellow Mosaic Virus and Rhizomania, Blakeman (1990).

1.2.3 The Field Scale.

A number of approaches have been suggested for estimating the dry matter production or yield of crops at the field scale. Direct relationships between spectral vegetation indices and productivity have been suggested by Tucker et al. (1979) and (1980). In these models, combinations of red and near infrared reflected energy were shown to relate to the dry matter production and grain yield. They integrated the spectral vegetation index and found that the highest correlations were in a spring window of development.

Work by Clevers (1986) has shown that reflectance data can be used to estimate Leaf Area Index and that field spectroscopy can be used to monitor field trials and provide information instantaneously and non-destructively.

Hatfield (1983) has suggested using a Stress Degree Day approach which combines thermal information with reflected vegetation index data. In this model, the spectral vegetation indices were used to define critical development stages in wheat and grain sorghum for canopy-air temperature difference summation. The summation of canopy-air temperature differences in this period acts as an indicator of stress and can be used to predict the yield.

Idso et al. (1977) first showed that midday canopy-air temperature differences (stress-degree-days) were related to yield when summed from heading to harvest. However, Walker (1980), cited from Hatfield (1983), showed that the period of accumulation of stress-degree-days was critical in reducing the residuals in the relationship between yield and accumulated stress degree days. In the work by Idso et al. (1977), the summation periods were related to observable phenological stages. This would limit the application of the technique from space borne sensors because of the difficulty in identifying stages of development.

Idso et al. (1980) showed a relationship between the rate of change of a Transformed Spectral Vegetation Index and grain yield, during the senescence phase following heading. This approach suggested that the faster the rate of senescence the larger the yield, because stressed wheat would begin senescence earlier. This technique is a measure of the duration of the green leaf area index.

Steven et al. (1983) combined remotely sensed and meteorological data to provide a growth model for sugar beet. In this model, spectral vegetation index data was used to estimate the proportion of light energy intercepted by the canopy. They found that the yield of sugar beet could be determined by summation of the solar energy intercepted by the canopy multiplied by an energy conversion factor. This factor was the net efficiency of conversion of solar energy to biomass. There is evidence to suggest that the efficiency factor is relatively stable in green healthy crops and it has a value in the range 1.5 - 2 g MJ^{-1}, Monteith (1977); Kumar and Monteith (1982); Monteith and Elston, (1983); Asrar et al. (1984). However, variations due to disease, nitrogen nutrition and irrigation have been noted, e.g. Steven and Demetriades-Shah, (1987). This technique has been applied operationally at the field scale to estimate the yield of sugar beet in East Anglia. The model was found to estimate the sugar yield with errors of 0.7% and 5% for 1987 and 1988 respectively, Jaggard and Clark (1990). This type of modelling has been applied to the estimation of grain yield in cereals, Daughtry et al. (1983), Maas (1988).

One of the problems with vegetation index data, is that leaf chlorosis can affect the precsion of the measurement. Work by Steven et al. (1992) has shown that it is possible to combine crop colour sensitive indices with crop colour insensitive indices to produce an index of chlorosis in sugar beet. It should therefore be possible to apply compensation factors to vegetation indices measured on stressed canopies once the degree of chlorosis has been quantified.

Recent advances in high resolution scanning radiometers (spectroradiometers) has meant that vegetation canopy reflectance can now be characterised in great detail under field conditions. These spectroradiometers typically have a resolution of 0.01 μm in the visible and near infrared wavelengths. This in turn has led to the development of high resolution vegetation indices based on the first derivative of the reflectance spectra, Demetriades-Shah et al. (1990). Steven et al. (1992) demonstrate that high spectral resolution indices based on the near- and middle-infrared regions of the spectrum can be used to estimate biomass independently of canopy stress. Other researchers have shown that such data can be used to estimate foliar chemical content. This technique assumes that a foliar spectrum is the sum of the absorption features of each chemical weighted by its concentration, Curran (1989).

1.3 Aims of this Work.

1.3.1 Development Stage Estimation Using Remote Sensing.

At the field scale, it has become apparent that more efficient use of inputs is required in order to maximise yields. There is pressure on farmers to reduce the amounts of inputs to their crops. This is because of the damage now perceived to have occurred to underground water supplies and water quality especially in the East Anglia region of the UK. This has in turn led to more detailed investigations on the optimum timing of management applications, for example the apical timing of spring nitrogen in winter sown cereals. This management technique has demanded accurate and timely crop calendar information. This can now be provided by models which can simulate apex development using long term averages of photoperiod and temperature. A potential use of remote sensing is to provide crop calendar information on apex development. To be useful at the field scale, such information must come from low cost sensors and at least achieve an accuracy as good as or better than existing models based on meteorological data. Remote sensing technology which can meet these requirements is available in the form of boom held or hand-held radiometers. The relationship of spectral data to apex development stages has not been investigated. An objective of this study was to investigate the relationship of spectral data to winter wheat apex phenology using such technology.

1.3.2 The Relationship of Spectral Data to Winter Wheat Grain Yield.

Also at the field level it has become apparent that spatial mapping of yield at harvest time can provide useful information on areas in a field which require attention for the following season. This reduces the requirement for blanket applications of for example nitrogen. Another use of remote sensing is to provide indicators of yield potential. For winter sown wheat, relationships between grain yield and spectral data have been proposed at various stages in the development cycle of the crop. However, the effect of sowing date, variety and disease on these performance indicators has not received detailed investigation. Any model that can be used to predict potential yield must be independent of these management variables. Another aim of this work was to investigate the relationship of spectral data to winter wheat grain yield for dry land farming in the UK using hand-held radiometers. This investigation was conducted in conjunction with a commercial seed breeding company, Nickersons RPB Ltd. Nickersons' maintain an active an extensive breeding site at Woolpit near Bury St. Edmunds. It was at this site that data was collected over the 1989 and 1990 growing seasons.

CHAPTER 2. THE APPLICATION OF REMOTE SENSING FOR CROP MONITORING

2.1 The Interaction of light energy with plant canopies.

2.1.1 The Energy Balance Equation and Reflected Energy.

Plant leaves reflect, absorb and transmit radiation in a manner that is dependent on wavelength. These relationships can be shown by the energy balance equation:

$$I(\lambda) = R(\lambda) + A(\lambda) + T(\lambda) \quad \text{eq. 2.1}$$

where I denotes incident energy, R denotes energy reflected, A denotes energy absorbed and T denotes energy transmitted. As most radiometers which operate in the 0.3 to 3.0 μm range measure only reflected energy, it is more useful to think of this relationship in the form of:

$$R(\lambda) = I(\lambda) - (A(\lambda) + T(\lambda)) \quad \text{eq. 2.2}$$

i.e. reflected energy is equal to the incident energy which is not absorbed or transmitted.

2.1.2 The Spectral Reflectance of Green Healthy Vegetation.

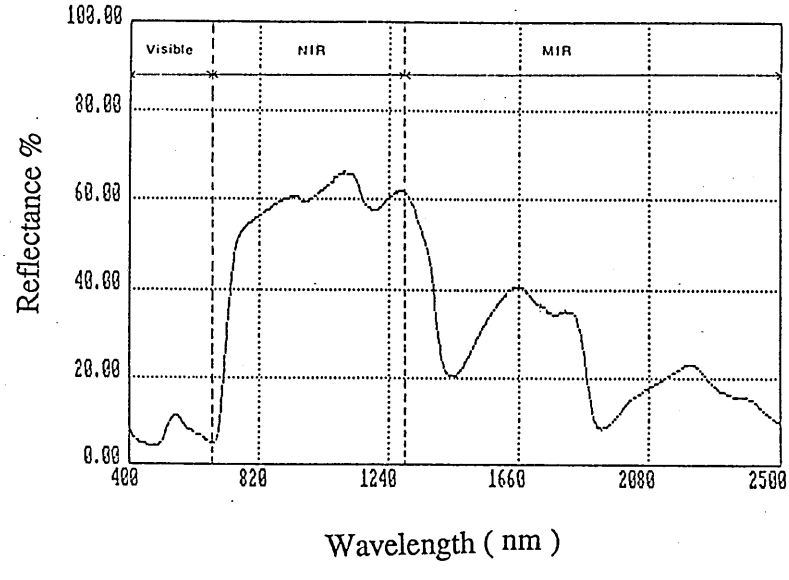
The spectral reflectance of green healthy vegetation is variable over wavelength. Figure 2.1 shows the spectral reflectance curve for green vegetation and identifies 3 spectral response regions of importance:

(i) Visible region, 0.3 - 0.7 μm;

(ii) Near Infrared region (NIR), 0.7 - 1.3 μm;

(iii) Middle Infrared (MIR) region, 1.3 - 3.0 μm, Grant (1987).

FIGURE 2.1 REFLECTANCE OF GREEN VEGETATION AS A FUNCTION OF WAVELENGTH.



2.1.3 Visible, NIR and MIR Energy Interactions.

In the visible region, pigmentation dominates the spectral response of plants, chlorophyll is important. In the near infrared region, the reflectance rises notably because the leaf absorbs little of the incoming radiation. Air and cell wall interfaces are important. In the middle infrared region, water absorbs energy at particular wavelengths. As green leaves have high moisture content, these water absorption bands dominate the spectral response. In green healthy vegetation, high reflectance in the near infrared is associated with low reflectance in the red wavelengths. Light reflectance from plant canopies is an integrated response of various plant structures, the soil background, multiple leaf layering, shade, leaf air content, canopy thickness and adherents to vegetative and reproductive appendages.

2.1.4 Reviews on the Nature of Green Vegetation Reflectance.

Grant (1987) and Hoffer (1978) provide excellent reviews of the nature of green leaf reflectance. Models of canopy reflectance and their use in the estimation of biophysical parameters from reflectance data are reviewed by Goel (1987) and Milton and Wardley (1987). The principles of field spectroscopy are reviewed by Milton (1987).

2.2 Vegetation Indices and Crop Monitoring.

2.2.1 Definition of a Spectral Vegetation Index.

A spectral vegetation index (VI) is a quantity obtained directly or by ratioing, differencing or otherwise transforming spectral data to represent plant canopy characteristics such as leaf area index, biomass, per cent cover, Jackson et al.(1980). The derivation of spectral indices is explained in detail by the same authors. This has involved the use of narrow bands or wavebands of the electromagnetic spectrum, usually Red and near infrared reflectance data.

2.2.2 Use of VI's in Crop Monitoring.

Reference to Figure 2.2 shows the changes in spectral reflectance for a wheat canopy from emergence through to heading measured by the use of hand held radiometers. At emergence, the spectral reflectance looks something like that for bare soil, i.e. reflectance increases with wavelength. As the vegetation amount or leaf area increases, spectral reflectance changes. Visible energy is absorbed so reflectance decreases. Near infrared reflectance increases because energy is refracted and scattered by cell wall and water interfaces. In the middle infrared, water absorbs energy. As green leaves have high water content the reflectance decreases. Figure 2.3 reveals what happens after heading and anthesis. Loss of pigmentation and cell structural collapse causes the reflectance pattern to change back to a pattern

similar to that for bare soil. Rouse et al. (1973) have proposed using a transformation of visible and infrared remotely sensed data to monitor such changes. They used the Normalised Difference Vegetation Index or NDVI where:

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \qquad \text{eq. 2.3}$$

FIGURE 2.2 CHANGES IN THE SPECTRAL REFLECTANCE OF A WHEAT CANOPY OVER TIME, MEASURED USING HAND HELD RADIOMETERS. BURY UK 1989. EMERGENCE TO HEADING

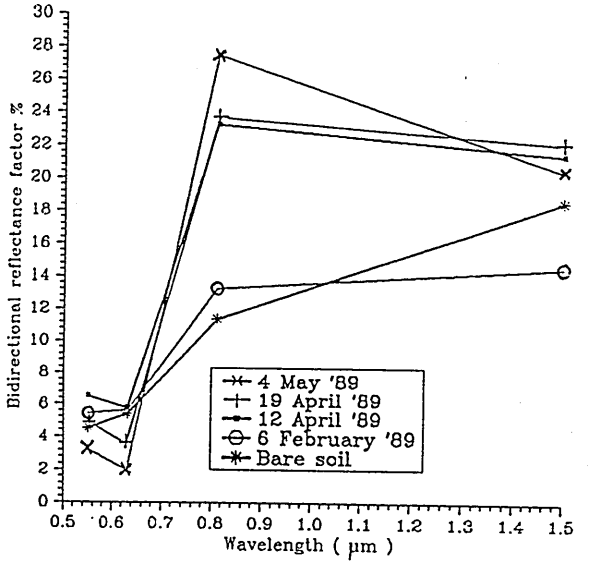
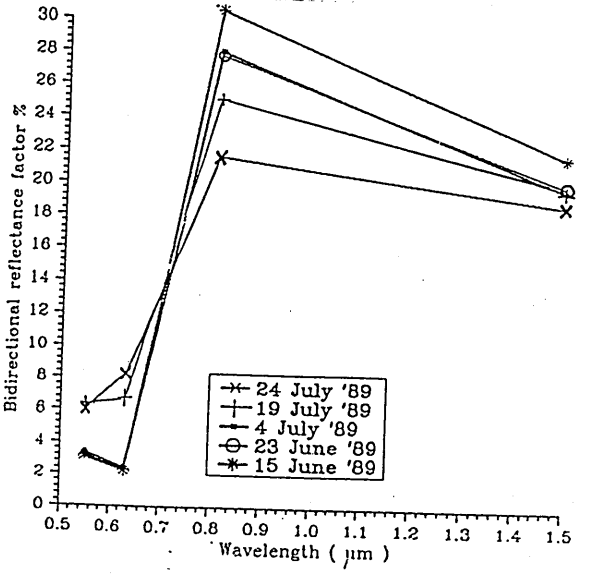
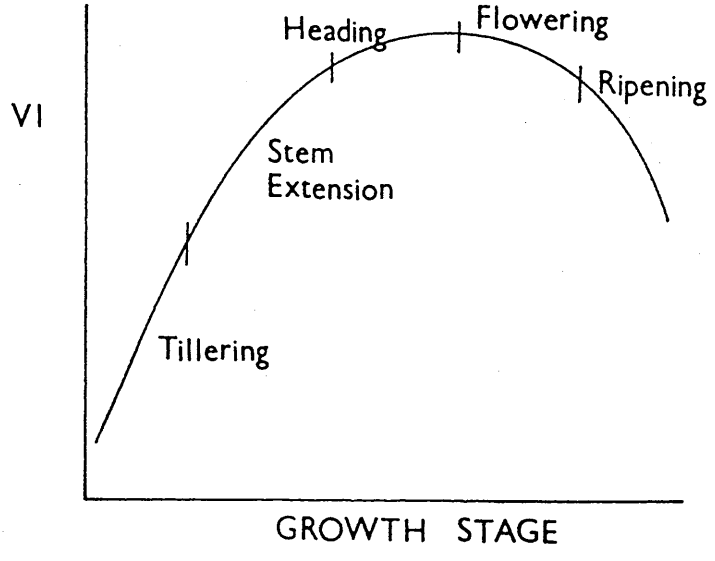


FIGURE 2.3 CHANGES IN THE SPECTRAL REFLECTANCE OF A WHEAT CANOPY OVER TIME, MEASURED USING HAND HELD RADIOMETERS, BURY UK, 1989. HEADING TO HARVEST.



These changes in the vegetation index with time, have been used for assessing biomass and phenological development of plants. Such a curve can be described as a profile of spectral development over time or as a spectral temporal profile. Figure 2.4 shows such an idealised curve for cereals. The profile is characterised by a minimum value generally representing the vegetation index of bare soil. The curve then shows a green up phase from emergence to heading in which there is expansion of green leaf area. Beyond critical biomass levels the vegetation index becomes insensitive to further changes. This occurs at the heading stage. After the heading stage and anthesis, grain fill and senescence occurs until harvest, hence the vegetation index declines. Such spectral temporal profiles have been used to separate species in the agricultural scene from satellite altitudes as the rate of green up and plateau saturation levels are unique for an area depending on the sowing date and the location.

FIGURE 2.4 SPECTRAL TEMPORAL PROFILE FOR CEREALS, SHOWING RELATIONSHIP TO PHENOLOGICAL STAGE.



2.2.3 Reviews Of The Work Using VI's For Crop Monitoring.

Richardson and Weigand (1977) have proposed using a look up table approach for mapping vegetation cover and crop development by the use of NIR and red reflectance data. Kauth and Thomas (1976) have developed a spectral technique for characterising the soil brightness and green vegetation development for wheat and other crops. Their approach used information in all LANDSAT MSS bands. Many publications have used spectral data for estimating green leaf biomass, and or monitoring the green leaf area over time. These publications were reviewed by Tucker et al.(1980). In small grain cereals, different parts of the profiles have been used to predict the grain yield.

2.3 Yield Indicators in Small Grain Cereal Crops Using Remote Sensing.

2.3.1 Single Date May Time Measurements of the Vegetation Index.

This is expressed as:

$$\text{Yield} = \alpha + ß\,(VI) \quad \text{eq. 2.4}$$

The single date measurement is performed before maximum leaf area is reached and just before the heading stage in the development of the crop. This corresponds to early May in the North-western sphere of agricultural production. High correlations for this relationship have been reported, e.g. Tucker et al. (1980) and Ashcroft et al. (1987), Figure 2.5.

Tucker et al. (1980) investigated the relationship of spectral data to within field grain yield variation. They found that single date regressions were highest in a 40 day period, Julian days 112 - 152. However the regression coefficients they derived were not constant during this period, Table 2.1. This suggests that single date regressions could not be used on a regional or even local basis.

TABLE 2.1 REGRESSION DERIVED ESTIMATES FOR α AND ß USING NDVI TO PREDICT FINAL GRAIN YIELD. AFTER TUCKER ET AL. (1980).

Julian Date	α	ß	r^2
112	69.1	365	0.61
118	85.6	350	0.67
121	96.6	327	0.68
123	116.8	321	0.62
131	15.8	413	0.61
139	-70.3	512	0.65
146	-26.8	476	0.57
152	-51.2	534	0.6

2.3.2 Integration of Areas Under the Spectral Profile.

This is expressed as:

$$\text{Yield} = \alpha + ß\,(\int f(VI)dt) \quad \text{eq. 2.5}$$

The work on the single date measurement of the vegetation index suggests that the spectral response of the canopy is not constant as a function of time. Tucker et al. (1980) and Tucker et al. (1980b) integrated areas under the vegetation index profile and found a window in which the spectral data was most highly correlated to grain yield and biomass. This occured in early spring which was the plateau portion of their curves using radiance data (Julian dates 112 - 152). This corresponded to the period of maximum leaf biomass, Figure 2.6.

FIGURE 2.5 THE RELATIONSHIP OF GRAIN YIELD TO NDVI, EARLY MAY, WINTER WHEAT. ASHCROFT ET AL.(1988).

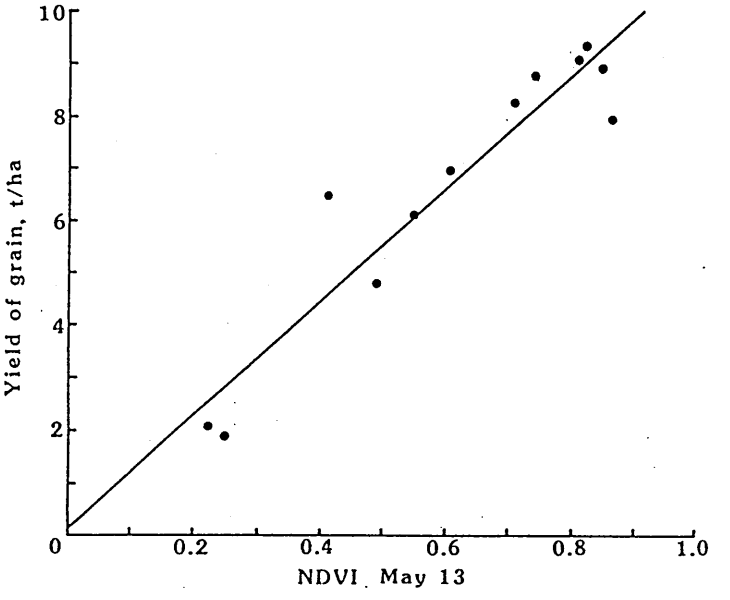
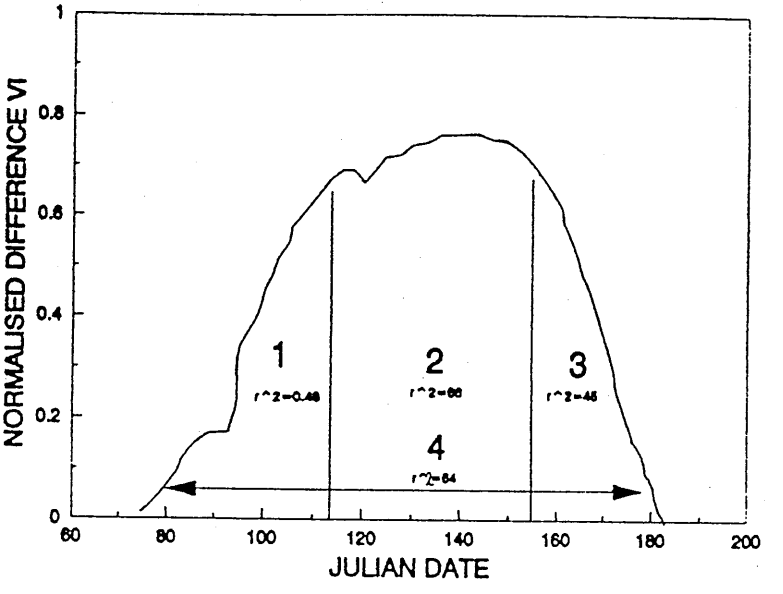


FIGURE 2.6 COEFFICIENTS OF DETERMINATION RESULTING FROM JULIAN DATE INTEGRATIONS FOR 4 DIFFERENT TIME PERIODS. 1. JD 80 - 112, 2. JD 112 - 152, 3. JD 152 - 174, 4. JD 80 - 174. AFTER TUCKER ET AL.(1980).



2.3.3 The Rate of Change of a Transformed Vegetation Index (TVI) With Time and Grain Yield.

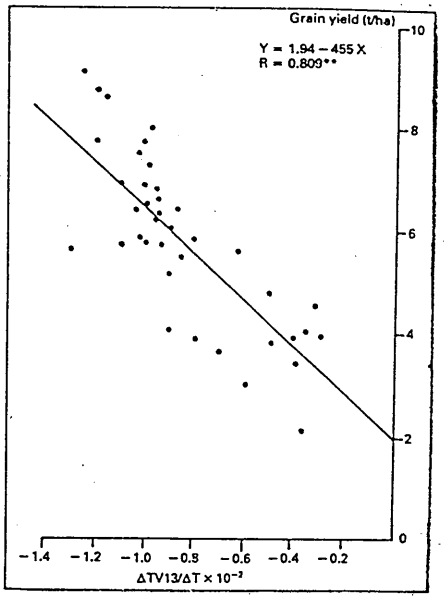
This expressed as:

$$\text{Yield} = \acute{A} + ß\,(\,dTVI/dt\,) \quad \text{eq. 2.6}$$

$$TVI = (NDVI + 0.5)^{0.5} \quad \text{eq. 2.7}$$

The TVI is highly indicative of green leaf area and is responsive to the loss of chlorophyll which is associated with senescence. During senescence, changes occur in the plant colour, plant morphology, plant moisture content, cell structure and plant pigments. Idso et al.(1980), have shown a relationship between the rate of change of the TVI and grain yield for irrigated plots in the U.S.A. This method has been applied to dry land cereal production in the UK, Figure 2.7. However, attempts to confirm the technique have showed that disease and lodging cause departures in the reflectance patterns, Zmuda (1987).

FIGURE 2.7 GRAIN YIELD AS A FUNCTION OF THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX, AFTER MORE (1981).



2.4 Estimation of Crop Phenology Stages in Cereals Using Remote Sensing.

2.4.1 Previous Work on Modelling of Development Stages.

Tucker et al.(1980) stressed that successful applications for regional predictions of grain yield using remote sensing must be able to account for within region differences in winter wheat crop phenology. As the single date regression coefficients varied, crop phenology differences within a given region would preclude effective use of one or two remotely sensed data sets acquired during the critical six week period. They suggested that accurate crop calendar information must be available. To achieve this, they suggested using spectral data and accumulated temperature units, Figure 2.8.

2.4.2 Use of the Greenness VI for Corn and Soybeans.

Badhwar and Henderson (1981) used LANDSAT data to model corn phenology on the Hanway scale. They proposed using a 4 band translation of LANDSAT data space using visible and near infrared reflectance data. The spectral profiles for corn were modelled using a non-linear least squares approach. This was adopted because the start and end points of the spectral profiles could be well determined. The model included a term for the estimation of spectral emergence. The non-linear least squares model they used had the effect of smoothing the spectral information. They suggested that fractional areas under profiles of spectral development were directly related to development stages on the Hanway scale, Figure 2.9.

Unlike Tucker et al. (1980), they used an integrated approach which was independent of meteorological data basing their model on Julian days. Their model worked well with differences in soil background, cultivar, planting density, and sowing date. This technique has been applied to Soybean development stage estimation and again found to work well with differences in soil background, cultivar, sowing date and planting density, Henderson and Badhwar (1984).

FIGURE 2.8 A POSSIBLE SPECTRAL CROP CALENDAR USING THE NDVI AND ACCUMULATED TEMPERATURE UNITS, (I.E. GROWING DEGREE DAYS). SOURCE TUCKER ET EL. (1980).

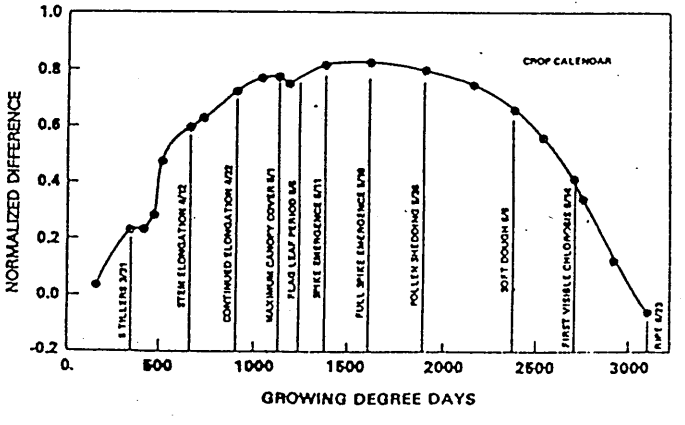
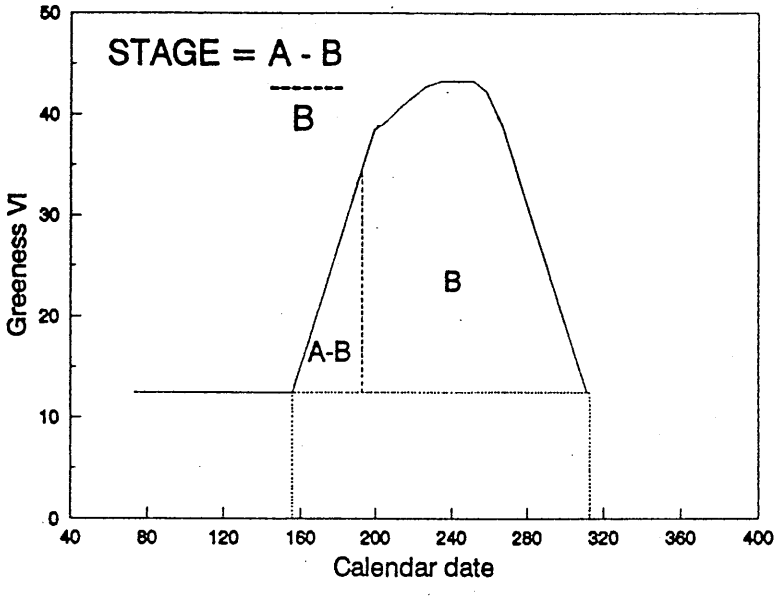


FIGURE 2.9 SPECTRAL MODEL USING GREENNESS TO ESTIMATE DEVELOPMENT STAGES ON THE HANWAY SCALE. AFTER BADHWAR AND HENDERSON (1981).



2.4.3 Relationship of Cardinal Points of Profiles to Crop Phenology Stage.

Badhwar (1984) has shown that cardinal points of spectral profiles correspond to specific crop phenology stages in spring small grain cereals. These cardinal points are the inflexion points on the green up and green down (t1 and t2) and the maximum turning point, tp. Badhwar (1984) found that tp corresponded to heading, t1 to jointing and t2 to the hard/soft dough stage. Badhwar modelled the vegetation index development over time using a non-linear least squares fit. The first and second order derivatives of this model were found to relate to specific development stages.

2.5 Approach and Objectives of this Study.

2.5.1 The Effect of Development Stage, Variety, Sowing Date and Disease on the Relationship of Spectral Data to Winter Wheat Grain Yield.

Variety and sowing date effects on the relationship between spectral data to grain yield have not been investigated for dry land farming in the UK. The objectives of this study were to design field experiments and test for the effects of development stage, sowing date and variety on the relationship between spectral data and winter wheat grain yield. Field radiometers were considered to be an ideal tool for this kind of investigation. Using Milton Multiband Radiometers, three hypotheses were tested on varieties of winter wheat sown on different dates. These were that:

(i) Instantaneous measurement of spectral data in early May showed a direct relationship to grain yield;

(ii) Time integrated vegetation index data in a spring window of development showed a direct relationship to grain yield;

(iii) The rate of change of the Transformed vegetation index with time in the senescence phase, showed a negative relationship to grain yield.

The effect of fungal disease on remotely sensed yield indicators has not received attention. A second objective of this study was to set up independent field experiments and test the validity of the spectral models using wheat receiving different levels of fungicide treatment.

2.5.2 The Effect of Sowing Date, Variety and Disease on the Relationship of Spectral Data to Development Stages.

As spectral data has been shown to be related to grain yield during a spring window of development, then application of such a model would require precise crop calendar information. This would enable researchers to focus on the best time for prediction purposes. In the last 15 years, attention has been paid to apex development pioneered by Kirby (1977). The development stage of the apex has proved important in management at the field scale. This is because maximum yield can be better achieved by timing the inputs in relation to the stage of apex development, Biscoe and Willington (1983). Kirby and Appleyard (1987), have identified stages of apex development from vegetative through to harvest ripe grain. However, the attainment of these stages is dependent on photoperiod, temperature and vernalisation requirement, Kirby and Appleyard (1987). A model has now been developed in the UK, which can predict apex phenology stages based on long term averages of temperature and photoperiod, Porter (1990). This is the sub model of the AFRC WHEAT model developed by Weir et al. (1984). AFRC WHEAT receives detailed description in Hay and Walker (1989). Spectral data could be used to model stages of apex development. The ideal model would be:

(i) independent of sowing date;

(ii) sensitive to variety;

(iii) independent of soil background;

(iv) be applicable to areas the size of fields;

(v) have between region and year comparison utility.

The relationship of spectral data to the stage of apex development had not been investigated. An objective of this study, was to investigate the relationship of spectral data to development stages of the apex. A two band approach was proposed, using red and near infrared reflectance data transformed into the NDVI. Because long term weather data may not available at the local scale, the proposed model was independent of meteorological data.

Following Badhwar's (1984) model, it was hypothesized that cardinal points of spectral temporal profiles corresponded with apex phenology stages in winter sown wheat. Using field experiments with different varieties and sowing dates this hypothesis was tested. Again the impact of fungal disease on such modelling had not been investigated. It was an objective of this study to investigate the impact of fungal disease on apex development stage estimation using remote sensing. An independent field experiment consisting of wheat treated and untreated with fungicide was used to assess the impact of fungal disease on such modelling.

2.5.3 Summary of The Aims of This Project.

To summarise, the aims of this project were:

(i) To investigate the effect of development stage, variety, sowing date and disease on the spectral response of winter wheat;

(ii) To investigate the effect of development stage, variety, sowing date and disease on the relationship of spectral data to winter wheat grain yield;

(iii) To investigate the effect of fungal disease on remotely sensed yield indicators;

(iv) Develop a model based on spectral data to estimate the timing of apex development stages;

(v) To assess the impact of fungal disease on apex development stage modelling using remote sensing.

CHAPTER 3. TECHNIQUES AND EXPERIMENTAL METHODS

3.1 Field Radiometry.

3.1.1 The Measurement of Reflectance Under Field Conditions.

The reflectance field of targets can be thought of as comprising two hemispherical distributions of electromagnetic radiation, one incoming, one outgoing. This is the Bidirectional Reflectance Distribution Function (BRDF). The ratio of these two fields represents energy reflected. Because solar azimuth and zenith vary, complete specification of the reflectance field would necessitate measurement at all possible source and sensor positions. In reality this is difficult if not impossible to achieve. Therefore reflectance factors are used as a surrogate measure of the BRDF.

The Bidirectional Reflectance Factor (BRF) can be defined as the standardisation of reflected radiance by the use of a panel, specified to be perfectly diffuse, completely reflecting and viewed under the same irradiation conditions as the target, Milton (1986). As perfect diffuse standards do not exist, correction factors must be applied. Measurement of reflectance factors help us to understand the inter-relationships between spectral radiometric characteristics of objects and their biophysical attributes in the field, Milton (1986). Instruments used to measure reflectance factors under field conditions are called radiometers. There are 2 designs:

(i) up/down configuration, Duggin (1980);
(ii) the biconical configuration, Milton (1986).

In the up/down configuration, reflectance factors are measured with a cosine corrected sensor which has a 180° field of view mounted on top of the radiometer. Thus this is referred to as the cos conical configuration. Two sensors are employed. The first measures sky irradiance, the second measures target radiance. Measurements of radiance and irradiance are made simultaneously. The field of view of the target sensor is typically 8° - 20°. An example of this type of device is the MSP 1000 radiometer. This was a prototype instrument built in the UK and used for research purposes, Moore (1981), Hindley (1987) and Zmuda (1987). The device must be calibrated against a standard panel over a range of solar zenith angles. Such a calibration has been performed for the MSP 1000. The instrument shows strong sun angle response which is wavelength dependent, Zmuda (1987). Software has been developed using these calibration coefficients to correct data given inputs such as latitude, longitude, date and time of observation, Zmuda (1987).

The biconical configuration requires a standard reflectance panel as a pre-requisite. The panel is used to measure the irradiance in the same geometry as the target. One sensor head can be used to measure the target and panel sequentially or two sensor heads can be employed to measure the target and panel simultaneously. An example is the Series 100 Milton Multiband radiometer, Milton (1986). This device comes with an optional data logger which facilitates rapid storage and interchange of data with a desk top PC. Although the heads are matched, it is necessary to carry out an intercalibration of the heads for the simultaneous method. The series 100 employs Kodak grey cards as the reference standard. These are relatively cheap and are stable under field conditions, Milton (1989).

3.1.2 Instrumentation Used in this Study.

The radiometer system used in this study was the Series 100 Milton system. This is a light weight radiometer designed to measure the spectral reflectance of targets under field conditions. The series 100 consisted of:

(i) 2 MMR heads, MMR1 and MMR2;
(ii) 1 output unit;
(iii) Reference panels (Kodak grey cards);
(iv) Li-Cor data logger.

Two modes of operation were possible with the radiometer:

(i) sequential mode, in which the target and the reference panel were measured alternately using one sensor head;

(ii) simultaneous mode, in which the target and the reference panel were measured at the same time using two senor heads.

As two heads were available, it was possible to measure the target and reference panel simultaneously. The control unit had 8 analogue stores which sampled the voltage from the sensor bands of the heads. The sequential mode of operation was only adopted on two occasions when breakdown of the output unit occurred and a temporary unit was used.

The MMR's, Kodak grey card and Li-Corr logger were mounted on a Dexion frame. MMR1 was positioned so that measurements of target radiance could be made with the instrument pointing vertically downwards. MMR2 was positioned so that it measured panel radiance from a height of 40cm at nadir, Plate 3.1.

3.1.3 Wavebands on the Series 100 MMR's.

The series 100 MMR's employed broad band width wavebands. These were 1 green, 1 red, 1 near infrared band (NIR) and 1 middle infrared (MIR) band. Response functions for the visible and NIR bands are shown in Figures 3.1 and 3.2. Response functions for the MIR bands on MMR1 and MMR2 are shown in Figure 3.3. Peak response and 50% response functions are shown in Table 3.1.

PLATE 3.1 MEASUREMENT CONFIGURATION FOR THE SERIES 100 MMR's.

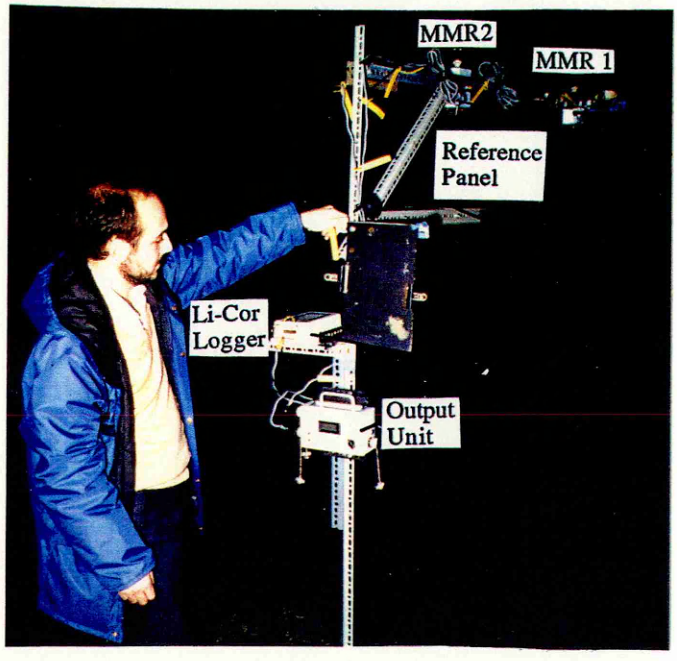


FIGURE 3.1 RESPONSE FUNCTION IN THE VISIBLE AND NIR PORTION OF THE SPECTRUM FOR MMR1.

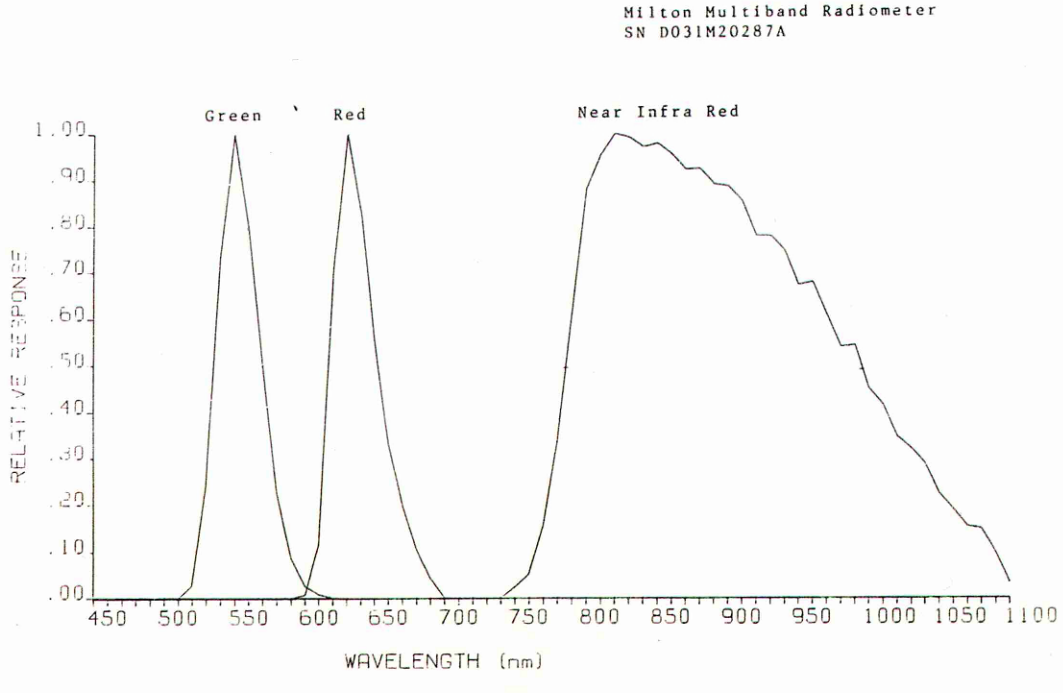


FIGURE 3.2 RESPONSE FUNCTION IN THE VISIBLE AND NIR PORTION OF THE SPECTRUM FOR MMR2.

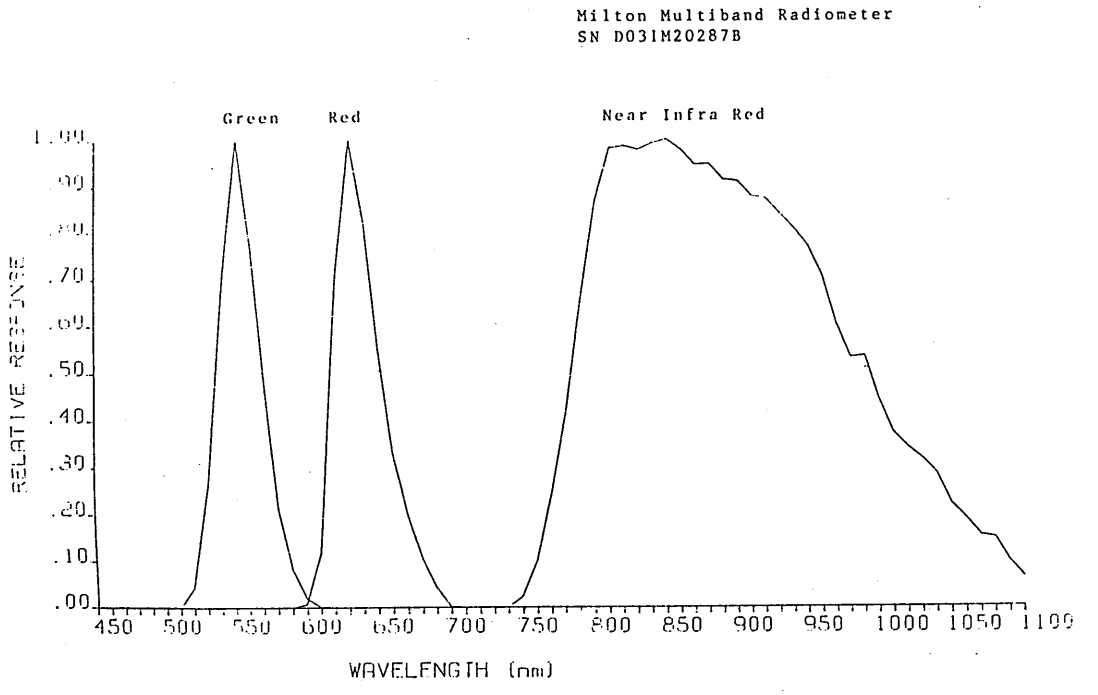


FIGURE 3.3 RESPONSE FUNCTIONS FOR THE MIR PORTION OF THE SPECTRUM FOR MMR1 (A) AND MMR2 (B).

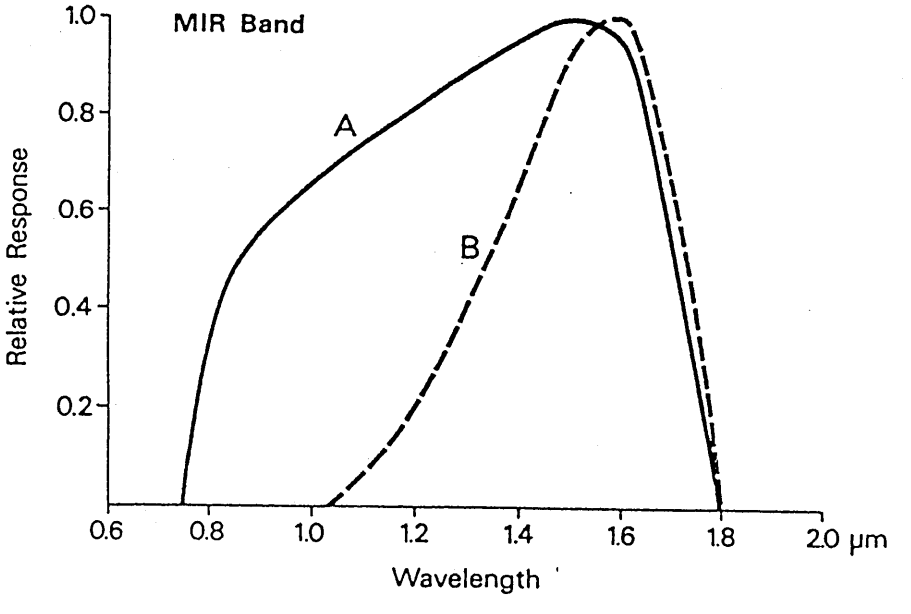


TABLE 3.1 50% RESPONSE FUNCTIONS AND PEAK RESPONSE FOR A. MMR1 AND B. MMR2.					
	BAND	50% RESPONSE		TM EQUIVALENT	PEAK RESPONSE
A. MMR1					
	GREEN	0.53	0.57μm	BAND 2	0.55μm
	RED	0.61	0.65μm	BAND 3	0.63μm
	NIR	0.78	1.00μm	BAND 4	0.81μm
	MIR	0.85	1.70μm	BAND 5	1.5 μm
B. MMR2					
	GREEN	0.54	0.57μm	BAND 2	0.55μm
	RED	0.62	0.65μm	BAND 3	0.63μm
	NIR	0.78	0.99μm	BAND 4	0.85μm
	MIR	1.33	1.75μm	BAND 5	1.60μm

3.1.4 Intercalibration Procedure for the Series 100 MMR's.

The simultaneous method of operation requires that the sensor heads be intercalibrated over the range of radiance levels. This was achieved by deriving a least squares fit to the data from the two sensor heads as they viewed the same diffuse surface over a range of solar zenith angles and levels of radiation, Milton (1986).

Apparatus was constructed to mount the radiometer pair vertically upwards, free from all shadow and reflecting surfaces, Plate 3.2. An intercalibration for the MMR's was carried out on the 4.4.89 on the grounds of the Cranfield Institute of Technology, Silsoe Campus. A sheet of sand blasted perspex was fixed horizontally above the sensor units approximately 2cm from the front of their field stops, Plate 3. Measurements of diffuse sky irradiance were made at 15 minute intervals from 10.00am until 2.00pm. Dark current measurements were taken every hour and subtracted from raw data. The wind run on the 4.4.89 was 236.5 miles/day.(Silsoe Campus meteorological station). This gave a wide range of solar irradiance conditions ranging from bright direct light to diffuse light, Plates 3.4 and 3.5.

PLATE 3.2 DEXION FRAME USED TO MOUNT MMR1 AND MMR2 FOR THE INTERCALIBRATION PROCEDURE, 4.4.89.

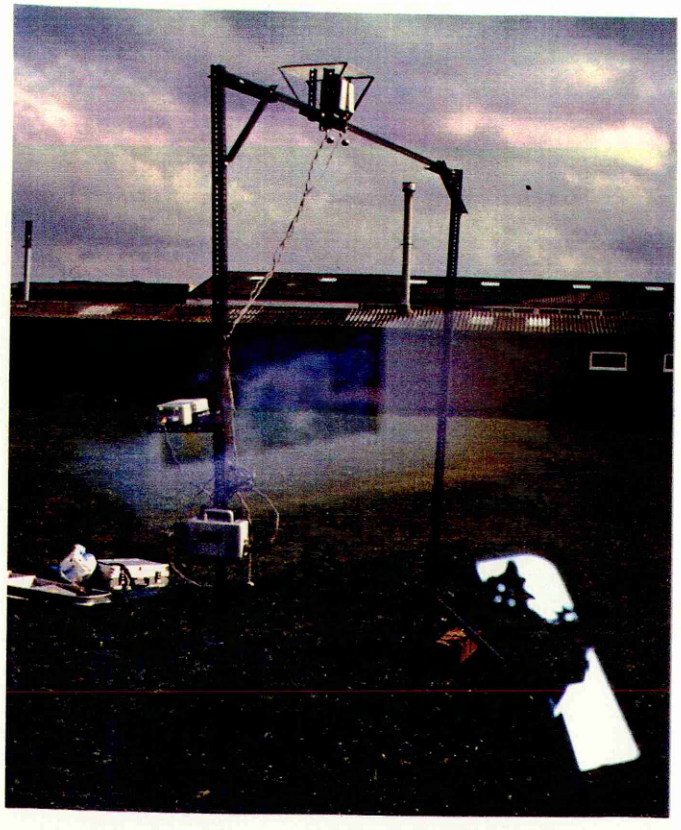


PLATE 3.3 SAND BLASTED PERSPEX MOUNTED ABOVE THE FIELD STOPS OF MMR1 AND MMR2.

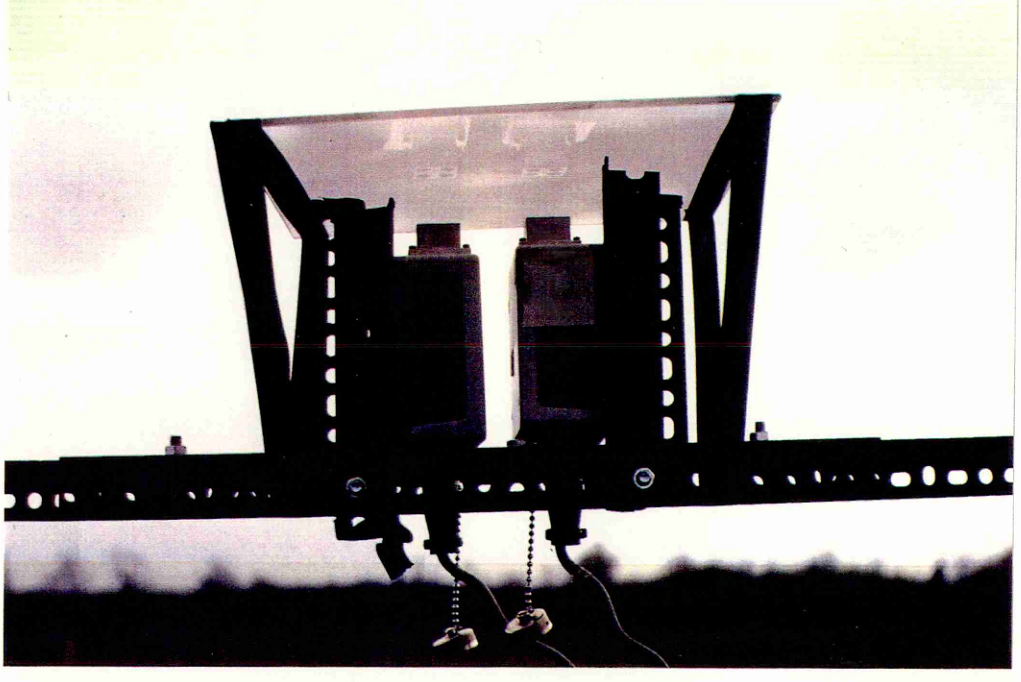


PLATE 3.4 BRIGHT DIRECT SKYLIGHT CONDITIONS DURING THE INTERCALIBRATION PROCEDURE, 4.4.89.

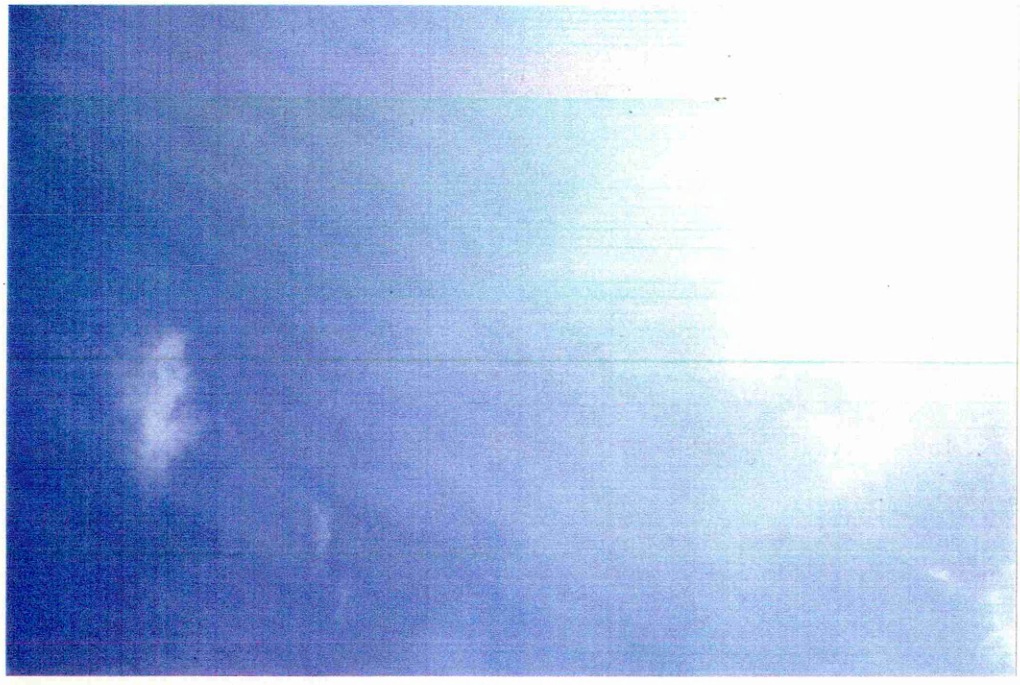
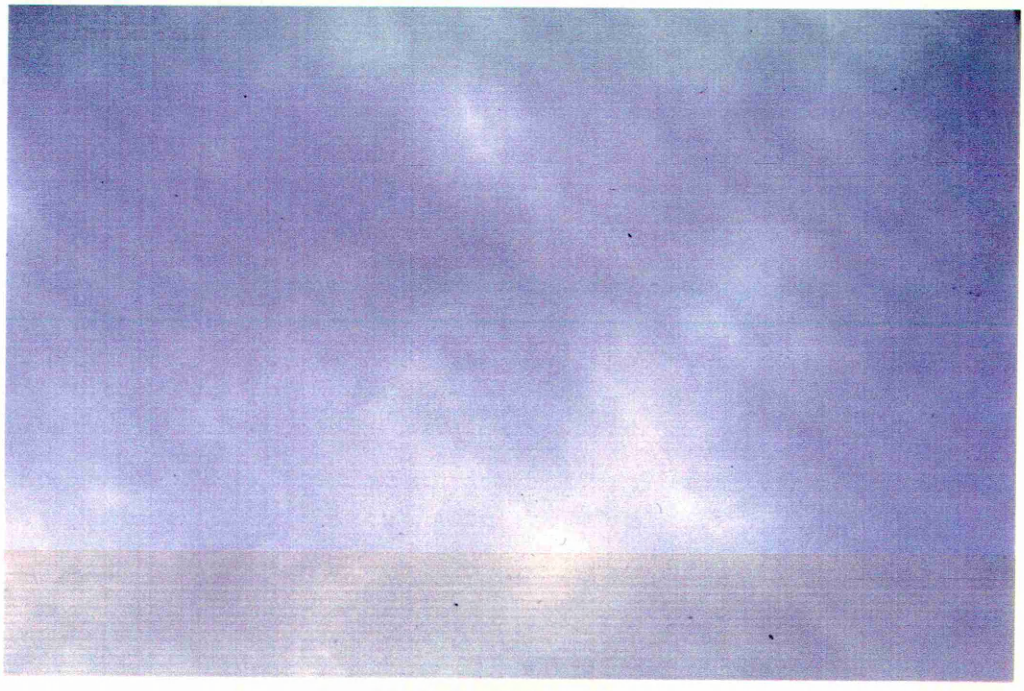


PLATE 3.5 BRIGHT DIFFUSE SKYLIGHT CONDITIONS DURING THE INTERCALIBRATION PROCEDURE, 4.4.89.

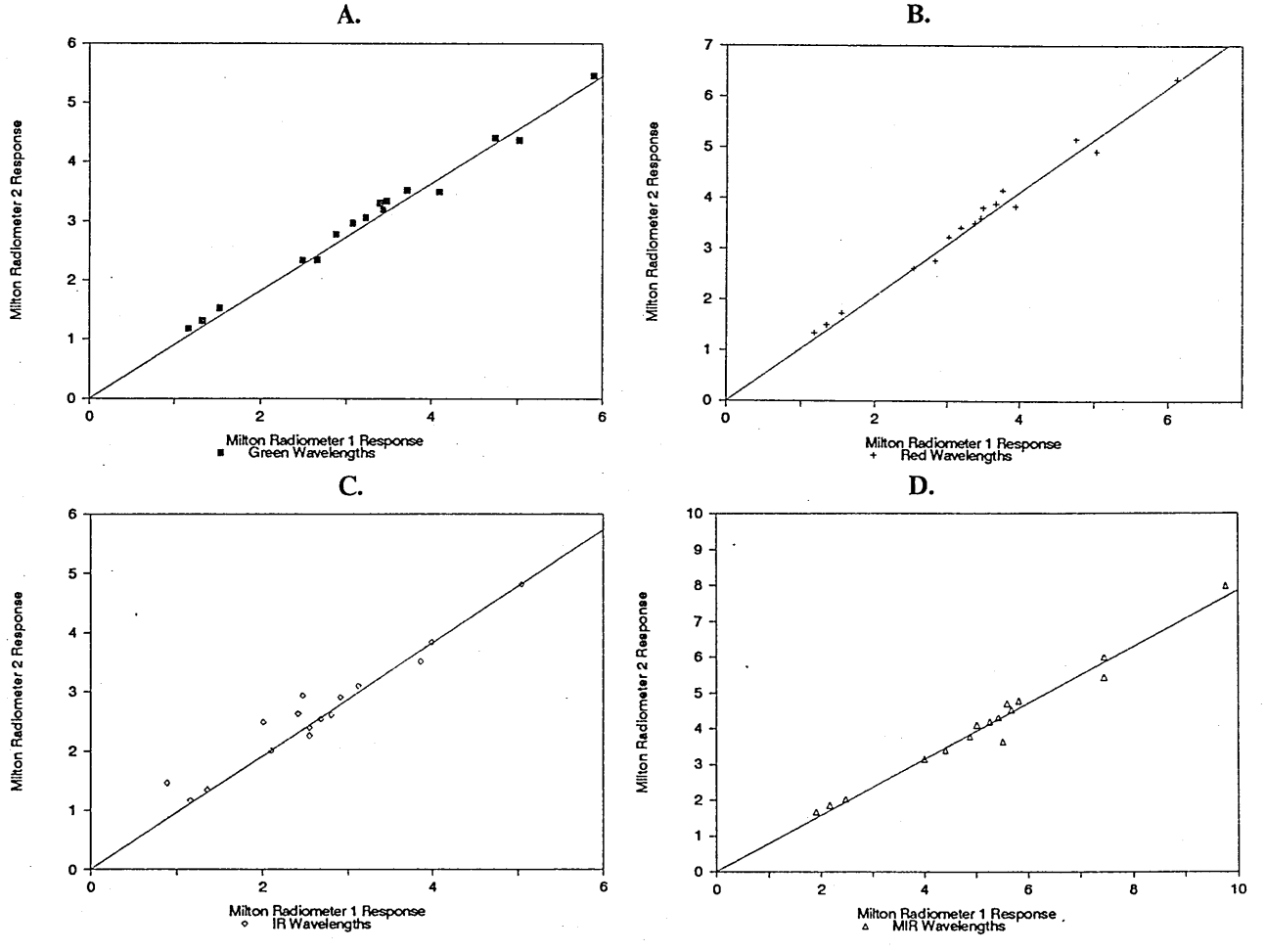


The relationship between the same spectral bands for the 2 sensor heads was established by fitting a best line fit through the data points. The results of the intercalibration procedure performed on the 4.4.89 are given in Table 3.2. The least squares regression lines are shown in Figure 3.4. These coefficients were used to normalise MMR2 to MMR1.

TABLE 3.2. LEAST SQUARES FIT OF INTERCALIBRATION OF MMR2 AGAINST MMR1, 4.4.89. LINE FITTED THROUGH THE ORIGIN.

BAND	FIT	R^2 %
GREEN	MMR2 = 0.92 MMR1	99
RED	MMR2 = 1.042 MMR1	99
NIR	MMR2 = 0.984 MMR1	91
MIR	MMR2 = 0.791 MMR1	97

FIGURE 3.4 REGRESSION LINES RESULTING FROM INTERCALIBRATION OF MMR2 AND MMR1. A GREEN, B RED, C NIR, D MIR BANDS.



3.1.5 Calculation of Bi-directional Reflectance Factors (BRF's).

Milton (1986) defines the bi-directional reflectance factor as the standardisation of reflected radiance by the use of a panel specified to be perfectly diffuse, completely reflecting and viewed in the same irradiation conditions as the target. The radiance of the target is then measured as a proportion of the radiance of the standard panel. Because in practice perfect diffuse reflectors do not exist, a correction is made to account for the spectral reflectance of the panel. Thus:

$$BRF(\lambda) = \frac{dLT(\lambda) - DC(\lambda)}{dLP(\lambda) - DC(\lambda)} \times Kr(\lambda) \quad \text{eq. 3.1}$$

(λ) = wavelength
dLT = target radiance
dLP = panel radiance
Kr = panel correction factor
DC = Dark Current

Measurements of BRF's were made ± two hours either side of noon. This measurment period was adopted in order to limit the changes in reflectance factors which have been noted to occur at large solar zenith angles, Duggin (1977).

3.1.6 Calibration Procedure for Kodak Grey Cards.

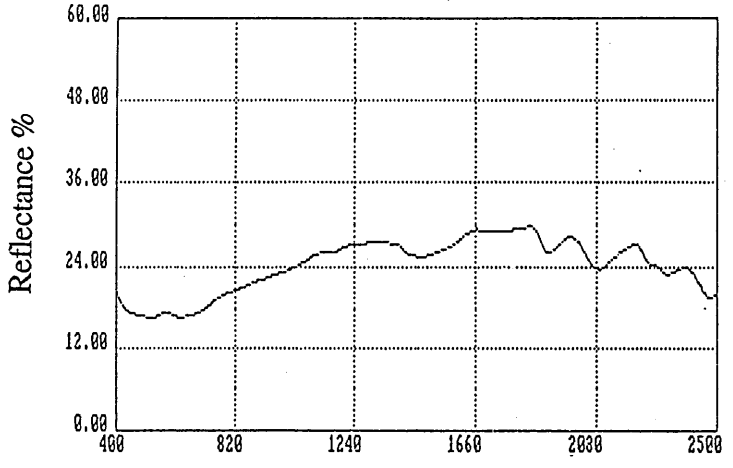
Because Kr in the previous section was wavelength dependent, calibration of 2 grey cards was performed against a standard. Grey card 1 was used as a field reference over 2 seasons. Grey card 2 was used as a field spare. The calibration was carried out by the Equipment Pool for Field Spectroscopy (EPFS) at the University of Southampton in December 1988.

A GER IRIS Mk IV spectroradiometer was used to measure the reflected flux from a rectangular area 2 x 1 cm on each grey card and simultaneously from a similar sized area of a calibrated barium sulphate panel, with a sampling interval of 2.5 nm in the 0.4 - 1.1 μm range and 4.5 nm in the 1.1 - 2.5 μm region of the spectrum. Measurements were made in a 0/45 degree geometry with illumination provided by a 1000 W quartz halogen lamp. Four measurements were made of each grey card by rotating the card through 90 degrees. The reflectance values presented are derived as the mean of four measurements. The tabulated values (Table 3.3) give the per cent reflectance of each card relative to a near perfect diffuse standard for the MMR bands. Raw data is given in Appendix 1. Grey card reflectance for the two cards are shown in Figure 3.5

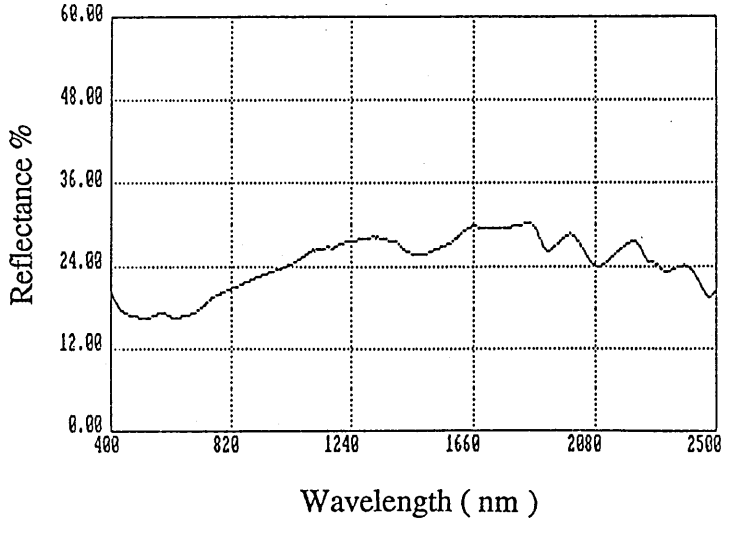
TABLE 3.3 PER CENT MMR BAND REFLECTANCE FOR 2 KODAK GREY CARDS RELATIVE TO A NEAR PERFECT DIFFUSE STANDARD-COURTESY OF THE EQUIPMENT POOL FOR FIELD SPECTROSCOPY.				
GREY CARD	GREEN	RED	NIR	MIR
1.	16.87	16.72	21.58	27.22
2.	16.81	16.69	21.84	27.59

FIGURE 3.5 GREY CARD REFLECTANCE FROM THE VISIBLE TO THE MIDDLE INFRARED WAVELENGTHS, A GREY CARD 1, B GREY CARD 2.

A.



B.



3.1.7 How Many Radiometric Samples are Required to Characterise a Surface ?

Curran and Williamson (1985) have suggested using pilot surveys to determine the sample number (Sn) to characterise the reflectance of homogeneous, transitional and heterogeneous surfaces. They have used the relationship:

$$Sn = (CV\ t/e)^2 \quad \text{eq. 3.3}$$

where t is the students t value at the 95% level of confidence and e is the acceptable error, CV is the coefficient of variation. Table 3.4 shows the sample number required for a 5% and 25% error of the mean for a range of surface types. Using Curran and Williamsons (1985) data, 3 samples were made to characterise the spectral response of each wheat plot and bare soil with 10% error at the 5% level. Because of the large number of plots involved, a small sample size was deemed acceptable in order to measure all plots within the critical 4 hour period. The use of semivariance to optimize the sample number is probably not appropriate in this case due to the small size of the plots, Curran (1988).

TABLE 3.4 NUMBER OF RADIOMETRIC SAMPLES REQUIRED TO CHARACTERISE SURFACES. SOURCE: CURRAN AND WILLIAMSON (1985).

Surface type	Land Cover	n	NIR/R			Sn(error)	
			XBar	S.D.	CV	5%	25%
Homogeneous	Metaled road	5	1.03	0.03	0.03	3	1
	Car Park	10	0.98	0.04	0.04	4	1
	Grass Park	10	3.24	0.16	0.05	5	1
	Rape	12	6.09	0.37	0.06	8	1
Transitional	Grazed grass	9	2.77	0.21	0.08	13	1
	Bare soil	12	1.17	0.10	0.09	15	1
	Winter wheat	10	3.07	0.29	0.10	19	1
Heterogeneous	Kale	9	4.51	0.63	0.14	42	2
	Long grass	11	4.7	0.89	0.19	72	3

Because of the narrow plot size, the radiometer was kept at a constant 1.5m above the ground surface. This was in order to avoid the ground cell viewing bare soil either side of the wheat plots and to avoid the edge effects of wheat growing without competition. The procedure adopted by Daughtry et al. (1982) for determining the optimum height of the radiometer above the ground is therefore not applicable in this case.

3.1.8 Data Handling.

The MMR's output unit was connected to a data logger i.e. the Li-Cor 1000-32. An RS232C cable was constructed which allowed interfacing with an AMSTRAD PC or compatible, Plate 3.6. Data was transferred into an ASCII file using the loggers' output and KERMIT software. The ASCII file could then be imported into LOTUS 1-2-3 (1988). LOTUS 1-2-3 supports graphics, stand alone software and intrinsic functions which make it a powerful tool for data analysis. Figure 3.6 shows the procedure.

PLATE 3.6 INTERFACING OF THE LI-COR 1000-32 LOGGER WITH AN OPUS IV COMPUTER USING AN RS232C CABLE.

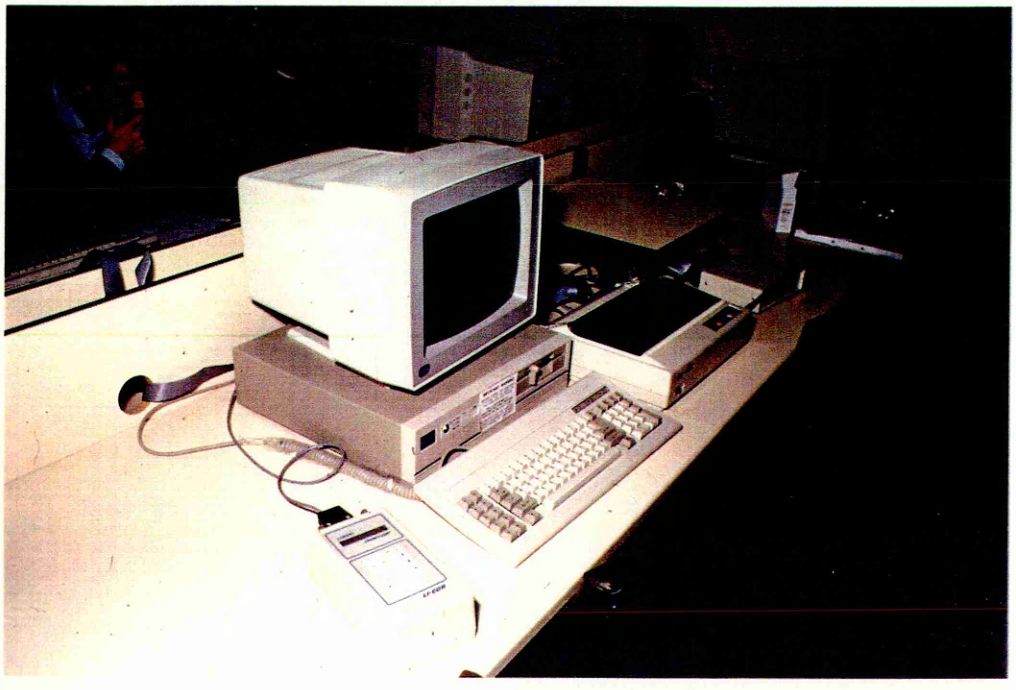
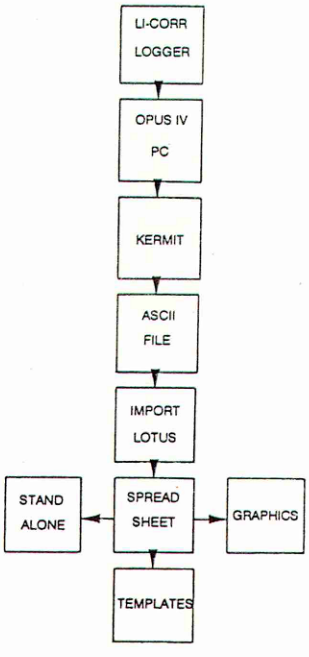


FIGURE 3.6 DATA HANDLING FROM THE LI-COR 1000-32 LOGGER TO SPREADSHEET SOFTWARE.



3.1.9 Estimation of Per Cent Cover.

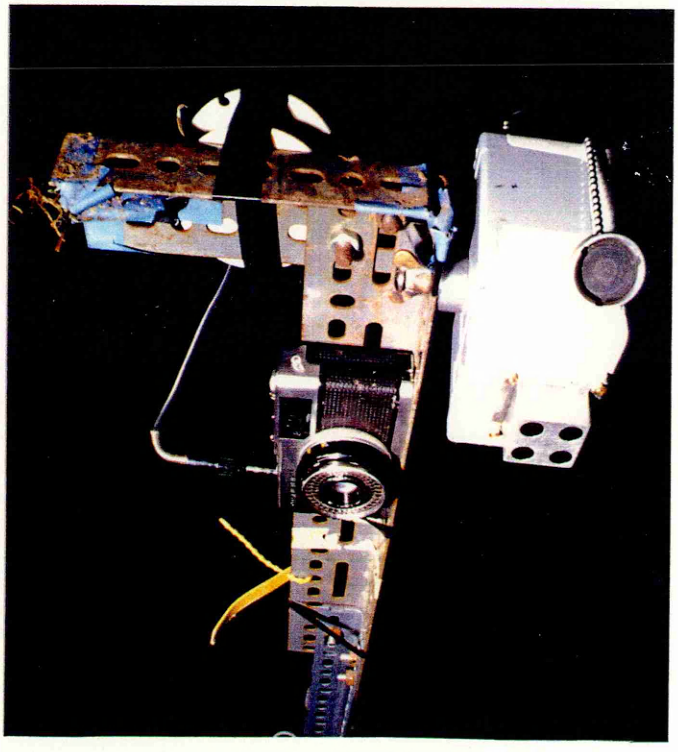
An Olympus trip camera was mounted on the boom apparatus so that the field of view of the camera and MMR1 were coincident when over the target in nadir view. Black and white photographs were taken on most site visits using 50 an 100 ISO film. Weather was a limiting factor. The slow film speed gave good contrast between soil and vegetation especially the 50 ISO film. These photographs provided:

(i) an historical record of crop condition at the time of radiometry;

(ii) estimates of per cent cover, soil and shadow either by grid method, Steven et al (1986) or by grey level analysis using an image processing system.

The camera shutter was activated by using a pneumatic release from the operator end of the boom, Plate 3.7.

PLATE 3.7 OLYMPUS TRIP CAMERA, MOUNTED SO THAT THE FIELD OF VIEW OF THE CAMERA AND MMR1 WERE COINCIDENT.



3.1.10 Reflectance Data and Vegetation Indices (VI's).

Radiance data from the target and panel in each of the 4 bands were converted into reflectance using equation 3.1. Eleven VI's were computed from reflectance data. Three VI's were based on visible and NIR bands, three on NIR and MIR wavebands, one on visible and MIR bands and four were linear recombinations of visible, NIR and MIR wavebands. VI's computed from visible and NIR bands were:

Ratio VI (RVI)

$$RVI = \frac{NIR}{R} \qquad \text{eq. 3.2}$$

Normalised Difference VI (NDVI)

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \qquad \text{eq. 3.3}$$

Transformed VI (TVI)

$$TVI = (NDVI + 0.5)^{0.5} \qquad \text{eq. 3.4}$$

VI's computed from NIR and MIR bands were:
Middle ratio VI (MRVI)

$$MRVI = \frac{NIR}{MIR} \qquad \text{eq. 3.5}$$

Middle Normalised Difference VI2 (MDVI2)

$$MNDVI2 = \frac{(NIR - MIR)}{(NIR + MIR)} \qquad \text{eq. 3.6}$$

Middle Transformed VI (MTVI)

$$MTVI = (MNDVI2 + 0.5)^{0.5} \qquad \text{eq. 3.7}$$

The VI computed from visible and MIR bands was the Middle Normalised Difference VI1 (MNDVI1)

$$MNDVI1 = \frac{(MIR - R)}{(MIR + R)} \qquad \text{eq. 3.8}$$

VI's which are linear recombinations of reflectance data can be calculated in 2,3,4...n dimensional space depending on the number of bands available, Jackson (1983). For the MMR data, one 2D and three 4D indices were calculated. The 2D index was the Perpendicular Vegetation Index (PVI) of Richardson and Weigand (1977) and was based on red and NIR wavebands. Three 4D indices were computed using the 2 visible and both NIR and MIR bands. These indices are described by Kauth and Thomas (1976) as Soil Brightness (SBI), Greenness (GVI) and Non-such. Coefficients were derived for the 2D and 4D indices using dry soil, wet soil, high density green and senescent wheat reflectance, Table 3.5.

TABLE 3.5 BRF'S MEASURED WITH MMR's FOR WET SOIL, DRY SOIL, GREEN AND SENESCENT WHEAT. BURY ST. EDMUNDS UK, 1989.

	MMR CHANNEL			
SURFACE	GREEN	RED	NIR	MIR
WET SOIL	5.27	6.7	14.14	15.52
DRY SOIL	9.18	11.19	18.06	19.55
GREEN WHEAT	3.57	2.25	37.45	25.73
SENESCENT WHEAT	8.18	11.55	31.81	25.20

Coefficients for the conversion of reflectance to linear recombination indices were calculated using formulae described by Jackson (1983). These coefficients are shown in Table 3.6.

TABLE 3.6 COEFFICIENTS FOR CALCULATION OF 2D PVI AND 4D SBI, GVI AND NON-SUCH FOR SERIES 100 MILTON SYSTEM RADIOMETERS.

	BAND COEFFICIENTS			
INDEX	GREEN	RED	NIR	MIR
PVI	0.0	0.657	0.754	0.0
SBI	0.476	0.547	0.477	0.497
GVI	-0.351	-0.514	0.764	0.169
Non-such	-0.586	0.652	0.259	-0.406

As a check of independence, orthogonality was computed between these indices. Orthogonality is given in Table 3.7.

TABLE 3.7 ORTHOGONALITY BETWEEN SBI, GVI AND NON-SUCH.

INDEX COMPARISON	ORTHOGONALITY
SBI AND GVI	0.0
SBI AND Non-such	0.0
GVI AND Non-such	0.0

3.1.11 Spectral Temporal Profiles - Model Fitting.

In this study, two types of equations were used to model the spectral temporal development of winter wheat. The first was a modified non-linear least squares model. The equation was of the form:

$$NDVI = constant + \alpha t^{c} . \exp[D(B^2 - t^2)] + Et^2 \quad \text{eq. 3.9}$$

constant= soil background
α = A / B
A = linear scalar
B = time of spectral emergence (in days)
C = crop and condition specific constant
D = crop and condition specific constant
E = linear constant
t = time from sowing in days

The model is a modification of that produced for corn by Badhwar and Henderson (1981). The major difference is in the last term (E). It was necessary to include this term because of the steep decline in the vegetation index reponse in the grain filling period in both the 1989 and 1990 seasons.

The first order derivative of this function was used to give the maximum turning moment (tp). The second order derivative was found to give the inflexion points t1 and t2 respectively.

The first order derivative of equation 3.9 is given by:

$$\frac{dNDVI}{dt} = \alpha t^{c-1} \exp[D(B^2-t^2)].[-2Dt^2+C] + 2Et \quad \text{eq. 3.10}$$

= 0 for maximum NDVI

The second order derivative of equation 3.9 is given by:

$$\frac{d^2NDVI}{dt^2} = \alpha t^{c-2} \exp[D(B^2-t^2)].[4D2t^4-2(2C+1)Dt^2+ C(C-1)] + 2E \qquad \text{eq. 3.11}$$

$$= 0 \text{ at points of inflexion}$$

The second type of model used in this study was a high order polynomial of degree 7. All terms were used in the regression because in some instances the non-linear model did not well approximate the spectral temporal development of the wheat canopy especially in the spring period. The polynomial model was of the form:

$$NDVI = \alpha + ß_1t + ß_2t^2 + ß_3t^3 + ß_4t^4 + ß_5t^5 + ß_6t^6 + ß_7t^7 \qquad \text{eq. 3.12}$$

NDVI = spectral variable
t = time from sowing in days

3.2 Measurement of Cereal Development Stages.

3.2.1 Descriptions of Plant Development.

Currently there are numerous published scales of cereal development. These scales describe particular development stages defined by the external appearance and are usually supplemented by a diagram. For example:

(i) The Growth Stage Identification Key - Cereals, Tottman, Long Ashton Research Station;
(ii) Feekes, Large (1954);
(iii) Zadoks Scale, Zadoks, Chang and Konzak (1974);
(iv) Agricultural Development and Advisory Scale, (1978).

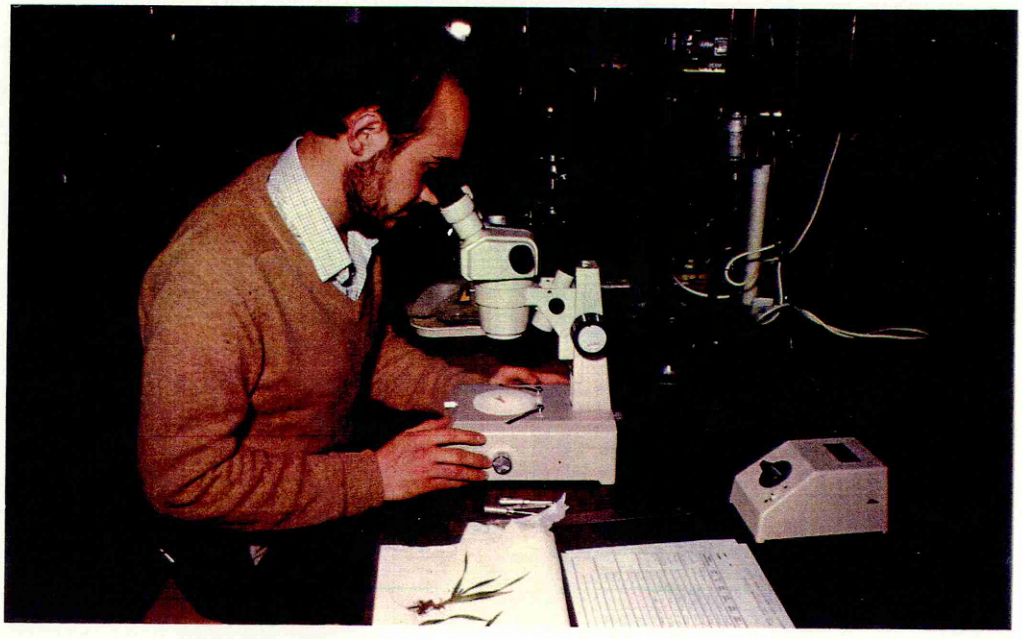
Other scales have sought to identify a critical stage of development. These scales tend to rely on measurements of plant attributes rather than descriptions involving the number of parts or plant morphology. Examples of this type of measurement are the length of the longest leaf sheath, Tottman (1977)

and 'ear at 1cm', Couvreur et al (1980). These scales assign a numerical code to each stage, suitable for quick recording.

3.2.2 Apex Development Stages of Cereals.

From the germination stage until maturity at harvest, the cereal plant develops through an orderly series of phases. The embryo in a cereal will contain up to four leaf primordia and a shoot apex. After germination further leaf primordia are produced and later the spikelet primordia are formed, Kirby and Appleyard (1987). Each structure of the plant originates from a single primordium, which is formed by cell division in the shoot apex of the growing point. In the young plant, the shoot apex is small and is hidden within the enfolding leaves. In order to observe the early stages of apex development, it is necessary to dissect the cereal plant using a binocular microscope, Plate 3.8. The technique involves unfolding the later formed leaves to reveal the main shoot growing point. The technique and stages of apex development are described in detail by Kirby and Appleyard (1987).

PLATE 3.8 NIKON X 30 BINOCULAR MICROSCOPE USED TO IDENTIFY STAGES OF APEX DEVELOPMENT.



Cereal plants develop and grow at different rates depending on their environment. The main factors which influence development are temperature, day length and variety. Because of these factors, it is difficult to give specific dates at which stages are reached. Hence apex dissection is the most precise form of recording a stage even though models do exist which can estimate the timing of stages based on long term averages of temperature and photoperiod, Porter et al (1990).

3.2.3 Relationship of Apex Stage to External Plant Appearance.

Zadoks Section 1 (Seedling growth) covers a major part of the pre-anthesis life cycle, for during this period the ear achieves considerable growth and initiates structures. Leaf number is a good measure of plant development, leaves emerge at regular intervals and therefore a leaf count divides the growth cycle into increments. However, the number of leaves at a particular development stage is related to total number of leaves and this varies with crop husbandry, particularly with sowing date. There is not complete correspondence between number of emerged leaves and apex stage, Kirby and Appleyard (1987). It is possible however to estimate the apex development stage using look up tables which relate the time of sowing to the total number of leaves and then using the number of leaves emerged at the double ridge stage in wheat to give the apex stage, Kirby and Appleyard (1987).

3.2.4 Scoring of Development Stages.

For this study a development scale was used to give a numerical score to a development stage, Table 3.8. It should be emphasised that no published scales of apex development could be found therefore the scale used in this study was one developed by a commercial company involved in simulation modelling. This scale conveniently partitions the development cycle into five main phases of development, Table 3.9. It also allowed quick recording of stages to be made in the field.

It was found that during dissection of the individual wheat plants, the stage of apex development varied considerably from plant to plant. In order to score a stage therefore, the modal class of a frequency distribution using this scale was used to represent the stage of development within each treatment.

TABLE 3.8 APICAL DEVELOPMENT SCALE FOR WINTER WHEAT.		
CODE		APEX DEVELOPMENT STAGE.
5.16	-	VEGETATIVE STAGE
5.165	-	APPROACHING LATE VEGETATIVE STAGE
5.17	-	LATE VEGETATIVE STAGE
5.185	-	EARLY DOUBLE RIDGE
5.19	-	DOUBLE RIDGE
5.195	-	LATE DOUBLE RIDGE
5.205	-	EARLY GLUME PRIMORDIUM
5.21	-	GLUME PRIMORDIUM
5.215	-	LATE GLUME PRIMORDIUM
5.225	-	EARLY LEMMA PRIMORDIUM
5.23	-	LEMMA PRIMORDIUM
5.235	-	LATE LEMMA PRIMORDIUM
5.245	-	EARLY FLORET PRIMORDIUM
5.25	-	FLORET PRIMORDIUM
5.225	-	LATE FLORET PRIMORDIUM
5.265	-	EARLY TERMINAL SPIKELET
5.27	-	TERMINAL SPIKELET
5.275	-	LATE TERMINAL SPIKELET
7.10	-	WHITE ANTHER
7.12	-	GREEN ANTHER
7.15	-	YELLOW ANTHER
7.18	-	ANTHESIS
9.7	-	WATER RIPE STAGE
9.8	-	EARLY MILK STAGE
9.9	-	MEDIUM MILK STAGE
9.10	-	SOFT DOUGH STAGE
9.11	-	HARD DOUGH STAGE
9.12	-	HARVEST RIPE GRAIN

3.3 Meteorological Variables.

3.3.1 Brooms Barn Meteorological Station.

Brooms Barn meteorological station is situated 52° 12' N, 0° 42' E, Figure 3.8. Daily weather information was obtained via modem from the main Cranfield Campus and from the Rothamsted archive. Long term averages of weather are shown in Table 3.10

TABLE 3.9 FIVE MAJOR STAGES OF APEX DEVELOPMENT.		
	MAJOR STAGE	MINOR STAGE
1.	VEGETATIVE	vegetative
2.	DOUBLE RIDGES AND EAR DEVELOPMENT	double ridges glume primordium lemma primordium floret primordium
3.	TERMINAL SPIKELET	early terminal spikelet terminal spikelet late terminal spikelet
4.	EAR GROWTH AND ANTHESIS	white anther green anther yellow anther anthesis
5.	GRAIN FILL AND MATURITY	water ripe stage early milk stage medium milk stage soft dough stage hard dough stage harvest ripe grain

FIGURE 3.7 MAP SHOWING LOCATION OF BROOMS BARN METEOROLOGICAL STATION.

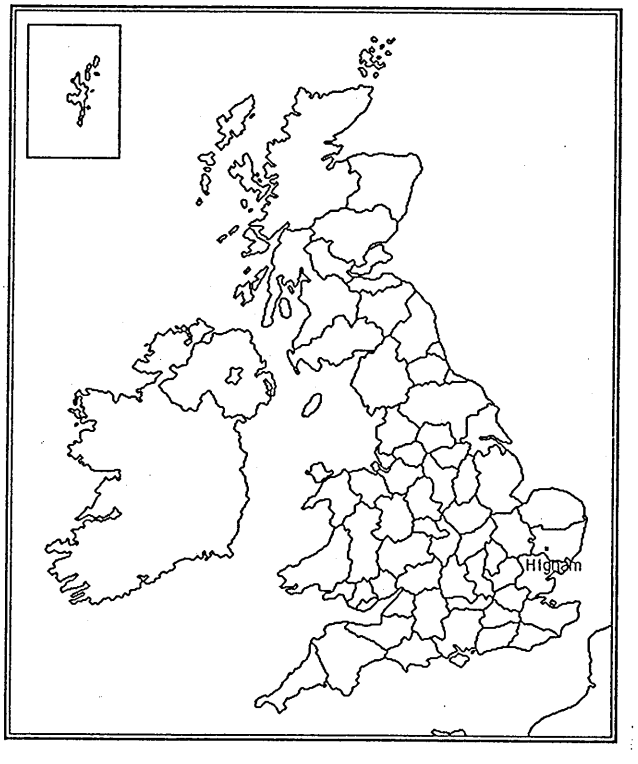


TABLE 3.10 AVERAGE WEATHER FOR SUFFOLK REGION (AREA 29), SOURCE: THE AGRICULTURAL CLIMATE OF ENGLAND AND WALES.								
Month	**Temp Air °C**	**30cm above Earth**	**Rain mm**	**PT mm**	**Sun hrs/ day**	**Day Length hrs**	**Rad mw-hr per cm^2**	**Ill. kilolx hrs**
JAN	2.9	3.7	50	1	1.7	9.6	65	75
FEB	3.3	3.7	40	10	2.4	11.1	120	135
MAR	5.5	5.1	40	33	3.8	13.0	225	270
APR	8.5	8.6	39	57	5.6	15.1	335	420
MAY	11.5	12.1	46	85	6.6	17.2	455	545
JUNE	14.6	15.4	49	97	7.1	18.4	510	605
JULY	16.6	17.2	58	97	6.2	17.8	460	565
AUG	16.2	17.1	62	79	8.9	15.9	380	475
SEP	14.4	15.3	51	49	4.8	13.8	285	355
OCT	11.0	11.8	51	22	3.4	11.8	165	205
NOV	6.6	7.7	60	5	2.0	10.1	85	100
DEC	4.1	5.2	52	0	1.5	9.1	55	60

3.3.2 Calculation of Soil Water Deficits.

Daily weather variables obtained from Brooms Barn such as the reference crop evapotranspiration and rainfall data were fed into the Irrigation Management Services Software (IMS) developed at the Cranfield Institute of Technology, Silsoe Campus. The IMS program is an irrigation scheduling program based on the water balance method. It uses weather data in conjunction with information on the crop and soil, to estimate daily changes in the soil water storage. The model has three components:

(i) a reference crop evapotranspiration model to estimate the influence of weather on water use;
(ii) a daily water balance model to estimate the soil water content in the root zone in each day;
(iii) an irrigation model to estimate the timing of the next irrigation.

For the purposes of this study, the model was used to calculate soil water deficits from early April until harvest at the study site. The soil was assumed to be at field capacity from the beginning of April in each of the two years of the study. Soil water deficits were therefore set at zero at this time.

3.3.3 Calculation of Growing Degree Days.

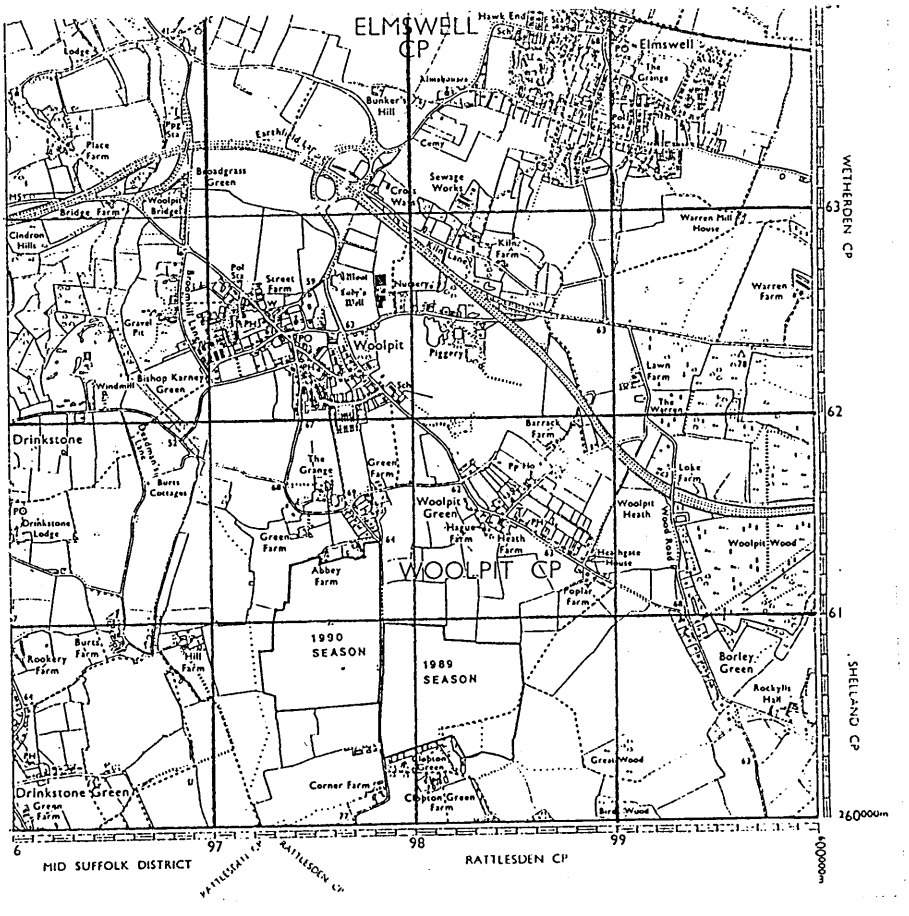
Because of the relationship between temperature and biologic activity, maximum and minimum air temperatures were used as inputs to a program to calculate degree days, Stephens (1990). The program uses the sine wave method for calculation of thermal time, Allen (1976). Daily degree days were them summed to give the accumulated thermal time for the two growing seasons in question.

3.4 Field Experiment Management.

3.4.1 Location of the Trial Site.

In both the 1989 and 1990 growing seasons, the work for this study was carried out in conjunction with a commercial seed breeding company, Nickersons RBP Ltd. Nickersons' maintain a breeding facility at Woolpit near Bury St. Edmunds in the UK, Figure 3.8. This was an ideal site for the study because Nickersons were using managed wheat plots and also conducting experiments of the effect of fungal diseases on wheat cultivars. Inoculated wheat varieties were placed in the field at critical stages in the development cycle to act as spreading centres. For these reasons Nickersons were approached for collaboration with the study.

FIGURE 3.8 MAP SHOWING THE LOCATION OF THE BREEDING SITE RUN BY NICKERSONS RBP LTD, BURY ST. EDMUNDS UK.



3.4.2 Soil Analysis of the Trial Site.

Soil textual analysis revealed that the texture was a sandy clay loam, Figure 3.9. The soil moisture characteristic curve is typical of that for a clay soil, Figure 3.10. Data for the textual analysis and soil moisture curve were made by dividing the field site into quarters and sampling the top soil when walking a W pattern in each of the quarters. Density rings were used to take samples for dry soil bulk density analysis. The results of the soil moisture characteristic determination are shown in Appendix 2. Dry bulk soil density was 1.47 g/cm^3

FIGURE 3.9 PROPORTIONS OF SOIL PARTICLES FOR TRIAL SITE AT WOOLPIT, BURY ST. EDMUNDS UK.

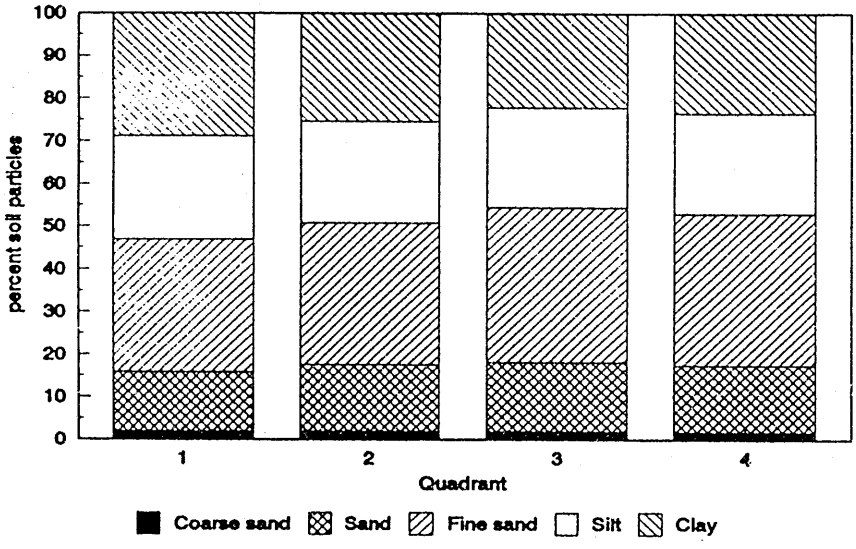
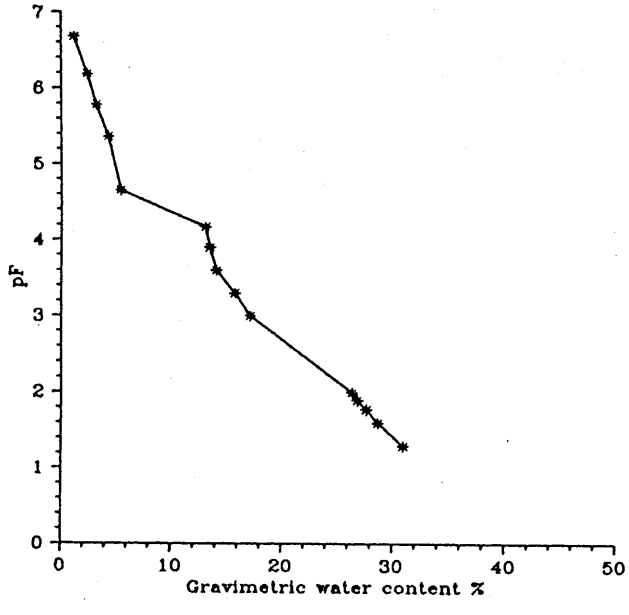


FIGURE 3.10 SOIL MOISTURE CHARACTERISTIC CURVE, FOR THE TOP SOIL LAYER, TRIAL SITE, BURY ST. EDMUNDS UK.



3.4.3 Plot Design in the 1989 Season.

Two experiments were used in hypothesis testing. These were both based on the Patterson design, Patterson (1988). This was not a randomised block design, rather treatments were separated into blocks.

Experiment 1 was a time of sowing trial. Eight varieties were sown on 3 different dates, each sowing date being in a separate block, Figure 3.11. The three sowing dates were the 4.10.88, 17.10.88 and the 1.11.88. Sowing rates were 350 seeds/m^2, 380 seeds/m^2 and 420 seeds/m^2 for the 3 dates respectively.

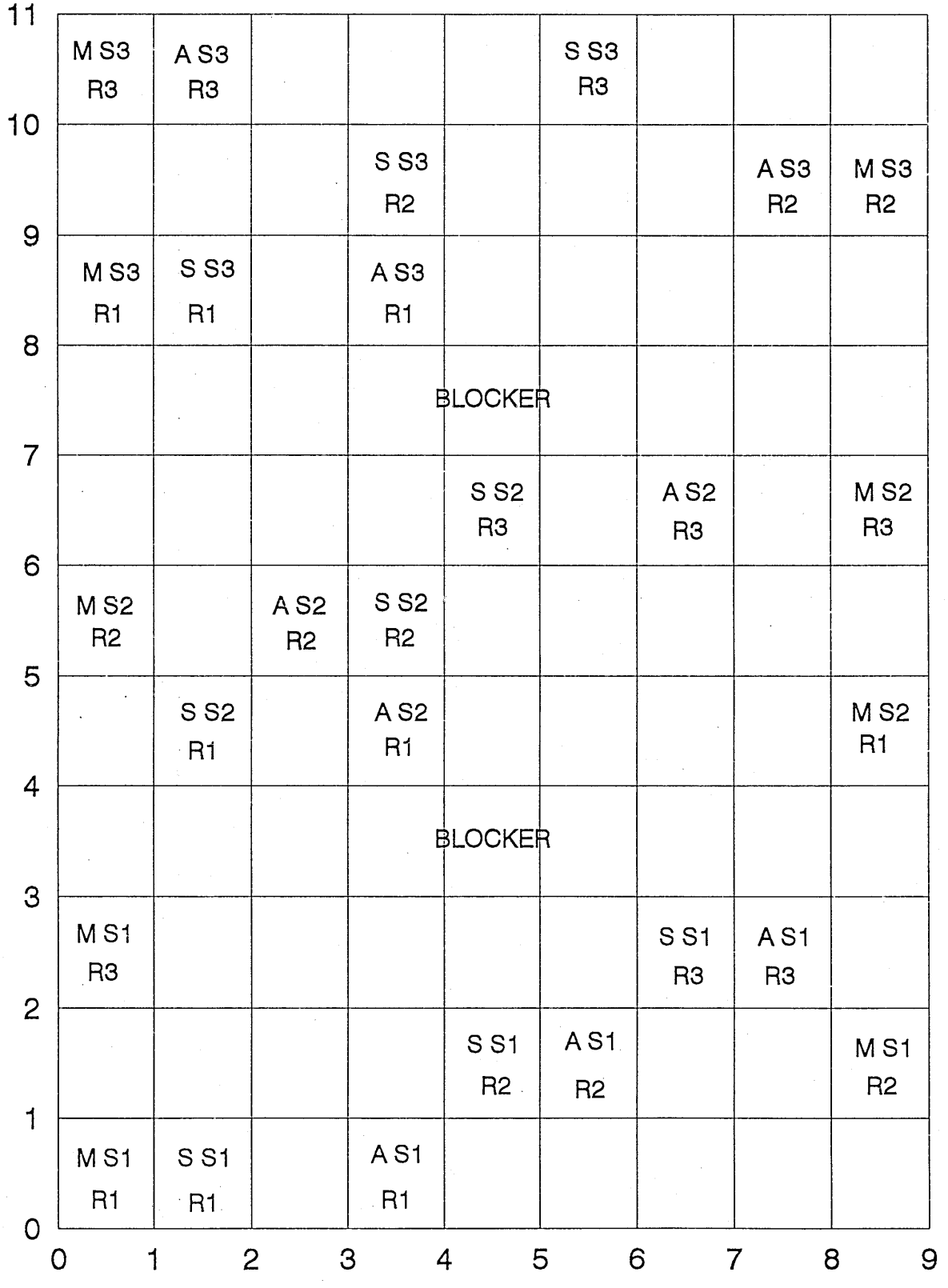
Experiment 2 consisted of cultivars of wheat sown in fungicide treated and untreated blocks, Figure 3.12. Sowing dates for experiment 2 were 2-3.10.88. The sowing rate was 350 seeds/m^2. Three varieties were chosen for the study from experiment 1. These were Mission, Avalon and Slejpner. These are known to be differential varieties in terms of their yield potentials. Also they are known to be fast, medium and slow developers in relation to apex development stages. Three replications of each cultivar were monitored in each sowing block. Cultivars chosen from experiment 2 were Mission and Slejpner. Four replications of each cultivar in each treatment block were monitored. Plot dimensions were 4.62m long by 1.65m wide. Varieties, fungicide application and number of plots used in the 1989 season are shown in Table 3.12. Field management and applications for the two experiments are shown in Appendix 3.

TABLE 3.11 SOWING DATES, VARIETIES, FUNGICIDE APPLICATION AND NUMBER OF PLOTS USED IN THE 1989 SEASON.

EXPERIMENT 1.	VARIETY	FUNGICIDE	NUMBER OF PLOTS
SOWING DATE 4.10.88	MISSION	+	3
	AVALON	+	3
	SLEJPNER	+	3
SOWING DATE 17.10.88	MISSION	+	3
	AVALON	+	3
	SLEJPNER	+	3
SOWING DATE 1.11.88	MISSION	+	3
	AVALON	+	3
	SLEJPNER	+	3
EXPERIMENT 2	VARIETY	FUNGICIDE	NUMBER OF PLOTS
SOWING DATE 2.10.88	MISSION	+	4
	MISSION	-	4
	SLEJPNER	+	4
	SLEJPNER	-	4

FIGURE 3.11 PLOT DESIGN FOR EXPERIMENT 1, 1989 SEASON, BURY ST.EDMUNDS UK (NOT TO SCALE)

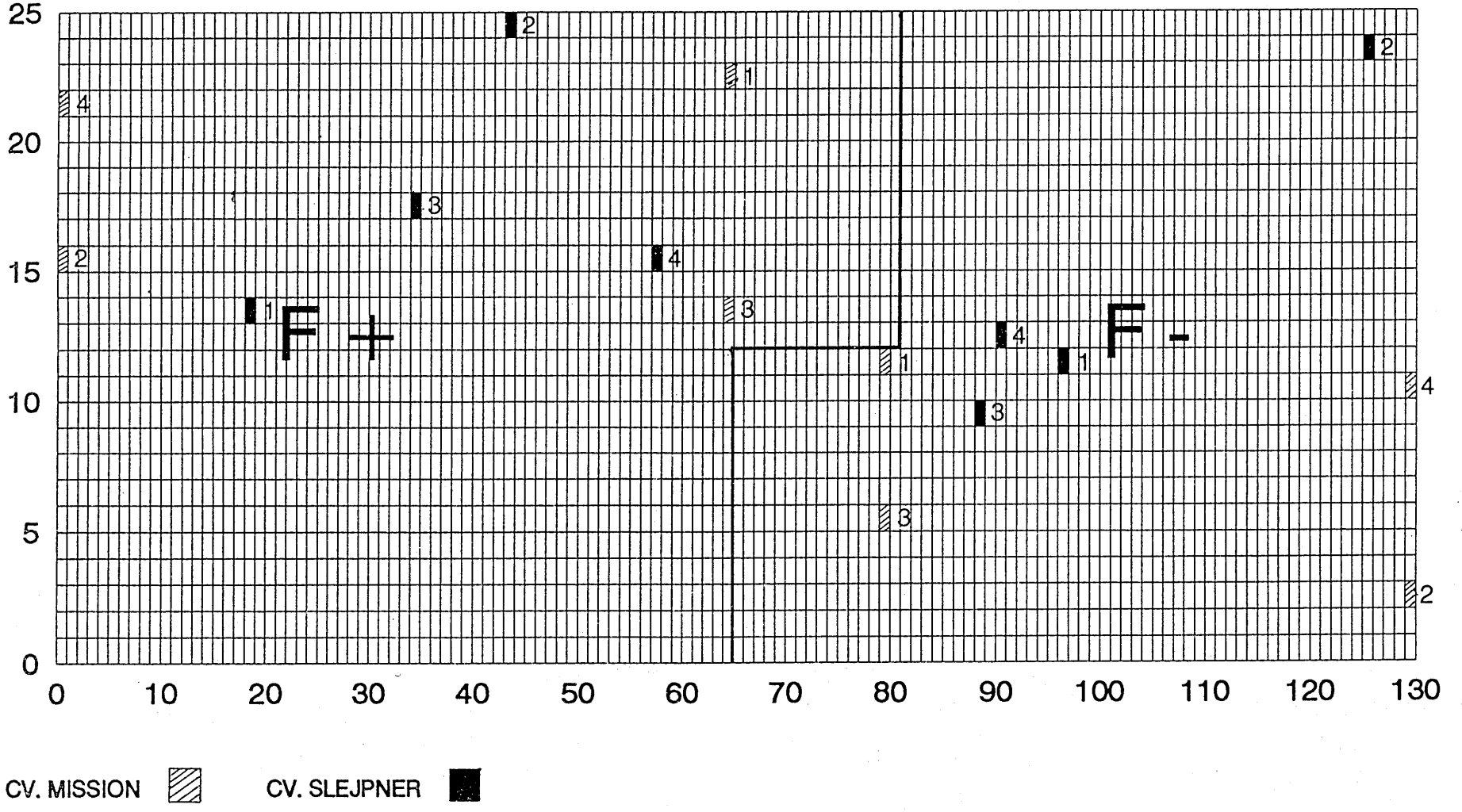
BLANK AREAS WERE PLOTS USED IN NICKERSONS EXPERIMENTATION



S1 = 4.10.88 S2 = 17.10.88 S3 = 1.11.88

M = CV.MISSION, A = CV.AVALON, S = CV.SLEJPNER R = REPLICATION

FIGURE 3.12 PLOT DESIGN FOR EXPERIMENT 2, 1989 SEASON, BURY ST. EDMUNDS UK. F+ FUNGICIDE TREATED, F - FUNGICIDE UNTREATED (NOT TO SCALE)



BLANK AREAS WERE PLOTS USED IN NICKERSONS EXPERIMENTATION

Radiometric data was taken over bare soil throughout the growing season. This enabled coefficients for PVI, SBI, GVI and YVI to be determined. To investigate the relationship between spectral data and agronomic data, destructive sampling was necessary. Four plants were taken on a regular basis when management allowed and the following measurements were made; Leaf number, Tiller number, Leaf total, plant length, Node length, Apex length, Apical development stage. Apex length and node length in the early stages of development were determined by the use of a high power microscope fitted with an eyepiece graticule.

3.4.4 Plot Design in the 1990 Season.

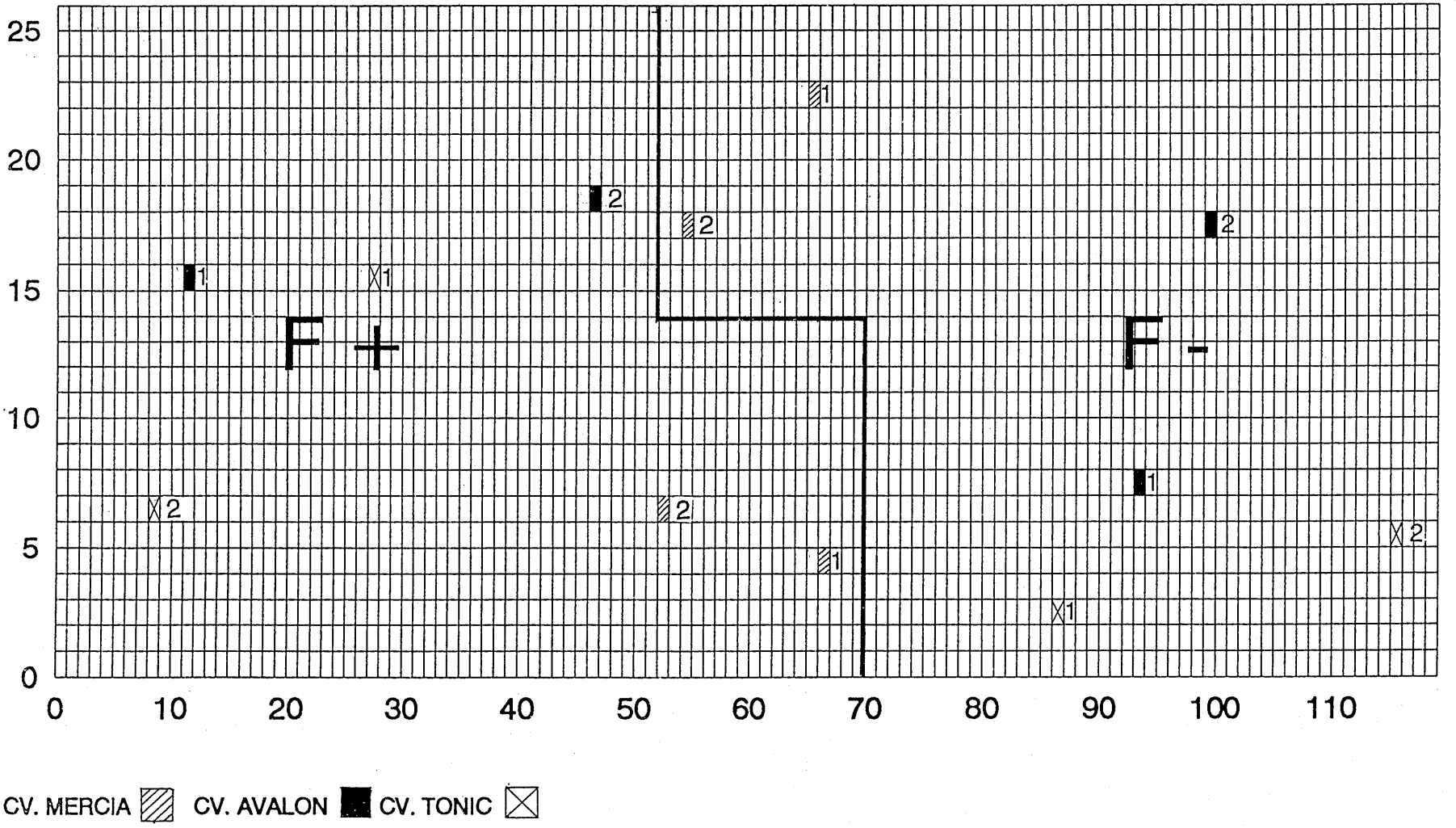
For the second seasons work, due to reasons beyond the authors control it was not possible to exactly repeat the experimental design of the previous season. Therefore, the best possible combinations of treatments were chosen to emulate the previous seasons results. For repeatability and validation purposes limited data was collected on varieties sown on different dates and having different levels of fungicide treatment. The location of the trials in the 1990 season was physically moved to another field. However, the numbers of replicates did not correspond between the sowing dates. Two sowing dates were used more than a calendar month apart. These were the 27.9.89 and 30.10.89. The varieties chosen were Avalon, Mercia and Tonic. Varieties, number of replicates and fungicide application are shown in Table 3.13. Plot dimensions were again 4.2m long by 1.65m wide.

TABLE 3.12 SOWING DATES, VARIETIES, FUNGICIDE APPLICATION AND NUMBERS OF PLOTS USED IN THE 1990 SEASON.

	VARIETY	FUNGICIDE	NUMBER OF PLOTS
SOWING DATE 27.9.89	AVALON	+	2
	MERCIA	+	2
	TONIC	+	2
	AVALON	-	2
	MERCIA	-	2
	TONIC	-	2
SOWING DATE 30.10.89	AVALON	+	3
	MERCIA	+	3
	TONIC	+	3

The plot designs for the two sowing dates are shown in Figures 3.13 and 3.14 respectively. Management and applications for the 1990 season are shown in Appendix 4.

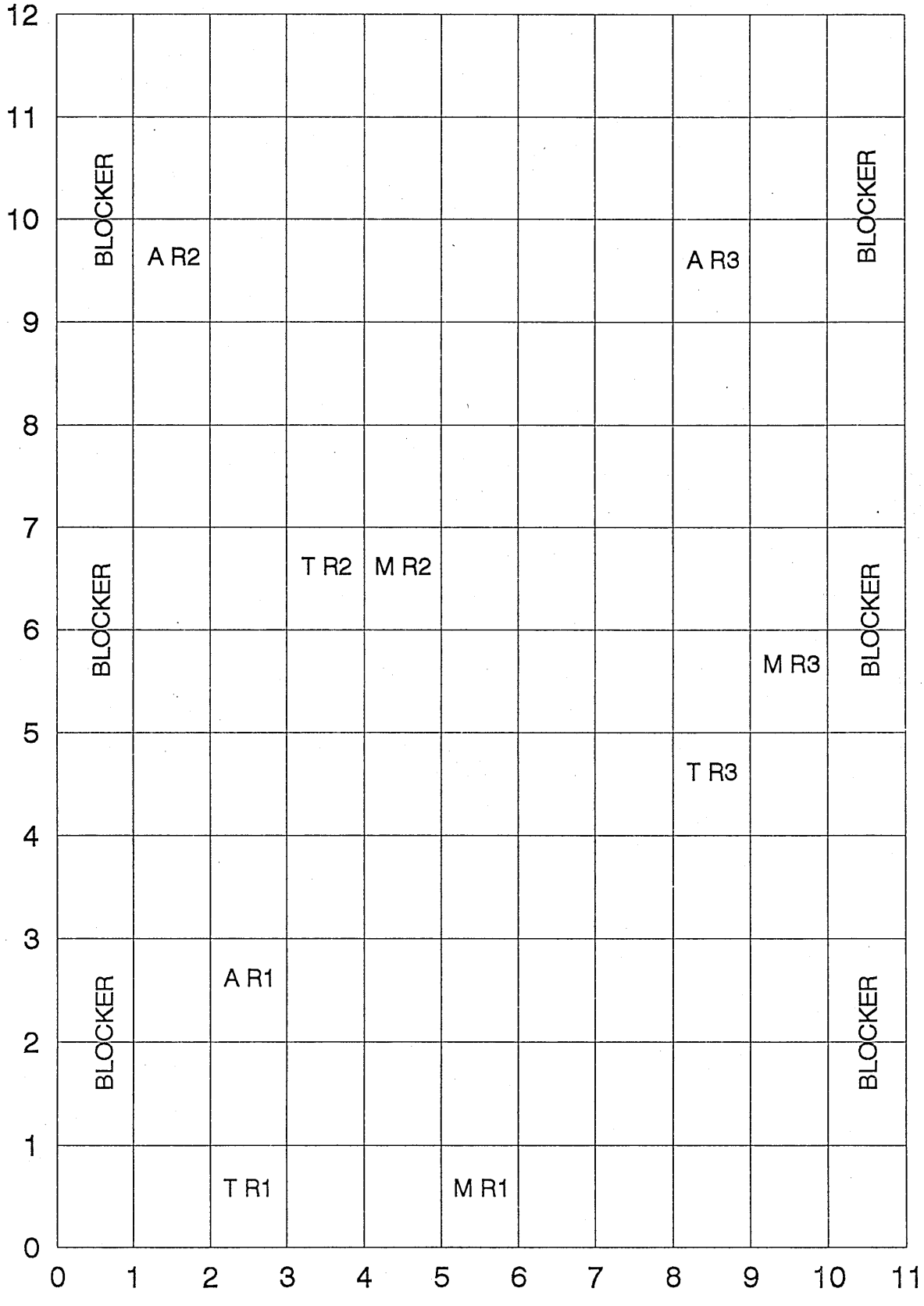
FIGURE 3.13 PLOT DESIGN FOR SOWING DATE 1, 1990 SEASON, BURY ST. EDMUNDS UK. F+ FUNGICIDE TREATED, F - FUNGICIDE UNTREATED (NOT TO SCALE)



BLANK AREAS WERE PLOTS USED IN NICKERSONS EXPERIMENTATION

FIGURE 3.14 PLOT DESIGN FOR SOWING DATE 2, 1990 SEASON, BURY ST. EDMUNDS UK (NOT TO SCALE)

BLANK AREAS WERE PLOTS USED IN NICKERSONS EXPERIMENTATION



M = CV. MERCIA, A = CV. AVALON, T = CV. TONIC R = REPLICATION

CHAPTER 4. THE EFFECTS OF DEVELOPMENT STAGE, VARIETY, SOWING DATE AND DISEASE ON THE SPECTRAL RESPONSE OF WINTER WHEAT.

4.1 Results of the 1989 Season.

4.1.1 Summary of the 1989 Results.

The spectral response of winter wheat for the two experiments outlined in section 3.4.3, showed complex patterns in relation to the apex development stage, sowing date, variety and fungicide treatment. The sections following this summary describe in detail the analyses used to support the experimental findings. The non-statistician may find these sections labourious or difficult to comprehend. Therefore the results of the 1989 season are summarised as follows:

(i) Two-way analysis of variance on Expt. 1 revealed that the sowing date component of the spectral response of winter wheat disappeared by initiation of the main stem terminal spikelet stage of apex development;

(ii) Two key phases of apex development were found in which variety differences in the spectral response occured. These were the terminal spikelet and grain filling stages respectively;

(iii) Differences in the spectral response of winter wheat were found between cultivars treated and untreated with fungicide. This was because untreated wheat was attacked by fungal disease. The effects were shown to variety and treatment dependent.

4.1.2 Field Radiometer Data Collection.

A total of 22 site visits were made during the season, in what can only be described as an exceptional year for field radiometry. Radiometric measurement was hampered by breakdown of the output unit. This resulted in:

(i) data loss on seven different occasions;

(ii) loan of a second output unit from Southampton University which had sequential measurement capability;

(iii) loan of a third output unit from Nottingham University which facilitated collection of data at the end of the season. This unit had simultaneous measurement capability.

Due to the high incidence of cloud free days in the 1989 season, a high proportion of cloud free radiometric data was obtained. Hence excellent spectral temporal profiles were produced over the growing season. The end of March saw an infestation of wheat bulb fly (Delia coarctata) in the time of sowing trial. This resulted in death of the leading leaf. Insecticide application caused leaf scorching. Table 4.1 shows the record of site visits made and data collected on each site visit.

Experiment 2 was re-organised in early February. The number of plots monitored by the author was increased from two to four replications. Cultivar Avalon was rejected as too few replications were present, only 2 in each block. Replications were increased for cultivars Slejpner and Mission.

Cultivar Slejpner in the fungicide untreated block was attacked by yellow rust (Puccinia striiformis). This caused chlorosis by June and total leaf area collapse by the end of July. Consequently this affected the reflectance patterns and the shape of the spectral temporal profiles.

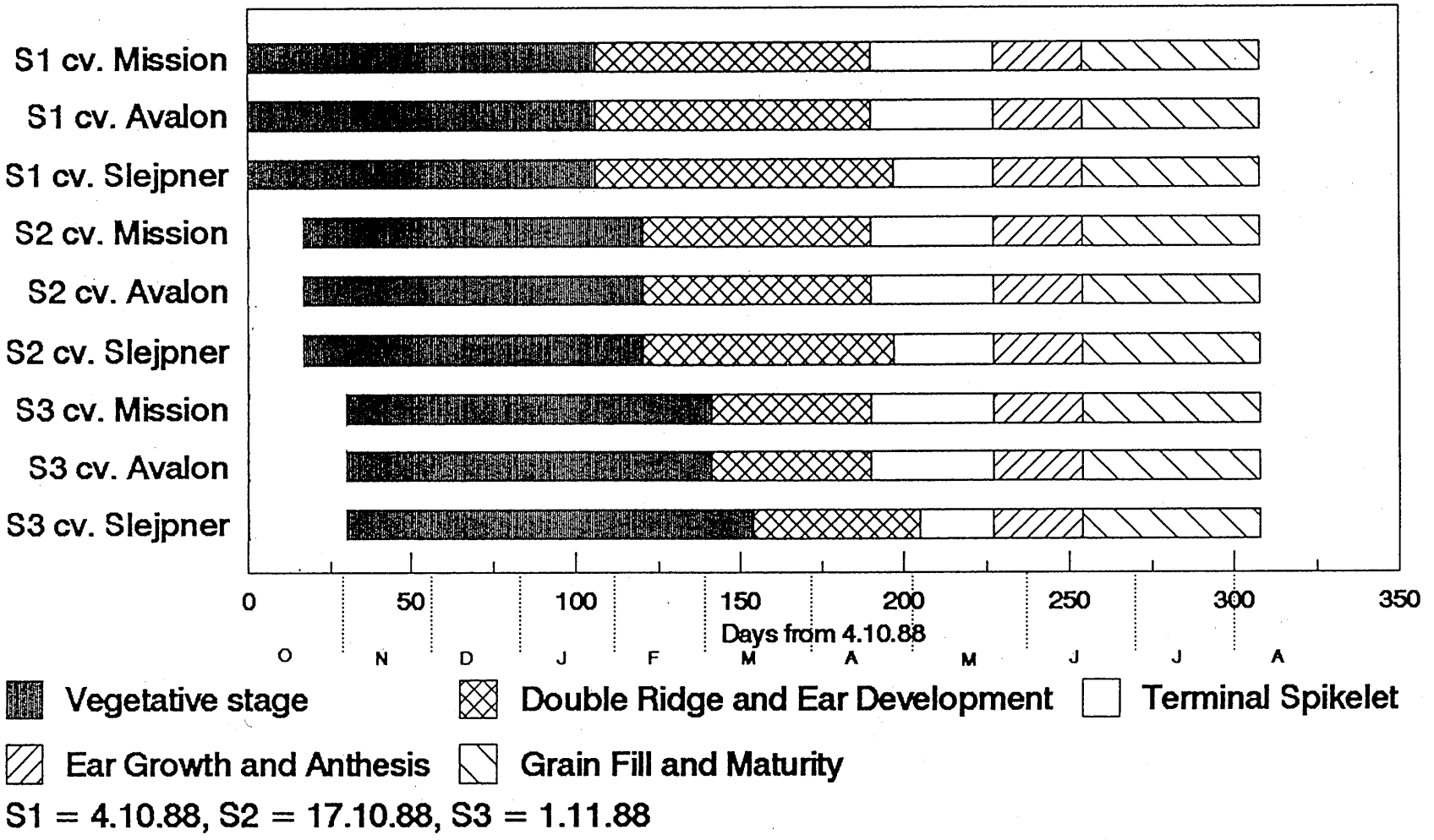
Cultivar Mission in the untreated block remained unaffected by yellow rust but lodging of all plots had taken place by the end of June. Both varieties in the treated block remained healthy and standing throughout the season.

TABLE 4.1 RECORD OF SITE VISITS IN THE 1989 SEASON.							
SITE VISIT NO.	DATE	SOLAR ELEVATION 10 am	2 pm	CLOUD COVER (OCTA)	RADIOMETRY SQ/SM	%COVER	GROUND TRUTH
1	22.11.88	18	17	0	SM	+	+
2	06.12.88	11	13	8	SM	-	+
3	18.01.89	14	15	0	SM	+	+
4	06.02.89	18	20	0	SM	+	+
5	15.02.89	20	22	8	-	-	+
6	07.03.89	28	30	8	-	-	+
7	15.03.89	30	32	8	-	+	-
8	30.03.89	35	37	0	SM	+	+
9	12.04.89	40	40	DIFFUSE	SM	+	+
10	19.04.89	42	43	DIFFUSE	SM	+	+
11	04.05.89	48	48	0	SM	+	+
12	10.05.89	49	50	1	SM	+	+
13	19.05.89	50	48	0	SQ	+	+
14	25.05.89	51	49	8	-	+	+
15	31.05.89	52	52	8	SQ	+	+
16	09.06.89	53	53	8	SM	+	+
17	15.06.89	54	54	0	SM	+	+
18	23.06.89	55	55	0	SM	+	+
19	04.07.89	55	53	0	SM	+	+
20	12.07.89	54	54	8	SM	+	+
21	19.07.89	54	54	0	SM	+	+
22	24.07.89	53	52	0	SM	-	+
13 dates of radiometric data (SM simultaneous, SQ sequential measurement) 20 dates of ground truth information Solar Elevations are in degrees							

4.1.3 The Effects of Development Stage on the Spectral Response of Winter Wheat.

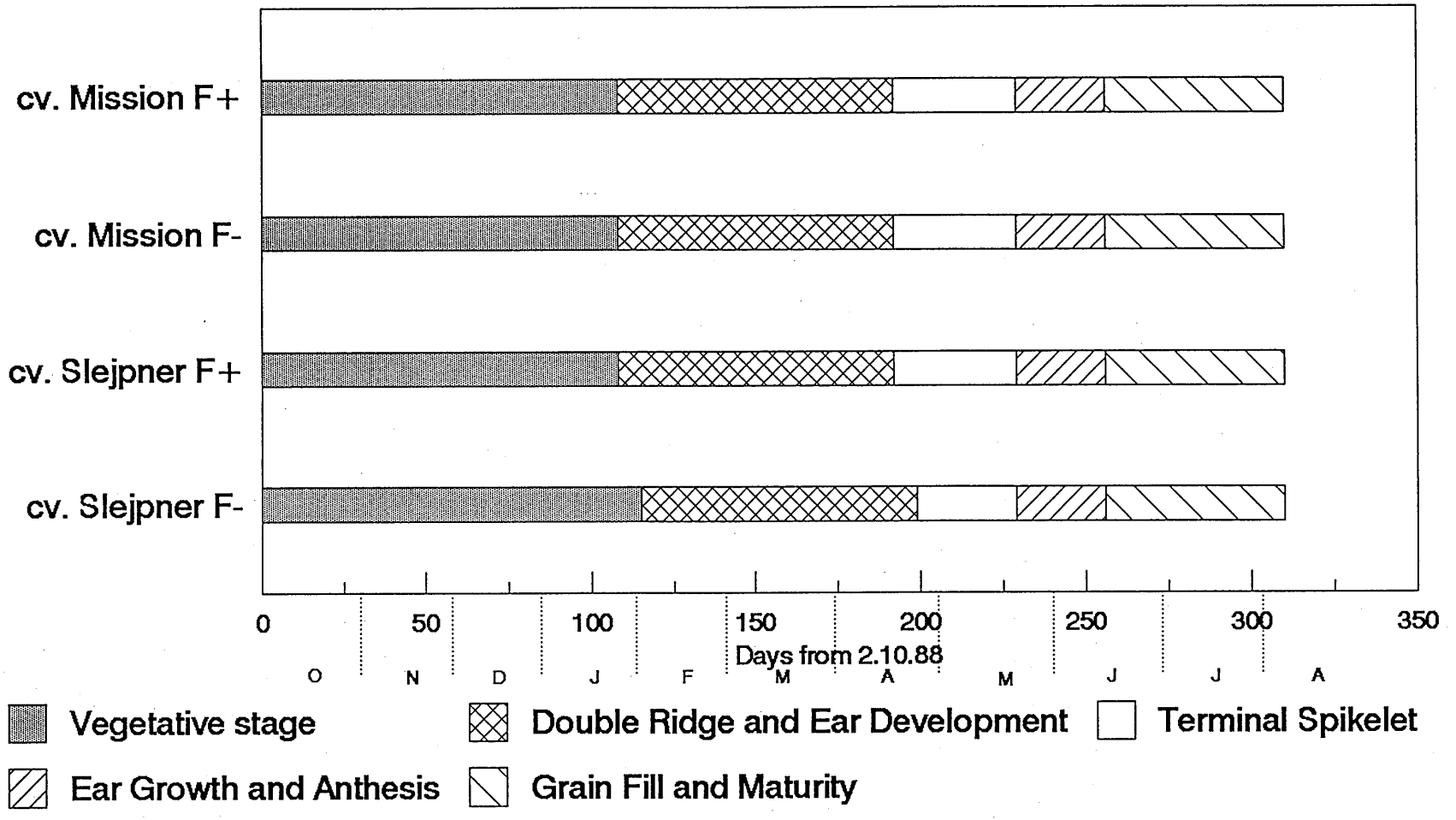
Reference to Figure 4.1 shows the results of the apex development stage recording, for experiments 1 and 2. It can be seen that within a sowing date, the varieties developed at similar rates through the growing season. Over the winter months when temperatures were at their lowest and day lengths were at their shortest, wheat remained dormant in the vegetative stage. When the wheat had undergone vernalisation, and day length and temperatures had increased in the early spring, floral structures developed on the apex. Comparison of sowing dates shows that by the initiation of the terminal spikelet stage the variability in development had disappeared. There was however a lag time of approximately seven days for cultivar Slejpner. By initiation of the main stem terminal spikelet stage, all varieties and sowing dates had caught up.

FIGURE 4.1a **THE EFFECTS OF SOWING DATE (S) AND VARIETY ON THE APEX DEVELOPMENT OF WINTER WHEAT, EXPT.1 BURY ST.EDMUNDS UK 1989 SEASON**



S1 = 4.10.88, S2 = 17.10.88, S3 = 1.11.88

FIGURE 4.1b **THE EFFECTS OF VARIETY AND FUNGICIDE TREATMENT (F) ON THE APEX DEVELOPMENT OF WINTER WHEAT, EXPT. 2, BURY UK 1989 SEASON**



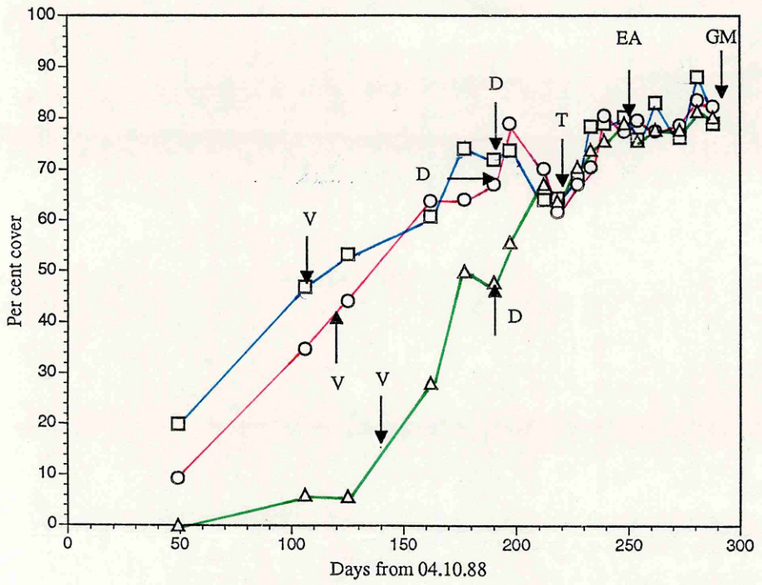
ALL WHEAT SOWN ON THE 2.10.88

For example, 100 days after the earliest sowing the cover ranged from < 10 % for sowing date 3 to > 40 % for sowing date 1. This was because the earliest sowing dates were in the ground when soil temperatures and day length encouraged emergence and establishment. By early November, soil temperatures and day length had decreased, hence the latest sowing was retarded in terms of the number of emerged leaves and hence cover. By the end of the double ridge and ear development stage, the per cent covers had converged so that the variance due to sowing date had disappeared. By the end of the terminal spikelet stage, the per cent cover remained fairly constant until maturity. It is interesting to note that the cover did not reach one hundred per cent. This was because:

(i) lower canopy leaves which were shaded by the upper canopy were counted as shadow;
(ii) gaps in the canopy were counted as soil background.

Figure 4.3 shows the spectral temporal development of the wheat canopies measured by the Normalised Difference Vegetation Index. Again, it is apparent that the variance due to sowing date was greatest during the vegetative and double ridge stages. The earlier two sowing dates show a marked trough in the spectral response at the end of the double ridges and ear development stage. By initiation of the terminal spikelet phase, the spectral profiles had converged.

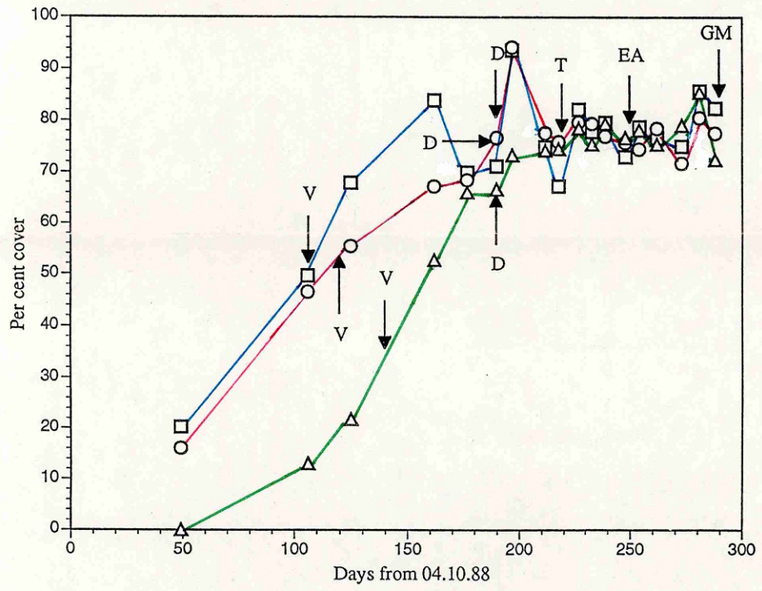
FIGURE 4.2 CHANGES IN MEAN PER CENT COVER OVER TIME, EXPT.1, 1989
ARROWS DENOTE AN END OF STAGE



A. cv. Mission

Sow Date 1 04.10.88
Sow Date 2 17.10.88
Sow Date 3 01.11.88

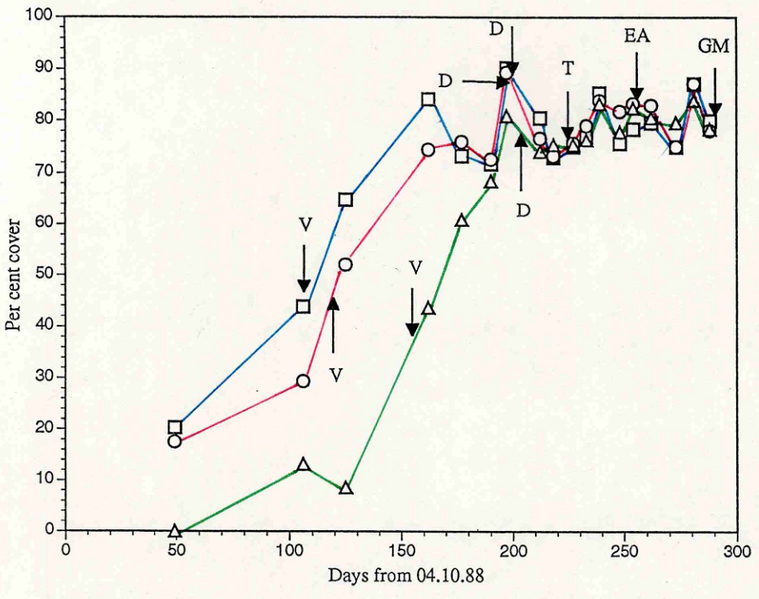
APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity



B. cv. Avalon

Sow Date 1 04.10.88
Sow Date 2 17.10.88
Sow Date 3 01.11.88

APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity

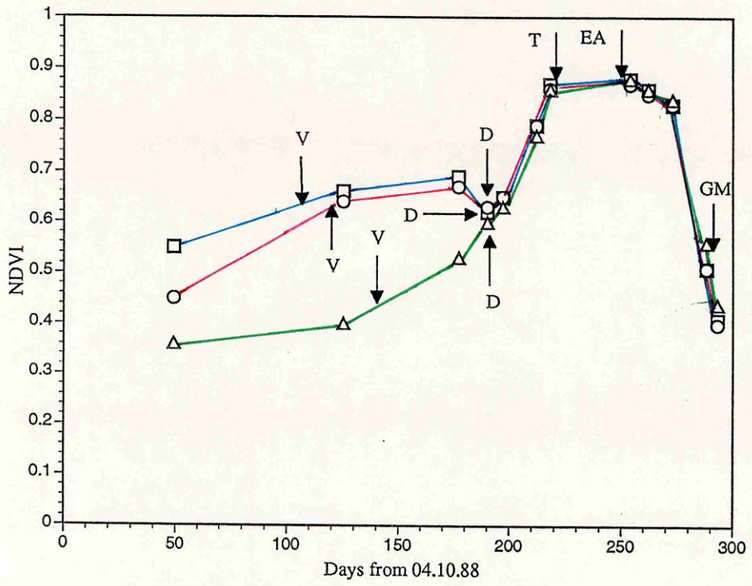


C. cv. Slejpner

Sow Date 1 04.10.88
Sow Date 2 17.10.88
Sow Date 3 01.11.88

APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity

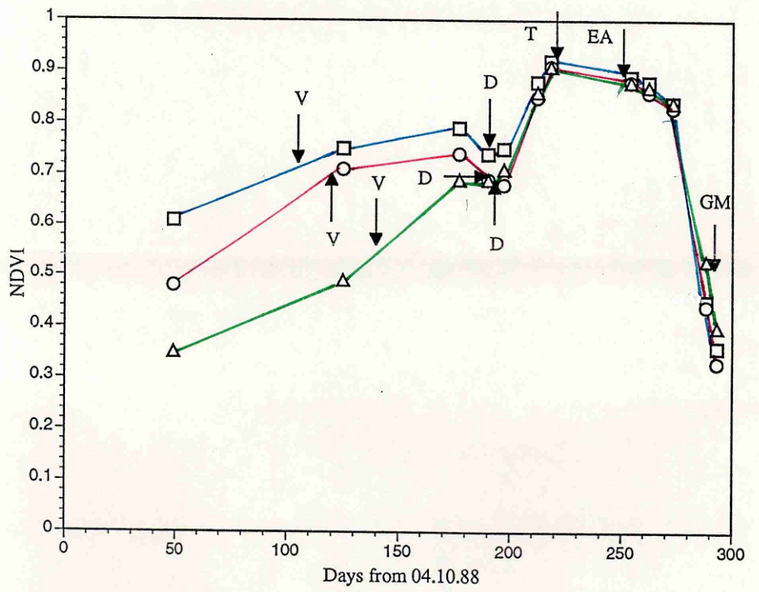
FIGURE 4.3 CHANGES IN MEAN NDVI OVER TIME, EXPT.1, 1989
ARROWS DENOTE AN END OF STAGE



A. cv. Mission

Sow Date 1 04.10.88
Sow Date 2 17.10.88
Sow Date 3 01.11.88

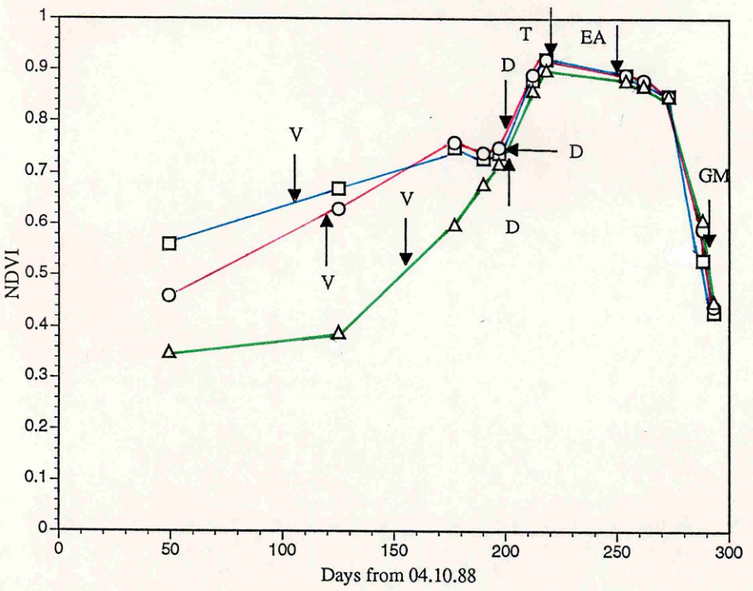
APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity



B. cv. Avalon

Sow Date 1 04.10.88
Sow Date 2 17.10.88
Sow Date 3 01.11.88

APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity



C. cv. Slejpner

Sow Date 1 04.10.88
Sow Date 2 17.10.88
Sow Date 3 01.11.88

APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity

During the terminal spikelet phase of main stem apex development, the vegetation index increased linearly until the end of terminal spikelet.

During ear growth, the vegetation index became insensitive to further changes in the crop. The maximum NDVI was reached during this period. After anthesis, the vegetation index declined as the crop matured. By the end of grain fill and maturity, the vegetation index had returned to the level of the soil background. All three varieties showed similar spectral response in relation to the development of the main stem apex.

4.1.4 The Effects of Sowing Date and Variety on the Spectral Response of Winter Wheat.

Figure 4.4 shows the results of the two-way analysis of variance on per cent cover over time for experiment 1. The variance ratios are shown for variety, sowing date and the interaction term. This diagram shows that by initiation of the main stem terminal spikelet stage, the differences in per cent cover due to sowing date became non-significant. There was a cross-over in the variance ratio where by the differences due to variety exceeded that due to sowing date ($P < 0.05$). Per cent cover showed variety differences up to the beginning or the ear growth and anthesis stage. After this period, variety and sowing date differences became non-significant. There was no significant interaction ($P < 0.05$) throughout the season.

FIGURE 4.4 CHANGES IN PER CENT COVER VARIANCE RATIOS OVER TIME, FOR SOWING DATE, VARIETY AND INTERACTION. EXPERIMENT 1, 1989.

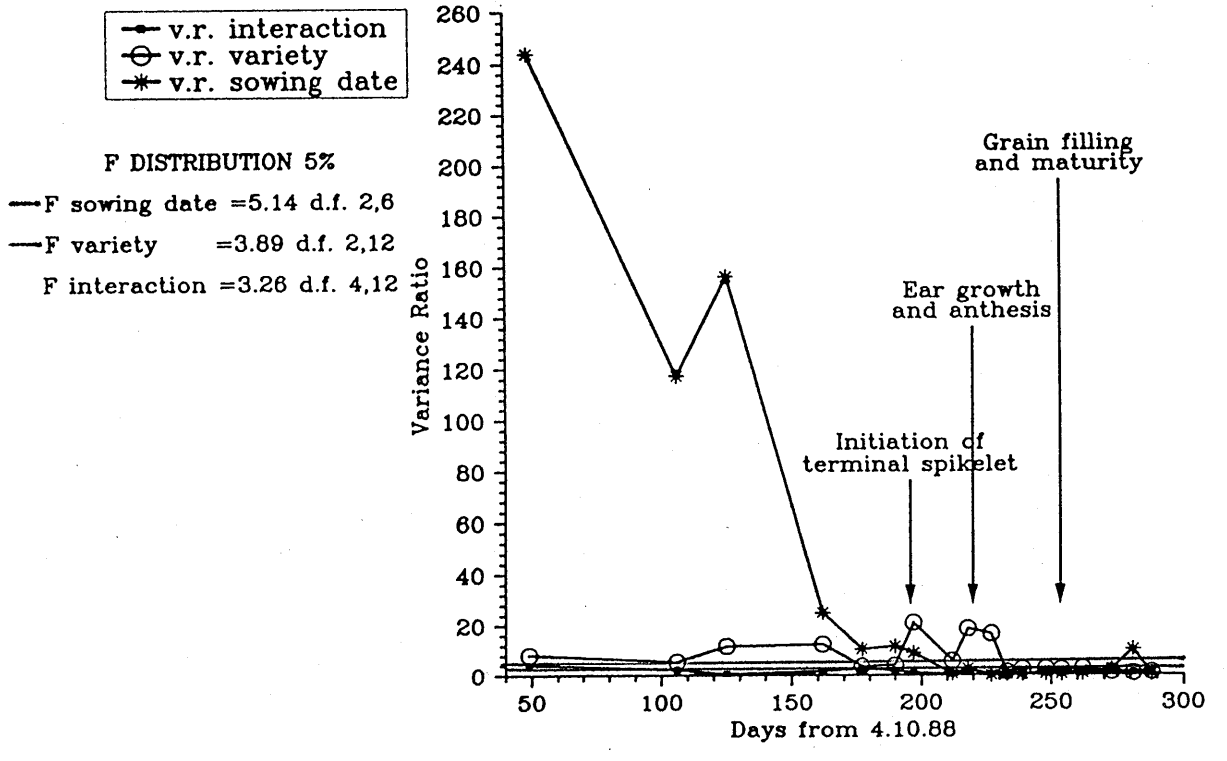
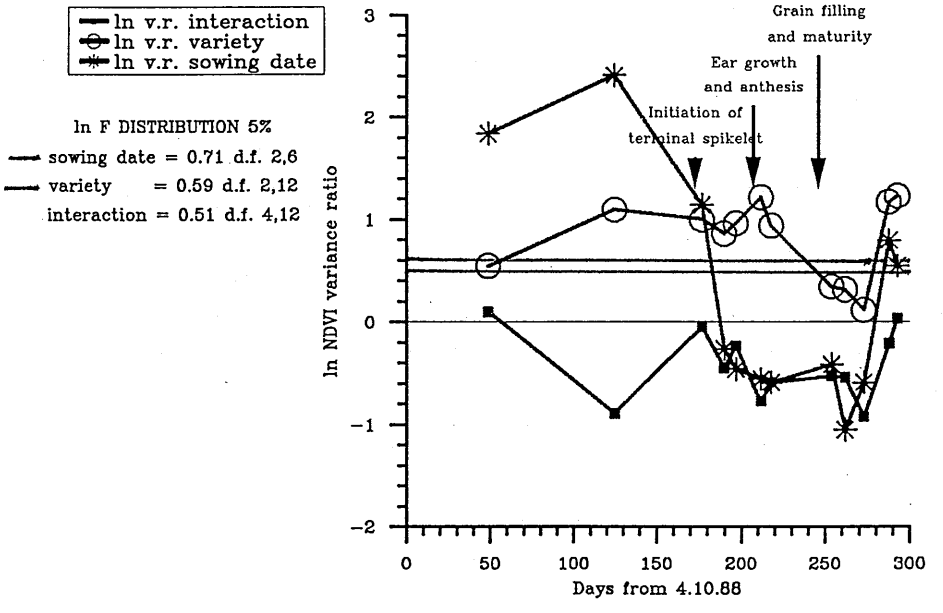


Figure 4.5 summarises the results of the two-way analysis of variance on the NDVI response over time for experiment 1. Again, this diagram reveals that by initiation of the terminal spikelet phase, the sowing date component became non-significant ($P < 0.05$) and remained so for the rest of the season. Again the variance due to variety exceeded that due to sowing date in the terminal spikelet phase. By the beginning of ear growth, the variance due to sowing date and variety became non-significant. This was during saturation of the NDVI. At the end of grain fill, significant variety differences were found ($P < 0.05$). There was no significant interaction for the duration of the experiment. The spectral temporal response of wheat canopies showed a complex pattern in relation to sowing date and variety. To summarise:

(i) The variance due to sowing date disappeared by initiation of the terminal spikelet phase;

(ii) Two key phases of apex development were found in which there were significant differences in spectral response due to variety but not sowing date ($P < 0.05$). These were the terminal spikelet and grain filling phases respectively.

FIGURE 4.5 CHANGES IN LOG_E NDVI VARIANCE RATIOS OVER TIME FOR SOWING DATE, VARIETY AND INTERACTION. EXPERIMENT 1, 1989.



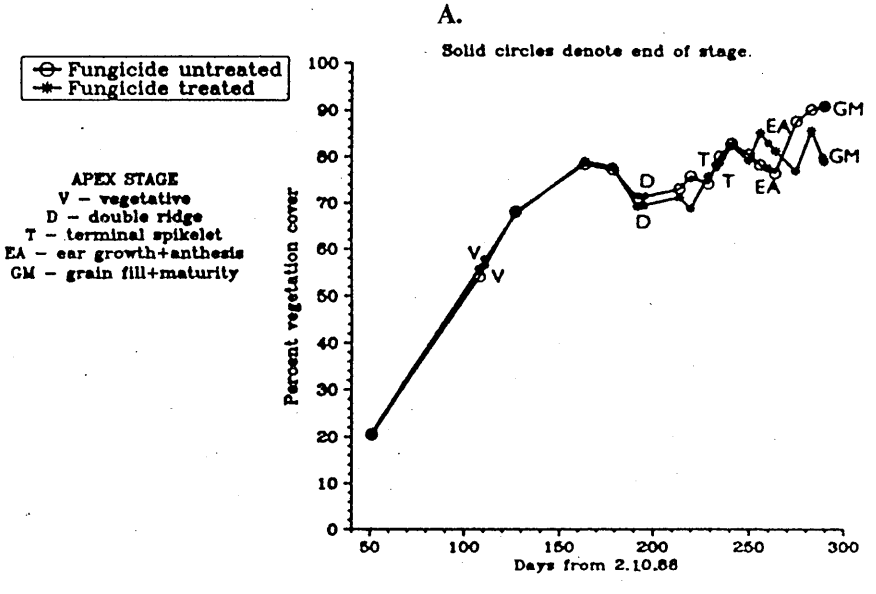
4.1.5 The Effects of Disease on the Spectral Response of Winter Wheat.

Figure 4.6 shows the changes in per cent cover over time for experiment 2 and the major stages of apex development. The two varieties show similar patterns of cover development up until the grain filling phase. It is interesting to note that by the end of the double ridge stage, both treatments show a marked trough in the spectral profiles.

During the grain filling phase, fungicide untreated Slejpner showed differences compared to the treated wheat. For reasons discussed earlier, the cover does not reach one hundred per cent. The reduction in cover of the fungicide deficient Slejpner at the end of the season can be attributed to the growth of the fungal disease, yellow rust (Puccinia striiformis). By the heading stage, the untreated blocks were well infested with rust, Plate 4.1. This caused chlorosis of the leaves. By July, the green leaf area had collapsed for the fungicide untreated block compared to the treated block, Plate 4.2. By maturity, at the end of July, there were obvious differences in the head density and in the proportion of ground covered by vegetation, Plate 4.3.

Figure 4.7 shows the changes in the spectral response of wheat treated and untreated with fungicide. The profiles for healthy wheat are comparable to those of experiment 1. The NDVI shows gradual increase in the vegetative and double ridge stages. Again, there was evidence of a trough in the spectral profiles during the terminal spikelet stage. By the time that ear growth and anthesis was reached, the vegetation index showed saturation and then declined after anthesis in the grain filling phase. Reference to Figure 4.7b shows that fungicide untreated Slejpner showed early decline of the NDVI when compared to the treated wheat. This departure can be attributed to attack by yellow rust. The vegetation index then returned to the level of the soil background by maturity.

FIGURE 4.6 CHANGES IN MEAN PER CENT COVER OVER TIME, EXPT. 2, 1989. A: CV. MISSION, B: CV. SLEJPNER



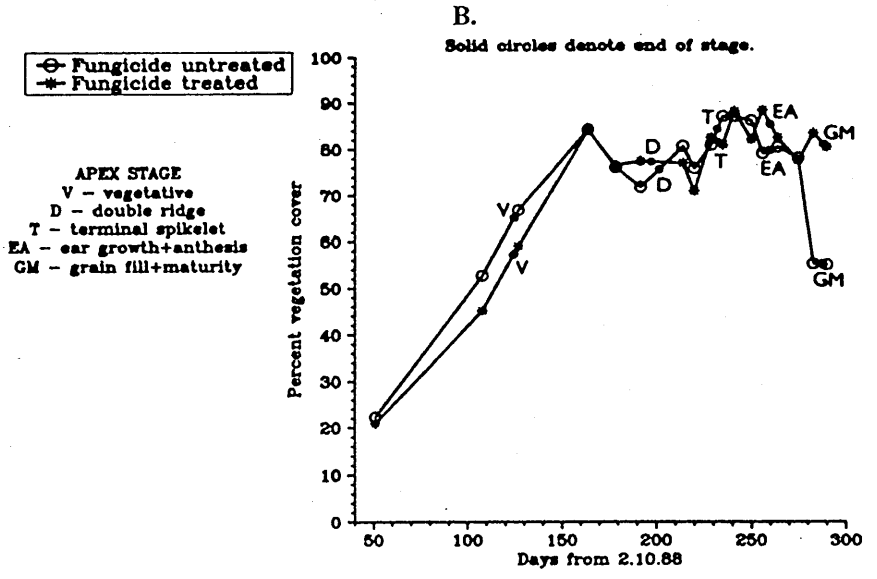


FIGURE 4.7 CHANGES IN MEAN NDVI OVER TIME, EXPT. 2, 1989.

A: CV. MISSION B: CV. SLEJPNER

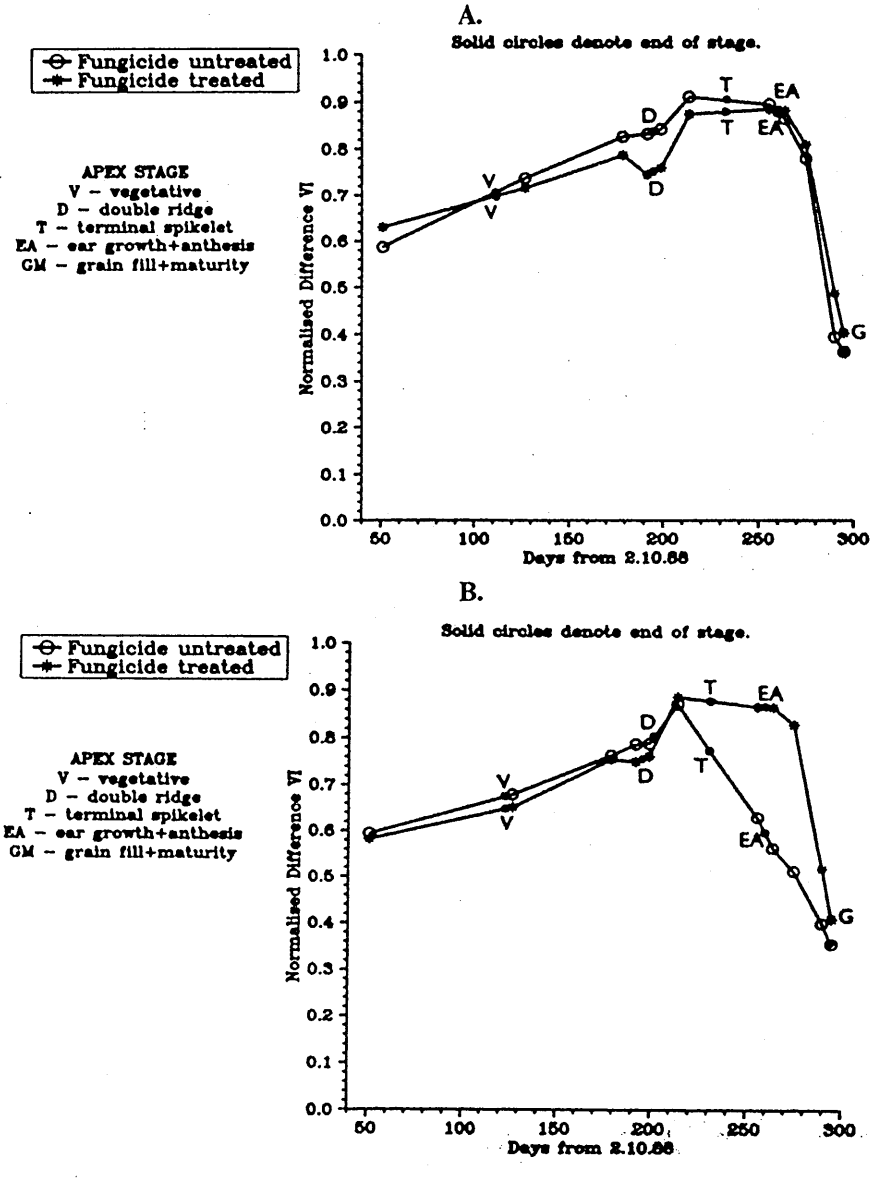


PLATE 4.1 FUNGICIDE TREATED (A) VS FUNGICIDE UNTREATED WHEAT (B), CV. SLEJPNER, EXPT. 2, 15.06.89. EAR GROWTH STAGE



A.

B.



PLATE 4.2 FUNGICIDE TREATED (A) VS FUNGICIDE UNTREATED WHEAT (B), CV. SLEJPNER, EXPT.2, 4.7.89 GRAIN FILL.



A.

B.

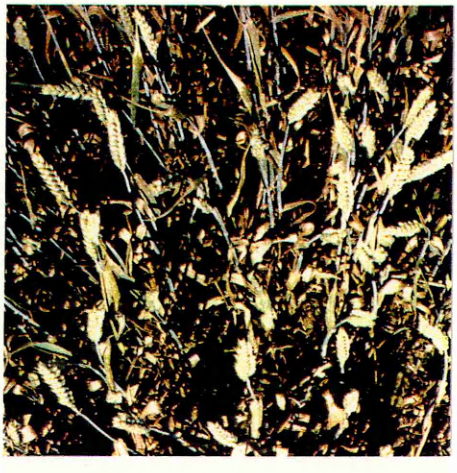


PLATE 4.3 FUNGICIDE TREATED (A) VS FUNGICIDE UNTREATED WHEAT (B), CV. SLEJPNER, EXPT. 2, 24.7.89 MATURITY.



A.

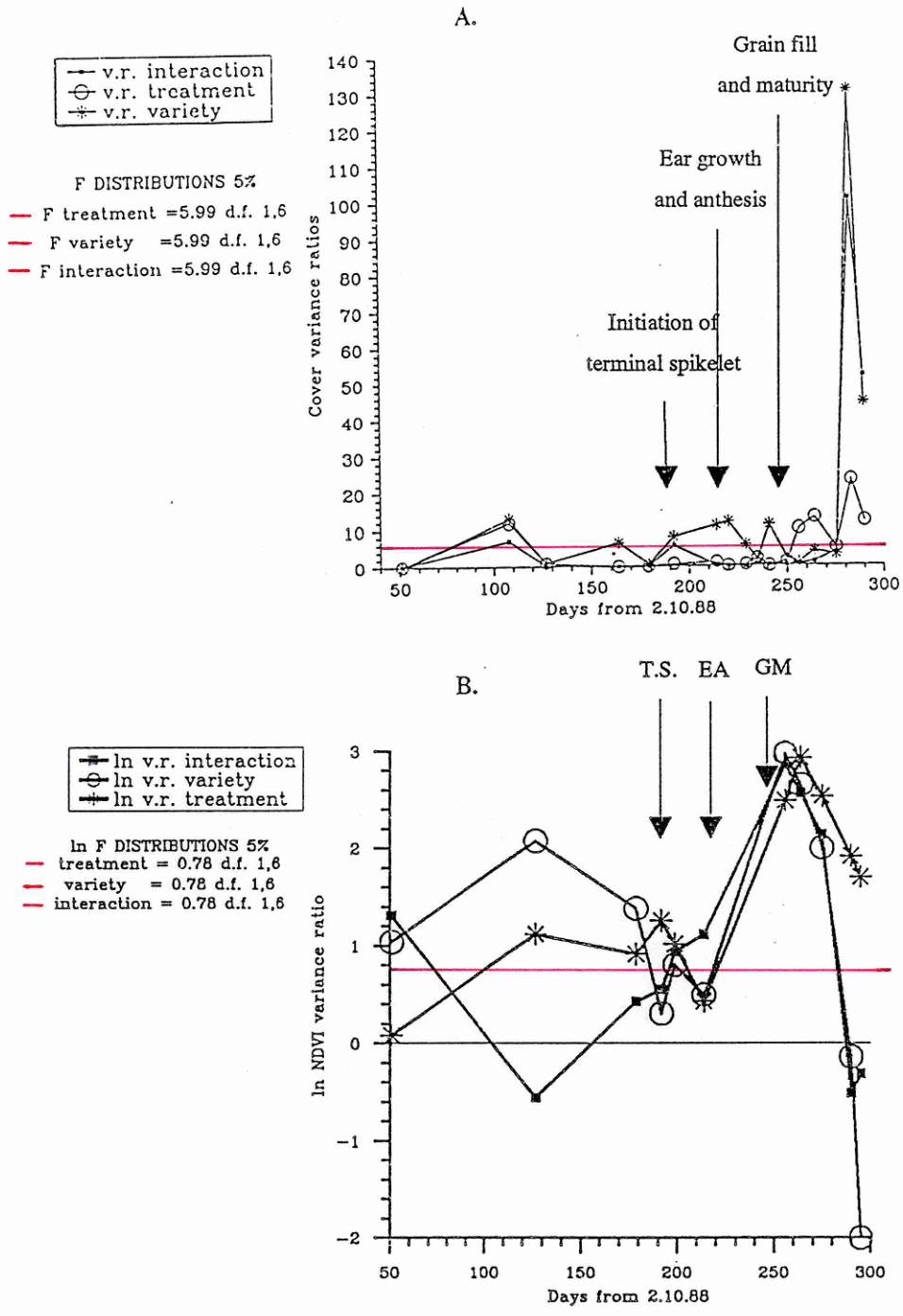
B.



Figure 4.8 shows the results of the two-way analysis of variance on cover and the NDVI by fungicide treatment and variety on experiment 2. It can be seen that at the beginning of the season, significant differences in cover and NDVI were found ($P<0.05$). This can probably be attributed to the faster development rate of cv. Mission. By the end of terminal spikelet, significant spectral, treatment and interaction differences occurred ($P<0.05$). This can be attributed to the attack by yellow rust of the untreated Slejpner blocks. The interaction term indicates that the differences in spectral and cover response did not occur uniformly on the experiment. This was because cv. Mission was resistant to yellow rust, and the treatment of cv. Slejpner by fungicide, prevented attack during the later stages of the crops development cycle. The analysis of variance reveals that very significant differences were found in the spectral and cover responses of the canopies. These differences were at their greatest during the ear development and grain filling stages. The differences in spectral response and cover were fungicide treatment and variety dependent. Comparison of means (Figure 4.6 and 4.7), shows that the cover and spectral response of the untreated Slejpner blocks showed rapid decline during these periods. These differences could then be attributed to attack of the crop by yellow rust.

FIGURE 4.8 CHANGES IN VARIANCE RATIOS OVER TIME FOR VARIETY, FUNGICIDE TREATMENT AND INTERACTION. EXPT. 2, 1989.

A: PER CENT COVER, B: LOG_E NDVI.



4.2 Results of the 1990 Season.

4.2.1 Summary of the 1990 Results.

During the Autumn of 1989, drought conditions prevailed at the trial site. Therefore, although wheat was sown more than a calandar month apart, very dry soil conditions prohibited emergence until the first major rain storm event. This meant that all the plots were effectively late sown. The spectral response of the wheat was very different compared to the previous season as there was effectively no early sowing date effect. Also due to reasons beyond the authors control it was not possible to exactly repeat the experimental design of the previous season. However an attempt was made to validate the findings using varieties of wheat sown on different dates. The results of the 1990 season can be summarised as follows:

(i) The findings of the previous season were not confirmed;

(ii) Differences in the spectral response of wheat were found within sowing dates blocks. This was attributable to particularly late emergence of some blocks because of drought and problems with seed bed preparation;

(iii) Sowing date differences in the spectral response of winter wheat were found during the grain filling period.

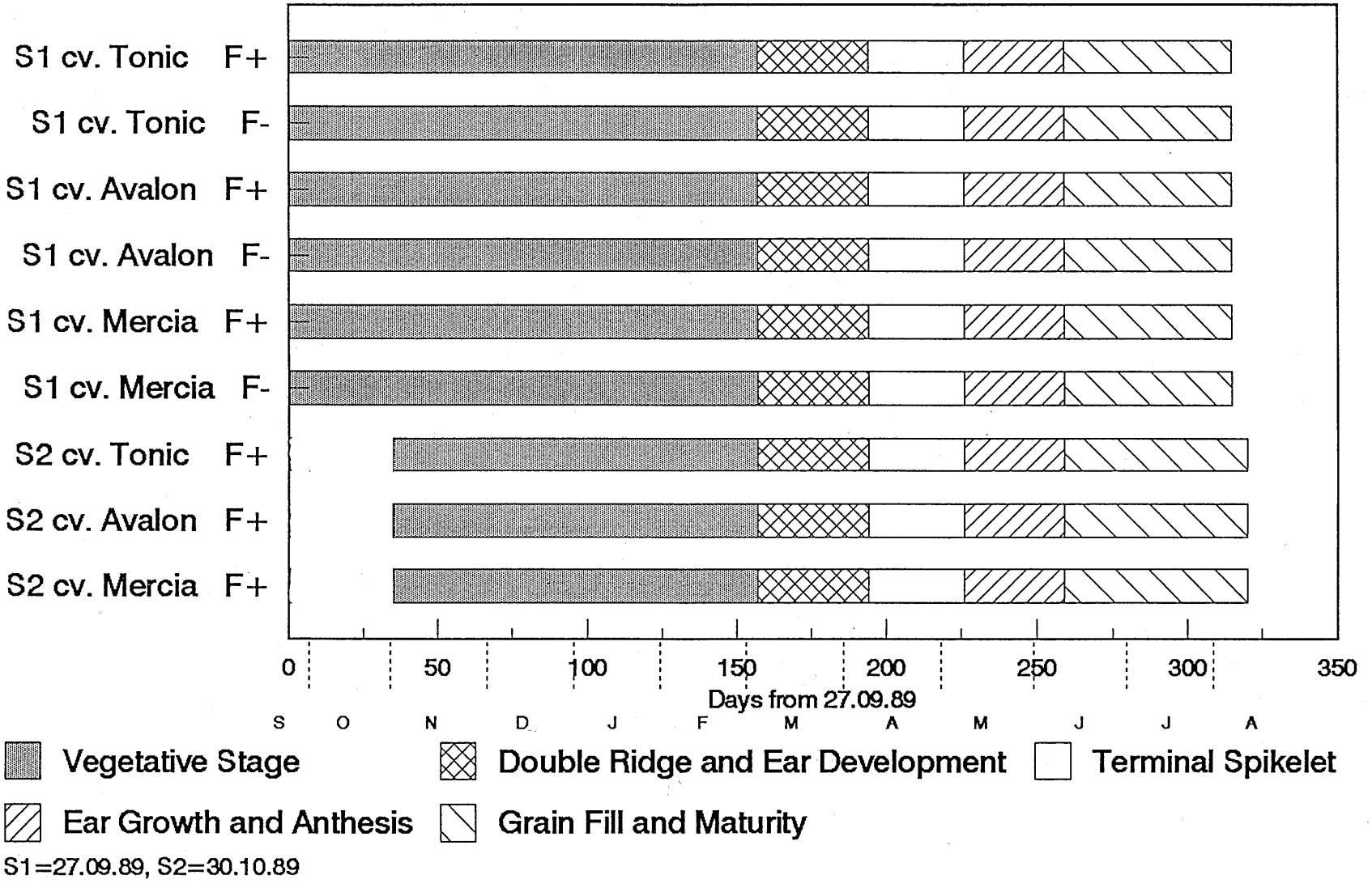
4.2.2 Field Radiometer Data Collection.

A total of twenty four site visits were made in the 1990 season. Again the season could be described as an exceptional year for field radiometry. Repair of the output unit allowed data collection to be continued uninterrupted. However due to the very dry ground conditions at the time of sowing, the different sowing dates did not emerge until a major rain storm event. Therefore, all sowing dates were effectively late sown and consequently vegetation cover remained low throughout the winter months. Sowing date 1 was particularly badly effected because of poor seed bed preparation. The resulting spectral information for the 1990 season was very different compared to the previous cropping year. Table 4.2 shows the record of site visits made and data collected on each site visit.

4.2.3 The Effect of Development Stage on the Spectral Response of Winter Wheat.

Figure 4.9 shows the effects of sowing date, variety and fungicide application on the apex development of winter wheat. Because of the environmental conditions at the time of sowing and establishment, there appeared to be little or no effect of sowing date, variety and fungicide application on the rates of apex development of winter wheat for the 1990 season. In terms of the development of the main stem apex, all

FIGURE 4.9 **THE EFFECTS OF SOWING DATE (S), VARIETY AND FUNGICIDE TREATMENT (F) ON THE APEX DEVELOPMENT OF WINTER WHEAT. BURY ST.EDMUNDS UK 1989 1990**



S1=27.09.89, S2=30.10.89

varieties were effectively sown on the same date. Compared to the previous year, sowing date and variety differences did not disappear until the terminal spikelet stage. Whereas in the 1990 season there were apparently no differences in the stage of the apex from the end of the vegetative stage.

TABLE 4.2 RECORD OF SITE VISITS IN THE 1990 SEASON.

SITE VISIT NO.	DATE	SOLAR ELEVATION 10 am	SOLAR ELEVATION 2 pm	CLOUD COVER (OCTA)	RADIOMETRY SQ/SM	%COVER	GROUND TRUTH
1	10.11.89	17	20	8	-	+	-
2	24.11.89	13	15	0	SM	+	-
3	05.12.89	13	12	2	SM	+	-
4	18.01.90	12	11	0	SM	+	-
5	16.02.90	20	22	0	SM	+	+
6	09.03.90	28	30	8	-	-	+
7	21.03.90	33	34	8	-	-	+
8	26.03.90	35	35	8	-	-	-
9	30.03.90	35	35	0	SM	+	-
10	09.04.90	40	42	2	SM	+	+
11	24.04.90	44	45	0	SM	+	+
12	30.04.90	47	48	2	SM	+	+
13	03.05.90	48	49	0	SM	+	-
14	10.05.90	49	50	7	-	-	+
15	17.05.90	50	51	8	-	-	+
16	24.05.90	51	52	8	-	-	+
17	31.05.90	51	53	3	SM	+	-
18	06.06.90	52	53	8	-	-	+
19	13.06.90	53	54	8	-	-	+
20	27.06.90	54	54	7	-	-	+
21	11.07.90	53	54	0	SM	+	+
22	18.07.90	53	53	1	SM	+	+
23	25.07.90	51	51	0	SM	+	+
24	01.08.90	50	50	0	SM	+	+

14 dates of radiometric data (SM simultaneous, SQ sequential measurement)
Solar Elevations are given in degrees
16 dates of ground truth information

Figure 4.10 shows the changes in mean per cent cover over time for the second year's data. It can be seen that for the 1990 season, the variance in per cent cover due to sowing date was not as great as the preceding season. Throughout the winter months the vegetation cover remained low until spring. The earliest sowing dates did not emerge until the first major rain storm event following a dry summer and autumn. However, during the spring period the vegetation cover rapidly increased, so that by the end of the ear development stage, the per cent cover had reached over 80%. During the terminal spikelet stage, for cultivars Mercia and Avalon there was a noticeable trough in the data, so that by the end of terminal spikelet, the vegetation cover had reached a stable level. This was maintained through ear growth and anthesis, up until the harvest ripe stage.

Figure 4.11 shows the spectral temporal development for the wheat varieties measured by the NDVI. The end of the major stages of apex development are also shown. Initially during the vegetative stage, the variance in NDVI due to sowing date was not as large as the previous season. This was due to factors already discussed. However, by the end of the double ridge stage, the spectral profiles appeared to converge. By the end of the terminal spikelet stage, the NDVI had reached saturation, in which maximum NDVI was reached. Following anthesis, the vegetation index declined sharply in response to the loss of pigments, cellular water and collapse of cell structure.

FIGURE 4.10 CHANGES IN MEAN PER CENT COVER OVER TIME, 1990
ARROWS DENOTE AN END OF STAGE

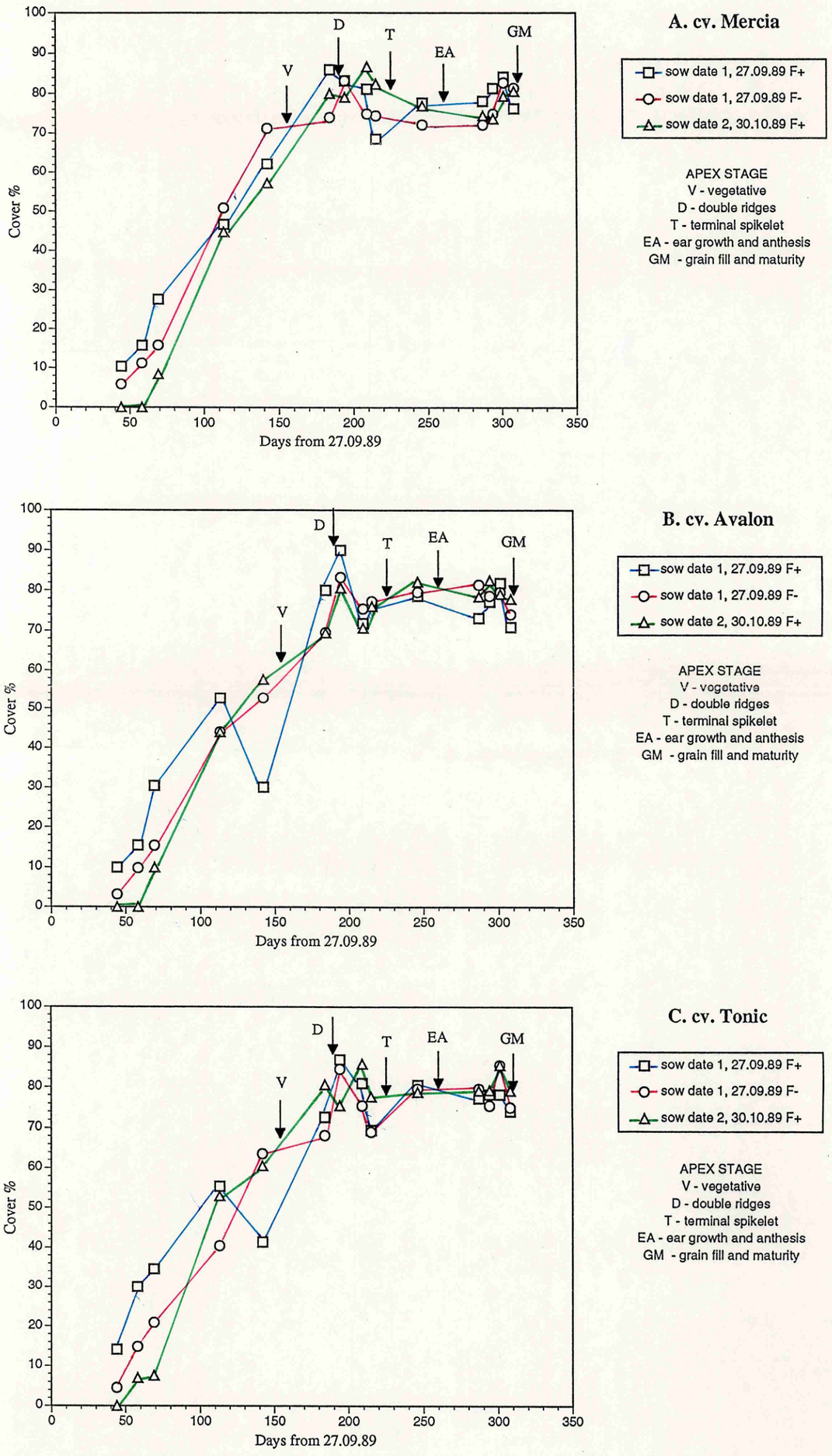
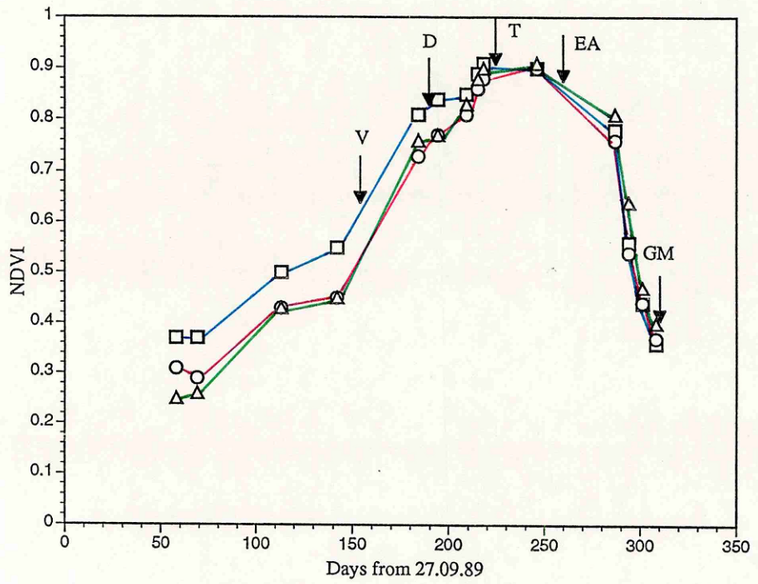


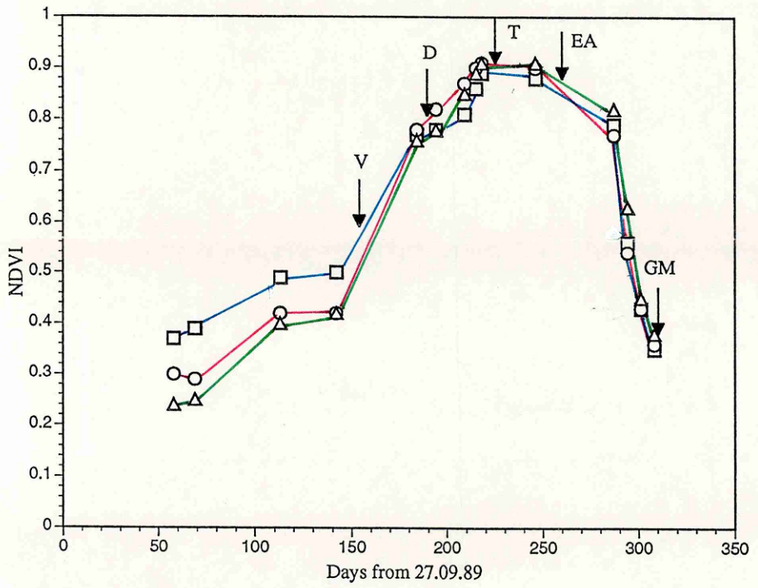
FIGURE 4.11 CHANGES IN MEAN NDVI OVER TIME, 1990
ARROWS DENOTE AN END OF STAGE



A. cv. Mercia

sow date 1, 27.09.89 F+
sow date 1, 27.09.89 F-
sow date 2, 30.10.89 F+

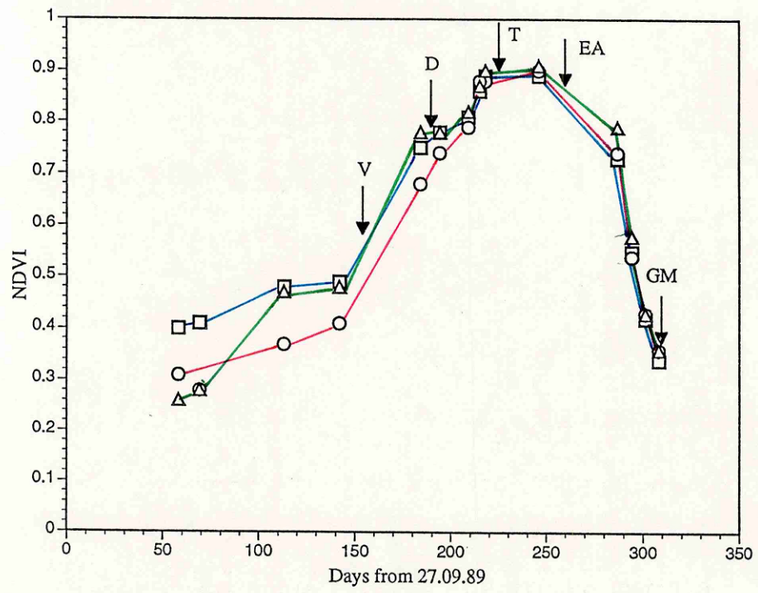
APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity



B. cv. Avalon

sow date 1, 27.09.89 F+
sow date 1, 27.09.89 F-
sow date 2, 30.10.89 F+

APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity



C. cv. Tonic

sow date 1, 27.09.89 F+
sow date 1, 27.09.89 F-
sow date 2, 30.10.89 F+

APEX STAGE
V - vegetative
D - double ridges
T - terminal spikelet
EA - ear growth and anthesis
GM - grain fill and maturity

4.2.4 The Effects of Sowing Date and Variety on the Spectral Response of Winter Wheat.

In the 1990 season, the spectral development of the canopies showed a complex pattern of development. Early on in the vegetative and double ridge stages of apex development, the variance in cover and the NDVI both showed significant differences due to sowing date ($P < 0.05$), Figures 4.12 and 4.13. Radiometrically, the variance due to sowing date disappeared when the wheat was in the vegetative stage. However, it is interesting to note that significant differences were found in the sowing date block factor ($P < 0.05$). This remained until the initiation of the terminal spikelet. This can probably be attributed to the differential rates of development of some of the blocks in sowing date 1. In 1990, field position of the blocks proved to be an important factor early on in the season.

This was because the soil and weather conditions at the time of establishment prevented uniform emergence. This was evident both in terms of the per cent cover and in the radiometric response of the canopies. At the end of the season, during the grain filling stage, significant differences due to sowing date were found ($P < 0.05$). This was a different pattern compared to the previous seasons data.

FIGURE 4.12 CHANGES IN THE PER CENT COVER VARIANCE RATIOS OVER TIME, FOR SOWING DATE, VARIETY AND INTERACTIONS, 1990.

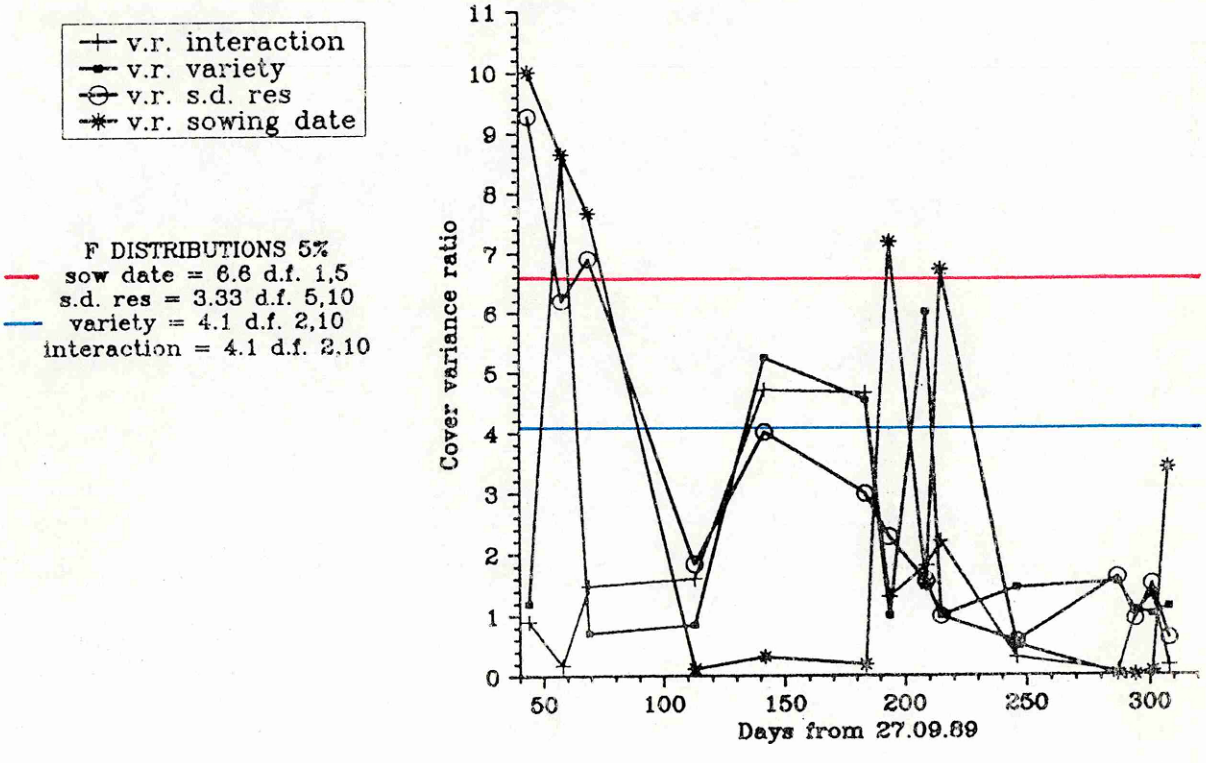
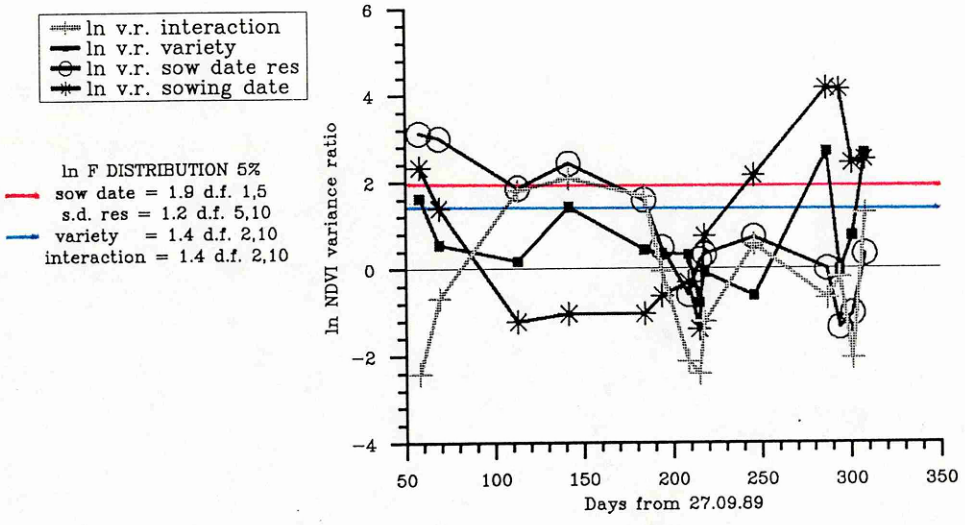


FIGURE 4.13 CHANGES IN THE LOG$_E$ VARIANCE RATIOS OVER TIME, FOR SOWING DATE, VARIETY AND INTERACTIONS, 1990.



4.3 Discussion.

4.3.1 The Effect of Apex Development Stage on the Spectral Response of Winter Wheat.

For the 1989 season, the earliest sowing dates showed large differences in the spectral response in the vegetative and double ridge stages of apex development. The crop development calendar revealed that during the winter months, the rate of development of the apex remained slow. However, by the middle of April, the spectral temporal profiles had converged. This occurred at the initiation of the terminal spikelet phase. The earliest sowing dates showed a pronounced dip in the spectral response during this period of apex development, Figure 4.3. This is interesting because for the 1989 growing season there were significant differences in the plant population densities after winter kill, Table 4.3. This was when the plants were in the double ridge stage of apex development.

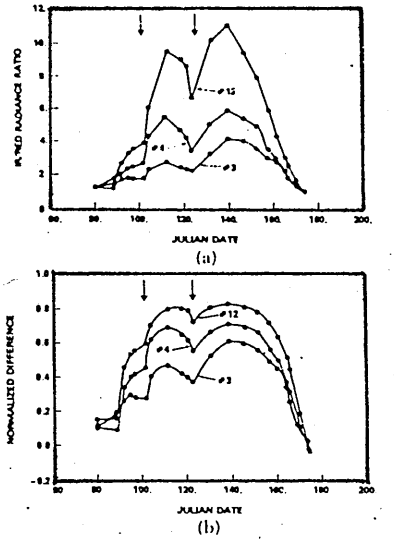
TABLE 4.3 PLANT POPULATION DENSITIES M^{-2} MEASURED AFTER WINTER KILL (ZADOK'S GROWTH STAGE 16:23), EXPT. 1, 1989. STANDARD DEVIATIONS IN BRACKETS.

SOWING DATE	VARIETY MISSION	AVALON	SLEJPNER
4.10.88	196.9 (2.85)	198.7 (4.4)	226.2 (4.4)
17.10.88	234.7 (2.0)	258.7 (2.31)	249.8 (2.59)
1.11.88	158.7 (3.05)	200.4 (4.36)	184.4 (4.3)

A two-way analysis of variance by variety and sowing date (Appendix 5), revealed that there were significant differences in the plant populations due to variety and sowing date ($P < 0.05$). This was also apparent in terms of the spectral response of the canopies. By initiation of the terminal spikelet phase, the sowing date component had disappeared developmentally, radiometrically and in terms of the per cent cover. This remained so throughout the rest of the season. The initiation of the main stem terminal spikelet stage was therefore a critical period.

Tucker et al.(1980) also showed a dip in the spectral response of wheat in the spring period using radiance data, Figure 4.14. They attributed this as a manifestation of wheat canopy water stress. They postulated that the water stress influenced the leaf chlorophyll density and/or the canopy geometry. It is interesting to note that this trough occurred during Julian Dates 112-123, i.e. the end of April to early May. This is exactly the same period as found in the 1989 experimental data at Bury St. Edmunds in the UK, which corresponded with the terminal spikelet phase of apex development.

FIGURE 4.14 THE IR/R RADIANCE RATIO (A) AND THE NORMALISED DIFFERENCE VI (B) FROM THREE 2 BY 3 M PLOTS PLOTTED AGAINST JULIAN DATE. VERTICAL ARROWS REPRESENT EPISODES OF RAINFALL. (SOURCE TUCKER ET AL 1980).



During the grain filling period, significant differences in the spectral response were found due to variety ($P < 0.05$). This can probably be attributed to differences in the duration of photosynthetic activity or the duration of the green leaf area.

In the 1990 season, the patterns were somewhat different. No dips in the spectral profiles were found during the terminal spikelet phase. Also, sowing date canopy convergence during the terminal spikelet phase could not be confirmed. This was because both sowing dates, although more than a calendar month apart, were effectively late sown.

The spectral response of the canopies was much more complex than the preceding year. Early on in the season, there were significant differences in the block response, Figure 4.13. This can probably be attributed to the differential rates of emergence of some of the blocks. The field position of the plots was a more important factor in the 1990 season. Some of the blocks were very late in emerging. This led to a different cover development even within sowing date blocks.

A secondary reason why this might have occurred is that it was assumed that the first sowing date was a single block. Infact it was a split block receiving different levels of fungicide treatment. Even though analysis of variance on the grain yield at the end of the season revealed that there were no differences in yield due to fungicide treatment ($P<0.05$). Table 4.4 shows the mean plant populations m^{-2} at growth stage 13:21 for the 1990 season. The two-way analysis of variance by variety and sowing date (Appendix 6) revealed significant differences in plant populations m^{-2} due to sowing date ($P<0.05$). The earliest sown wheat actually had a lower plant population m^{-2} than the later sown wheat. This was a reverse trend compared to the previous season.

TABLE 4.4 PLANT POPULATION DENSITIES M^{-2} (ZADOK'S GROWTH STAGE 13:21), 1990. STANDARD DEVIATIONS IN BRACKETS

	VARIETY		
SOWING DATE	MERCIA	AVALON	TONIC
27.09.89	271.3 (5.6)	229.0 (8.4)	237.4 (6.8)
30.10.89	318.2 (6.8)	297.8 (4.5)	323.6 (4.3)

The late sowing of the 1990 season could be attributed to the soil and weather conditions during the Autumn of 1989. What was different about the 1990 season was that the canopies showed significant differences due to sowing date in the grain filling period. This could well be a response to late sowing and drought conditions during this phase.

4.3.2 The Effect of Sowing Date and Variety on the Spectral Response of Winter Wheat.

In the 1989 season, large differences in the spectral response of the canopies were found prior to the initiation of the main stem terminal spikelet, Figure 4.3. With the onset of the terminal spikelet phase, the sowing date component no longer had a significant effect on the spectral response. The response of the canopies was a function of the varieties. This was therefore, an important period in the spectral development of winter wheat. This phenomenon can probably be explained in terms of the tiller demography.

Work by Biscoe and Willington (1984) and Hay (1986) has shown that the most important factor determining final ear population density appears to be tiller mortality during and just before, and including, the achievement of crop growth stage 31 and mainstem apex terminal spikelet, Figure 4.15.

In a number of cases, this mortality has been reduced by accurately-timed application of fertilizer, because terminal spikelet marks the beginning of the most rapid phase of crop growth, when intra plant competition is at its greatest, Kirby and Appleyard (1984b), Appleton and Hagger (1985).

Figure 4.16 shows the changes in the tiller population density m^{-2} for experiment 1 in the 1989 season. The three varieties exhibited similar production of mainstem tillers. The first two sowing dates had by spring produced markedly more tillers than the latest sown wheat. However, by initiation of the terminal spikelet phase, the tiller population changed.

FIGURE 4.15 TIME COURSES OF STEM POPULATION DENSITY OF CROPS OF WINTER WHEAT CV. AVALON GROWN IN SE ENGLAND AT DIFFERENT LEVELS OF NITROGEN FERTILIZATION: (A) 90 KG N / HA; (B) 330 KG N / HA. MS REFERS TO THE MAINSTEM; T1 TO T4, TILLERS AT SUCCESSIVE NODES; T>4, TILLERS AT HIGHER NODES; AND TS INDICATES THE TIMING OF MAINSTEM TERMINAL SPIKELET STAGE. (AFTER BISCOE AND WILLINGTON 1984, FROM HAY AND WALKER 1989).

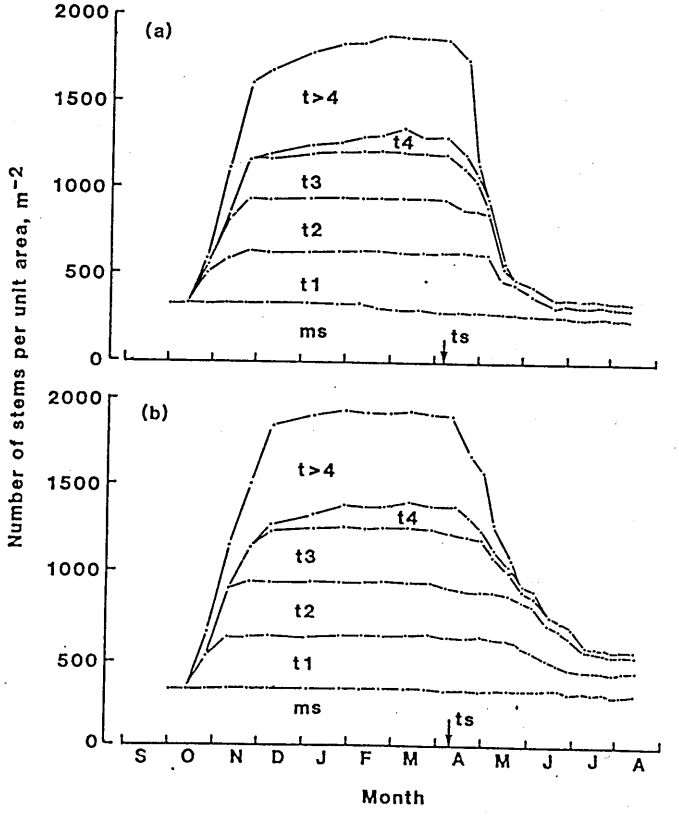
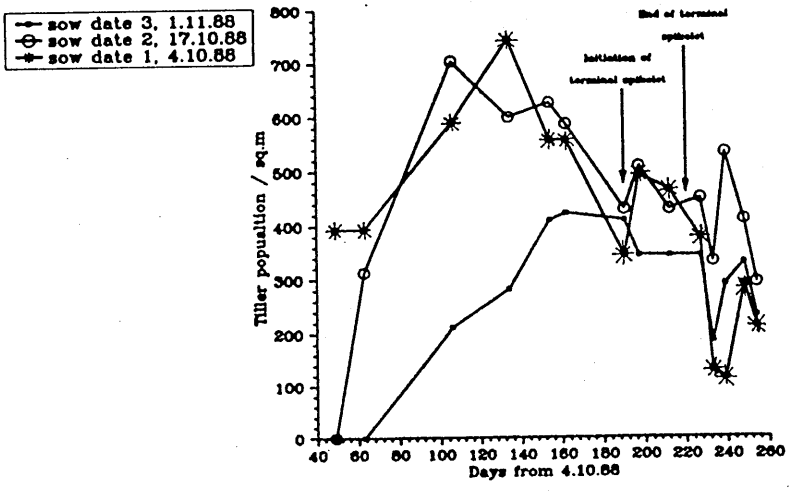
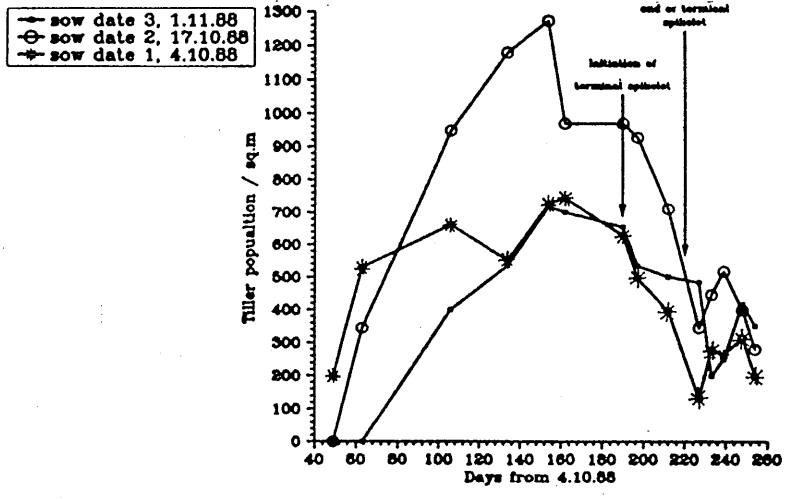


FIGURE 4.16 CHANGES IN TILLER POPULATION DENSITY M^{-2} OVER TIME, EXPERIMENT 1, 1989. A: CV. MISSION, B: CV. AVALON, C: CV. SLEJPNER.

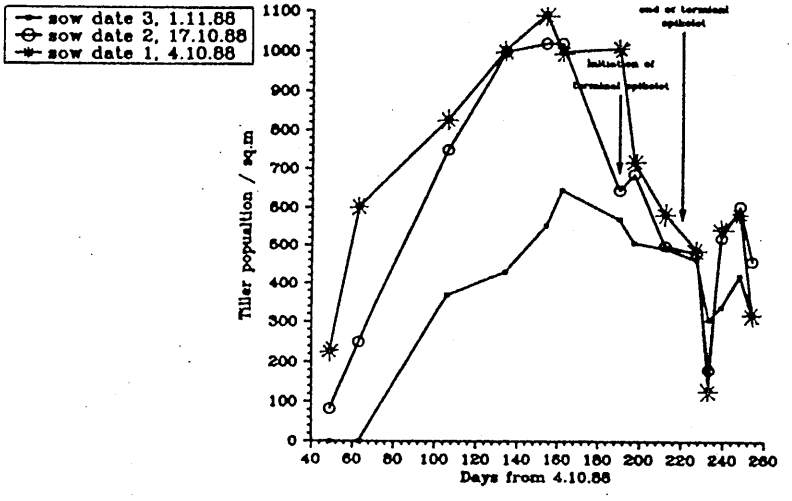
A.



B.



C.

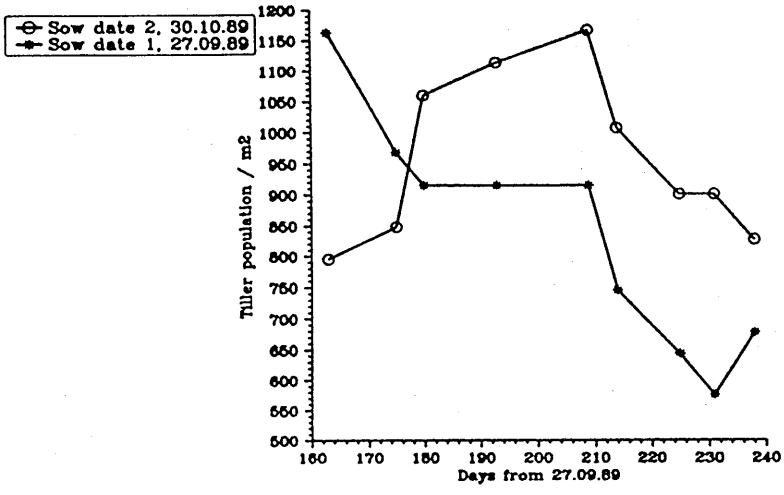


Tiller mortality reduced the tiller populations of the earliest sowing dates to the level of the latest sown wheat. This could be why the spectral data showed a marked dip at the initiation of this stage of apex development. The end of the terminal spikelet stage then marks an important phase in terms of the yield potential of wheat. No more spikelet primordia are initiated on the ear and the numbers of ears surviving to maturity are determined.

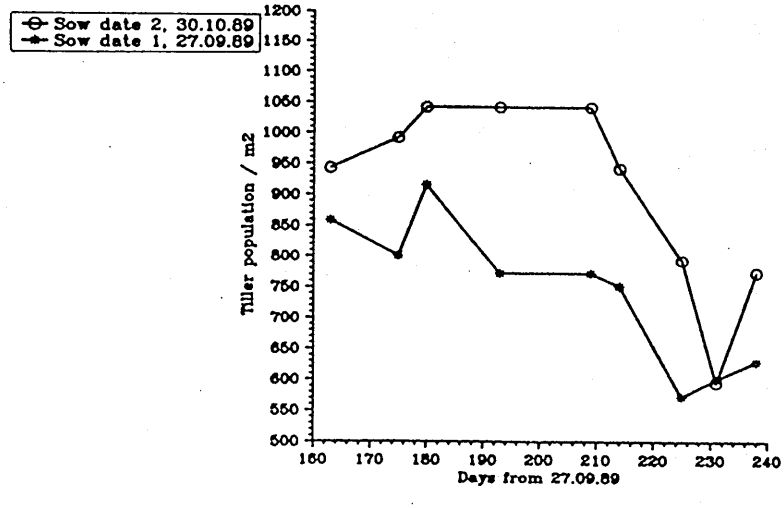
As all the wheat was late sown in the following season, the low production of tillers in the spring period would mean that there would not have been significant tiller mortality in the terminal spikelet phase, because of less intra-species competition, Figure 4.17. Hence, the spectral profiles were not characterised by dips in the response during this period.

FIGURE 4.17 CHANGES IN TILLER POPULATION DENSITY M^{-2} OVER TIME, 1990. A: CV. MERCIA, B: CV. AVALON, C: CV. TONIC.

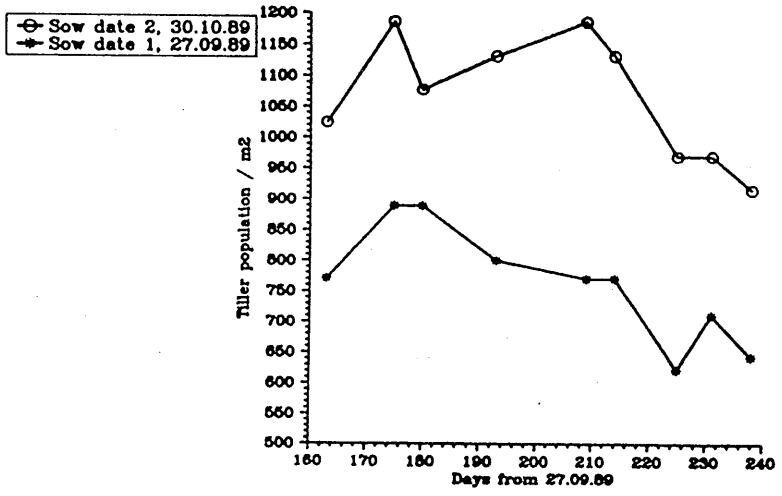
A.



B.



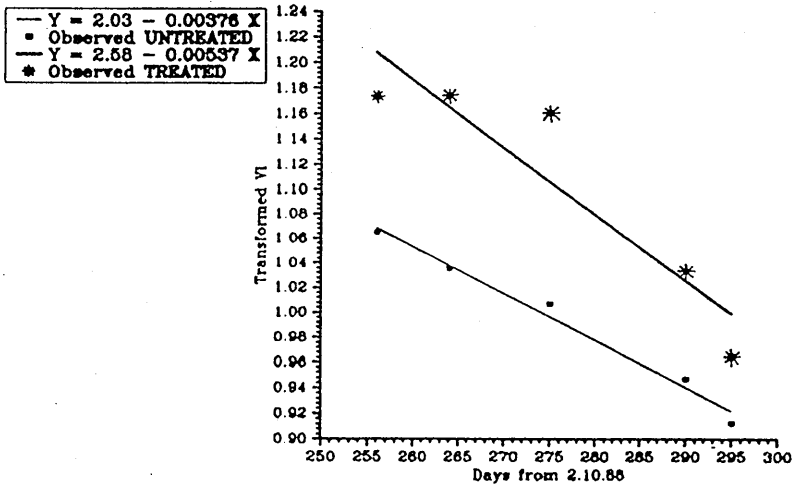
C.



4.3.3 The Effect of Fungal Disease on the Spectral Response of Winter Wheat.

In 1989 the effect of fungal disease on the spectral response of winter wheat was investigated using varieties of wheat treated and untreated with fungicide. Significant differences were found in the spectral response during the grain filling period. These effects were found to be treatment and variety dependent. Fungal disease only attacked cv. Slejpner, untreated with fungicide. Figure 4.18 shows the rate of change of the leaf area duration with time as measured by the Transformed Vegetation Index. It was apparent that the plots attacked by yellow rust experienced early spectral senescence as the rate of change of the index was lower compared to plots treated with fungicide.

FIGURE 4.18 THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME, CV. SLEJPNER, EXPT. 2, 1989.



This was because yellow rust caused leaf chlorosis and total leaf area collapse by the beginning of July. This was confirmed from per cent cover information which was estimated from black and white photographs. The disease could be detected much sooner from the spectral data compared to the panchromatic photographic data. The spectral vegetation index showed rapid decline at the end of the terminal spikelet stage compared to the photographic data which showed decline at the end of senescence when the brown leaf area had collapsed revealing the soil background. This early collapse in the spectral data can be attributed to changes in the crop colour, which affected the reflectance in the visible regions, and changes in the structure of the spongy mesophyll layer. Wheat leaves infested with rust diseases typically show collapse of the spongy mesophyll layer which is important in determining the amount of energy reflected in the infrared wavelengths. The spongy mesophyll either becomes flaccid or plugged with hyphae of the fungus, Colwell (1956).

CHAPTER 5. RELATIONSHIP OF SPECTRAL DATA TO GRAIN YIELD IN WINTER WHEAT.

5.1 Results of the 1989 Season.

5.1.1 Summary of the 1989 Results.

The following sections describe in detail the analyses used to examine the relationship of spectral data to winter wheat grain yield. In particular, the analysis concentrates on the effects of apex development stage, variety, sowing date and fungal disease. For the non-statistician, this may prove difficult to follow as the chapter contains tables on the analysis of variance on the regression sums of squares. The relationships are therefore summarised as follows:

(i) Single date regressions of spectral data to grain yield. Highest correlations were found during the terminal spikelet phase of apex development. The relationship between the natural log of the grain yield regressed against spectral data was found to be independent of sowing date and variety. However, further analyis showed that the slope of this line was not constant as a function of time;

(ii) Time integrated spectral data to grain yield. A 30 day integration period corresponding to the duration of the main stem terminal spikelet phase was used to find the areas under spectral temporal profiles. The natural log of the grain yield was found to highly correlated to this integration period ($r = 0.95$). This relationship was independent of sowing date and variety;

(iii) The rate of change of the TVI with time to grain yield. High correlations were found for this relationship in the senescence phase, however the relationship was found to be independent of sowing date but not variety;

(iv) These spectral models were used to predict the yield of wheat receiving different levels of fungicide. Large errors in grain yield estimation were found if untreated wheat was attacked by late stage fungal disease.

5.1.2 Yield results.

The average grain yield for experiments 1 and 2 are shown in Table 5.1 and Table 5.2 respectively. Means of head counts per plot for experiments 1 and 2 are shown Tables 5.3 and 5.4.

TABLE 5.1 MEAN GRAIN YIELD (T/HA) AND STANDARD DEVIATIONS FOR EXPERIMENT 1, 1989.

SOWING DATE	VARIETY					
	MISSION		AVALON		SLEJPNER	
	YIELD	S.D.	YIELD	S.D.	YIELD	S.D.
04.10.88	8.37	(0.79)	9.22	(0.69)	10.7	(0.6)
17.10.88	8.31	(1.58)	9.43	(0.78)	10.7	(0.38)
01.11.88	7.51	(0.81)	8.54	(0.29)	9.7	(0.37)

TABLE 5.2 MEAN GRAIN YIELD (T/HA) AND STANDARD DEVIATIONS FOR EXPERIMENT 2, 1989.

TREATMENT	VARIETY			
	MISSION		SLEJPNER	
	YIELD	S.D	YIELD	S.D
FUNGICIDE +	9.68	(1.11)	11.69	(0.48)
FUNGICIDE -	9.0	(0.73)	3.23	(0.06)

TABLE 5.3 HEAD COUNTS FOR EXPERIMENT 1 MEANS OF 3 COUNTS IN EACH BLOCK, 1989.

SOWING DATE	VARIETY		
	MISSION	AVALON	SLEJPNER
04.10.88	94.0	108.7	101.0
17.10.88	87.1	99.0	109.9
01.11.88	83.3	90.7	104.3

Reference to these Tables reveals evidence of differential performance in yield according to variety in experiment 1 and differential performance due to fungicide treatment and variety in experiment 2. A two-way analysis of variance on yield and head counts for experiment 1 (Appendices 7 and 8) revealed that cv. Slejpner had the highest yield, followed by cv. Avalon and then Mission. There was no significant sowing date effect or interaction. Variety performances were significantly different ($P<0.05$).

TABLE 5.4 HEAD COUNT FOR EXPERIMENT 2 MEANS OF 3 COUNTS IN EACH BLOCK, 1989		
	VARIETY	
TREATMENT	MISSION	SLEJPNER
FUNGICIDE +	100.9	93.2
FUNGICIDE -	127.6	60.0

For experiment 2, the two-way analyses of variance on head density and yield, revealed differential performance according to fungicide treatment and variety (Appendices 9 and 10). Cultivar Slejpner was impaired by lack of fungicide treatment. However, significant interaction was found ($P<0.05$) and the disease effect was shown to be variety and fungicide treatment specific.

5.1.3 Single Date Regressions of Spectral Data to Grain Yield.

Spectral vegetation indices measured from plots in experiment 1, were regressed against the grain yield at harvest. Table 5.5 shows the correlation coefficients as a function of time. From this analysis it was found that three vegetation indices were highly correlated to grain yield ($P<0.01$). These were the RVI, NDVI and MNDVI1 indices.

TABLE 5.5 CORRELATION COEFFICIENTS FOR THE RELATIONSHIP BETWEEN GRAIN YIELD (T/HA) AND SPECTRAL VEGETATION INDICES. EXPT. 1 1989 SEASON.

SAMPLING PERIOD	JULIAN DATE	RVI	NDVI	MNDVI1
2	37	0.31	0.33	0.31
3	89	0.65*	0.68*	0.68*
4	102	0.75*	0.83*	0.81*
5	109	0.78*	0.84*	0.8 *
6	124	0.84*	0.89*	0.88*
7	130	0.82*	0.85*	0.84*
8	166	0.56*	0.6 *	0.36
9	174	0.67*	0.69*	0.5 *
10	185	0.58*	0.62*	0.42
11	200	0.01	0.04	0.14
12	205	0.01	0.04	0.16

* SIGNIFICANT ($P<0.01$)

Table 5.6 shows the regression derived estimates for the intercept and slope coefficients for the period in the year in which the vegetation indices were most highly correlated to grain yield, i.e. Julian Dates 101-132. Figure 5.1 shows the coefficient of determination of the relationship between NDVI and grain yield. From this figure it can be seen that the highest correlations to grain yield for experiment 1 occurred during the terminal spikelet phase of main stem apex development. Figure 5.2 shows the relationship between the grain

yield and the NDVI for experiment 1 during this phase. It can be clearly seen that the slope of this regression relationship rotates and becomes steeper with time. The intercepts also change accordingly.

TABLE 5.6 REGRESSION DERIVED ESTIMATES FOR Á AND ß FOR JULIAN DATES 101 - 132 USING THE RVI, NDVI AND MNDVI1 INDICES TO PREDICT GRAIN YIELD, EXPT. 1, 1989. EQUATION OF THE LINE WAS OF THE FORM, YIELD = Á + ß (SPECTRAL VARIABLE).

SAMPLING PERIOD	JULIAN DATE	RVI Á	RVI ß	NDVI Á	NDVI ß	MNDVI1 Á	MNDVI1 ß
4	102	5.23	0.71	-0.4	14.1	-0.24	14.82
5	109	4.54	0.78	-2.47	16.65	-8.56	18.53
6	124	5.35	0.3	-8.04	20.44	-6.44	19.58
7	130	4.89	0.22	-19.47	31.94	-14.87	27.71

FIGURE 5.1 COEFFICIENT OF DETERMINATION FOR THE RELATIONSHIP OF GRAIN YIELD AGAINST NDVI, EXPERIMENT 1, 1989. THE INITIATION AND END OF THE TERMINAL SPIKELET PHASE OF APEX DEVELOPMENT ALSO SHOWN.

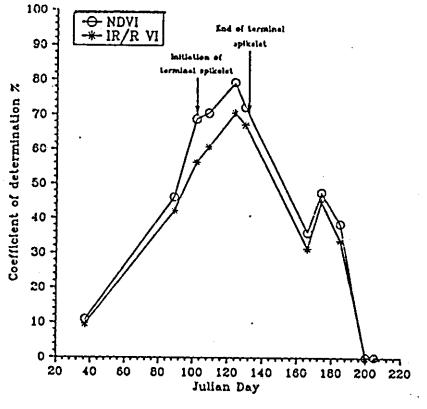
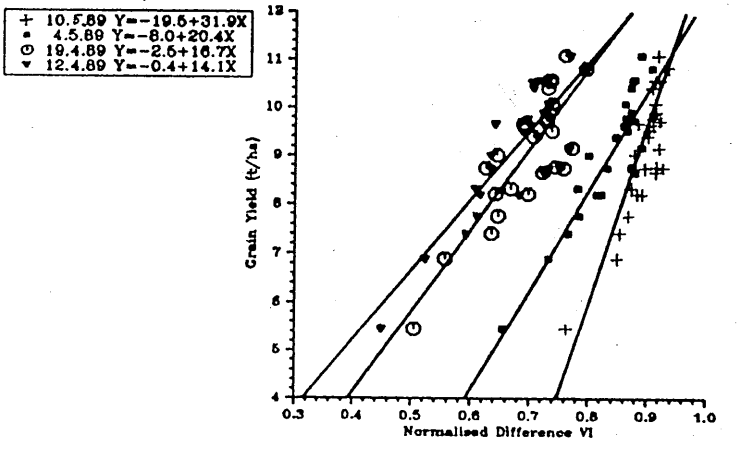
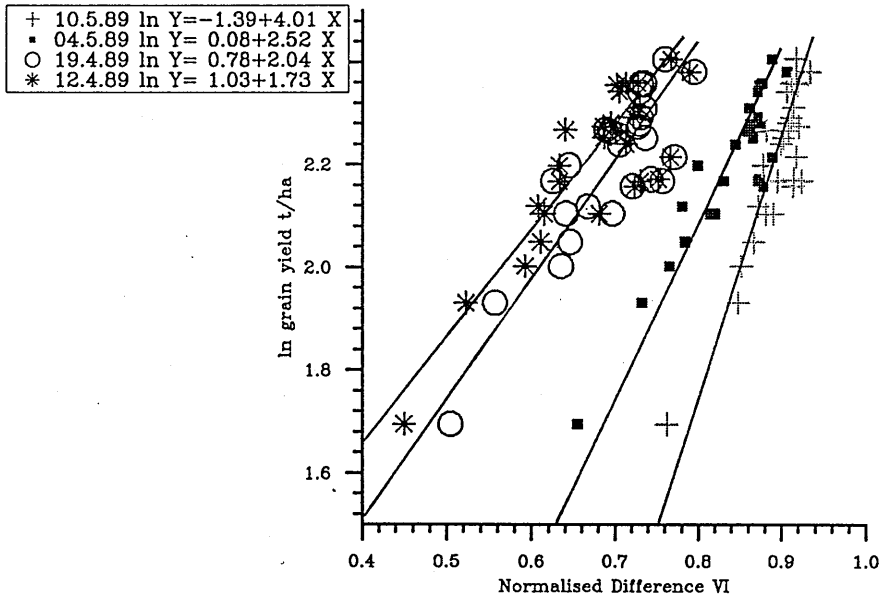


FIGURE 5.2 REGRESSION OF GRAIN YIELD AGAINST NDVI IN THE TERMINAL SPIKELET PHASE OF APEX DEVELOPMENT, EXPT. 1, 1989.



The relationships between grain yield and the NDVI were transformed by taking the natural log of the grain yield. This was performed to produce a linear relationship. The resulting transformations are shown in Figure 5.3.

FIGURE 5.3 REGRESSION OF LOG_E GRAIN YIELD AGAINST NDVI - TERMINAL SPIKELET PHASE OF APEX DEVELOPMENT, EXPT. 1, 1989.



Comparison of the single date regression lines revealed that over time the relationships changed and were not constant (Appendices 11, 12 and 13). This suggests that different regression relationships would have to be applied to predict the grain yield depending on time from initiation of the terminal spikelet phase. A multiple regression relationship was investigated which related the grain yield to the NDVI and time in days from initiation of the terminal spikelet phase. The equation was of the form:

$$\log_e \text{Yield} = Á + ß1\,(\text{NDVI}) + ß2\,(T - T0) \quad \text{eq. 5.1}$$

where T represents the time in Julian days when the spectral variable was measured and T0 represents the time in days from initiation of the terminal spikelet stage. Table 5.7 reveals that such a relationship explained 67% of the variation in grain yield.

The effect of sowing date and variety on the relationship of grain yield to the spectral variable is summarised in Table 5.8. The components of the regression sums of squares have been calculated using GENSTAT5. From Table 5.8, it can be concluded that there was no significant sowing date effect ($P < 0.01$), but significant variety differences were apparent at the end of the terminal spikelet stage of development. Such a multiple regression relationship, would probably have to be calibrated by variety to account for these differences.

TABLE 5.7 MULTIPLE REGRESSION RELATIONSHIP WHICH RELATES LOG_E GRAIN YIELD WITH SPECTRAL DATA AND TIME FROM INITIATION OF THE TERMINAL SPIKELET PHASE OF DEVELOPMENT, EXPT. 1, 1989.

A. COEFFICIENTS, ST. DEVIATIONS AND T-RATIOS.

PREDICTOR	COEF	ST.DEV	T-RATIO
CONSTANT	0.82825	0.09369	8.84 *
NDVI	2.0762	0.1399	14.84 *
T-T0	-0.016916	0.001369	-12.36 *

R-SQ(ADJ) = 67.1%

B. ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	VR
REGRESSION	2	1.72276	0.86138	110.11 *
ERROR	105	0.82138	0.00782	
TOTAL	107	2.54414		

SOURCE	DF	SEQ.SS		
NDVI	1	0.52784	0.52784	67.5 *
T-T0	1	1.19491	1.19491	152.8 *

* SIGNIFICANT (P < 0.01)

TABLE 5.8 BREAKDOWN OF THE REGRESSION SUMS OF SQUARES IN THE RELATIONSHIP OF LOG_E GRAIN YIELD TO SPECTRAL VARIABLE (NDVI), EXPT. 1, A. 12.04.89, B. 19.04.89, C. 04.05.89, D. 10.05.89.

	CHANGE	DF	SS	MS	VR
A.12.04.89	+ X	1	0.4597	0.4597	79.63 *
	+ X.SD	2	0.0093	0.0047	0.81
	+ X.SD.BLOCK	6	0.0149	0.0025	0.43
	+ X.VAR	2	0.067	0.0335	5.8
	+ X.SD.VAR	4	0.0215	0.0054	0.93
	RESIDUAL	11	0.0635	0.0058	
	TOTAL	26	0.636		

B.19.04.89	+ X	1	0.4667	0.4667	79.01 *
	+ X.SD	2	0.024	0.0119	2.01
	+ X.SD.BLOCK	6	0.0139	0.0023	0.39
	+ X.VAR	2	0.0401	0.02	3.39
	+ X.SD.VAR	4	0.0266	0.0067	1.13
	RESIDUAL	11	0.065	0.0059	
	TOTAL	26	0.636	0.0245	
C.04.05.89	+ X	1	0.5299	0.5299	317.68 *
	+ X.SD	2	0.0194	0.0097	5.83
	+ X.SD.BLOCK	6	0.0044	0.0007	0.44
	+ X.VAR	2	0.049	0.0245	14.68 *
	+ X.SD.VAR	4	0.015	0.0037	2.24
	RESIDUAL	11	0.0183	0.00167	
	TOTAL	26	0.636	0.0245	
D.10.05.89	+ X	1	0.5026	0.5026	296.92 *
	+ X.SD	2	0.0215	0.0107	6.34
	+ X.SD.BLOCK	6	0.0047	0.0008	0.46
	+ X.VAR	2	0.0774	0.0387	22.87 *
	+ X.SD.VAR	4	0.0113	0.0028	1.66
	RESIDUAL	11	0.0186	0.0017	
	TOTAL	26	0.636	0.0245	

* SIGNIFICANT ($P < 0.01$)

5.1.4 The Relationship Between Grain Yield and Integrated NDVI.

Because the single date regression coefficients were not constant with respect to time, the NDVI was integrated in the terminal spikelet phase. Equation 3.9 was used to fit a model of spectral temporal development to the observed NDVI values. GENSTAT5 was used to calculate the parameters of the model. The program code is shown in Appendix 14. The model parameters for the NDVI are shown in Appendices 15 and 16 for experiments 1 and 2 respectively. Simpson's Rule was used to integrate the NDVI in a 30 day period corresponding to the duration of the main stem terminal spikelet. The relationship between the grain yield and the integrated NDVI in the terminal spikelet phase is shown in Figure 5.4. It was apparent that the relationship was variety dependent. Table 5.9 shows the breakdown of the regression sums of squares.

FIGURE 5.4 REGRESSION OF GRAIN YIELD VS INTEGRATED NDVI - TERMINAL SPIKELET PHASE (NON-LINEAR MODEL), EXPT. 1, 1989.

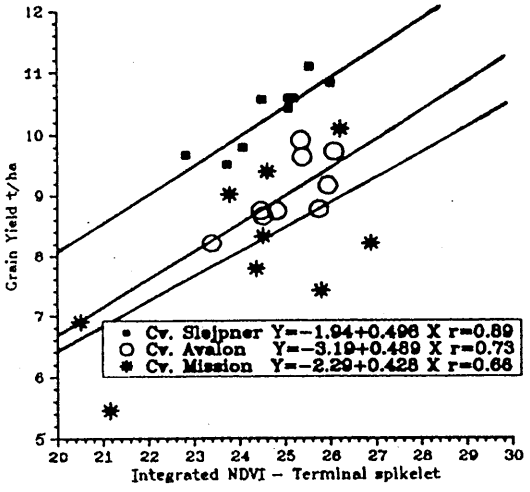


TABLE 5.9 BREAKDOWN OF THE REGRESSION SUMS OF SQUARES IN THE RELATIONSHIP OF GRAIN YIELD TO INTEGRATED NDVI - TERMINAL SPIKELET PHASE (NON-LINEAR MODEL), EXPT. 1, 1989.

CHANGE	DF	SS	MS	VR
+ X	1	13.2738	13.2738	29.17 *
+ X.SD	2	1.9838	0.9919	2.18
+ X.SD.BLOCK	6	2.5131	0.4189	0.92
+ X.VAR	2	20.4188	10.2094	22.44 *
+ X.SD.VAR	4	0.9328	0.2332	0.51
RESIDUAL	11	5.0048	0.455	
TOTAL	26	44.1271	1.6972	

* SIGNIFICANT ($P < 0.01$)

From Table 5.9 it can be seen that the relationship was independent of sowing date but not variety and that the spectral variable was significantly related to grain yield ($P < 0.01$). A t- test was performed on the slopes to test if there were any significant variety differences ($P < 0.05$). Table 5.10 shows the results. The test used was of the form:

$$t = \frac{S^2 V1 - S^2 V2}{SE\ (V1\ V2)} \qquad \text{eq. 5.2}$$

TABLE 5.10 T - TEST ON THE INTERCEPT AND SLOPE COEFFICIENTS IN THE RELATIONSHIP OF GRAIN YIELD TO INTEGRATED NDVI - TERMINAL SPIKELET PHASE (NON-LINEAR MODEL), EXPT. 1, 1989.		
VARIETY COMPARISON	T VALUE	
A. INTERCEPTS		
MISSION VS SLEJPNER	2.22	*
MISSION VS AVALON	1.21E-03	-
AVALON VS SLEJPNER	-2.32	*
B. SLOPES		
MISSION VS SLEJPNER	-0.02	-
MISSION VS AVALON	0.23	-
AVALON VS SLEJPNER	0.14	-
* SIGNIFICANT, - NOT SIGNIFICANT (P < 0.05)		

Table 5.10 reveals evidence of no significant differences in the slopes between varieties, but significant differences in the intercepts between cultivars Slejpner, Mission and Avalon ($P < 0.05$). The analysis suggests that cultivars Mission and Avalon lie on a coincident line but that the relationship for cultivar Slejpner is parallel to this line. These relationships are shown in Figure 5.5. Figure 5.6 shows the 95% confidence and prediction intervals for these parallel lines.

FIGURE 5.5 REGRESSION OF GRAIN YIELD AGAINST INTEGRATED NDVI -TERMINAL SPIKELET PHASE (NON-LINEAR MODEL), EXPT. 1, 1989. PARALLEL LINE ANALYSIS.

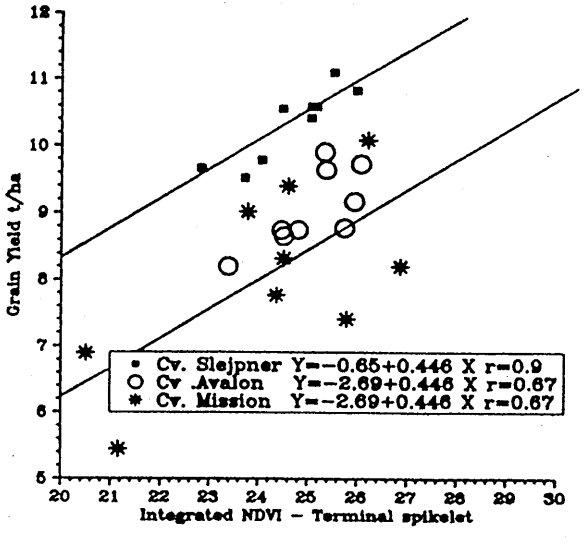
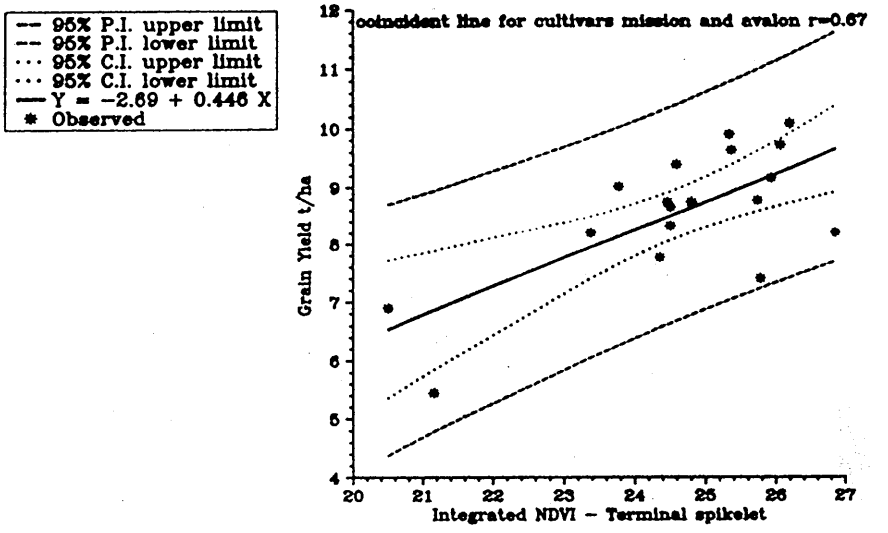


FIGURE 5.6 REGRESSION OF GRAIN YIELD AGAINST INTEGRATED NDVI - TERMINAL SPIKELET STAGE (NON LINEAR MODEL), EXPT. 1, 1989.
95% CONFIDENCE AND PREDICTION INTERVALS SHOWN.
A: CULTIVARS MISSION AND AVALON, B: CULTIVAR SLEJPNER

A.



B.

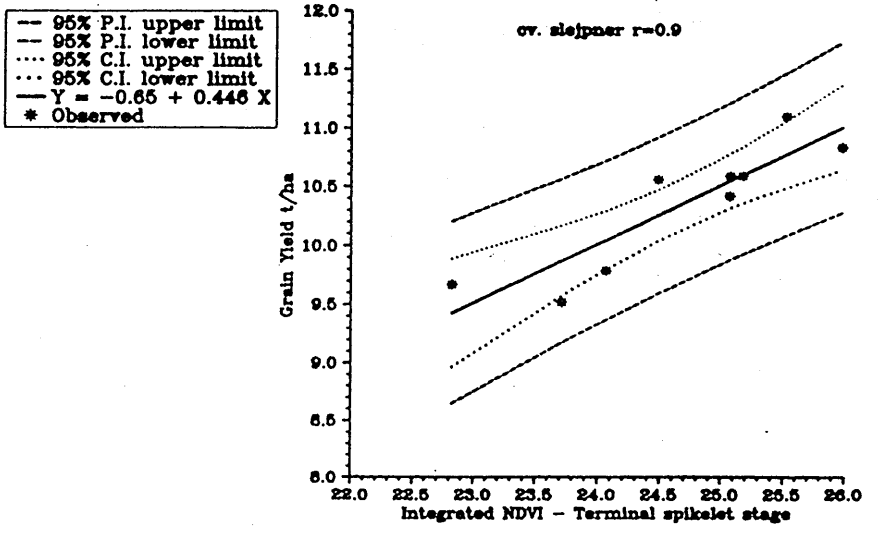
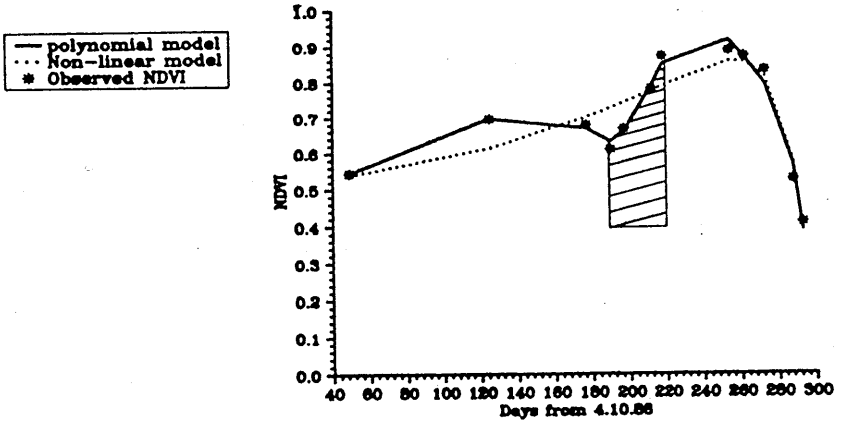


Figure 5.7 shows the difference between the non-linear model and a high order polynomial regression model fitted through the same data. This figure reveals that the non-linear model does not well describe the data in the critical period, i.e. the main stem terminal spikelet phase. In the earlier sowing dates in experiment 1, the vegetation index showed a pronounced depression during this period.

FIGURE 5.7 OBSERVED NDVI WITH 2 MODEL FITS, CV. MISSION REPLICATE 1, EXPT. 1, 1989. SHADED AREA REPRESENTS THE DURATION OF THE MAIN STEM TERMINAL SPIKELET.



Equation 3.12 was used to find the area under the profiles by definite integration during the terminal spikelet stage of apex development (30 day period). The polynomial model parameters for experiments 1 and 2 are shown in Appendices 18 and 19. The regression of the natural log of the grain yield with the integrated NDVI is shown in Figure 5.8. The t-tests on the coefficients and the analysis of variance on the regression are shown in Table 5.11. Breakdown of the regression sums of squares into its components revealed that the relationship was independent of sowing date but not variety ($P < 0.05$), Table 5.12.

FIGURE 5.8 REGRESSION OF LOG_E GRAIN YIELD AGAINST INTEGRATED NDVI - (7^{TH} ORDER POLYNOMIAL MODEL), EXPT. 1, 1989.

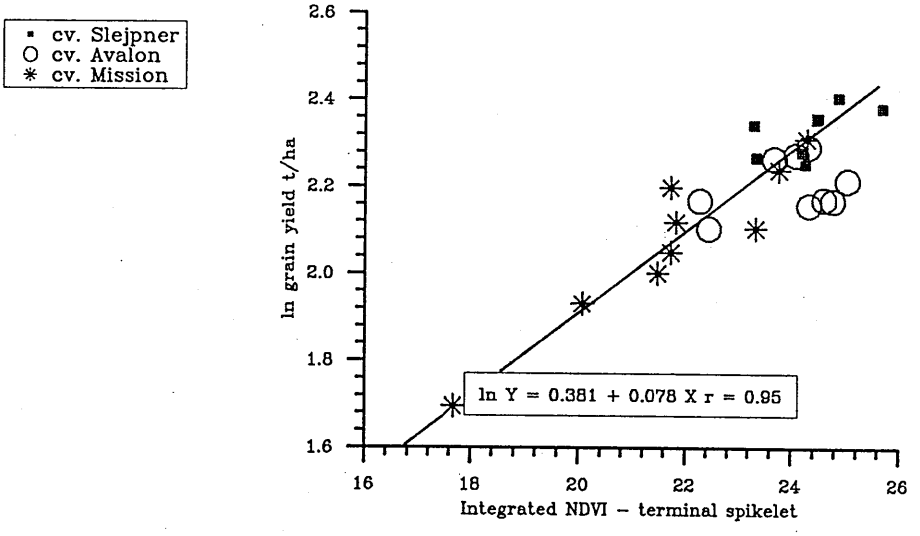


TABLE 5.11 REGRESSION RELATIONSHIP BETWEEN LOG_E GRAIN YIELD AND INTEGRATED NDVI - TERMINAL SPIKELET PHASE (POLYNOMIAL MODEL), EXPT. 1 1989.

A. COEFFICIENTS, ST. DEVIATIONS AND T-RATIOS.

PREDICTOR	COEF	ST.DEV	T-RATIO	
CONSTANT	0.3807	0.206	1.85	-
NDVI	0.0703	0.0088	8.87	*

$R^2 = 0.87$ *

B. ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	VR
REGRESSION	1	0.4827	0.4827	78.73 *
ERROR	25	0.1533	0.0061	
TOTAL	26	0.6360		

* SIGNIFICANT, - NOT SIGNIFICANT ($P < 0.05$)

TABLE 5.12 BREAKDOWN OF THE REGRESSION SUMS OF SQUARES IN THE RELATIONSHIP OF LOG_E GRAIN YIELD TO INTEGRATED NDVI - TERMINAL SPIKELET PHASE (POLYNOMIAL MODEL), EXPT. 1, 1989.

CHANGE	DF	SS	MS	VR
+ X	1	0.4827	0.4827	131.71 *
+ X.SD	2	0.0288	0.0144	3.89
+ X.SD.BLOCK	6	0.0092	0.0015	0.42
+ X.VAR	2	0.0501	0.025	6.83 *
+ X.SD.VAR	4	0.0248	0.0062	1.69
RESIDUAL	11	0.0403	0.0037	
TOTAL	26	0.636	0.0245	

* SIGNIFICANT ($P < 0.05$)

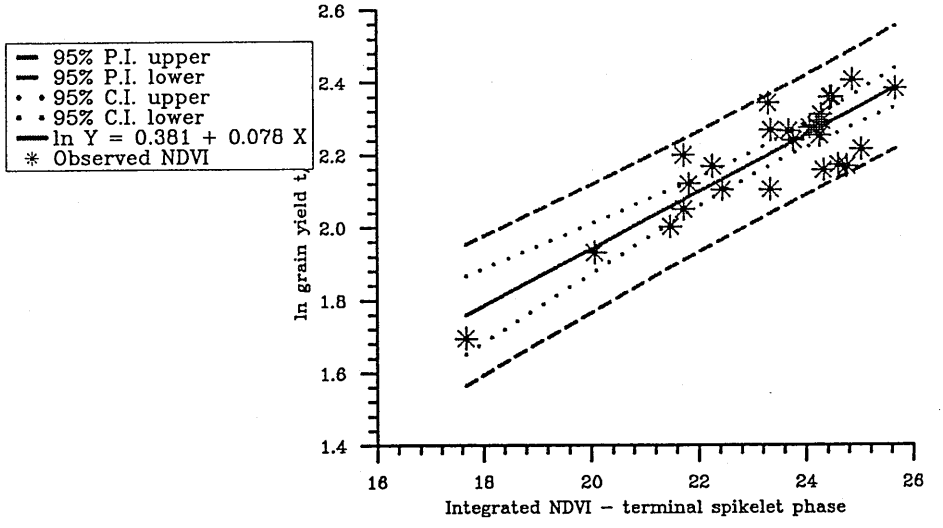
Table 5.13 shows the results of an analysis of variance on the slope and intercepts of the different varieties for experiment 1. This Table reveals that there were no significant differences in the slope between varieties and that the intercepts were not significantly different ($P < 0.05$). Thus there was evidence to suggest that the regression lines for the varieties were coincident. Therefore a general linear model could be used to describe the relationship between the log_e of grain yield and integrated spectral data. This relationship was independent of sowing date and variety. The 95% confidence and prediction intervals for the relationship are shown in Figure 5.9.

TABLE 5.13 T-TEST ON THE INTERCEPT AND SLOPE COEFFICIENTS IN THE RELATIONSHIP OF LOG_E GRAIN YIELD TO INTEGRATED NDVI - TERMINAL SPIKELET PHASE (POLYNOMIAL MODEL), EXPT. 1, 1989.

VARIETY COMPARISON	T VALUE	
A. INTERCEPTS		
MISSION VS SLEJPNER	0.21	-
MISSION VS AVALON	0.02	-
AVALON VS SLEJPNER	-0.24	-
B. SLOPES		
MISSION VS SLEJPNER	-0.16E-02	-
MISSION VS AVALON	0.01	-
AVALON VS SLEJPNER	0.63E-02	-

- NOT SIGNIFICANT ($P < 0.05$)

FIGURE 5.9 REGRESSION OF LOG_E GRAIN YIELD AGAINST INTEGRATED NDVI - (7TH ORDER POLYNOMIAL MODEL), EXPT. 1, 1989.
95% CONFIDENCE AND PREDICTION INTERVALS SHOWN.



5.1.5 The Relationship of Spectral Senescence Rate to Grain Yield.

The relationship between the grain yield and the rate of change of the Transformed Vegetation Index (TVI) with time was investigated for all plots in experiment 1. Table 5.14 shows the results of the regression analysis.

TABLE 5.14 REGRESSION RELATIONSHIP BETWEEN GRAIN YIELD AND THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME, EXPT. 1, 1989.

A. COEFFICIENTS, ST. DEVIATIONS AND T-RATIOS.

PREDICTOR	COEF	ST.DEV	T-RATIO	
CONSTANT	7.369	1.375	5.36	*
dTVI/dT	-319.6	241.7	-1.32	-
		R = 0.25 -		

B. ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	VR	
REGRESSION	1	2.884	2.884	1.75	-
ERROR	25	41.244	1.65		
TOTAL	26	44.127			

- NOT SIGNIFICANT, * SIGNIFICANT (P < 0.05).

Breakdown of the regression sums of squares revealed that the relationship was independent of sowing date but not variety ($P < 0.05$), Table 5.15.

TABLE 5.15 BREAKDOWN OF THE REGRESSION SUMS OF SQUARES IN THE RELATIONSHIP BETWEEN GRAIN YIELD AND THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME, EXPT. 1, 1989.

CHANGE	DF	SS	MS	VR	
+ X	1	2.8836	2.8836	5.48	*
+ X.SD	2	2.1192	1.0596	2.01	
+ X.SD.BLOCK	6	7.1069	1.1845	2.25	
+ X.VAR	2	25.0951	12.5475	23.83	*
+ X.SD.VAR	4	1.1305	0.2826	0.54	
RESIDUAL	11	5.7918	0.5265		
TOTAL	26	44.1271	1.6972		

* SIGNIFICANT ($P < 0.05$)

Analysis of variance on the slope coefficients revealed that there were significant differences in the slopes between varieties ($P < 0.05$), Table 5.16. Therefore, variety dependent relationships were investigated. The results of this analysis are shown in Table 5.17. The variety dependent relationships are shown Figure 5.10.

TABLE 5.16 T - TEST ON THE SLOPE COEFFICIENTS IN THE RELATIONSHIP BETWEEN GRAIN YIELD AND THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME, EXPT. 1, 1989.

VARIETY COMPARISON	T VALUE	
SLOPES		
MISSION VS SLEJPNER	-109.17	*
MISSION VS AVALON	-118.23	*
AVALON VS SLEJPNER	53.98	*

* SIGNIFICANT ($P < 0.05$)

FIGURE 5.10 GRAIN YIELD AS A FUNCTION OF THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME, EXPT. 1, 1989.

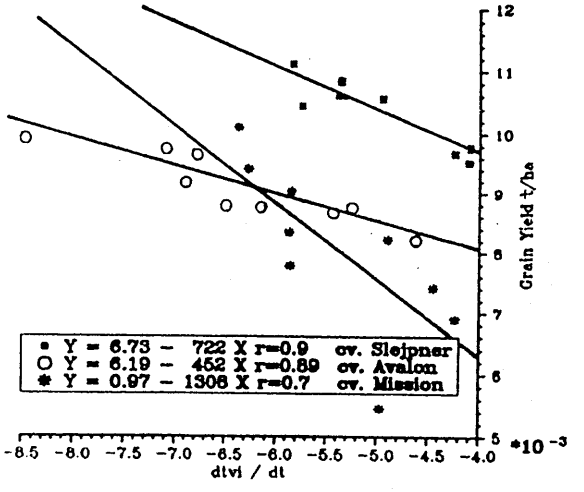


TABLE 5.17 REGRESSION RELATIONSHIPS BETWEEN GRAIN YIELD AND THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME, EXPT. 1, 1989. A: CV. MISSION, B: CV. AVALON, C: CV. SLEJPNER

A. COEFFICIENTS, ST. DEVIATIONS AND T-RATIOS, MISSION.

PREDICTOR	COEF	ST.DEV	T-RATIO	
CONSTANT	0.972	2.429	0.4	-
dTVI/dT	-1308.1	443.8	-2.95	*

R = 0.7

A. ANALYSIS OF VARIANCE ON MISSION

SOURCE	DF	SS	MS	VR	
REGRESSION	1	8.638	8.638	8.69	*
ERROR	7	6.9596	0.9942		
TOTAL	8	15.5976			

B. COEFFICIENTS, ST. DEVIATIONS AND T-RATIOS, AVALON.				
PREDICTOR	COEF	ST.DEV	T-RATIO	
CONSTANT	6.194	0.5252	11.79	*
dTVI/dT	-451.72	81.4	-5.55	*
	R = 0.89			

B. ANALYSIS OF VARIANCE ON AVALON					
SOURCE	DF	SS	MS	VR	
REGRESSION	1	2.1776	2.1776	30.79	*
ERROR	7	0.495	0.0707		
TOTAL	8	2.6726			

C. COEFFICIENTS, ST. DEVIATIONS AND T-RATIOS, SLEJPNER				
PREDICTOR	COEF	ST.DEV	T-RATIO	
CONSTANT	6.7277	0.6194	10.86	*
dTVI/dT	-721.7	122.7	-5.88	*
	R = 0.9			

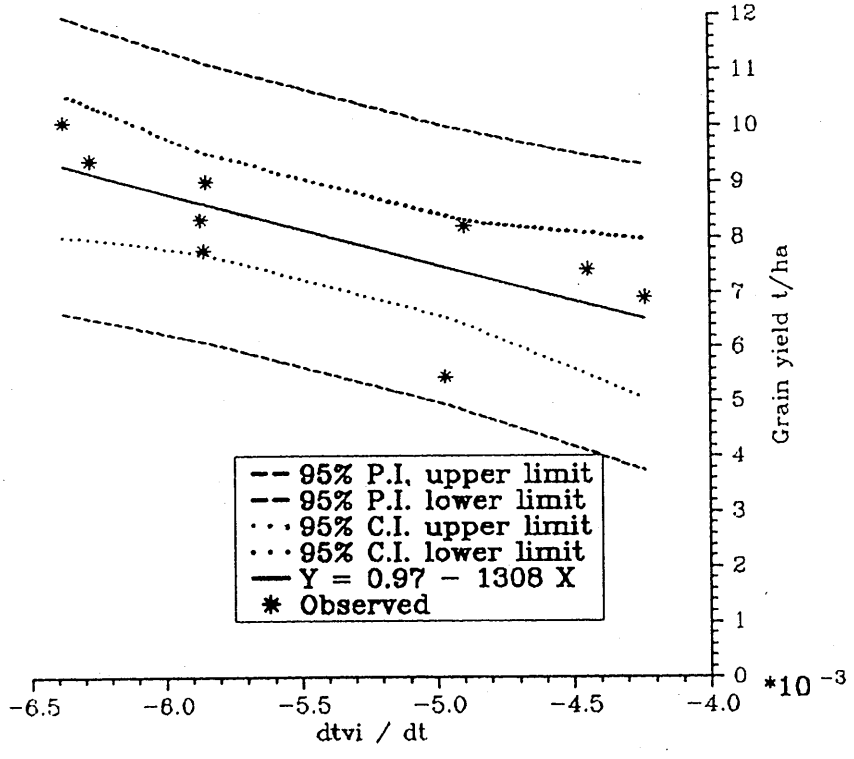
C. ANALYSIS OF VARIANCE ON SLEJPNER					
SOURCE	DF	SS	MS	VR	
REGRESSION	1	2.014	2.014	34.62	*
ERROR	7	0.4073	0.0582		
TOTAL	8	2.4213			

- NOT SIGNIFICANT, * SIGNIFICANT ($P < 0.05$).

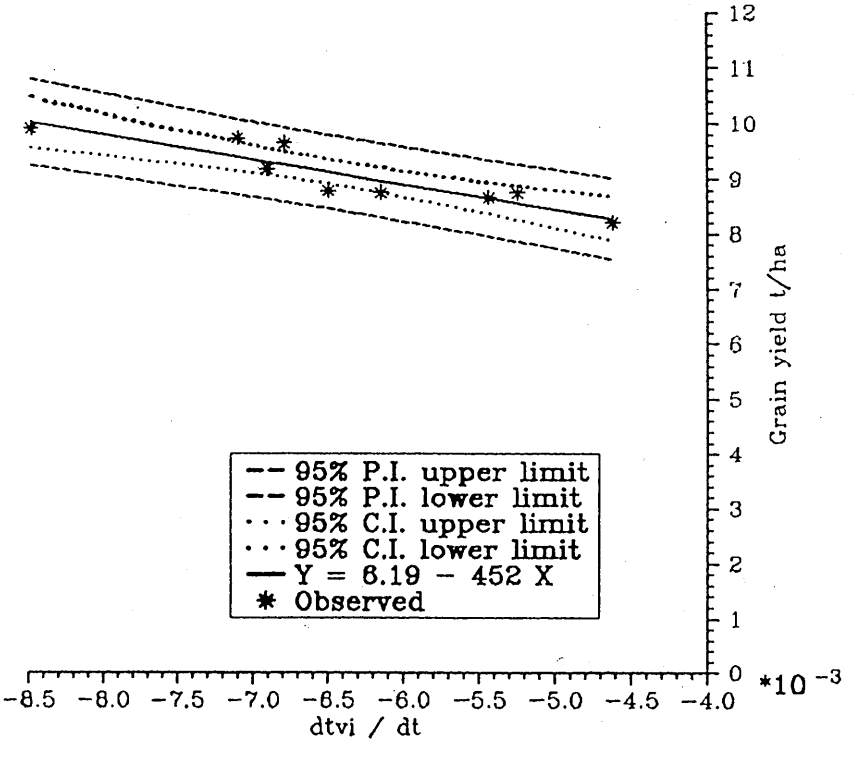
This regression analysis showed that for the three varieties, the slopes of the relationships were significantly different from zero ($P < 0.05$). Therefore the grain yield was significantly related to the rate of change of the Transformed Vegetation Index. It can be concluded that the relationships were independent of sowing date, but not variety. Figure 5.11 shows the 95% confidence and prediction intervals for the relationships.

FIGURE 5.11 GRAIN YIELD AS A FUNCTION OF THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME. 95% CONFIDENCE AND PREDICTION INTERVALS SHOWN, EXPT. 1, 1989.

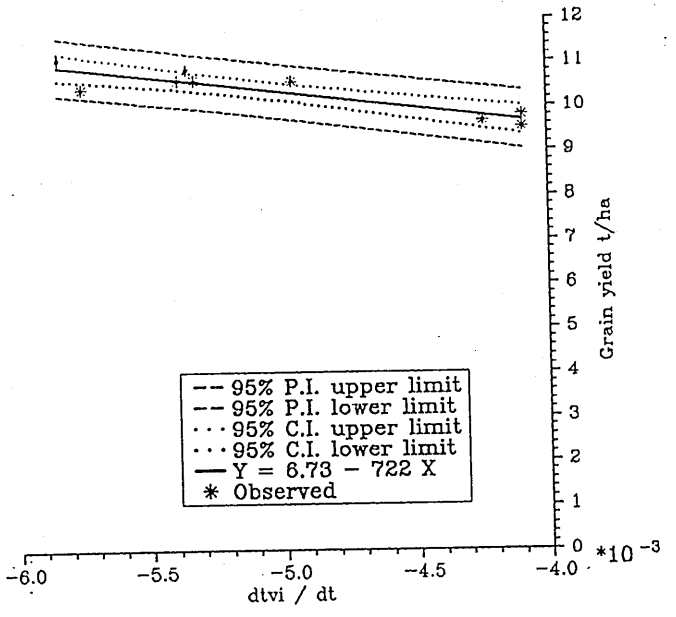
A. CV. MISSION



B. CV. AVALON



C. CV. SLEJPNER



5.1.6 The Effect of Fungal Disease on Remotely Sensed Yield Indicators.

The relationship between the $\log_e$ of grain yield and integrated NDVI in the terminal spikelet phase, was used to predict the grain yield of plots in experiment 2. As this equation was independent of variety and sowing date, the spectral profiles were integrated in a period corresponding the duration of the main stem terminal spikelet phase, Figure 5.12. The results of the prediction exercise are shown in Table 5.18.

FIGURE 5.12 SPECTRAL TEMPORAL PROFILES FOR CV. SLEJPNER, SHOWING INTEGRATION PERIOD IN THE TERMINAL SPIKELET PHASE (SHADED AREA). EXPT. 2, 1989.

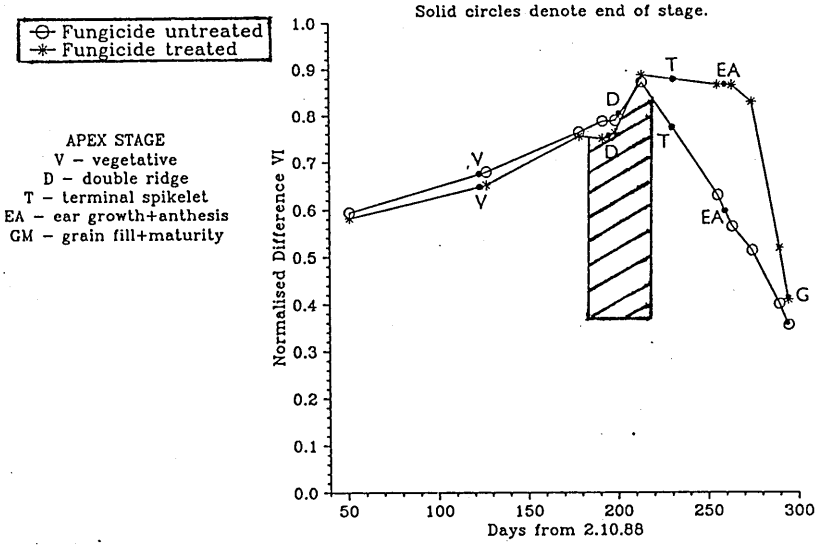


TABLE 5.18 MEAN INTEGRATED NDVI - TERMINAL SPIKELET PHASE, ACTUAL YIELD (T/HA), PREDICTED YIELD (T/HA) AND ERRORS (T/HA) FOR EXPT. 2, 1989.

VARIETY	FUNG.	(NDVI) MEAN S.D.	ACTUAL YIELD S.D.	PREDICTED YIELD S.D.	ERRORS
MISSION	+	25.5 (0.48)	9.68(1.11)	9.91(0.36)	+0.23
MISSION	-	26.15(0.45)	9.0 (0.73)	11.62(0.39)	+2.62
SLEJPNER	+	24.79(0.62)	11.69(0.48)	10.14(0.49)	-1.55
SLEJPNER	-	25.13(0.51)	3.23(0.06)	10.41(0.41)	+7.18

For the cultivars receiving fungicide, the grain yield was estimated to within 1.6 t/ha. For the cultivars receiving no fungicide, larger errors in grain yield estimation were found. Cultivar Slejpner untreated with fungicide was particularly bad, this was because late stage fungal disease had lowered the yield potential. Hence the yield prediction equation proved unreliable if the crop was attacked by fungal disease.

The variety dependent relationships between the grain yield and the rate of change of the Transformed Vegetation Index with time, were used to predict the yield of the plots in experiment 2. The results are presented in Table 5.19.

TABLE 5.19 MEAN dTVI/dT, ACTUAL YIELD (T/HA), PREDICTED YIELD (T/HA) AND ERRORS (T/HA) FOR EXPT. 2, 1989.

VARIETY	FUNG.	dTVI/dT MEAN S.D.	ACTUAL YIELD S.D.	PREDICTED YIELD S.D.	ERRORS
MISSION	+	-0.0062(0.02)	9.68(1.11)	9.08(0.55)	0.56
MISSION	-	-0.0072(0.01)	9.0 (0.73)	10.32(0.19)	1.32
SLEJPNER	+	-0.0057(0.02)	11.69(0.48)	10.87(0.27)	0.82
SLEJPNER	-	-0.0034(0.02)	3.23(0.06)	9.21(0.21)	5.99

For the varieties treated with fungicide, the yield was predicted to within a tonne per hectare. However, large errors in grain yield estimation for cultivar Slejpner, untreated with fungicide were found.

5.2 Results of the 1990 Season.

5.2.1 Summary of the 1990 Results.

In the 1990 season the relationships of spectral data to grain yield in winter wheat was investigated. Again the effects of apex development stage, sowing date and variety were tested for. Because of the weather conditions at the time of sowing, all plots in the experiment were late sown. Compared to the 1989 season, the results were markedly different. Again, the non-statistician may find the following sections difficult to follow because of the nature of the analysis and the problems encountered in repeating the experiments. The relationships can be summarised as follows:

(i) Single date regressions of spectral data to grain yield. No direct relationships were found for the 1990 season.

(ii) Time integrated spectral data to grain yield.
No direct relationship was found between the natural log of the grain yield and time integrated vegetation index data in the terminal spikelet phase. The relationship was found to be sowing date and variety dependent;

(iii) The rate of change of the TVI with time to grain yield. In the 1990 season, no direct relationship was found between grain yield and spectral senescence rate. However, the relationship was found to be variety and sowing date dependent.

5.2.2 Yield Results.

The yield results for the 1990 season are presented in Table 5.20, for wheat sown on the 29.09.89. An analysis of variance was performed in order to test that there were no differences in yield due to fungicide treatment. The results of this analysis (Appendix 20) revealed that this was infact the case. Therefore, wheat sown on the 27.09.89 was compared to that sown on the 30.10.89 ignoring the effect of fungicide treatment. Thus four replicates of each variety for sowing date 1, were compared with three replicates of each variety in sowing date 2 . The mean yields in this analysis are presented in Table 5.21.

TABLE 5.20 MEAN YIELDS (T/HA) AND STANDARD DEVIATIONS FOR SOWING DATE 1, 1990 SEASON.

SOWING DATE	VARIETY	FUNG.	YIELD	S.D.
27.09.89	MERCIA	+	8.88	(0.48)
27.09.89	AVALON	+	8.6	(0.59)
27.09.89	TONIC	+	8.86	(0.15)
27.09.89	MERCIA	-	8.42	(0.0)
27.09.89	AVALON	-	8.34	(0.39)
27.09.89	TONIC	-	8.28	(0.27)

TABLE 5.21 MEAN YIELDS (T/HA) AND STANDARD DEVIATIONS FOR THE 1990 SEASON, ALL PLOTS.

SOWING DATE	VARIETY	YIELD	S.D.
27.09.89	MERCIA	8.65	(0.54)
27.09.89	AVALON	8.47	(0.62)
27.09.89	TONIC	8.57	(0.58)
30.10.89	MERCIA	7.81	(0.71)
30.10.89	AVALON	6.03	(0.55)
30.10.89	TONIC	7.91	(0.88)

The analysis of variance by sowing date and variety (Appendix 21) showed that there were significant differences in yield due sowing date and variety ($P < 0.05$). Also these differences were variety and sowing date dependent as the interaction term was significant ($P < 0.05$). Reference to Table 5.21 shows that cultivar Avalon sown on the 30.10.89, yielded 2.5 t/ha less compared to that sown on the 27.09.89. This can probably be attributed to the effect of very late sowing and drought conditions at the end of the season.

5.2.3 Single Date Regressions of Spectral Data to Grain Yield.

For each of the 14 dates that radiometric data was collected, the natural log of grain yield was regressed against the NDVI. The resulting regression and correlation coefficients are shown in Table 5.22.

TABLE 5.22 REGRESSION AND CORRELATION COEFFICIENTS IN THE RELATIONSHIP OF LOG_E GRAIN YIELD TO SPECTRAL DATA. EQUATION WAS OF THE FORM LOG_E GRAIN YIELD = Á + ß (NDVI). STANDARD DEVIATIONS ALSO SHOWN, 1990.

DATE	Á	S.D.	ß	S.D.	r
26.11.89	1.61	(0.13)	1.51	(0.41)	0.65 *
05.12.89	1.68	(0.13)	1.29	(0.43)	0.57 *
18.01.90	1.62	(0.27)	1.02	(0.61)	0.36
16.02.90	1.63	(0.27)	0.95	(0.59)	0.35
30.03.90	2.31	(0.57)	-0.31	(0.75)	0.3
09.04.90	1.93	(0.7)	0.18	(0.89)	0.14
24.04.90	3.08	(0.69)	-1.22	(0.83)	0.32
30.04.90	3.87	(1.14)	-2.04	(1.29)	0.34
03.05.90	4.99	(1.42)	-3.25	(1.58)	0.43
31.05.90	8.74	(1.84)	-7.39	(2.04)	0.64 *
11.07.90	4.23	(0.54)	-2.77	(0.69)	0.68 *
18.07.90	2.91	(0.31)	-1.44	(0.53)	0.53 *
25.07.90	2.97	(0.64)	-2.04	(1.46)	0.3
01.08.90	2.96	(0.53)	-2.44	(1.43)	0.36

* SIGNIFICANT ($P < 0.05$)

Reference to Table 5.22 shows that there were few dates when the spectral data was significantly correlated to the natural log of the grain yield ($P < 0.05$). Also during the terminal spikelet stage of apex development, the slopes became negative and remained so up until harvest ripe grain. The changes in the coefficient of determination with time are shown in Figure 5.13.

5.2.4 Relationship of Grain Yield to Integrated NDVI.

The non-linear least squares model (eq. 2.8) was applied to the spectral profiles and the area under the curve during the terminal spikelet phase was determined. The coefficients for the profile model for all plots for the 1990 season are shown in Appendix 17. The grain yield was regressed against the integrated NDVI and the relationship investigated, Figure 5.14 shows the scatter plot.

FIGURE 5.13 CHANGES IN THE COEFFICIENT OF DETERMINATION OVER TIME, FOR THE RELATIONSHIP BETWEEN GRAIN YIELD AND NDVI, 1990.

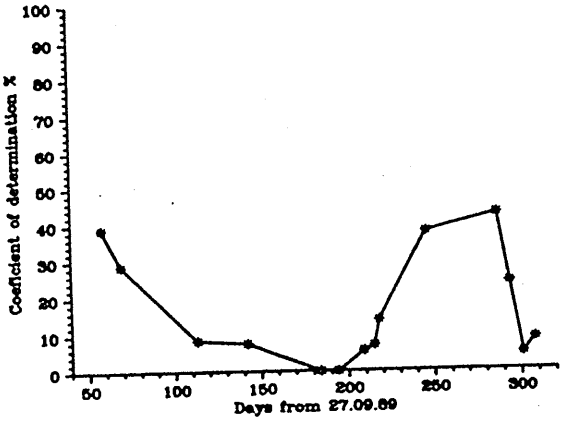
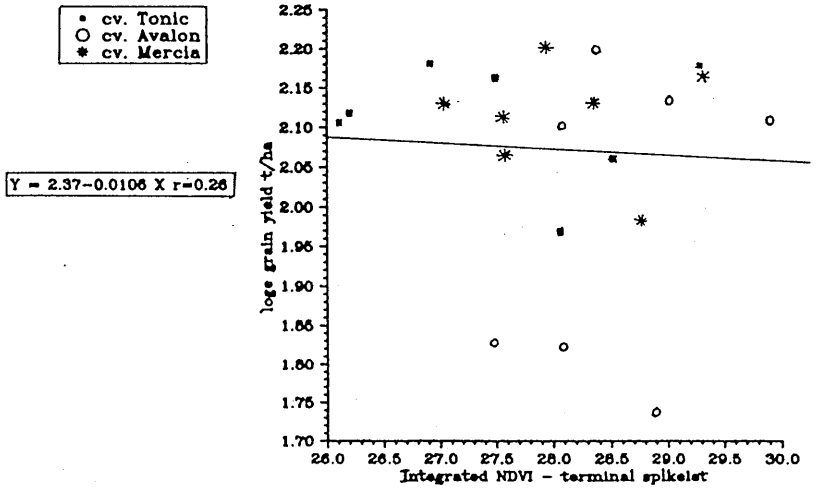


FIGURE 5.14 RELATIONSHIP BETWEEN LOG_E GRAIN YIELD AND INTEGRATED NDVI - TERMINAL SPIKELET PHASE, 1990.



The analysis of variance on the relationship is shown in Table 5.23. The slope was found not to be significantly different from zero. Also the variance ratio was not significant ($P < 0.05$). Therefore, it can be concluded that there was no relationship between grain yield and time integrated spectral data in the terminal spikelet phase. Table 5.24 shows the breakdown of the regression sums of squares into its components.

TABLE 5.23 RELATIONSHIP BETWEEN GRAIN YIELD AND INTEGRATED NDVI - TERMINAL SPIKELET PHASE, 1990.

COEFFICIENTS, ST. DEVIATIONS AND T-RATIOS

PREDICTOR	COEF	ST.DEV	T-RATIO	
CONSTANT	2.3701	0.8444	2.81	*
NDVI	-0.0106	0.0309	-0.35	-
		r = 0.26	-	

ANALYSIS OF VARIANCE

SOURCE	DF	SS	MS	VR	
REGRESSION	1	0.0023	0.0023	0.12	-
ERROR	19	0.3425	0.018		
TOTAL	20	0.3448			

- NOT SIGNIFICANT, * SIGNIFICANT (P < 0.05).

TABLE 5.24 BREAKDOWN OF THE REGRESSION SUMS OF SQUARES IN THE RELATIONSHIP BETWEEN GRAIN YIELD AND INTEGRATED NDVI - TERMINAL SPIKELET PHASE, 1990.

CHANGE	D.F	SS	MS	VR	
+ X	1	0.0023	0.0023	4.13	-
+ X.SD	1	0.1612	0.1612	295.70	*
+ X.SD.BLOCK	5	0.036	0.0072	13.22	*
+ X.VAR	2	0.088	0.044	80.78	*
+ X.SD.VAR	2	0.0523	0.0262	48.02	*
RESIDUAL	9	0.0049	0.0005		
TOTAL	20	0.3448	0.0172		

- NOT SIGNIFICANT, * SIGNIFICANT (P < 0.05)

From this Table, it can be seen that there were significant sowing date, variety and interaction effects in the regression of grain yield against integrated NDVI (P < 0.05). Integrated NDVI was infact non-significant (P < 0.05). This analysis indicated that for the 1990 season, the integrated NDVI was not related to the natural log of grain yield.

5.2.5 Relationship of Spectral Senescence Rate to Grain Yield.

The rate of change of the Transformed Vegetation Index with time was regressed against the grain yield and the relationship investigated, Figure 5.15, Table 5.25.

FIGURE 5.15 GRAIN YIELD AS A FUNCTION OF THE RATE OF CHANGE OF THE TVI WITH TIME, 1990.

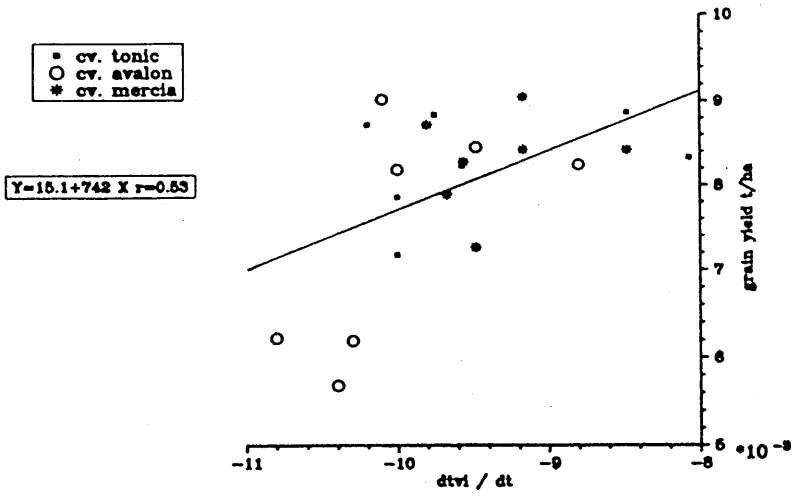


TABLE 5.25 RELATIONSHIP BETWEEN GRAIN YIELD AND THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME, 1990.				
COEFFICIENTS, ST. DEVIATIONS AND T-RATIOS				
	PREDICTOR	COEF	ST.DEV	T-RATIO
	CONSTANT	15.113	2.592	5.83 *
	NDVI	741.9	269.8	2.75 *
			r = 0.53	*

ANALYSIS OF VARIANCE				
SOURCE	DF	SS	MS	VR
REGRESSION	1	5.2917	5.2917	7.56 *
ERROR	19	13.2963	0.6998	
TOTAL	20	18.588		
* SIGNIFICANT (P < 0.05)				

Table 5.25 shows that the slope was significantly different from zero ($P < 0.05$), also the variance ratio was significant ($P < 0.05$). It can be concluded that the grain yield was directly related to the rate of change of the Transformed Vegetation Index with time. However, the slope was positive in the 1990 season and this is the opposite direction compared to the preceding seasons data. Table 5.26 shows the breakdown of the regression sum of squares into its components. All components were significant ($P < 0.05$), therefore the relationship was dependent on sowing date, variety and interaction between sowing date and variety. It can be concluded that on the basis of this experiment, the grain yield could not be directly related to the rate of change of the Transformed Vegetation Index with time even as a function of variety.

TABLE 5.26 BREAKDOWN OF THE REGRESSION SUMS OF SQUARES IN THE RELATIONSHIP BETWEEN GRAIN YIELD AND THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME, 1990.

CHANGE	D.F	SS	MS	V.R	
+ X	1	5.2917	5.2917	105.16	*
+ X.SD	1	4.4118	4.4118	87.67	*
+ X.SD.BLOCK	5	3.2094	0.6419	12.76	*
+ X.VAR	2	2.5667	1.2833	25.5	*
+ X.SD.VAR	2	2.6557	1.3278	36.39	*
RESIDUAL	9	0.4529	0.0503		
TOTAL	20	18.588	0.9294		

* SIGNIFICANT ($P < 0.05$)

5.3 Discussion.

5.3.1 The Effect of Development Stage.

In the 1989 season, two key phases of apex development were found in which spectral data was highly correlated grain yield. These were:

(i) the terminal spikelet phase and;
(ii) the grain filling period respectively.

The relationships in the terminal spikelet phase were found to be independent of variety and sowing date. Under section 4.3.2, the reasons for this were explained in terms of canopy convergence due to tiller mortality. In the grain filling period, the grain yield was found to be related to the rate of change of the Transformed Vegetation Index with time. The period of measurement was taken to be from anthesis to harvest ripe grain. If relationships such as these were to be used on an operational basis, timely and precise estimates of these apex development stages would be required.

This could be achieved using the dissection technique described by Kirby and Appleyard (1987) or by the use of agro-meteorological models such as the apex development simulation sub-model of AFRC WHEAT, Porter (1990) personal communication.

The dissection technique, although the most precise method of recording a stage, is time consuming. The agro-meteorological models require long term averages of the thermal regime of a region at least dating back ten years.

In the 1989 season, the cardinal points of the spectral profiles were found to correspond to apex development stages in winter wheat. These points could be employed as markers for the timing of stages. The inflexion point on the green up was found to correspond to the terminal spikelet phase of apex development. Continued measurement of the spectral profiles up until the heading stage would help to further delineate the stage of development. In both the 1989 and 1990 seasons the end of the terminal spikelet phase was associated with the onset of saturation of the vegetation index i.e. when the vegetation index reached an asymptote. Further the earlier sowing dates showed a pronounced trough in the spectral data at the initiation of the terminal spikelet stage.

A logistic model might not be the best approach. First order derivatives of a high order polynomial would show this as a turning moment. Using the derivatives of a polynomial equation or of a logistic model it would be possible to estimate the timing and duration of the terminal spikelet phase from the spectral temporal profile information alone. This would make the spectral models a powerful tool in management decisions at the field scale as both the potential yield and stages of apex development could be estimated using remote sensing.

It could be argued however, that the results of the 1990 season showed that there were no relationships between spectral data and grain yield in either the terminal spikelet or grain filling phases. In which case why bother to try to estimate the stages if the relationships cannot be applied on a year to year basis.

5.3.2 The Effect of Sowing Date and Variety.

In the 1989 season, single date relationships were found which related the natural log of grain yield to the instantaneous NDVI. These relationship was found to be independent of sowing date but not variety. High correlations with grain yield were found in the terminal spikelet phase of apex development. This agrees with the work by Tucker et al.(1980) who also showed high correlations to grain yield in a spring window of development. This corresponded to the period of maximum leaf biomass present. Tucker et al.(1980), also point out that the coefficients in the relationship of spectral data to grain yield were not constant. The work in 1989 at Bury St. Edmunds showed a similar trend. Again, this could well be related to tiller mortality in

the terminal spikelet phase. The 1989 data suggests that the slopes in the relationship of grain yield to spectral data change, becoming steeper with time from initiation of the main stem terminal spikelet. This trend suggests that the yield potential of the crop changes during this period. This is exactly what happens because the tiller demography changes.

A multiple regression model was suggested, which could relate the natural log of grain yield to spectral data and time from the initiation of the main stem terminal spikelet. However, it was shown that the relationship was independent of sowing date but not variety. This would mean that such a relationship would probably have to be calibrated for variety.

Time integrated vegetation index data in the terminal spikelet phase was found to be related to grain yield. The relationship was independent of sowing date and variety. A high order polynomial model was used to describe the profiles. These models better estimated the areas under the profiles during the terminal spikelet phase compared to a non-linear least squares model. This was because the polynomials took into account troughs in the data during the integration period. The integration period used was a 30 day window, from mid April to mid May. Tucker et al.(1980) used a 40 day integration period which was more highly correlated to grain yield than earlier or later. This period was from Julian date 112 - 152 i.e. the end of April to the end of May.

In the grain filling period, grain yield was found to be related to the rate of change of the Transformed Vegetation Index with time. The relationship was found to be independent of sowing date but not variety. Idso et al.(1980), showed that grain yield was related to the rate of change of the Transformed Vegetation Index with time and that the relationship was independent of variety and had year to year comparison utility. However, their investigation was conducted on irrigated cereal plots. It is well known that grain yields for dry land cereal production are lower than those for irrigated cereals. Therefore, for irrigated cereals the relationship may well be variety independent, but for dry land cereals the relationship may well show variety dependence. This may be especially true if the crop is under water stress during the grain filling period as varieties will respond differently to water stress. Shortage of water can affect most aspects of the growth and physiology of cereal crops. In particular, the rate of net assimilation can be depressed by stomatal closure and increased respiration on the one hand, and by reduced leaf area expansion and accelerated tissue senescence on the other, Day et al.(1981).

In the 1990 season, no relationship was found between grain yield and integrated spectral data in the spring period and also in the grain filling period. The relationships were found to be variety and sowing date dependent as well as exhibiting interaction effects between these two factors.

There is now strong experimental evidence to suggest that delays in sowing reduce cereal grain yields. This is because late sown crops have to develop at an accelerated rate. This means that the duration of each stage

of development is progressively reduced with increased delay in sowing. The number of leaves per stem declines, Hay (1986), because the length of the period of leaf initiation decreases. This in turn, reduces the maximum numbers of tillers initiated, which is also broadly related to the number of leaf nodes, Kirby and Ellis (1980). However, this reduction in the ear bearing tillers per plant does not necessarily lead to lower ear population densities. The number of ears per unit area is dependent upon the established plant population density and upon the environmental conditions at the time of terminal spikelet.

Most studies have shown a fall in the ear population density with delay in the sowing of both winter and spring cereals. Harris (1984) has shown a progressive decline in ear population density with later sowing owing to a reduction in plant establishment and in the number of fertile tillers per plant for winter barley. Green et al.(1985) gave similar results for winter wheat.

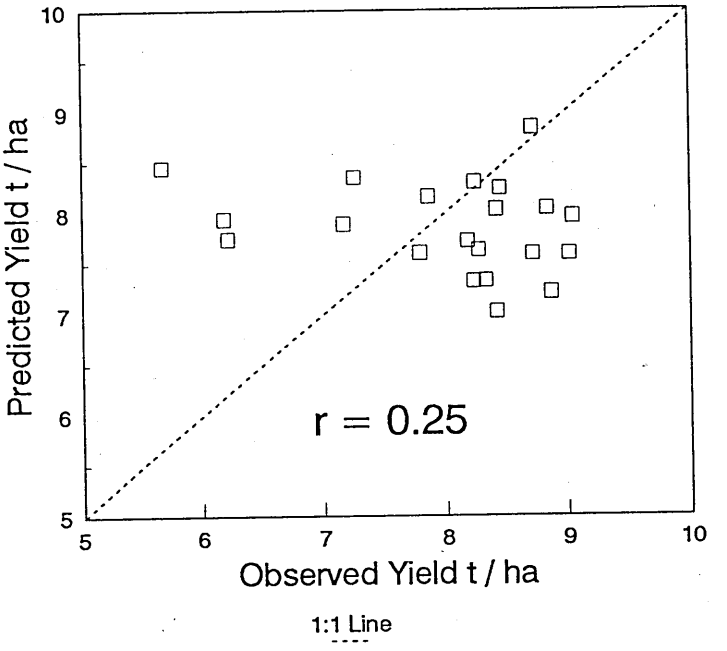
In the 1990 season, all of the wheat was effectively late sown because of the environmental conditions at the time of establishment. This presents problems for the use of models of grain yield prediction on an inter annual basis. Because what may be true for one year might not hold for the next. This was exactly the case for the 1989 and 1990 seasons. In the 1989 season, the experimental data suggested that there were no differences in grain yield due to sowing date. However, in the following season, the experimental data suggested that there were sowing date differences in the grain yield.

5.3.3 Annual Yield Predictions Based on Remotely Sensed Data.

Figure 5.16 shows the relationship between observed and predicted grain yield for the 1990 season based on a calibration model derived at the same site from the preceding season. In 1989, the calibration relationship was found to be independent of sowing date and variety, therefore it was reasoned that the relationship could be used to predict the yield of winter wheat irrespective of the variety. The model is based on the integral of the spectral profile in the terminal stage of apex development. However, the prediction equation poorly estimated the potential yield. The correlation between observed and predicted yield was not significant ($P < 0.05$). One can see that compared to the one to one line, the yield prediction equation over and under-estimated the grain yield for the 1990 season. It would have been desirable to use the same varieties in the 1990 season as used in the 1989 season. However, due to reasons beyond the control of the author, this was not possible.

As the relationships between grain yield and the rate of change of the Transformed Vegetation Index were found to be variety dependent in the 1989 season, a yield prediction exercise for the 1990 season was not attempted.

FIGURE 5.16 ACCURACY ASSESSMENT OF PREDICTED VS OBSERVED GRAIN YIELD, 1990 SEASON, USING YIELD PREDICTION EQUATION FROM THE 1989 SEASON.



5.3.4 The Effect of Fungal Disease.

In the 1989 season, the potential yield of wheat, treated and untreated with fungicide was estimated using models which related grain yield to spectral data. In the green up period, the grain yield was estimated using the integrated vegetation index in the terminal spikelet phase. For wheat treated with fungicide, the yield prediction equation could predict the grain yield to within 1.5 t ha^{-1}. For wheat untreated with fungicide, larger errors were found (7.2 t ha^{-1}). This was especially true for wheat which was attacked by late stage fungal disease. For green healthy vegetation, the estimation of potential grain yield worked well. This prediction could be applied 12 weeks before harvest and at a stage where management inputs could still have effect on the potential grain yield. This was because the timing of the yield prediction corresponded with a period of tiller mortality. Other work has shown that tiller survival can be promoted by application of nitrogen fertilizer in the terminal spikelet phase.

In the grain filling period, the potential grain yield of wheat treated and untreated with fungicide was estimated using a relationship which related grain yield to the rate of change of the Transformed Vegetation Index with time. For wheat treated with fungicide, the potential grain yield could be estimated to within 1.0 t ha^{-1}. This yield estimate was obtained a fortnight before harvest. For wheat untreated with fungicide, the potential yield was poorly estimated, especially if the crop was attacked by late stage fungal disease (errors of 6.0 t ha^{-1}). It could be argued that this type of prediction comes too late to be of use to the farmer or advisers at the field level. Further, other work has shown that rogues in the crop can interfere with the

reflectance patterns as they remain green as the wheat senesced, Moore (1981). Also, lodging in the grain filling period can interfere with the reflectance patterns, Zmuda (1987). This leads to spurious data being fed into yield prediction equations using remote sensing.

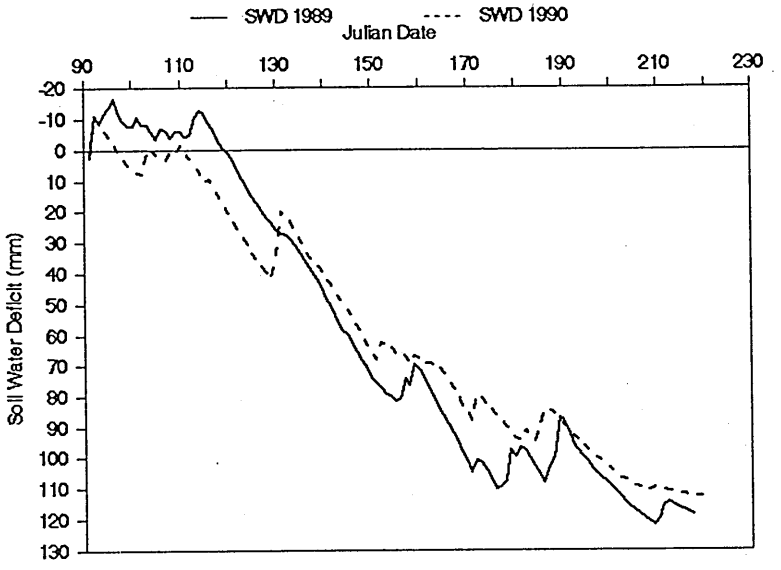
In both the predictive windows of apex development, the potential yield of winter wheat could be usefully estimated if the crop remained healthy and free of fungal disease. In the grain filling period, variety dependent relationships were used to estimate the grain yield. For an operational system at the field scale, expert systems could be employed to relate spectral data to grain yield given information on varieties. As there are many recommended varieties on the N.I.A.B list, a dedicated site would have to established to find the relationships between spectral data and grain yield for the recommended varieties.

5.3.5 The Effect of Weather Patterns.

For remote sensing to be useful at the field scale, it would be necessary to be able to apply calibration relationships from year to year and achieve a constant level of accuracy. Ideally, the models used should be independent of variety and sowing date. The accuracy assessment performed for the 1990 data suggests that a yield prediction equation cannot be applied with success on an inter-annual basis. The reasons for this can probably be attributed to weather patterns.

At the time of establishment, for the 1990 season, the wheat was effectively late sown irrespective of the time that the wheat went into the ground. This meant that the grain yields at harvest time showed differences due to sowing date. This was not the case for the preceding season. Figure 5.17 shows the soil water deficits built up from the beginning of April up until harvest in the 1989 and 1990 seasons. At the end of the growing season, the deficits approached the long term maximum median deficit of 114mm. In the 1989 season, the maximum long term deficit was exceeded.

FIGURE 5.17 CHANGES IN SOIL WATER DEFICITS OVER TIME, WINTER WHEAT, BURY UK, 1989 AND 1990 SEASONS.



Figures 5.18 and 5.19 show the average daily temperature and precipitation for the 2 seasons compared to the long term averages. It can be seen that 1990 was a hotter and drier year than average.

FIGURE 5.18 AVERAGE DAILY TEMPERATURES ^{0}C FOR THE 1989 AND 1990 SEASONS, COMPARED WITH THE LONG TERM AVERAGE, BROOMS BARN METEOROLOGICAL STATION.

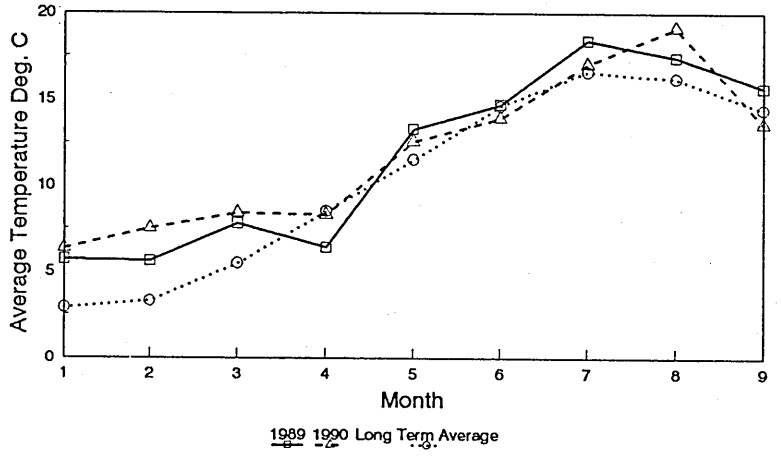


FIGURE 5.19 AVERAGE DAILY PRECIPITATION MM/DAY FOR THE 1989 AND 1990 SEASONS, COMPARED WITH THE LONG TERM AVERAGE, BROOMS BARN METEOROLOGICAL STATION.

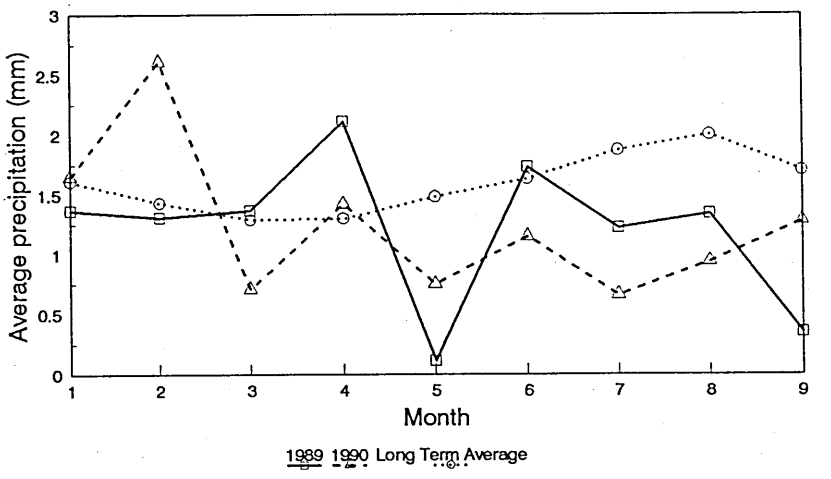


Figure 5.20 shows the accumulated precipitation over the 1989 and 1990 seasons. It can be seen that during the grain filling period, from Julian Date 190, the wheat received 30mm of rain less than in the preceding season. This could well have effected the senescence rate during grain fill. Figure 5.21 shows the distributions of the rate of change of the Transformed Vegetation Index with time for 1989 and 1990.

FIGURE 5.20 ACCUMULATED PRECIPITATION FROM THE BEGINNING OF APRIL UNTIL HARVEST FOR THE 1989 AND 1990 SEASONS.

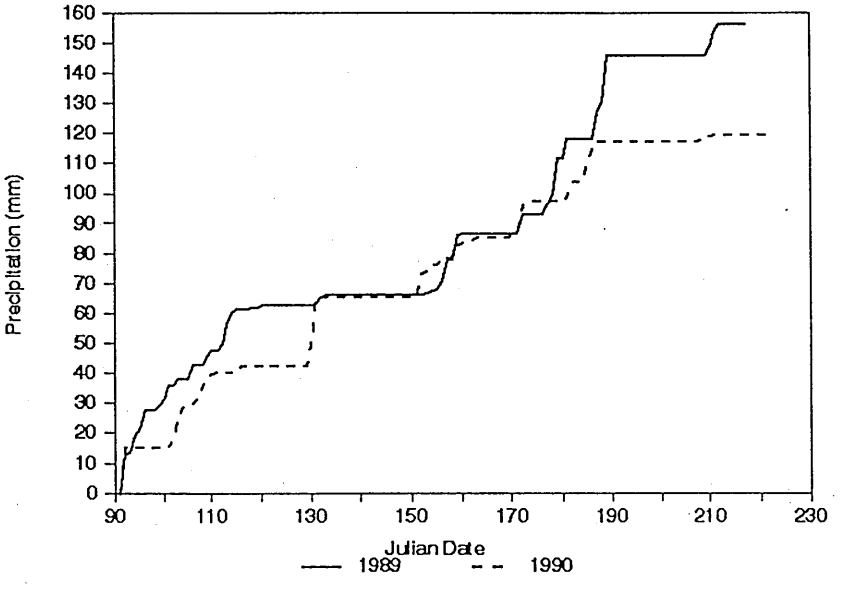
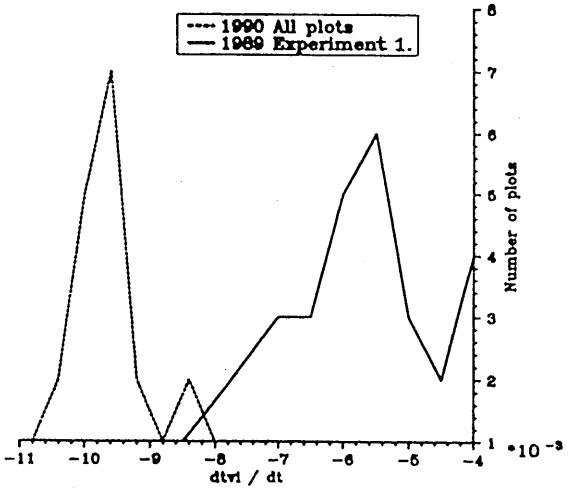


FIGURE 5.21 DISTRIBUTIONS OF THE RATE OF CHANGE OF THE TRANSFORMED VEGETATION INDEX WITH TIME FOR THE 1989 AND 1990 SEASONS.



From Figure 5.21, it can be seen that the spectral senescence rates for the 1990 season were much steeper compared to the previous season. For 1990 the rate of green down in the crop was nearly twice that compared to 1989. This could well be a response to crop water stress and would explain why no relationships were found between spectral senescence rate and grain yield for that year. This however, could well be an extreme observation. It could be that the probability of obtaining data such as this is low. The experimentation needs to be carried out over a much longer period before any firm conclusions can be drawn on the year to year comparison utility of the spectral models.

CHAPTER 6 ESTIMATION OF APEX PHENOLOGY STAGES IN WINTER WHEAT USING REMOTE SENSING.

6.1 Relationship of Cardinal Points of Spectral Profiles to apex Phenology stages, 1989 season

6.1.1 Relationships of tp, t1 and t2 to Apex Development Stages, Experiment 1.

Table 6.1 shows the relationships of the turning and inflexion points of the spectral profiles to apex development stages for experiment 1. The maximum turning point was found to correspond to the anthesis stage or a stage approaching anthesis. This was in the first nine days of June, Table 6.2. The inflexion point, t1, was found to correspond to the terminal spikelet stage or a stage approaching terminal spikelet. Inflexion occurred during the first three weeks of April 1989, Table 6.2. The inflexion point t2, was not found for all sowing dates and varieties in experiment 1.

6.1.2 Relationship of tp, t1 and t2 to Apex Development Stages, Experiment 2.

The maximum turning point in experiment 2, was found to correspond to the anthesis stage or a stage approaching anthesis, Table 6.3. This occurred in early June, Table 6.4. For wheat which was attacked by fungal disease, large errors in the estimation of timing were found. This was in the order of 60 days for cultivar Slejpner. Yellow rust had the effect of altering profile shape, Figure 6.1, so that the turning moment occurred when the crop was at the floret primordium stage.

The inflexion point, t1, was found to correspond to the terminal spikelet phase for wheat treated with fungicide, Table 6.3. This occurred in late April for the two treatments receiving fungicide, Table 6.4. Again inflexion point t2 was not found for all treatments in experiment 2, Table 6.4.

FIGURE 6.1 OBSERVED AND MODELLED NDVI FOR FUNGICIDE TREATED AND UNTREATED WHEAT, CV. SLEJPNER. UNTREATED WHEAT ATTACKED BY YELLOW RUST, EXPT. 2, 1989.

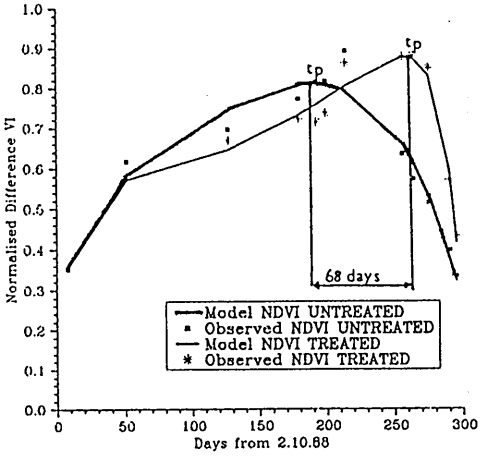


TABLE 6.1 RELATIONSHIPS OF INFLEXION POINTS T1 AND T2, AND MAXIMUM TURNING POINT TP, TO APEX PHENOLOGY STAGES IN WINTER WHEAT. T.S TERMINAL SPIKELET, F.P FLORET PRIMORDIUM, A ANTHESIS, W.R.S WATER RIPE STAGE, L.P LEMMA PRIMORDIUM, Y.A YELLOW ANTHER, G.A GREEN ANTHER, G.P GLUME PRIMORDIUM, 1989.

CULTIVAR	SOW DATE	T1 DAYS FROM SOWING	APEX STAGE	TP DAYS FROM SOWING	APEX STAGE	T2 DAYS FROMAPEX SOWING STAGE
MISSION	1	199	T.S	248	A	NO INFLEXION
	1	208	T.S	253	W.R.S	NO INFLEXION
	1	190	T.S	244	A	NO INFLEXION
	2	171	T.S	229	A	NO INFLEXION
	2	199	T.S	244	W.R.S	NO INFLEXION
	2	174	T.S	230	A	NO INFLEXION
	3	172	T.S	214	Y.A	NO INFLEXION
	3	165	L.P	213	Y.A	NO INFLEXION
	3	179	T.S	216	Y.A	NO INFLEXION
AVALON	1	190	T.S	243	A	NO INFLEXION
	1	190	T.S	243	A	NO INFLEXION
	1	190	T.S	240	A	NO INFLEXION
	2	168	T.S	225	Y.A	NO INFLEXION
	2	176	T.S	231	A	NO INFLEXION
	2	167	T.S	225	Y.A	NO INFLEXION
	3	163	G.P	218	A	NO INFLEXION
	3	161	G.P	218	A	NO INFLEXION
	3	148	G.P	204	G.A	NO INFLEXION
SLEJPNER	1	194	T.S	247	Y.A	NO INFLEXION
	1	193	T.S	246	Y.A	NO INFLEXION
	1	192	T.S	245	Y.A	NO INFLEXION
	2	170	F.P	231	Y.A	NO INFLEXION
	2	168	L.P	232	Y.A	NO INFLEXION
	2	163	L.P	227	G.A	NO INFLEXION
	3	148	G.P	215	Y.A	NO INFLEXION
	3	165	G.P	213	G.A	NO INFLEXION
	3	150	G.P	208	G.A	NO INFLEXION

TABLE 6.2 MEAN TIME, IN DAYS FROM SOWING, JULIAN DATE AND CALENDAR DATE FOR A. INFLEXION POINT T1 AND B. MAXIMUM TURNING POINT, TP, EXPERIMENT 1, 1989.

A. INFLEXION POINT T1

CULTIVAR	SOW DATE	DAYS FROM SOWING	JULIAN DATE	CALENDAR DATE
MISSION	1	199	111	APRIL 21st
	2	181	106	APRIL 16th
	3	172	112	APRIL 22nd
AVALON	1	190	102	APRIL 12th
	2	170	95	APRIL 5th
	3	157	97	APRIL 7th
SLEJPNER	1	193	105	APRIL 15th
	2	167	92	APRIL 2nd
	3	154	94	APRIL 4th

B. MAXIMUM TURNING POINT, TP

CULTIVAR	SOW DATE	DAYS FROM SOWING	JULIAN DATE	CALENDAR DATE
MISSION	1	248	160	JUNE 9th
	2	234	159	JUNE 8th
	3	214	154	JUNE 3rd
AVALON	1	242	154	JUNE 3rd
	2	227	152	JUNE 1st
	3	213	153	JUNE 2nd
SLEJPNER	1	246	158	JUNE 7th
	2	230	155	JUNE 4th
	3	212	152	JUNE 1st

TABLE 6.3 RELATIONSHIP OF INFLEXION POINTS T1, T2 AND MAXIMUM TURNING POINT, TP, TO APEX PHENOLOGY STAGES IN WINTER WHEAT. F.P FLORET PRIMORDIUM, T.S TERMINAL SPIKELET, G.A GREEN ANTHER, Y.A YELLOW ANTHER, A ANTHESIS, W.R.S WATER RIPE STAGE. EXPERIMENT 2, 1989.

CULTIVAR +REP.	FUNG.	DAYS FROM SOWING	APEX STAGE	DAYS FROM SOWING	APEX STAGE	DAYS FROM SOWING	STAGE
MISSION							
1	+	202	T.S	249	A	NO INFLEXION	
2	+	202	T.S	250	A	NO INFLEXION	
3	+	193	T.S	244	A	NO INFLEXION	
4	+	208	T.S	252	A	NO INFLEXION	
MISSION							
1	-	172	T.S	233	G.A	NO INFLEXION	
2	-	181	T.S	240	Y.A	NO INFLEXION	
3	-	175	T.S	236	G.A	NO INFLEXION	
4	-	177	T.S	237	G.A	NO INFLEXION	
SLEJPNER							
1	+	215	T.S	257	W.R.S	NO INFLEXION	
2	+	190	T.S	245	Y.A	NO INFLEXION	
3	+	202	T.S	251	Y.A	NO INFLEXION	
4	+	198	T.S	248	Y.A	NO INFLEXION	
SLEJPNER							
1	-	-	NO INFLEXION	189	F.P	NO INFLEXION	
2	-	-	NO INFLEXION	196	F.P	NO INFLEXION	
3	-	-	NO INFLEXION	182	F.P	NO INFLEXION	
4	-	-	NO INFLEXION	192	F.P	NO INFLEXION	

TABLE 6.4 MEAN TIME, IN DAYS FROM SOWING, JULIAN DATE ANDCALENDAR DATE FOR A. INFLEXION POINT T1 AND B. MAXIMUM TURNING POINT TP. EXPT. 2, 1989.

A. INFLEXION POINT T1

CULTIVAR	FUNGICIDE	DAYS FROM SOWING	JULIAN DATE	CALENDAR DATE
MISSION	+	202	112	APRIL 22ND
MISSION	-	176	86	MARCH 27TH
SLEJPNER	+	201	111	APRIL 21ST
SLEJPNER	-	NO INFLEXION	-	NO INFLEXION

B. MAXIMUM TURNING POINT, TP

CULTIVAR	FUNGICIDE	DAYS FROM SOWING	JULIAN DATE	CALENDAR DATE
MISSION	+	249	159	JUNE 8th
MISSION	-	237	147	MAY 27th
SLEJPNER	+	250	160	JUNE 9th
SLEJPNER	-	189	99	APRIL 9th

6.2 Relationship of Cardinal Points of Spectral Profiles to Apex Phenology Stages, 1990 Season.

6.2.1 Relationship of tp, t1 and t2 to Development Stages.

In the 1990 season, the inflexion point t1, was found to correspond to the glume primordium stage of apex development, Table 6.5. This occurred in the middle of March, Table 6.6. The maximum turning point tp, was found to correspond to the yellow anther stage, Table 6.5. This occurred at the end of May and the beginning of June, Table 6.6. The inflexion point t2, was not found for all varieties and sowing dates. Compared to the previous season, the time of inflexion for t1, was much earlier. In the 1989 season, t1 was inflecting at the terminal spikelet stage. This may be attributed to the fact that the effective time of sowing was delayed. Spectral emergence was therefore difficult to estimate.

TABLE 6.5 RELATIONSHIP OF INFLEXION POINTS T1 AND T2, AND MAXIMUM TURNING POINT TP, TO APEX PHENOLOGY STAGES IN WINTER WHEAT. T.S TERMINAL SPIKELET, F.P FLORET PRIMORDIUM, A ANTHESIS, W.R.S WATER RIPE STAGE, L.P LEMMA PRIMORDIUM, Y.A YELLOW ANTHER, G.A GREEN ANTHER, G.P GLUME PRIMORDIUM, 1990.

CULTIVAR	SOW DATE	T1 DAYS FROM SOWING	T1 APEX STAGE	TP DAYS FROM SOWING	TP APEX STAGE	T2 DAYS FROM SOWING	T2 APEX STAGE
MERCIA	1	163	G.P	238	Y.A	NO INFLEXION	
	1	173	G.P	237	Y.A	NO INFLEXION	
	1	170	G.P	244	Y.A	NO INFLEXION	
	1	166	G.P	240	Y.A	NO INFLEXION	
	2	137	G.P	213	Y.A	NO INFLEXION	
	2	149	G.P	217	Y.A	NO INFLEXION	
	2	142	G.P	215	Y.A	NO INFLEXION	
AVALON	1	153	D.R	234	G.A	NO INFLEXION	
	1	171	G.P	244	Y.A	NO INFLEXION	
	1	171	G.P	244	Y.A	NO INFLEXION	
	1	169	G.P	240	Y.A	NO INFLEXION	
	2	137	G.P	212	Y.A	NO INFLEXION	
	2	143	G.P	215	Y.A	NO INFLEXION	
	2	144	G.P	215	Y.A	NO INFLEXION	
TONIC	1	172	G.P	242	Y.A	NO INFLEXION	
	1	171	G.P	239	Y.A	NO INFLEXION	
	1	192	F.P	250	Y.A	NO INFLEXION	
	1	170	G.P	240	Y.A	NO INFLEXION	
	2	137	G.P	213	Y.A	NO INFLEXION	
	2	137	G.P	212	Y.A	NO INFLEXION	
	2	141	G.P	214	Y.A	NO INFLEXION	

TABLE 6.6 MEAN TIME, IN DAYS FROM SOWING, JULIAN DATE AND CALENDAR DATE FOR A. INFLEXION POINT T1 AND B. MAXIMUM TURNING POINT, TP, 1990.

A. INFLEXION POINT T1

CULTIVAR	SOW DATE	DAYS FROM SOWING	JULIAN DATE	CALENDAR DATE
MERCIA	1	168	73	14 MARCH
	2	143	81	22 MARCH
AVALON	1	166	71	12 MARCH
	2	141	79	20 MARCH
TONIC	1	176	81	22 MARCH
	2	138	76	17 MARCH

B. MAXIMUM TURNING POINT, TP

CULTIVAR	SOW DATE	DAYS FROM SOWING	JULIAN DATE	CALENDAR DATE
MERCIA	1	240	145	25 MAY
	2	215	153	2 JUNE
AVALON	1	241	146	26 MAY
	2	214	154	1 JUNE
TONIC	1	243	148	28 MAY
	2	213	151	31 MAY

6.3 Discussion on the Relationship of Spectral Data to Apex Development Stages.

6.3.1 The Effect of Variety and Sowing Date.

In the 1989 season, the cardinal points of spectral profiles were found to correspond to apex development stages in winter wheat. These stages were terminal spikelet and anthesis. Irrespective of the sowing date and variety, the profiles were found to inflect at initiation of the terminal spikelet stage. This was when developmentally and radiometrically, the canopies converged. However, the derivatives of the non-linear model (eq. 5.2) were used to find the cardinal points of the profiles. It could be that derivatives of polynomials of cubic spline functions would estimate the timing of stages more precisely. These linear functions would take into account the troughs in the spectral profiles encountered during the terminal spikelet stage. Thus the inflexion point t1, may therefore be a turning moment as opposed to an inflexion point. This would be given by the first order derivative of a linear function.

6.3.2 The Effect of Fungal Disease.

In the 1989 season, the derivatives of the non-linear least squares model (eq. 5.2) were used to give the inflexion points of wheat untreated and treated with fungicide. It was found that for wheat infected with fungal disease, the profile shape was altered. The inflexion point t1 was not found. Also, the maximum turning point was found to occur much earlier. Large errors in the timing of the stage of apex development were found. This suggests that the modelling of apex development stage using remote sensing is unreliable if the crop does not remain green and healthy.

6.3.3 Year to Year Comparison Utility.

Table 6.7 shows the accumulated thermal time from initiation to the end of the terminal spikelet phase for wheat sown on three different dates in the 1989 season. It can be seen that irrespective of the sowing date, the duration of the terminal spikelet stage is the same number of thermal days in length. It is known that the duration of these phases of apex development are dependent on accumulated thermal time and photoperiod. Therefore, a model which combined remotely sensed data and accumulated thermal time, would provide information on the timing and duration of the terminal spikelet stage. This would be especially important for year to year comparisons, and for area estimation under the spectral temporal profiles on a year to year basis.

TABLE 6.7 ACCUMULATED THERMAL TIME (°C BASE) FOR THE DURATION OF THE TERMINAL SPIKELET PHASE, EXPT. 1, 1989.

	SOWING DATE		
	4.10.88	17.10.88	1.11.88
INITIATION T.S.	1318	1177	1011
END OF T.S.	1579	1439	1272
TOTALS	261	262	261

In the 1990 season, the inflexion point t1, was found to correspond to the glume primoridium stage. This stage occurred well before the initiation of terminal spikelet in the apex development of wheat. The difference in the stage correspondence between years can probably be attributed to the non-linear model. Again, first and second order derivatives of this function were used to give the timing of the cardinal points on the spectral profiles. The model depends on the date of spectral emergence as this fixes the time that the curve 'greens up'. In the 1990 season, because of the late sowing, the vegetation development rate remained low throughout the winter months. Therefore, spectral emergence was much later compared to the previous season. It was difficult to interpret when the profiles actually became spectrally emergent. This could be critical to the success of estimating the timing of stages using remote sensing.

In both the 1989 and 1990 seasons, the maximum turning point was found to correspond to the anthesis stage or a stage approaching anthesis. This would have application in the estimation of grain yield using the spectral senescence technique. This stage marks the beginning of the reproductive phase of growth.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions.

7.1.1 The Spectral Response of Winter Wheat.

(i) In the 1989 season, a key phase of apex development was found in which canopy convergence occurred so that the sowing date component of the spectral response disappeared. This was the terminal spikelet phase.

(ii) This could not be confirmed in the following season. Effectively, all the plots were late sown. How ever, sowing date differences in the spectral response were found in the grain filling period.

(iii) In the 1989 season, two key phases of main stem apex development were found in which variety differences in the spectral response occurred. These were the terminal spikelet phase and the grain filling period respectively.

(iv) This could not be confirmed for the 1990 season.

7.1.2 The Relationship of Spectral Data to Grain Yield in Winter Wheat.

(i) Single date regressions - $\log_e$ models.
In the 1989 season, highest correlations were found in a spring window of development. This was the terminal spikelet stage. The relationships were found to be independent of sowing date but not variety. The coefficients in the relationships were not constant, the slopes became steeper with time. This was found to be a period of yield adjustment associated with tiller death. No correlation was found between grain yield and spectral data in the terminal spikelet phase in the following season;

(ii) Integrated NDVI - terminal spikelet phase.
In the 1989 season, a spring window of development was found in which the natural log of grain yield was related to the area under the spectral temporal profile. This corresponded with the terminal spikelet phase of apex development. The relationship was found to be independent of sowing date and variety. In the 1990 season, no significant relationship was found between the $\log_e$ of grain yield and time integrated vegetation index data in the terminal spikelet phase.
The relationship was found to be variety and sowing date dependent;

(iii) Spectral senescence rate.

In the 1989 season, high correlations were found between grain yield and the rate of change of the Transformed Vegetation Index with time in the grain filling period. The relationships were found to be independent of sowing date but not variety. In the 1990 season, no direct correlations were found between grain yield and the rate of change of the Transformed Vegetation Index with time. The relationships were found to be variety and sowing date dependent;

(iv) Year to year comparison utility.

The 1989 calibration equation which related the $\log_e$ of grain yield to integrated vegetation index data was used to predict the yield of wheat in the 1990 season. This calibration equation was independent of variety and sowing date. No relationship was found between observed and predicted yield for the 1990 season. Therefore, the use of calibrated spectral models for annual yield estimation must be questioned. It would appear that weather patterns at the time of establishment and during the grain filling period play an important role in determining the grain yield of cereals.

7.1.3 Effect of Fungal Disease on Remotely Sensed Yield Indicators.

(i) Time integrated Vegetation Index - terminal spikelet phase.

In the 1989 season, a calibration relationship which related spectral data to the $\log_e$ of grain yield was used to predict the yield of plots treated and untreated with fungicide. For plots treated with fungicide, the calibration relationship could predict the yield to within 1.5 t/ha. The model could be used therefore to predict the potential yield approximately 3 months before harvest. For plots untreated with fungicide, large errors in the estimation of grain yield were found to occur. This was especially true if the plots were attacked by yellow rust (Puccinia striiformis). This demonstrates the dangers inherent in this type of prediction, as late stage disease can lower the yield potential of winter sown cereals;

(ii) Spectral senescence rate.

In the 1989 season, variety dependent relationships were used to predict the yield of plots treated and untreated with fungicide. These relationships related the grain yield to the rate of change of the Transformed Vegetation Index with time. For plots treated with fungicide, the yield could be estimated to within 1 $t.ha^{-1}$. This prediction could be obtained a fortnight before harvest. However, for plots untreated with fungicide, large errors in the estimation of grain yield were found. These were of the order of 6 $t.ha^{-1}$. This could be attributed to attack of the wheat by yellow rust (Puccinia striiformis). This had the effect of lowering the yield potential so that the calibration equation overestimated the grain yield.

7.1.4 Apex Development Stage Modelling Using Remote Sensing.

(i) In the 1989 season, cardinal points of profiles were found to correspond to apex development stages in winter sown wheat. The inflexion point t1, was found to correspond to the terminal spikelet stage. This occurred in the first three weeks of April. The turning moment tp, was found to correspond to the anthesis stage or a stage approaching anthesis. This occurred in early June. The inflexion point t2, was not found;

(ii) For winter wheat treated and untreated with fungicide, healthy wheat unaffected by fungal disease was found to inflect at the terminal spikelet stage in April. The turning moment tp, was found to occur in early June at the time of anthesis. For wheat untreated with fungicide and attacked by yellow rust, large errors in timing of stages were found. This was because the fungal disease altered the profile shape. The turning moment tp, was found to occur at the floret primordium stage;

(iii) In the following year, the inflexion point t1, was found to occur at the glume primordium stage. This was much earlier compared to the 1989 season. However the maximum turning point tp, was again found to occur in the first weeks of June, close to the anthesis stage.

7.2 Recommendations.

7.2.1 Limitations of the Study.

In the field experiments described here, the random component i.e. the blocks, were contained within the sowing dates. GENSTAT5 was used to perform analyses of variance. In GENSTAT5, the random component in the variance model can be declared to be within sowing dates. However, because soils are inherently variable, the use of blocks within sowing date does not take into account the problem of field position. Spatially, in the 1989 season the blocks were situated in only a small part of a large field. This was especially true of the time of sowing trial (Experiment 1). In the 1990 season, although the sowing date blocks were situated in different parts of the field, the area covered by the blocks was again small compared to the size of the field. One way around this problem, would have been to randomize the treatments by variety and sowing dates within blocks spread around the field. In this way, the problem of field position would have better considered. In the 1990 season, field position was an important factor especially at the time of emergence. Problems in seed bed preparation led to different established populations for the same sowing date block.

Ideally, the design in the 1990 season, should have been similar to the previous season in terms of varieties sown, the numbers of replications and the number of sowing dates. This would have led to a

better comparison of data between years. As it stands, two different varieties were used in the 1990 season, the varieties used and the number of sowing dates was beyond the control of the project. However an attempt has been made to repeat the findings of the 1989 data using varieties of wheat sown on different dates. Before any firm conclusions can be drawn on the relationships of spectral data to winter wheat grain yield, the experimentation needs to be carried on over more seasons. Unusual weather patterns in the Autumn of 1989 led to late sowing of all plots. This could well have had an effect on the grain yields which was certainly highlighted at the end of the season.

7.2.2 Improvements for Future Work.

Daughtry (1988) and Daughtry et al. (1983) suggest that correlations of grain yield with spectral of agronomic data may be spurious and should be treated with caution due to disease and weather interactions. Maas et al.(1985) have proposed combining remotely sensed and meteorological data to model the dry matter production over the growing season. In this model, spectral data is used as a surrogate measure of the Leaf Area Index (LAI). Remotely sensed spectral data, provides a non-destructive and rapid measure of LAI which is a key driving variable used to estimate the absorbed photosynthetically active radiation (APAR). The daily increase in above ground dry matter is calculated by multiplying APAR by an efficiency factor which is crop specific, Maas et al.(1985). Grain yield can be estimated by the use of an empirical relationship between dry matter production at a given stage of development and grain yield, i.e. the harvest index, Maas et al.(1985). Steven et al. (1983) have shown how remotely sensed data can be used to estimate APAR from measurements of transmitted quantum flux made with tube solarimeters. Green (1988) has shown how one tube solarimeter can be used to measure quantum flux transmitted by the canopy using a crop specific power function. Gallagher and Biscoe (1978) describe how transmitted quantum flux can be used to measure APAR. Green (1988) also demonstrates how measurements of per cent cover can be used to estimate APAR in a technique devised by Steven et al.(1986). Clearly, APAR can be measured in a number of ways.

This project could have been improved by including the measurement of APAR using tube solarimeters and a solar radiometer to measure the incident irradiance at the site. Spectral data could then be directly related to the fraction of light energy absorbed by the canopy which could then be used to estimate APAR. In the light of the work presented here, spectral data was found to be related to grain yield in a critical period of apex development i.e. the terminal spikelet stage. This relationship was found to be independent of sowing date and variety. Measurement of APAR during this period regressed against grain yield may also suggest a model which is independent of sowing date and variety. The slope of this line would be an estimate of the efficiency of the conversion of light energy to grain yield in the terminal spikelet stage. This needs investigation as it has potential application for crop performance monitoring at regional as well as at the field scale. The suggested model is attractive since variables would have to be measured in a key stage of development rather than over an entire season.

APPENDIX 1.

CALIBRATION OF KODAK GREY CARDS AGAINST A STANDARD BASO4 PANEL, DEC. 1988. COURTESY OF THE EQUIPMENT POOL FOR FIELD SPECTROSCOPY, UNIVERSITY OF SOUTHAMPTON.

1. Grey Card SC1 Reflectance

File : E:GREY1.AB1

WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%
343.37	40.40	556.58	16.89	756.26	19.20	943.26	22.55	1141.67	26.13	1539.38	26.22	1920.79	26.08
345.10	39.89	558.23	16.94	757.80	19.26	944.71	22.57	1144.96	26.11	1542.45	26.28	1925.64	26.22
346.84	39.08	559.87	16.97	759.35	19.32	946.15	22.59	1148.25	26.13	1545.51	26.39	1930.49	26.39
348.58	35.42	561.52	16.98	760.90	19.33	947.59	22.59	1151.54	26.16	1548.57	26.43	1935.34	26.62
350.31	34.04	563.16	17.01	762.44	19.37	949.03	22.63	1154.83	26.15	1551.63	26.47	1940.18	26.81
352.05	32.36	564.80	17.04	763.98	19.42	950.47	22.66	1158.12	26.24	1554.69	26.49	1945.02	27.02
353.78	33.04	566.44	17.05	765.53	19.48	951.91	22.68	1161.40	26.26	1557.74	26.53	1949.86	27.21
355.51	31.39	568.08	17.07	767.07	19.50	953.34	22.72	1164.68	26.26	1560.80	26.58	1954.69	27.38
357.24	29.67	569.72	17.10	768.61	19.54	954.78	22.75	1167.96	26.16	1563.85	26.66	1959.52	27.54
358.98	28.82	571.36	17.11	770.15	19.55	956.22	22.76	1171.24	26.08	1566.90	26.69	1964.34	27.68
360.71	27.77	573.00	17.11	771.69	19.57	957.65	22.76	1174.52	26.06	1569.95	26.78	1969.16	27.93
362.44	26.36	574.64	17.12	773.23	19.60	959.08	22.81	1177.80	26.17	1572.99	26.81	1973.98	28.03
364.17	24.80	576.28	17.13	774.77	19.66	960.52	22.82	1181.07	26.37	1576.03	26.84	1978.79	28.20
365.90	24.14	577.91	17.12	776.31	19.70	961.95	22.84	1184.34	26.47	1579.08	26.91	1983.60	28.23
367.62	23.40	579.55	17.14	777.85	19.74	963.38	22.87	1187.61	26.58	1582.12	27.02	1988.41	28.28
369.35	22.49	581.18	17.14	779.38	19.77	964.81	22.90	1190.88	26.59	1585.15	27.10	1993.21	28.28
371.08	22.19	582.82	17.14	780.92	19.78	966.24	22.91	1194.15	26.68	1588.19	27.26	1998.01	28.17
372.80	20.90	584.45	17.14	782.45	19.82	967.67	22.91	1197.41	26.69	1591.22	27.36	2002.81	28.06
374.53	20.38	586.08	17.12	783.99	19.86	969.10	22.89	1200.67	26.79	1594.26	27.46	2007.60	27.89
376.25	19.92	587.71	17.11	785.52	19.85	970.53	22.91	1203.94	26.78	1597.29	27.56	2012.39	27.71
377.98	19.55	589.35	17.09	787.05	19.89	971.95	22.94	1207.20	26.83	1600.31	27.69	2017.17	27.42
379.70	19.08	590.98	17.08	788.58	19.96	973.38	22.97	1210.45	26.88	1603.34	27.81	2021.95	27.14
381.42	19.02	592.60	17.03	790.11	19.96	974.80	22.96	1213.71	26.96	1606.36	27.88	2026.73	26.72
383.14	19.15	594.23	16.98	791.64	19.99	976.22	23.00	1216.96	27.08	1609.39	28.04	2031.50	26.39
384.86	19.13	595.86	16.94	793.17	20.01	977.65	23.03	1220.22	27.07	1612.41	28.13	2036.28	26.05
386.58	19.33	597.49	16.92	794.70	20.03	979.07	23.05	1223.47	27.13	1615.42	28.21	2041.04	25.72
388.30	19.50	599.11	16.90	796.23	20.03	980.49	23.05	1226.72	27.10	1618.44	28.41	2045.81	25.31
390.02	19.84	600.74	16.87	797.75	20.08	981.91	23.08	1229.96	27.13	1621.46	28.46	2050.57	25.03
391.74	19.86	602.37	16.85	799.28	20.13	983.33	23.10	1233.21	27.15	1624.47	28.53	2055.33	24.67
393.46	19.89	603.99	16.80	800.80	20.10	984.75	23.14	1236.45	27.16	1627.48	28.64	2060.08	24.41
395.17	20.00	605.61	16.77	802.33	20.15	986.16	23.16	1239.70	27.18	1630.49	28.73	2064.83	24.18
396.89	20.02	607.24	16.72	803.85	20.16	987.58	23.18	1242.94	27.24	1633.49	28.78	2069.58	24.03
398.60	20.08	608.86	16.69	805.37	20.21	989.00	23.19	1246.17	27.25	1636.50	28.83	2074.32	23.90
400.32	20.09	610.48	16.65	806.89	20.24	990.41	23.22	1249.41	27.25	1639.50	28.86	2079.06	23.79
402.03	20.13	612.10	16.64	808.41	20.22	991.83	23.22	1252.65	27.27	1642.50	28.92	2083.80	23.71
403.75	19.87	613.72	16.63	809.93	20.26	993.24	23.22	1255.88	27.24	1645.50	29.00	2088.53	23.63
405.46	19.78	615.34	16.60	811.45	20.29	994.65	23.27	1259.11	27.30	1648.50	29.04	2093.27	23.66
407.17	19.54	616.95	16.58	812.97	20.34	996.06	23.29	1262.34	27.28	1651.49	29.10	2097.99	23.75
408.88	19.49	618.57	16.57	814.49	20.39	997.47	23.28	1265.57	27.32	1654.48	29.15	2102.72	23.83
410.59	19.37	620.19	16.54	816.00	20.36	998.88	23.32	1268.79	27.32	1657.47	29.24	2107.44	23.98
412.30	19.12	621.80	16.54	817.52	20.39	1000.29	23.33	1272.02	27.33	1660.46	29.21	2112.16	24.08
414.01	18.94	623.42	16.53	819.03	20.44	1001.70	23.36	1275.24	27.30	1663.45	29.27	2116.87	24.31
415.72	18.77	625.03	16.52	820.55	20.48	1003.10	23.36	1278.46	27.39	1666.43	29.27	2121.58	24.53
417.42	18.64	626.65	16.51	822.06	20.45	1004.51	23.41	1281.68	27.42	1669.42	29.28	2126.29	24.65
419.13	18.54	628.26	16.51	823.57	20.50	1005.92	23.43	1284.90	27.47	1672.40	29.22	2131.00	24.83
420.84	18.32	629.87	16.51	825.08	20.52	1007.32	23.48	1288.11	27.52	1675.38	29.19	2135.70	24.98
422.54	18.28	631.48	16.53	826.59	20.53	1008.72	23.50	1291.33	27.55	1678.35	29.16	2140.40	25.17
424.25	18.18	633.09	16.54	828.10	20.59	1010.12	23.54	1294.54	27.57	1681.33	29.12	2145.10	25.29
425.95	18.05	634.70	16.55	829.61	20.60	1011.53	23.57	1297.75	27.63	1684.30	29.04	2149.79	25.50
427.65	17.98	636.31	16.55	831.12	20.60	1012.93	23.58	1300.96	27.68	1687.27	29.06	2154.48	25.69
429.36	17.92	637.92	16.56	832.63	20.64	1014.33	23.61	1304.16	27.65	1690.24	29.07	2159.16	25.92
431.06	17.79	639.52	16.55	834.13	20.69	1015.73	23.64	1307.37	27.64	1693.21	28.99	2163.85	25.97
432.76	17.75	641.13	16.58	835.64	20.67	1017.12	23.69	1310.57	27.65	1696.17	28.95	2168.53	26.15
434.46	17.68	642.73	16.57	837.14	20.70	1018.52	23.70	1313.77	27.66	1699.14	29.01	2173.21	26.34
436.16	17.65	644.34	16.59	838.65	20.73	1019.92	23.70	1316.97	27.66	1702.10	29.02	2177.88	26.53
437.86	17.53	645.94	16.60	840.15	20.72	1021.31	23.76	1320.17	27.69	1705.06	28.99	2182.55	26.64
439.55	17.47	647.55	16.62	841.65	20.77	1022.71	23.78	1323.36	27.68	1708.01	28.95	2187.22	26.76
441.25	17.44	649.15	16.63	843.15	20.82	1024.10	23.80	1326.56	27.68	1710.97	29.03	2191.89	26.84
442.95	17.36	650.75	16.65	844.65	20.83	1025.49	23.83	1329.75	27.67	1713.92	28.96	2196.55	27.00
444.64	17.32	652.35	16.67	846.15	20.85	1026.88	23.87	1332.94	27.63	1716.87	29.02	2201.21	27.10
446.34	17.35	653.95	16.68	847.65	20.91	1028.27	23.88	1336.13	27.57	1719.82	29.04	2205.87	27.14
448.03	17.29	655.55	16.70	849.15	20.89	1029.66	23.90	1339.31	27.58	1722.77	29.11	2210.52	27.25
449.73	17.22	657.15	16.70	850.65	20.96	1031.05	23.93	1342.50	27.58	1725.71	29.01	2215.17	27.21
451.42	17.21	658.75	16.73	852.14	20.96	1032.44	23.98	1345.68	27.56	1728.65	29.07	2219.82	27.12

459.87	17.04	666.72	16.89	857.81	21.10	1039.67	24.11	1363.83	27.21	1745.38	28.99	2247.19	25.44
461.56	17.02	668.32	16.84	861.11	21.13	1040.75	24.18	1364.74	27.30	1746.27	28.99	2247.65	25.44
463.25	17.01	669.91	16.86	862.60	21.17	1042.13	24.20	1367.91	27.21	1749.20	28.98	2252.28	25.01
464.94	16.97	671.50	16.89	864.09	21.17	1043.51	24.18	1371.08	27.27	1752.12	28.99	2256.91	24.68
466.62	16.97	673.09	16.91	865.57	21.20	1044.89	24.27	1374.24	27.32	1755.05	28.98	2261.53	24.45
468.31	16.94	674.68	16.93	867.06	21.24	1046.27	24.29	1377.41	27.33	1757.97	28.96	2266.15	24.30
469.99	16.88	676.27	16.92	868.55	21.28	1047.65	24.33	1380.57	27.28	1760.89	28.92	2270.77	24.39
471.68	16.85	677.86	16.94	870.04	21.27	1049.03	24.38	1383.73	27.27	1763.81	28.99	2275.39	24.34
473.36	16.85	679.45	16.95	871.52	21.31	1050.41	24.43	1386.89	27.14	1766.73	28.98	2280.00	24.28
475.04	16.82	681.03	16.98	873.01	21.34	1051.78	24.46	1390.04	27.15	1769.64	28.99	2284.61	24.31
476.72	16.83	682.62	17.00	874.49	21.39	1053.16	24.50	1393.20	27.06	1772.55	29.07	2289.22	24.12
478.40	16.79	684.20	17.03	875.97	21.43	1054.53	24.55	1396.35	27.05	1775.46	29.13	2293.82	23.95
480.09	16.75	685.79	17.05	877.45	21.47	1055.90	24.57	1399.50	26.85	1778.37	29.16	2298.43	23.77
481.76	16.73	687.37	17.07	878.94	21.49	1057.27	24.63	1402.65	26.69	1781.28	29.17	2303.03	23.61
483.44	16.73	688.95	17.10	880.42	21.54	1058.65	24.70	1405.80	26.57	1784.18	29.17	2307.62	23.32
485.12	16.71	690.54	17.12	881.89	21.53	1060.02	24.74	1408.95	26.45	1787.09	29.25	2312.22	23.18
486.80	16.70	692.12	17.15	883.37	21.55	1061.38	24.74	1412.09	26.32	1789.99	29.24	2316.81	23.02
488.48	16.73	693.70	17.21	884.85	21.56	1062.75	24.72	1415.23	26.20	1792.88	29.34	2321.40	22.89
490.15	16.71	695.28	17.23	886.33	21.62	1064.12	24.77	1418.38	26.10	1795.78	29.34	2325.99	22.76
491.83	16.67	696.86	17.25	887.80	21.63	1065.49	24.72	1421.51	26.01	1798.67	29.32	2330.57	22.79
493.50	16.65	698.43	17.29	889.28	21.66	1066.85	24.77	1424.65	25.88	1801.57	29.34	2335.15	22.86
495.18	16.67	700.01	17.33	890.75	21.67	1068.22	24.84	1427.79	25.85	1804.46	29.36	2339.73	22.93
496.85	16.66	701.59	17.36	892.23	21.72	1069.58	24.88	1430.92	25.83	1807.34	29.47	2344.31	23.03
498.52	16.61	703.16	17.40	893.70	21.75	1070.94	24.96	1434.05	25.78	1810.23	29.48	2348.89	23.16
500.19	16.59	704.74	17.44	895.17	21.78	1072.31	24.97	1437.18	25.71	1813.11	29.38	2353.46	23.28
501.86	16.58	706.31	17.48	896.64	21.82	1073.67	24.97	1440.31	25.67	1815.99	29.42	2358.03	23.38
503.53	16.56	707.88	17.54	898.11	21.83	1075.03	25.05	1443.43	25.63	1818.87	29.43	2362.60	23.54
505.20	16.53	709.46	17.59	899.58	21.83	1076.39	25.07	1446.55	25.63	1821.75	29.32	2367.16	23.60
506.87	16.51	711.03	17.63	901.05	21.88	1077.75	25.10	1449.68	25.58	1824.63	29.43	2371.72	23.63
508.54	16.49	712.60	17.65	902.52	21.87	1079.10	25.20	1452.80	25.56	1827.50	29.42	2376.28	23.78
510.21	16.49	714.17	17.70	903.99	21.89	1080.46	25.21	1455.91	25.52	1830.37	29.38	2380.84	23.71
511.87	16.48	715.74	17.75	905.45	21.89	1081.82	25.28	1459.03	25.51	1793.20	29.59	2385.40	23.74
513.54	16.42	717.31	17.81	906.92	21.94	1083.17	25.42	1462.14	25.47	1798.16	29.54	2389.95	23.82
515.20	16.42	718.87	17.87	908.38	21.96	1084.52	25.39	1465.26	25.40	1803.11	29.44	2394.50	23.69
516.87	16.40	720.44	17.91	909.84	21.94	1085.88	25.43	1468.37	25.41	1808.06	29.46	2399.05	23.68
518.53	16.38	722.01	17.98	911.31	22.00	1087.23	25.37	1471.48	25.31	1813.01	29.43	2403.60	23.60
520.19	16.39	723.57	18.02	912.77	22.01	1088.58	25.48	1474.58	25.36	1817.95	29.44	2408.14	23.43
521.86	16.40	725.14	18.08	914.23	22.05	1089.93	25.52	1477.69	25.32	1822.88	29.48	2412.69	23.28
523.52	16.38	726.70	18.10	915.69	22.08	1091.28	25.54	1480.79	25.38	1827.82	29.53	2417.23	22.95
525.18	16.39	728.26	18.17	917.15	22.06	1092.63	25.71	1483.89	25.41	1832.75	29.59	2421.77	22.76
526.84	16.39	729.82	18.24	918.61	22.11	1093.98	25.70	1486.99	25.44	1837.67	29.62	2426.30	22.38
528.50	16.40	731.39	18.30	920.06	22.12	1088.75	25.48	1490.09	25.51	1842.59	29.65	2430.83	22.15
530.15	16.42	732.95	18.41	921.52	22.14	1092.07	25.56	1493.18	25.55	1847.51	29.67	2435.37	21.75
531.81	16.45	734.51	18.44	922.98	22.16	1095.39	25.69	1496.28	25.58	1852.42	29.70	2439.90	21.42
533.47	16.45	736.06	18.50	924.43	22.20	1098.71	25.70	1499.37	25.62	1857.33	29.66	2444.42	21.12
535.12	16.48	737.62	18.57	925.88	22.23	1102.02	25.75	1502.46	25.69	1862.24	29.56	2448.95	20.56
536.78	16.51	739.18	18.62	927.34	22.27	1105.34	25.77	1505.55	25.75	1867.14	29.31	2453.47	20.17
538.43	16.53	740.74	18.71	928.79	22.27	1108.65	25.77	1508.63	25.76	1872.03	28.95	2457.99	20.03
540.09	16.58	742.29	18.76	930.24	22.31	1111.96	25.81	1511.71	25.84	1876.93	28.60	2462.51	19.63
541.74	16.62	743.85	18.83	931.69	22.32	1115.27	25.92	1514.80	25.90	1881.81	28.19	2467.03	19.51
543.39	16.65	745.40	18.86	933.14	22.33	1118.57	26.02	1517.88	25.96	1886.70	27.75	2471.54	19.34
545.04	16.70	746.95	18.92	934.59	22.37	1121.88	26.00	1520.96	25.98	1891.58	27.22	2476.06	19.30
546.69	16.73	748.51	18.98	936.04	22.41	1125.18	26.01	1524.03	26.04	1896.46	26.77	2480.57	19.33
548.34	16.74	750.06	19.03	937.48	22.43	1128.48	26.06	1527.11	26.14	1901.33	26.40	2485.08	19.36
549.99	16.78	751.61	19.09	938.93	22.48	1131.78	26.05	1530.18	26.13	1906.20	26.17	2489.58	19.64
551.64	16.79	753.16	19.13	940.38	22.52	1135.08	26.08	1533.25	26.18	1911.07	26.04	2494.09	19.81
553.29	16.82	754.71	19.17	941.82	22.53	1138.38	26.07	1536.32	26.18	1915.93	26.00	2498.59	0.00

C>

2. Grey Card SC2 Reflectance

File : B:GREY2.AB1

WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%	WAVELENGTH	R%
343.37	41.63	556.58	16.83	756.26	19.33	943.26	22.84	1141.67	26.56	1539.38	26.53	1920.79	26.25
345.10	40.84	558.23	16.85	757.80	19.38	944.71	22.85	1144.96	26.60	1542.45	26.57	1925.64	26.40
346.84	38.94	559.87	16.89	759.35	19.41	946.15	22.89	1148.25	26.60	1545.51	26.65	1930.49	26.59
348.58	37.81	561.52	16.91	760.90	19.48	947.59	22.91	1151.54	26.62	1548.57	26.73	1935.34	26.75
350.31	35.28	563.16	16.95	762.44	19.53	949.03	22.96	1154.83	26.68	1551.63	26.80	1940.18	26.97
352.05	33.49	564.80	16.97	763.98	19.57	950.47	22.97	1158.12	26.72	1554.69	26.84	1945.02	27.18
353.78	33.56	566.44	16.99	765.53	19.59	951.91	22.99	1161.40	26.71	1557.74	26.91	1949.86	27.39
355.51	32.20	568.08	17.02	767.07	19.63	953.34	23.02	1164.68	26.70	1560.80	26.94	1954.69	27.57
357.24	31.13	569.72	17.04	768.61	19.66	954.78	23.06	1167.96	26.60	1563.85	27.01	1959.52	27.71
358.98	29.10	571.36	17.06	770.15	19.72	956.22	23.05	1171.24	26.47	1566.90	27.05	1964.34	27.90
360.71	28.12	573.00	17.09	771.69	19.76	957.65	23.09	1174.52	26.47	1569.95	27.08	1969.16	28.13
362.44	26.98	574.64	17.08	773.23	19.80	959.08	23.11	1177.80	26.58	1572.99	27.18	1973.98	28.26
364.17	25.62	576.28	17.08	774.77	19.80	960.52	23.14	1181.07	26.75	1576.03	27.21	1978.79	28.36
365.90	24.65	577.91	17.10	776.31	19.83	961.95	23.15	1184.34	26.88	1579.08	27.24	1983.60	28.45
367.62	23.77	579.55	17.10	777.85	19.90	963.38	23.19	1187.61	26.97	1582.12	27.32	1988.41	28.53
369.35	22.88	581.18	17.11	779.38	19.93	964.81	23.21	1190.88	27.00	1585.15	27.43	1993.21	28.59
371.08	22.15	582.82	17.10	780.92	19.96	966.24	23.20	1194.15	27.10	1588.19	27.53	1998.01	28.42
372.80	21.10	584.45	17.11	782.45	19.93	967.67	23.23	1197.41	27.17	1591.22	27.65	2002.81	28.36
374.53	20.69	586.08	17.09	783.99	20.02	969.10	23.22	1200.67	27.23	1594.26	27.84	2007.60	28.17
376.25	20.03	587.71	17.08	785.52	20.03	970.53	23.26	1203.94	27.24	1597.29	27.93	2012.39	27.97
377.98	19.63	589.35	17.06	787.05	20.04	971.95	23.27	1207.20	27.23	1600.31	28.02	2017.17	27.74
379.70	19.48	590.98	17.04	788.58	20.09	973.38	23.30	1210.45	27.36	1603.34	28.11	2021.95	27.43
381.42	19.26	592.60	17.02	790.11	20.13	974.80	23.31	1213.71	27.39	1606.36	28.25	2026.73	26.99
383.14	19.40	594.23	16.96	791.64	20.18	976.22	23.32	1216.96	27.46	1609.39	28.39	2031.50	26.68
384.86	19.10	595.86	16.92	793.17	20.15	977.65	23.34	1220.22	27.53	1612.41	28.50	2036.28	26.31
386.58	19.36	597.49	16.90	794.70	20.17	979.07	23.38	1223.47	27.55	1615.42	28.60	2041.04	25.94
388.30	19.32	599.11	16.87	796.23	20.19	980.49	23.41	1226.72	27.57	1618.44	28.68	2045.81	25.56
390.02	19.62	600.74	16.82	797.75	20.26	981.91	23.42	1229.96	27.62	1621.46	28.84	2050.57	25.31
391.74	19.81	602.37	16.79	799.28	20.29	983.33	23.44	1233.21	27.62	1624.47	28.94	2055.33	25.00
393.46	19.96	603.99	16.76	800.80	20.31	984.75	23.49	1236.45	27.63	1627.48	29.05	2060.08	24.70
395.17	19.86	605.61	16.74	802.33	20.35	986.16	23.49	1239.70	27.60	1630.49	29.10	2064.83	24.44
396.89	20.09	607.24	16.69	803.85	20.32	987.58	23.53	1242.94	27.65	1633.49	29.22	2069.58	24.27
398.60	20.11	608.86	16.64	805.37	20.38	989.00	23.54	1246.17	27.69	1636.50	29.21	2074.32	24.10
400.32	20.07	610.48	16.63	806.89	20.41	990.41	23.56	1249.41	27.69	1639.50	29.30	2079.06	24.06
402.03	20.05	612.10	16.61	808.41	20.40	991.83	23.54	1252.65	27.72	1642.50	29.39	2083.80	23.93
403.75	20.04	613.72	16.57	809.93	20.41	993.24	23.56	1255.88	27.67	1645.50	29.43	2088.53	23.88
405.46	19.81	615.34	16.56	811.45	20.48	994.65	23.58	1259.11	27.69	1648.50	29.44	2093.27	23.90
407.17	19.58	616.95	16.54	812.97	20.52	996.06	23.62	1262.34	27.78	1651.49	29.60	2097.99	23.96
408.88	19.48	618.57	16.54	814.49	20.52	997.47	23.65	1265.57	27.81	1654.48	29.63	2102.72	24.04
410.59	19.31	620.19	16.50	816.00	20.56	998.88	23.67	1268.79	27.84	1657.47	29.65	2107.44	24.14
412.30	19.10	621.80	16.49	817.52	20.57	1000.29	23.69	1272.02	27.86	1660.46	29.64	2112.16	24.35
414.01	18.93	623.42	16.48	819.03	20.62	1001.70	23.72	1275.24	27.87	1663.45	29.66	2116.87	24.50
415.72	18.77	625.03	16.48	820.55	20.62	1003.10	23.74	1278.46	27.91	1666.43	29.71	2121.58	24.69
417.42	18.57	626.65	16.46	822.06	20.67	1004.51	23.78	1281.68	27.91	1669.42	29.68	2126.29	24.91
419.13	18.57	628.26	16.46	823.57	20.71	1005.92	23.79	1284.90	27.93	1672.40	29.64	2131.00	25.07
420.84	18.46	629.87	16.48	825.08	20.74	1007.32	23.81	1288.11	27.98	1675.38	29.61	2135.70	25.20
422.54	18.31	631.48	16.49	826.59	20.74	1008.72	23.85	1291.33	28.03	1678.35	29.62	2140.40	25.37
424.25	18.19	633.09	16.50	828.10	20.78	1010.12	23.88	1294.54	28.09	1681.33	29.53	2145.10	25.59
425.95	18.01	634.70	16.51	829.61	20.81	1011.53	23.90	1297.75	28.08	1684.30	29.53	2149.79	25.77
427.65	17.95	636.31	16.52	831.12	20.81	1012.93	23.92	1300.96	28.09	1687.27	29.41	2154.48	25.98
429.36	17.88	637.92	16.52	832.63	20.83	1014.33	23.95	1304.16	28.13	1690.24	29.50	2159.16	26.16
431.06	17.80	639.52	16.54	834.13	20.87	1015.73	24.00	1307.37	28.12	1693.21	29.44	2163.85	26.30
432.76	17.75	641.13	16.54	835.64	20.89	1017.12	24.06	1310.57	28.16	1696.17	29.44	2168.53	26.43
434.46	17.63	642.73	16.55	837.14	20.95	1018.52	24.07	1313.77	28.15	1699.14	29.40	2173.21	26.59
436.16	17.56	644.34	16.56	838.65	20.97	1019.92	24.12	1316.97	28.16	1702.10	29.41	2177.88	26.79
437.86	17.49	645.94	16.56	840.15	21.00	1021.31	24.12	1320.17	28.12	1705.06	29.36	2182.55	26.91
439.55	17.41	647.55	16.60	841.65	21.05	1022.71	24.15	1323.36	28.13	1708.01	29.38	2187.22	27.02
441.25	17.40	649.15	16.60	843.15	21.04	1024.10	24.17	1326.56	28.18	1710.97	29.39	2191.89	27.15
442.95	17.34	650.75	16.62	844.65	21.06	1025.49	24.17	1329.75	28.17	1713.92	29.33	2196.55	27.31
444.64	17.33	652.35	16.63	846.15	21.07	1026.88	24.22	1332.94	28.15	1716.87	29.42	2201.21	27.40
446.34	17.26	653.95	16.64	847.65	21.10	1028.27	24.27	1336.13	28.10	1719.82	29.45	2205.87	27.50
448.03	17.22	655.55	16.68	849.15	21.15	1029.66	24.30	1339.31	28.05	1722.77	29.45	2210.52	27.51
449.73	17.20	657.15	16.68	850.65	21.17	1031.05	24.32	1342.50	28.00	1725.71	29.49	2215.17	27.55
451.42	17.14	658.75	16.70	852.14	21.22	1032.44	24.35	1345.68	27.99	1728.65	29.47	2219.82	27.45
453.11	17.12	660.34	16.72	853.64	21.24	1033.83	24.35	1348.86	27.93	1731.60	29.42	2224.47	27.30

461.56	16.93	668.32	16.79	861.11	21.38	1040.75	24.53	1364.74	27.74	1746.27	29.32	2247.65	25.77
463.25	16.93	669.91	16.82	862.60	21.39	1042.13	24.57	1367.91	27.71	1749.20	29.35	2252.28	25.26
464.94	16.92	671.50	16.85	864.09	21.43	1043.51	24.60	1371.08	27.71	1752.12	29.34	2256.91	24.93
466.62	16.89	673.09	16.87	865.57	21.47	1044.89	24.64	1374.24	27.71	1755.05	29.35	2261.53	24.71
468.31	16.85	674.68	16.90	867.06	21.50	1046.27	24.70	1377.41	27.76	1757.97	29.32	2266.15	24.63
469.99	16.84	676.27	16.92	868.55	21.52	1047.65	24.72	1380.57	27.70	1760.89	29.29	2270.77	24.59
471.68	16.80	677.86	16.94	870.04	21.56	1049.03	24.77	1383.73	27.66	1763.81	29.42	2275.39	24.64
473.36	16.78	679.45	16.95	871.52	21.56	1050.41	24.78	1386.89	27.57	1766.73	29.35	2280.00	24.56
475.04	16.75	681.03	16.96	873.01	21.60	1051.78	24.91	1390.04	27.57	1769.64	29.43	2284.61	24.52
476.72	16.72	682.62	16.97	874.49	21.63	1053.16	24.90	1393.20	27.48	1772.55	29.48	2289.22	24.36
478.40	16.72	684.20	17.01	875.97	21.65	1054.53	24.91	1396.35	27.40	1775.46	29.52	2293.82	24.25
480.09	16.72	685.79	17.02	877.45	21.68	1055.90	24.94	1399.50	27.27	1778.37	29.49	2298.43	24.05
481.76	16.68	687.37	17.05	878.94	21.70	1057.27	25.03	1402.65	27.09	1781.28	29.48	2303.03	23.89
483.44	16.67	688.95	17.07	880.42	21.71	1058.65	25.04	1405.80	26.92	1784.18	29.57	2307.62	23.55
485.12	16.64	690.54	17.12	881.89	21.73	1060.02	25.11	1408.95	26.84	1787.09	29.60	2312.22	23.40
486.80	16.64	692.12	17.14	883.37	21.77	1061.38	25.11	1412.09	26.68	1789.99	29.60	2316.81	23.25
488.48	16.64	693.70	17.18	884.85	21.80	1062.75	25.12	1415.23	26.56	1792.88	29.73	2321.40	23.06
490.15	16.63	695.28	17.23	886.33	21.87	1064.12	25.17	1418.38	26.45	1795.78	29.76	2325.99	23.02
491.83	16.61	696.86	17.27	887.80	21.88	1065.49	25.17	1421.51	26.35	1798.67	29.79	2330.57	23.08
493.50	16.61	698.43	17.30	889.28	21.92	1066.85	25.20	1424.65	26.25	1801.57	29.79	2335.15	23.10
495.18	16.57	700.01	17.32	890.75	21.96	1068.22	25.27	1427.79	26.16	1804.46	29.82	2339.73	23.13
496.85	16.59	701.59	17.36	892.23	22.00	1069.58	25.31	1430.92	26.13	1807.34	29.75	2344.31	23.33
498.52	16.56	703.16	17.41	893.70	22.02	1070.94	25.31	1434.05	26.05	1810.23	29.84	2348.89	23.41
500.19	16.54	704.74	17.44	895.17	22.05	1072.31	25.36	1437.18	25.99	1813.11	29.80	2353.46	23.55
501.86	16.55	706.31	17.49	896.64	22.09	1073.67	25.47	1440.31	25.96	1815.99	29.72	2358.03	23.66
503.53	16.51	707.88	17.57	898.11	22.13	1075.03	25.47	1443.43	25.89	1818.87	29.74	2362.60	23.82
505.20	16.48	709.46	17.60	899.58	22.12	1076.39	25.52	1446.55	25.89	1821.75	29.84	2367.16	23.81
506.87	16.49	711.03	17.65	901.05	22.12	1077.75	25.51	1449.68	25.88	1824.63	29.81	2371.72	23.94
508.54	16.46	712.60	17.72	902.52	22.15	1079.10	25.61	1452.80	25.84	1827.50	29.80	2376.28	23.97
510.21	16.43	714.17	17.75	903.99	22.18	1080.46	25.63	1455.91	25.81	1830.37	29.73	2380.84	23.88
511.87	16.40	715.74	17.80	905.45	22.18	1081.82	25.62	1459.03	25.75	1793.20	29.99	2385.40	23.98
513.54	16.37	717.31	17.86	906.92	22.19	1083.17	25.72	1462.14	25.70	1798.16	29.92	2389.95	24.08
515.20	16.33	718.87	17.90	908.38	22.21	1084.52	25.75	1465.26	25.65	1803.11	29.83	2394.50	24.03
516.87	16.33	720.44	17.94	909.84	22.23	1085.88	25.83	1468.37	25.63	1808.06	29.87	2399.05	23.91
518.53	16.31	722.01	18.02	911.31	22.26	1087.23	25.83	1471.48	25.60	1813.01	29.83	2403.60	23.68
520.19	16.30	723.57	18.08	912.77	22.30	1088.58	25.82	1474.58	25.60	1817.95	29.85	2408.14	23.54
521.86	16.32	725.14	18.13	914.23	22.32	1089.93	25.92	1477.69	25.62	1822.88	29.91	2412.69	23.50
523.52	16.31	726.70	18.20	915.69	22.36	1091.28	25.96	1480.79	25.66	1827.82	29.94	2417.23	23.26
525.18	16.31	729.26	18.26	917.15	22.34	1092.63	26.05	1483.89	25.65	1832.75	30.02	2421.77	22.94
526.84	16.34	729.82	18.33	918.61	22.36	1093.98	26.14	1486.99	25.72	1837.67	30.07	2426.30	22.55
528.50	16.35	731.39	18.37	920.06	22.39	1088.75	25.93	1490.09	25.76	1842.59	30.08	2430.83	22.28
530.15	16.38	732.95	18.45	921.52	22.43	1092.07	25.98	1493.18	25.78	1847.51	30.06	2435.37	21.96
531.81	16.38	734.51	18.51	922.98	22.46	1095.39	26.05	1496.28	25.84	1852.42	30.06	2439.90	21.65
533.47	16.39	736.06	18.57	924.43	22.48	1098.71	26.12	1499.37	25.88	1857.33	30.08	2444.42	21.32
535.12	16.41	737.62	18.66	925.88	22.52	1102.02	26.20	1502.46	25.98	1862.24	29.95	2448.95	20.87
536.78	16.45	739.18	18.72	927.34	22.56	1105.34	26.29	1505.55	26.02	1867.14	29.70	2453.47	20.33
538.43	16.47	740.74	18.77	928.79	22.59	1108.65	26.32	1508.63	26.06	1872.03	29.35	2457.99	20.15
540.09	16.50	742.29	18.85	930.24	22.62	1111.96	26.26	1511.71	26.12	1876.93	29.00	2462.51	19.79
541.74	16.55	743.85	18.90	931.69	22.63	1115.27	26.32	1514.80	26.18	1881.81	28.49	2467.03	19.73
543.39	16.58	745.40	18.97	933.14	22.65	1118.57	26.42	1517.88	26.24	1886.70	28.06	2471.54	19.52
545.04	16.61	746.95	19.02	934.59	22.67	1121.88	26.46	1520.96	26.32	1891.58	27.51	2476.06	19.44
546.69	16.64	748.51	19.09	936.04	22.70	1125.18	26.48	1524.03	26.39	1896.44	27.00	2480.57	19.52
548.34	16.67	750.06	19.13	937.48	22.73	1128.48	26.48	1527.11	26.39	1901.33	26.66	2485.08	19.71
549.99	16.70	751.61	19.23	938.93	22.76	1131.78	26.46	1530.18	26.43	1906.20	26.39	2489.58	19.85
551.64	16.71	753.16	19.24	940.38	22.81	1135.08	26.48	1533.25	26.46	1911.07	26.23	2494.09	19.97
553.29	16.76	754.71	19.31	941.82	22.82	1138.38	26.52	1536.32	26.52	1915.93	26.17	2498.59	0.00

C>

APPENDIX 2.

SOIL MOISTURE CHARACTERISTIC DETERMINATION FOR SANDY CLAY LOAM, TRIAL SITE, BURY ST. EDMUNDS UK.

Mc at suction	Results of soil analysis for moisture characteristic curv			
pF	Quadrant 1	Quadrant 2	Quadrant 3	Quadrant 4
saturation	41.39	42.12	42.58	40.37
1.3	31.79	31.53	31.2	29.53
1.6	30	29.26	28.82	26.94
1.8	29.1	28.31	27.7	25.78
1.9	28.48	27.54	26.85	24.86
2.0	28.03	27.09	26.27	24.36
3.0	19.09	17.14	17.08	15.35
3.3	17.51	16.95	15.07	13.53
3.6	15.68	15.57	13.16	11.91
3.9	15.64	15.01	12.11	11.14
4.2	14.93	14.94	11.97	10.56
4.7	6.58	5.38	4.7	5.18
5.4	4.85	5.37	3.61	3.64
5.8	3.89	3.28	2.91	2.97
6.2	2.93	2.4	2.14	2.24
6.7	1.48	1.17	1.08	1.13

APPENDIX 3.

CROP HUSBANDRY FOR EXPERIMENTS 1 AND 2 IN THE 1989 SEASON.

Norman Marley	DATE	Applications
Clopton Green Woolpit		
Crop Winter wheat		
Previous Crop RAPE		
Seed Bed Fertilizer		FYM
CLUB slug pellet	8/9/88	BS. 5.5 Kg / metre CENTRELINER
DRILLED (HEGE)	30/9/88	BS, WA START
(OYJORD)	3/10/88	M.O. R.G. P.S. TIME OF SOWING AND FUNG 4 / 10
(OYJORD)	17/10/88	BS WA PS Y2 AGENCY, F2 MONOSEM 2ND SOWING
(OYJORD)	26/10/88	BS WA PS F2 S.WHEAT WW MULTS
(HEGE)	27/10/88	BS WA PATHOLOGY
(OYJORD)	1/11/88	BS WA PS TIME OF SOWING
SPRAY	2/11/88	BS TRIAL STOMP 4 LTR ARELON 2.25 AMBUSH 250MLS
SPRAY	3/11/88	BS PB AREA EMERGED STOMP ARELON AMBUSH
SPRAY	3/11/88	BS PB PRE EMERGED NO AMBUSH + ROADWAYS
SPRAY	25/3/89	TRIALS AND ROADWAY FOLIMAT 1.15 MLS/HTR
SPRAY	30/3/89	BS FUNGICIDE TRIAL AREAS SPORTAK 1 LTR CORBEL 1 LTR CYCOCEL 2.5 LTR
SPRAY	31/3/89	BS PATHWAYS ROUNDUP 3 LTRS/HTR 300 WATER SMALL 200 LTR HYBRID SPRAYER
FERT	15/4/89	BS TRIAL AND DEMO TIME OF SOWING ROADWAYS 400 KG PRODUCT 34.5% N
FERT	27/4/89	BS P.BREEDING BLOCK 250 KG/HTR PRODUCT 34.5% N
SPRAY	26/4/89	BS ARELON OYJORD FR. NEAR ROAD 3 LTR/HTR
FERT	11/5/89	BS ALL TRIALS AREA 200 KG/HRT PRODUCT
SPRAY	16/5/89	BS TRAIL (FUNGICIDE AREA) BAYLETON 0.5KG CORBEL 0.25 LTR
SPRAY	28/5/89	BS TRIAL FUNGICIDE AREA PATROL 0.75 + RADAR 0.5 LTR / HTR
SPRAY	20/6/89	BS TRIAL AREAS + F2 AREA NEAR ROADWAYS APHOX 230 GRAMMS / HTR
SPRAY	21/6/89	BS PLANT ROWS AND PATHOLOGY TOP ROADWAYS APHOX 280 GRAMMS / HTR

APPENDIX 4.

CROP HUSBANDRY FOR THE 1990 SEASON.

Norman Marley	DATE	Applications
Clopton Green Woolpit		
Crop Winter Wheat		
Previous crop RAPE		
DRILLED	27/9/89	
SPRAY	24/11/89	STOMP, ARELON, AMBUSH
SPRAY	6/4/90	CYCOCEL GROWTH REGULATOR
SPRAY	5/4/90	FUNGICIDE, CORBEL, SPOTRAK
FERT	18/4/90	400 Kg / ha of 34.5 % N (= 138 Kg N / HA)
SPRAY	14/5/90	FUNGICIDE, PATROL, RADAR
FERT	16/5/90	125 Kg / HA of 34.5 % N (= 43 Kg N / HA)
SRAY	12/6/90	FUNGICIDE, DORIN, BRAVO
SRAY	20/6/90	INSECTICIDE, APHOX

APPENDIX 5.

ANOVA ON PLANT DENSITIES M^{-2}, EXPT. 1, 1989 SEASON.

MEANS OF THREE COUNTS PER BLOCK

A. ANALYSIS OF VARIANCE TABLE.

Source of variation	D.F	S.S	M.S	V.R	F.PR
SD BLOCK stratum					
SD	2	60662.9	30331.5	35.37	<0.001
Residual	6	5144.9	857.5		
SD BLOCK VAR stratum					
VAR	2	9502.0	4751.0	11.56	0.002
SD.VAR	4	6014.4	1503.6	3.66	0.036
Residual	12	4931.6	411.0		
SD.BLOCK.VAR.UNITS	54	45440.0	841.5		
Total	80	131695.8			

F TEST BY SOWING DATE: SIGNIFICANT
F TEST BY VARIETY: SIGNIFICANT

It can be concluded that on the basis of this experiment, that there were significant sowing date and variety differences in plant densities at growth stage 16:23.

B. TABLE OF MEANS (PLANTS / M^2)

	S1	S2	S3
SD	207.3	247.7	181.2
	Mission	Avalon	Slejpner
Variety	196.7	219.3	220.1

Standard error of the differences (S.E.D) of means

	SD	VAR	SD*VAR
rep	27	27	9
S.E.D	7.97	5.52	11.15

C. STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION.

Stratum	D.F.	S.E.	CV %
SD.BLOCK	6	9.8	4.6
SD.BLOCK.VAR	12	11.7	5.5

APPENDIX 6.

ANOVA ON PLANT DENSITIES M^{-2}, SOWING DATES 1 AND 2, 1990.

MEANS OF THREE COUNTS PER BLOCK

A. ANALYSIS OF VARIANCE TABLE.

Source of variation	D.F	S.S	M.S	V.R	F.PR
SD BLOCK stratum					
SD	1	69873	69873	6.82	0.048
Residual	5	51227	10245	3.21	
SD BLOCK VAR stratum					
VAR	2	11408	5704	1.79	0.021
SD.VAR	2	3995	1998	0.63	0.554
Residual	10	31907	3191	3.04	
SD.BLOCK.VAR.UNITS	42	44096	1050		
Total	62	212506			

F TEST BY SOWING DATE: SIGNIFICANT
F TEST BY VARIETY: NOT SIGNIFICANT

It can be concluded that on the basis of this experiment, that there were significant sowing date differences in plant densities at growth stage 13:21.

B. TABLE OF MEANS (PLANTS / M^2)

	S1	S2	
SD	245.9	313.2	
	Mercia	Avalon	Tonic
Variety	291.4	258.5	274.3

B. STANDARD ERROR OF THE DIFFERENCES OF MEANS.

	SD	VAR	SD*VAR
rep	unequal	21	unequal
			min.rep 35.09
S.E.D	25.77	17.43	max-min 32.83
			max.rep 30.39

C. STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION.

Stratum	D.F.	S.E.	CV %
SD.BLOCK	5	33.74	12.3
SD.BLOCK.VAR	10	32.61	11.9
SD.BLOCK.VAR UNITS	42	32.4	11.8

APPENDIX 7.

ANOVA ON GRAIN YIELD, EXPT. 1, 1989 SEASON.

A. ANALYSIS OF VARIANCE TABLE.

Source of variation	D.F	S.S	M.S	V.R	F.PR
S.D. BLOCK stratum					
SD	2	2.1071	1.0535	1.9	0.23
Residual	6	3.3281	0.5547		
SD BLOCK VAR stratum					
VAR	2	10.6004	5.3002	16.48	0.001
SD.VAR	4	0.0578	0.0145	0.04	0.996
Residual	12	3.8583	0.3215		
Total	26	19.9517			

TEST F BY SOWING DATE: NOT SIGNIFICANT
TEST F BY VARIETY: SIGNIFICANT

It can be concluded that on the basis of this experiment, there were significant differences in yield due to variety.

B. TABLE OF MEANS (KG / PLOT)

	Slejpner	Avalon	Mission
Variety	6.95	6.09	5.42

Standard error of the differences (S.E.D) of means = 0.267

L.S.D. = S.E.D x t (12 d.f.)
= 0.267 x 2.179
= 0.582

For variety, L.S.D's are > 0.582, accept H_1 reject H_0

On the basis of this experiment there appeared to be differences in yield due to variety.

C. STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION.

Stratum	D.F.	S.E.	CV %
SD.BLOCK	6	0.43	7.0
SD.BLOCK.VAR	12	0.57	9.2

APPENDIX 8.

ANOVA ON HEAD DENSITY M^{-2}, EXPT. 1, 1989 SEASON.

MEANS OF THREE COUNTS PER BLOCK

A. ANALYSIS OF VARIANCE TABLE.

Source of variation	D.F	S.S	M.S	V.R	F.PR
SD BLOCK stratum					
SD	2	1012.67	506.33	1.2	0.365
Residual	6	2539.33	423.22		
SD BLOCK VAR stratum					
VAR	2	4012.07	2006.04	4.89	0.028
SD.VAR	4	1337.48	334.37	0.81	0.54
Residual	12	4923.78	410.31		
SD BLOCK VAR					
Stratum	54	5286.67	97.9		
Total	80	19112.0			

TEST F BY SOWING DATE: NOT SIGNIFICANT
TEST F BY VARIETY: SIGNIFICANT

It can be concluded on the basis of this experiment, that the varieties showed significant differences in head density.

B. TABLE OF MEANS (KG / PLOT)

	Slejpner	Avalon	Mission
Variety	105.1	99.4	88.1

Standard error of the differences (S.E.D) of means = 5.51

L.S.D. = S.E.D x t (12 d.f.)
= 5.51 x 2.179
= 0.582 x 2.179
= 12.01

For variety, L.S.D's are > 12.01, accept H_1 reject H_0

On the basis of this experiment there appeared to be variety differences in head density. Differences were found between cultivars Mission and Slejpner.

C. STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION.

Stratum	D.F.	S.E.	CV %
SD.BLOCK	6	6.86	7.0
SD.BLOCK.VAR	12	11.69	12.0
SD.BLOCK.VAR			
UNITS	54	9.89	10.1

APPENDIX 9.

ANOVA ON GRAIN YIELD EXPT. 2, 1989 SEASON.

A. ANALYSIS OF VARIANCE TABLE.

Source of variation	D.F	S.S	M.S	V.R	F.PR
TREATMENT.BLOCK stratum					
TREATMENT	1	37.577	37.577	194.06	<0.001
Residual	6	1.162	0.194		
TREATMENT BLOCK VAR stratum					
VAR	1	6.401	6.401	24.72	<0.003
TREATMENT.VAR	1	27.353	27.353	105.62	<0.001
Residual	6	1.554	0.259		
Total	15	74.046			

F TEST BY TREATMENT: SIGNIFICANT
F TEST BY VARIETY: SIGNIFICANT
F TEST INTERACTION: SIGNIFICANT

It can be concluded that yield differences existed due to treatment and variety interactions.

C. STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION.

Stratum	D.F.	S.E.	CV %
TREATMENT.BLOCK	6	0.311	5.5
TREATMENT.BLOCK.VAR	6	0.509	9.0

APPENDIX 10.

ANOVA ON HEAD DENSITY M^{-2}, EXPT. 2, 1989 SEASON.

MEANS OF THREE COUNTS PER BLOCK

A. ANALYSIS OF VARIANCE TABLE.

Source of variation	D.F	S.S	M.S	V.R	F.PR
TREATMENT.BLOCK stratum					
TREATMENT	1	18.75	18.75	0.17	0.694
Residual	6	661.92	110.32		
TREATMENT BLOCK VAR stratum					
VAR	1	13200.33	13200.33	77.33	<0.001
TREATMENT.VAR	1	7752.08	7752.08	45.41	<0.001
Residual	6	1024.25	170.71		
TREATMENT.BLOCK.VAR.					
UNITS STRATUM	32	2467.33	77.10		
Total	47	25124.67			

F TEST BY TREATMENT:	NOT SIGNIFICANT
F TEST BY VARIETY:	SIGNIFICANT
F TEST INTERACTION:	SIGNIFICANT

It can be concluded that yield differences existed due to treatment and variety interactions.

C. STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION.

Stratum	D.F.	S.E.	CV %
TREATMENT.BLOCK	6	4.29	4.4
TREATMENT.BLOCK.VAR	6	7.54	7.7
TREATMENT.BLOCK.VAR UNITS	32	8.78	9.0

APPENDIX 11.

COMPARISON OF SINGLE DATE REGRESSION MODELS, LOG_E YIELD = Á + ß (VI), 12 APRIL AND 19 APRIL, EXPERIMENT 1, 1989.

	S.S.	D.F.	M.S.
Resdiual variation for 12 April	0.17632	25	0.00705
Residual variation for 19 April	0.16931	25	0.00677
Sum of Residual variations	0.345663	50	6.0×10^{-3}
Residual variation about single line	0.37037	52	
Difference	0.02474	2	0.01237

$$F = \frac{\text{Difference M.S.}}{s^2} = 1.789$$

Hence the use of a single line was significantly better than the individual fits (P<5%). It can be concluded that the relationships were not different for the two dates.

APPENDIX 12.

COMPARISON OF SINGLE DATE REGRESSION MODELS, LOG_E YIELD = Á + ß (VI), 19 APRIL AND 4 MAY, EXPERIMENT 1, 1989.

	S.S.	D.F.	M.S.
Resdiual variation for 12 April	0.16931	25	0.00677
Residual variation for 19 April	0.10611	25	0.00424
Sum of Residual variations	0.27542	50	5.5×10^{-3}
Residual variation about single line	0.86277	52	
Difference	0.58735	2	0.2937

$$F = \frac{\text{Difference M.S.}}{s^2} = 53.31$$

Hence it can be concluded that the use of a single line was significantly worse than the individual fits (P<5%). Therefore, the relationships were different for the two dates.

APPENDIX 13.

COMPARISON OF SINGLE DATE REGRESSION MODELS, LOG_E YIELD = Á + ß (VI), 4 MAY AND 10 MAY, EXPERIMENT 1, 1989.

	S.S.	D.F.	M.S.
Resdiual variation for 12 April	0.10611	25	0.00424
Residual variation for 19 April	0.13347	25	0.00534
Sum of Residual variations	0.23958	50	4.79×10^{-3}
Residual variation about single line	0.54783	52	
Difference	0.30825	2	0.154125

$$F = \frac{\text{Difference M.S.}}{S^2} = 32.17$$

Hence it can be concluded that the use of a single line was significantly worse than the individual fits ($P < 5\%$). Therefore, the relationships were different for the two dates.

NB. The residual mean squares about the individual regression lines were similar, pooling of the residual means was reasonable.

APPENDIX 14. GENSTAT5 CODE FOR NON-LINEAR MODEL FITTING.

```
job 'andy's curve data'
unit [13]
open 'slr1trs1.dat'; ch=2
read [ch=2] x,y
calc x2=x*x
expression exp[1];valu=!e(first=((x/100)**c)* \
(exp (-(d*x*x)))*(exp(+(d*100*100))))
MODEL y; FITTEDVALUES=first
RCYCLE [maxcycle=40] c,d; INITIAL=2.4, 0.0000043
FITNONLINEAR [constant=e;PRINT=MONITOR,SUM,EST,corr,fitt; \
selin=yes;CALCULATION=exp] first,x2
RKEEP FITTEDVALUES=rhofit
GRAPH y,rhofit;x; METHOD=POINT,CURVE
end
```

APPENDIX 15. NDVI NON-LINEAR PARAMETERS, EXPERIMENT 1, 1989 SEASON.

EXPERIMENT 1 1989, SOWING DATE AND VARIETY TRIAL

R1 = REPLICATE 1, R2 = REPLICATE 2, R3 = REPLICATE 3

S1 = SOWING DATE 4.10.88

REPLICATE		CONSTANT	A	B	C	D	E
MISSION	S1 R1	0.5551	-0.20560	8	-2.3920	-0.000115000	0.00000650
MISSION	S1 R2	0.5240	-0.17190	8	-2.8050	-0.000134100	0.00000652
MISSION	S1 R3	0.5532	-0.20110	8	-1.9750	-0.000098200	0.00000666
AVALON	S1 R1	0.5779	-0.22610	8	-1.9950	-0.000099000	0.00000721
AVALON	S1 R2	0.5873	-0.23560	8	-2.0500	-0.000101300	0.00000712
AVALON	S1 R3	0.6821	-0.33000	8	-2.5250	-0.000116000	0.00000474
SLEJPNER	S1 R1	0.5321	-0.18040	8	-1.9810	-0.000099800	0.00000764
SLEJPNER	S1 R2	0.5354	-0.18330	8	-1.9500	-0.000098800	0.00000765
SLEJPNER	S1 R3	0.5776	-0.22550	8	-2.0350	-0.000099900	0.00000700

SOWING DATE 17.10.88

REPLICATE		CONSTANT	A	B	C	D	E
MISSION	S2 R1	0.5107	-0.16190	10	-1.3730	-0.000081800	0.00001115
MISSION	S2 R2	0.4401	-0.08880	10	-2.7400	-0.000141100	0.00000729
MISSION	S2 R3	0.5014	-0.15230	10	-1.4640	-0.000085900	0.00001075
AVALON	S2 R1	0.5861	-0.23760	10	-1.5370	-0.000083600	0.00000948
AVALON	S2 R2	0.5436	-0.19460	10	-1.7460	-0.000093700	0.00000925
AVALON	S2 R3	0.4791	-0.13100	10	-1.1630	-0.000078400	0.00001255
SLEJPNER	S2 R1	0.4715	-0.12120	10	-1.0230	-0.000070200	0.00001253
SLEJPNER	S2 R2	0.4974	-0.14790	10	-0.9460	-0.000063500	0.00001267
SLEJPNER	S2 R3	0.5253	-0.17610	10	-0.9750	-0.000064500	0.00001275

SOWING DATE 3 1.11.88

REPLICATE		CONSTANT	A	B	C	D	E
MISSION	S3 R1	0.4200	0.62e-08	22	10.2900	0.000103200	-0.00000730
MISSION	S3 R2	0.4018	0.34e-05	22	6.9100	0.000063500	-0.00001580
MISSION	S3 R3	0.4189	0.61e-12	22	15.3800	0.000159000	-0.00000412
AVALON	S3 R1	0.3097	-0.89e-10	22	9.3500	0.000001000	0.00001708
AVALON	S3 R2	0.3585	-0.00016	22	1.9507	-0.000056900	0.00001636
AVALON	S3 R3	0.4470	-1.58000	22	1.9791	-0.295e-06	0.00316000
SLEJPNER	S3 R1	0.5320	-0.22400	22	0.7900	-0.000016000	0.00006940
SLEJPNER	S3 R2	0.3946	0.15e-05	22	7.3200	0.000069700	-0.00001170
SLEJPNER	S3 R3	0.4150	0.04200	22	2.4200	0.000006100	-0.00016200

APPENDIX 16. NDVI NON-LINEAR PARAMETERS, EXPERIMENT 2, 1989 SEASON.

TR = FUNGICIDE TREATED, UN = FUNGICIDE UNTREATED

R1 = REPLICATE 1, R2 = REPLICATE 2, R3 = REPLICATE 3

	CONSTANT	A	B	C	D	E
MISSION R1 TR	0.6174	-0.2658	8	-2.8160	-0.0001281	0.000005090
MISSION R2 TR	0.6125	-0.2611	8	-2.6710	-0.0001213	0.000005220
MISSION R3 TR	0.6132	-0.2617	8	-2.2970	-0.0001070	0.000005380
MISSION R4 TR	0.6105	-0.2589	8	-3.1700	-0.0001424	0.000004650
MISSION R1 UN	0.6369	-0.2856	8	-1.4520	-0.0000744	0.000007480
MISSION R2 UN	0.5540	-0.2031	8	-1.5010	-0.0000801	0.000008380
MISSION R3 UN	0.5951	-0.2440	8	-1.4000	-0.0000746	0.000008530
MISSION R4 UN	0.5917	-0.2405	8	-1.4680	-0.0000769	0.000008000
SLEJPNER R1 TR	0.5580	-0.2065	8	-3.3440	-0.0001513	0.000005439
SLEJPNER R2 TR	0.5534	-0.2018	8	-1.8700	-0.0000937	0.000007230
SLEJPNER R3 TR	0.5573	-0.2059	8	-2.4390	-0.0001153	0.000006524
SLEJPNER R4 TR	0.5581	-0.2066	8	-2.3180	-0.0001106	0.000006050
SLEJPNER R1 UN	2.2900	-1.9300	8	-0.0620	-0.0000115	0.000025500
SLEJPNER R2 UN	1.7700	-1.4200	8	-0.0710	-0.0000129	0.000022300
SLEJPNER R3 UN	4.3000	-4.0000	8	-0.0270	-0.0000076	0.000034100
SLEJPNER R4 UN	11.5000	-11.1000	8	-0.0042	0.0000069	-0.000059000

APPENDIX 17. NDVI NON-LINEAR PARAMETERS, 1990 SEASON.

S1 = SOWING DATE 27.9.89, S2 = SOWING DATE 30.10.89

TR = FUNGICIDE TREATED, UN = FUNGICIDE UNTREATED

	CONSTANT	B1	B2	B3	B4
MERCIA R1 S1 TR	0.3296962	0.1852565e-02	-0.4003344e-04	0.4232059e-06	-0.101278e-08
MERCIA R2 S1 TR	-0.5426114e-01	0.127873e-01	-0.1417112e-03	0.7932938e-06	-0.1475537e-08
AVALON R1 S1 TR	-0.1815966	0.188095-01	-0.2068724e-03	0.1053556e-05	-0.1828827e-08
AVALON R2 S1 TR	0.4899473e-01	0.1055007e-01	-0.1422484e-03	0.8713763e-06	-0.165697e-08
TONIC R1 S1 TR	0.2719408	0.6408056e-02	-0.1052336e-03	0.726653e-06	-0.1462089e-08
TONIC R2 S1 TR	0.211675	0.7282982e-02	-0.1092165e-03	0.7198623e-06	-0.1426079e-08
MERCIA R1 S1 UN	-0.9200502e-02	0.111993e-01	-0.1424663e-03	0.8465713e-06	-0.1590645e-08
MERCIA R1 S1 UN	0.1632438	0.4303655e-02	-0.6747362e-04	0.5555658e-06	-0.1220674e-08
AVALON R1 S1 UN	0.4154386	-0.2462005e-02	-0.7910236e-05	0.3450757e-06	-0.9622713e-09
AVALON R2 S1 UN	0.5526037	-0.7224597e-02	0.4164616e-04	0.1436179e-06	-0.6811875e-09
TONIC R1 S1 UN	0.5212786	-0.3808272e-02	-0.1617582e-04	0.432617e-06	-0.1125969e-08
TONIC R2 S1 UN	0.2026337	0.4601979e-02	-0.8723895e-04	0.6762207e-06	-0.1419321e-08
MERCIA R1 S2 TR	0.1192741	0.6634121e-02	-0.7711081e-04	0.6406073e-06	-0.158104e-08
MERCIA R2 S2 TR	0.1114075	0.7606359e-02	-0.1031546e-03	0.8035013e-06	-0.1877813e-08
MERCIA R3 S2 TR	0.1236985	0.6016011e-02	-0.787572e-04	0.6764586e-06	-0.1662581e-08
AVALON R1 S2 TR	0.1559779	0.4161615e-02	-0.5081689e-04	0.5481883e-06	-0.1484187e-08
AVALON R2 S2 TR	0.1877212	0.3009291e-02	-0.5331652e-04	0.6216965e-06	-0.167091e-08
AVALON R3 S2 TR	0.1197274	0.6693304e-02	-0.9593062e-04	0.7990829e-06	-0.1919473e-08
TONIC R1 S2 TR	0.2280069e-01	0.1176539e-01	-0.1398765e-03	0.9200077e-06	-0.200728e-08
TONIC R2 S2 TR	0.1387643	0.6429563e-02	-0.8001871e-04	0.6724728e-06	-0.1660671e-08
TONIC R2 S2 TR	0.593428e-01	0.1024526e-01	-0.1297277e-03	0.902267e-06	-0.2010436e-08

APPENDIX 18. NDVI POLYNOMIAL MODEL PARAMETERS, EXPERIMENT 1, 1989 SEASON.

S1 = SOWING DATE 1 (4.10.88), S2 = SOWING DATE 2 (17.10.88),
S3 = SOWING DATE 3 (1.11.88)

R1 = REPLICATE 1, R2 = REPLICATE 2, R3 = REPLICATE 3

	A_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7
MISSION S1 R1	0.2328633e+03	-0.1158309e+02	0.2217453	-0.2191303e-02	0.1230932e-04	-0.3977515e-07	0.6901390e-10	-0.4989904e-13
MISSION S1 R2	0.2810094e+03	-0.1395691e+02	0.2666035	-0.2629701e-02	0.1475187e-04	-0.4762730e-07	0.8260449e-10	-0.5972103e-13
MISSION S1 R3	0.2267152e+03	-0.1123907e+02	0.2142256	-0.2106438e-02	0.1176699e-04	-0.3779138e-07	0.6513881e-10	-0.4676379e-13
MISSION S2 R1	0.8851345e+02	-0.5239748e+01	0.1136114	-0.1242117e-02	0.7624109e-05	-0.2671850e-07	0.5003652e-10	-0.3892295e-13
MISSION S2 R2	0.1501705e+03	-0.8905647e+01	0.1928732	-0.2104801e-02	0.1287940e-04	-0.4493608e-07	0.8366794e-10	-0.6461889e-13
MISSION S2 R3	0.8195037e+02	-0.4860477e+01	0.1057298	-0.1159932e-02	0.7143383e-05	-0.2511127e-07	0.4716017e-10	-0.3678136e-13
MISSION S3 R1	0.3262579e+02	-0.2596023e+01	0.6728322e-01	-0.8434018e-03	0.5814324e-05	-0.2259545e-07	0.4651038e-10	-0.3950655e-13
MISSION S3 R2	-0.9645261e+01	0.766296	-0.1800788e-01	0.1982802e-03	-0.1166707e-05	0.3759025e-08	-0.6176299e-11	0.3942477e-14
MISSION S3 R3	0.4919894e+02	-0.3917135e+01	0.1010073	-0.1258264e-02	0.8612437e-05	-0.3321036e-07	0.6779805e-10	-0.5708723e-13
AVALON S1 R1	0.1633671e+03	-0.8100122e+01	0.1546457	-0.1523770e-02	0.8536284e-05	-0.2751824e-07	0.4765709e-10	-0.3441372e-13
AVALON S1 R2	0.1216671e+03	-0.6054169e+01	0.1163257	-0.1154448e-02	0.6517580e-05	-0.2118356e-07	0.3700502e-10	-0.2696723e-13
AVALON S1 R3	0.2369640e+03	-0.1175275e+02	0.2242851	-0.2208640e-02	0.1236066e-04	-0.3978784e-07	0.6876594e-10	-0.4952407e-13
AVALON S2 R1	0.9602392e+02	-0.5684892e+01	0.1232529	-0.1346003e-02	0.8241598e-05	-0.2877594e-07	0.5363141e-10	-0.4148080e-13
AVALON S2 R2	0.1691949e+03	-0.1003611e+02	0.2174883	-0.2375973e-02	0.1456392e-04	-0.5093552e-07	0.9512200e-10	-0.7371957e-13
AVALON S2 R3	0.9596578e+02	-0.5679403e+01	0.1229693	-0.1342401e-02	0.8227524e-05	-0.2879317e-07	0.5385345e-10	-0.4184610e-13
AVALON S3 R1	0.2465516e+02	-0.1948110e+01	0.5013744e-01	-0.6241738e-03	0.4280780e-05	-0.1657908e-07	0.3406407e-10	-0.2892516e-13
AVALON S3 R2	0.3862074e+02	-0.3060009e+01	0.7846608e-01	-0.9713846e-03	0.6613822e-05	-0.2540446e-07	0.5173697e-10	-0.4352241e-13
AVALON S3 R3	0.5171135e+02	-0.4124376e+01	0.1065971	-0.1331528e-02	0.9145008e-05	-0.3540864e-07	0.7262337e-10	-0.6146094e-13
SLEJPNER S1 R1	0.1795956e+03	-0.8986433e+01	0.1735594	-0.1732788e-02	0.9843623e-05	-0.3218650e-07	0.5652971e-10	-0.4137666e-13
SLEJPNER S1 R2	0.2036649e+03	-0.1011450e+02	0.193389	-0.1909689e-02	0.1072644e-04	-0.3467723e-07	0.6022567e-10	-0.4360218e-13
SLEJONER S1 R3	0.1550623e+03	-0.7708143e+01	0.1478117	-0.1464830e-02	0.8261637e-05	-0.2683130e-07	0.4683250e-10	-0.3408958e-13
SLEJPNER S2 R1	0.1127703e+03	-0.6721728e+01	0.1469993	-0.1623933e-02	0.1007992e-04	-0.3572788e-07	0.6764826e-10	-0.5316312e-13
SLEJPNER S2 R2	0.1168430e+03	-0.6925137e+01	0.1501497	-0.1642202e-02	0.1008528e-04	-0.3536101e-07	0.6623503e-10	-0.5150614e-13
SLEJPNER S2 R3	0.8645324e+02	-0.5135042e+01	0.1119743	-0.1233130e-02	0.7633101e-05	-0.2699742e-07	0.5104487e-10	-0.4008859e-13
SLEJPNER S3 R1	0.3203075e+02	-0.2559444e+01	0.6687108e-01	-0.8473964e-03	0.5918383e-05	-0.2333210e-07	0.4375048e-10	-0.4203502e-13
SLEJPNER S3 R2	0.2748915e+02	-0.2200628e+01	0.5793832e-01	-0.7404413e-03	0.5212345e-05	-0.2068842e-07	0.4347018e-10	-0.3765526e-13
SLEJPNER S3 R3	0.1746036e+02	-0.1396228e+01	0.3721746e-01	-0.4823819e-03	0.3445879e-05	-0.1387365e-07	0.2954746e-10	-0.2592277e-13

APPENDIX 19. NDVI POLYNOMIAL MODEL PARAMETERS, EXPERIMENT 2, 1989 SEASON.

TR = FUNGICIDE TREATED, UN = FUNGICIDE UNTREATED

R1 = REPLICATE 1, R2 = REPLICATE 2, R3 = REPLICATE 3

	A_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7
MISSION R1 TR	0.1267942e+03	-0.6104541e+01	0.1138264	-0.109791e-02	0.6029558e-05	-0.1907566e-07	0.3245408e-10	-0.2304176e-13
MISSION R2 TR	0.147236e+03	-0.7143084e+01	0.134379	-0.1309196e-02	0.7267346e-05	-0.2324795e-07	0.3999504e-10	-0.2871197e-13
MISSION R3 TR	0.1168971e+03	-0.5602609e+01	0.1038025	-0.9926483e-03	0.5392712e-05	-0.1683861e-07	0.2821116e-10	-0.1968759e-13
MISSION R4 TR	0.1423628e+03	-0.6882374e+01	0.128903	-0.1249359e-02	0.68955e-05	-0.219247e-07	0.3748603e-10	-0.2674873e-13
MISSION R1 UN	-0.1021852e+03	0.5061065e+01	-0.966e-01	0.9588337e-03	-0.5432137e-05	0.1775334e-07	-0.3119628e-10	0.2283554e-13
MISSION R2 UN	-0.1121099e+01	0.1136577	-0.304e-02	0.4101536e-04	-0.2992534e-06	0.1202221e-08	-0.2492372e-11	0.2073328e-14
MISSION R3 UN	-0.9571643e+02	0.4724397e+01	-0.897e-01	0.8861126e-03	-0.4988638e-05	0.1618902e-07	-0.2822657e-10	0.2048683e-13
MISSION R4 UN	-0.1986650e+02	0.1049156e+01	-0.211e-01	0.2242286e-03	-0.1359885e-05	0.4756932e-08	-0.8919995e-11	0.6930796e-14
SLEJPNER R1 TR	0.1655649e+03	-0.8093445e+01	0.1536923	-0.1513858e-02	0.8503961e-05	-0.2754323e-07	0.4798486e-10	-0.3488126e-13
SLEJPNER R2 TR	0.4721972e+02	-0.2288013e+01	0.434e-01	-0.4293126e-03	0.2421295e-05	-0.788614-08	0.1384008e-10	-0.1015815e-13
SLEJPNER R3 TR	0.158845e+03	-0.7756711e+01	0.1471633	-0.1448716e-02	0.8136781e-05	-0.2635924e-07	0.4594297e-10	-0.3341744e-13
SLEJPNER R4 TR	0.164333e+03	-0.7988168e+01	0.1505836	-0.1471068e-02	0.8191646e-05	-0.2629222e-07	0.4538243e-10	-0.3268175e-13
SLEJPNER R1 UN	0.1291862e+03	-0.6367615e+01	0.1224253	-0.1222247e-02	0.6958008e-05	-0.2280984e-07	0.4013378e-10	-0.2938179e-13
SLEJPNER R2 UN	0.1974116e+03	-0.9656129e+01	0.1833452	-0.1805047e-02	0.1012702e-04	-0.3271835e-07	0.5675813e-10	-0.4099268e-13
SLEJPNER R3 UN	0.2094768e+03	-0.1026069e+02	0.1951763	-0.1925559e-02	0.1082779e-04	-0.3506665e-07	0.60983e-10	-0.4415446e-13
SLEJPNER R4 UN	0.7588062+02	-0.3722641e+01	0.714e-01	-0.7111612e-03	0.403694e-05	-0.1318916e-07	0.2310958e-10	-0.1683277e-13

APPENDIX 20.

ANOVA ON GRAIN YIELD ($T.HA^{-1}$), SOWING DATE 1, 1990 SEASON.

A. ANALYSIS OF VARIANCE TABLE.

Source of variation	D.F.	S.S.	M.S.	V.R.	F.PR
TREATMENT.BLOCK stratum					
TREATMENT	1	0.559	0.559	4.42	0.17
Residual	2	0.253	0.127	2.8	
TREATMENT.BLOCK.VAR stratum					
VAR	2	0.065	0.032	0.72	0.54
TREATMENT.VAR	2	0.051	0.025	0.56	0.61
Residual	4	0.181	0.045		
Total	11	1.108			

F TEST BY TREATMENT: NOT SIGNIFICANT
F TEST BY VARIETY: NOT SIGNIFICANT
F TEST INTERACTION: NOT SIGNIFICANT

It can be concluded on the basis of this experiment, that there were no significant differences in grain yield for varieties of winter wheat receiving different levels of fungicide.

B. STANDARD ERRORS OF DIFFERENCES OF MEANS

	TREATMENT	VAR	TREATMENT*VARIETY
REP.	6	4	2
S.E.D.	0.2054	0.1502	0.2688

C. STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION.

Stratum	D.F.	S.E.	CV %
TREATMENT.BLOCK	2	0.205	2.4
TREATMENT.BLOCK.VAR	4	0.213	2.5

APPENDIX 21.

ANOVA ON GRAIN YIELD ($T.HA^{-1}$), SOWING DATES 1 AND 2, 1990 SEASON.

A. ANALYSIS OF VARIANCE TABLE.

Source of variation	D.F.	S.S.	M.S.	V.R.	F.PR
SD.BLOCK stratum					
SD	1	8.859	8.859	18.23	0.008
Residual	5	2.43	0.486	9.25	
SD.BLOCK.VAR stratum					
VAR	2	3.4802	1.740	33.12	<0.001
SD.VAR	2	3.2996	1.65	31.4	<0.001
Residual	10	0.5255	0.0525		
Total	20	18.5946			

F TEST BY TREATMENT: SIGNIFICANT
F TEST BY VARIETY: SIGNIFICANT
F TEST INTERACTION: SIGNIFICANT

It can be concluded on the basis of this experiment, that there were significant differences in grain yield for varieties of winter wheat sown on different dates. This was shown to be variety and sowing date dependent.

B. STANDARD ERRORS OF DIFFERENCES OF MEANS

	SD	VAR	SD*VAR
REP.	Unequal	7	Unequal
S.E.D.	0.3074	0.123	0.3624

C. STRATUM STANDARD ERRORS AND COEFFICIENTS OF VARIATION.

Stratum	D.F.	S.E.	CV %
SD.BLOCK	5	0.4025	5.0
SD.BLOCK.VAR	10	0.2292	2.9

References

ADAS (1978). Decimal growth stage key for cereals. Short Term Leaflet 204. MAFF.

Allan, J.A. (1990). Sensors, platforms and applications; acquiring and managing remotely sensed data. Steven, M.D., and Clark, J.A. (Eds). Applications of Remote Sensing in Agriculture. Butterworths.

Allen, J.C. (1976). A modified sine wave method for calculating Degree Days. Environmental Entomology, Vol 5, No.3: 388-396.

Appleton, R.J. and Hagger, P.H.F. (1985). Apical timed N should add precision to ADAS recommendations. Arable Farming, Vol 12, No.2: 26-30.

Ashcroft, P.M., Catt, J.A., Curran, P.J., Munden, J.W., Webster, R. (1988). Relation between yield and reflected radiation on the Broadbalk experiment at Rothamsted. Proc. of the NERC (1987) Airborne Campaign Workshop. University of Southampton.

Asrar, G., Fuchs, M., Kanemasu, E.T., Hatfield, J.L. (1984). Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance of wheat. Agronomy Journal, 76: 300-306.

Badhwar, G.D. and Henderson, K.E. (1981). Estimating development stages of corn from spectral data - an initial model. Agronomy Journal. Vol 73: 748-755.

Badhwar, G.D. (1984). Use of LANDSAT derived profile features for spring small grains classification. International Journal of Remote Sensing, Vol 5, No.5: 783-797.

Baker, C.K. and Gallagher, J.N. (1983). The development of winter wheat in the field. 1. Relation between apical development and plant morphology within and between seasons. Journal of Agricultural Science, Cambridge. 101: 327-335.

Biscoe, P.V. and Willington, V.B.A. (1983). Role of physiology in the production of heavy wheat yields. In Yield of Cereals, course papers. NAC Arable Unit, Stoneleigh, Warwickshire.

Biscoe, P.V. and Willington, V.B.A. (1984). Cereal crop physiology - a key to accurate nitrogen timing. In Marketable Yield of Cereals. Course Papers. Arable Unit, NAC, Coventry. pp 67-74.

Blakeman, R.H. (1990). The identification of crop disease and stress by aerial photography. Steven, M.D. and Clark, J.A. (Eds). Applications of Remote Sensing in Agriculture, Butterworths.

Boatwright, G.O., Whitehead, V.S. (1986). Early warning and crop condition assessment research. IEEE Transactions on Geoscience and Remote Sensing. 24, No.1: 54-64.

Brenchley, G.H. (1966). The aerial photography of potato blight epidemics. Journal of the Royal Aeronautical Society. 70: 1082-1085.

Clevers, J.G.P.W. (1986). Application of remote sensing to agricultural field trials. Wageningen Agricultural University Papers 86-4, The Netherlands.

Colwell, R.N. (1956). Determining the prevalence of certain cereal crop diseases by means of aerial photography. Hillgardia, Vol 26, No.5.

Couvreur, F., Ingoat, G. and Masse, J. (1980). Les stades du ble. Institut technique des Cereales et des Fourrages, Paris.

Curran, P.J. and Williamson, H.D. (1985). How many ground data samples? A question for remote sensing. Proc. on Advanced Technology for Monitoring and processing Global Environmental Data, University of London. RSS & CERMA, 163-169.

Curran, P.J. (1988). The semivariogram in remote sensing: an introduction. Remote Sensing of Environment. 24: 493-507.

Curran, P.J. (1989). Remote Sensing of foliar chemistry. Remote Sensing of Environment. 30: 271-278.

Daughtry, C.S.T., Vanderbilt, V.C., Pollara, V.J. (1982). Variability of reflectance measurements with sensor altitude and canopy type. Agronomy Journal. 74: 744-751.

Daughtry, C.S.T., Gallo, K.P., Bauer, M.E. (1983). Spectral estimates of solar radiation intercepted by corn canopies. Agronomy Journal. 75: 527-531.

Daughtry, C.S.T. (1988). Estimating absorbed radiation and phytomass from multispectral reflectance of corn and soybeans. Proceedings IGARSS 1988 Symposium. Edinburgh, Scotland. 13-16 September. 821-824

Day, W., Lawler, D.W., Legg, B.J. (1981). The effects of drought on barley: soil and plant water relations. Journal of Agricultural Science, Cambridge. 96: 61-77.

De Bast A, and Palm R. (1990). Construction of an agro-meteorological model for forecasting agricultural production in the twelve countries of the European Community. Proceedings of the Application of Remote Sensing to Agricultural Statistics. Joint Research Centre, Commission of the European Communities, Varese, Italy. 253-260.

Demetriades-Shah, T.H., Steven, M.D., Clark, J.A. (1990). High resolution derivative spectra in remote sensing. Remote Sensing of Environment. 33: 55-64.

Duggin, M.J. (1977). Likely effects of solar elevation on the quantification of changes in vegetation with maturity using sequential Landsat imagery. Applied Optics. 16 No. 3: 521-523.

Duggin, M.J. (1980b). The field measurement of reflectance factors. Photogrammetric Engineering and Remote Sensing. 46: 643-647.

Gallagher, J.N. and Biscoe, B.V. (1978). Radiation transmitted through crop canopies to analyse stand growth. Delta-T Devices Ltd. Applications Note No. APL-3.

GENSTAT 5. release 1.2 (Vax/VMS4) Copyright (1987). Lawes Agricultural Trust (Rothamsted Experimental Station).

Goel, N.S. (1987). Models of vegetation canopy reflectance and their use in estimations of biophysical parameters from reflectance data. Harwood Academic Press.

Grant, L. (1987). Diffuse and specular characteristics of leaf reflectance. Remote Sensing of the Environment. 22: 309-322.

Green, C.F. (1988). Using observations of radiation transmitted through crop canopies to analyse stand growth. Delta-T Devices. Applications Note No: APL-3.

Green, C.F., Paulson, G.A., Ivins, J.D. (1985). Time of sowing and the development of winter wheat. Journal of Agricultural Science, Cambridge. 105: 217-21.

Greenwood, D.J., Neeteson, J.J. and Draycott, A. (1985). Response of potatoes to N fertiliser: dynamic model. Plant and Soil, 185: 185-203.

Harris, P.B. (1984). The effects of sowing date, disease, control, seed rate and the application of autumn nitrogen on the growth and yield of Igri winter barley. Research and Development in Agriculture. 1: 21-7.

Hatfield, J.L. (1983). Remote sensing estimators of potential and actual crop yield. Remote Sensing of the Environment. 13: 301-311.

Hay, R.K.M. and Walker, A.J. (1989). An Introduction to the Physiology of Crop Yield. Longman Scientific and Technical.

Hay, R.K.M. (1986). Sowing date and the relationships between plant and apex development in winter cereals. Field Crops Research. 14: 321-37.

Henderson, K.E. and Badhwar, G.D. (1984). An initial model for estimating soybean development stages from spectral data. Remote Sensing of the Environment. 14: 55-63.

Hindley, D. (1987). Relationship of spectral reflectance properties of onions and cabbages to crop cover and biomass at varying nitrogen levels. Unpublished thesis, Cranfield Institute of Technology, Silsoe Campus.

Hoffer, R.L. (1978). Biological and physical considerations in applying computer-aided analysis techniques to remote sensor data. (Eds) Swain, P.H. and Davis, S.M. Remote Sensing: The Quantitative Approach.

Idso, S.B., Jackson, R.D., Reginato. R.J. (1977). Remote sensing of crop yields. Science. 196: 19-25.

Idso, S.B., Pinter, P.J., Jackson, R.D., Reginato. R.J. (1980). Estimation of grain yields by remote sensing of crop senescence rates. Remote Sensing of the Environment. 9: 87-91.

IMS (1990). Irrigation Management Services, Irrigation Scheduling Program. Cranfield Institute of Technology, Silsoe Campus.

Jackson, R.D. (1983). Spectral indices in n-space. Remote Sensing of the Environment. 13: 409-421.

Jackson, R.D., Pinter, P.J., Reginato, R.J., Idso. S.B. (1980). Hand-held radiometry. A set of notes developed for use at the workshop on Hand-Held Radiometry. US Department of Agriculture Publication ARM-W-19.

Jaggard, K.W. and Clark, C.J.A. (1990). Remote sensing to predict the yield of sugar beet in England. Ed. Steven, M.D. and Clark, C.J. In Applications of Remote Sensing in Agriculture, Butterworths.

Kauth, R.J. and Thomas, G.S. (1976). The Tasselled cap - A graphic description of the spectral temporal development of agricultural crops as seen by LANDSAT. Proceedings of the 3rd Symposium of Machine Processing of Remotely Sensed Data. LARS Purdue University, Indiana, 41-49.

Kirby, E.J.M. (1977). The growth of the shoot apex and dome of barley during ear initiation. Ann. Bot. 41, 1297-1308.

Kirby, E.J.M. and Ellis, R.P. (1980). A comparison of spring barley grown in England and Scotland. 1. Shoot apex development. Journal of Agricultural Science, Cambridge. 95: 101-10.

Kirby, E.J.M. and Appleyard, M. (1984b). Cereal plant development - assessment and use. In The Nitrogen Requirements of Cereals. Reference Book 385, MAFF, HMSO; 21-38.

Kirby, E.J.M. and Appleyard, M. (1987). Cereal Development Guide, Plant Breeding Institute, Stoneleigh, Warwickshire.

Kirby, E.J.M., Porter, J.R., Day, W., Adam, J.S., Appleyard, M., Ayling, S., Baker, C.K., Belford, R.K., Biscoe, P.V., Chapman, A., Fuller, M.P., Hampson, J., Hay, R.K.M., Mathews, S., Thompson, W.J., Weir, A.H., Willington, V.B.A., Wood, D.W. (1987). An analysis of primordium initiation in Avalon winter wheat crops with different sowing dates at ten sites in England and Scotland. Journal of Agricultural Science, Cambridge 109: 123-34.

Klersy, R. (1990) Forward to the Proceedings on The Application of Remote Sensing to Agricultural Statistics. Joint Research Centre, Commission of the European Communities, Varese, Italy. 3.

Kumar, M. and Monteith, J.L. (1982). Remote sensing of crop growth. In Plants and the Daylight Spectrum. Ed. by H Smith. Academic Press, London.

Large, E.C. (1954). Growth stages in cereals. Illustrations of the 'Feekes' Scale. Plant Pathology 3: 128-129.

Lotus 1-2-3 (1988). Mastering 1-2-3. Carolyn Jorgensen. Publ. Sybex.

Maas, S.J., Richardson, A.J., Weigand, C.L and Nixon, P.R. (1985). Use of plant spectral and weather data in modelling corn growth. Proc 19th International Symposium on Remote Sensing of the Environment. Ann Arbor. 21-25.

Maas, S.J. (1988). Use of remotely-sensed information in agricultural crop growth models. Ecological Modelling, 41: 247-268.

MacDonald, R.B. and Hall, F.G. (1980). Global crop forecasting. Science, Vol. 208, 670-679.

Milton, E.J. (1986). Series 100 Milton Multiband Radiometers. Notes for users. Geodata Unit Faculty of Science. University of Southampton, UK.

Milton, E.J. and Wardley, N.W. (1987). Vegetation canopy reflectance models: a review. Discussion paper No.31, Dept. Geography, University of Southampton.

Milton, E.J. (1987). Principles of Field Spectroscopy. International Journal of Remote Sensing, Vol. 8, 1807 - 1827.

Milton, E.J. (1989). On the suitability of Kodak neutral test cards as reflectance standards. International Journal of Remote Sensing, Vol. 10, No.6, 1041 - 1047.

MINITAB Statistical Software, 7.2 (1989). Vax/VMS, Minitab Inc.

Monteith, J.L. (1977). Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society, London. Series B, 281, 277-294.

Monteith, J.L. and Elston, J. (1983). Performance and productivity of foliage in the field. In The Growth and Functioning of Leaves. Ed by J.E. Dale and F.I. Milthorpe. Cambridge University Press.

Moore H.M. (1981). Estimations of winter wheat yields by remote sensing of crop senescence rates. Unpublished MSc thesis, Cranfield Institute of Technology, Silsoe Campus.

Patterson, L.J., Wild, P. and Williams, E.R., (1988). An algorithm to generate designs for variety trials. Journal of Agricultural Science, Cambridge. 111: 133-136.

Porter, J.R. (1984). A model of canopy development in winter wheat. Journal of Agricultural Science, Cambridge 102: 383-92.

Porter, J.R, Kirby, E.J.M., Day, W., Adam, J.S., Appleyard, M., Ayling, S., Baker, C.K., Beale, P., Belford, R.K., Biscoe, P.V., Chapman, A., Fuller, M.P., Hampson, J., Hay, R.K.M., Hough, M.N., Mathews, S., Thompson, W.J., Weir, A.H., Willington, V.B.A., Wood, D.W. (1987). An analysis of morphological development stages in Avalon winter wheat crops with different sowing dates and at ten sites in England and Scotland. Journal of Agricultural Science, Cambridge 109: 107-21.

Porter, J.R. (1990). Personal communication on the AFRC wheat development sub-model, Long Ashton Research Station, Bristol.

Prince, S.D. (1990). High temporal frequency remote sensing of primary production using NOAA AVHRR data. Steven, M.D. and Clark, J.A. (Eds). Applications of Remote Sensing in Agriculture. Butterworths.

Remote Sensing Applications Consultants (1992). Temporal monitoring of soil moisture conditions using ERS-1 SAR data. Farnborough, Hants UK.

Richardson, A.J., Weigand, C.L. (1977). Distinguishing vegetation from soil background information. Photogrammetric Engineering and Remote Sensing. 43: 1541-1552.

Rouse, J.W., Haas, R.H., Schell, J.A., Deering, D.W. (1973). Monitoring vegetation systems in the Great Plains with ERTS. Third ERTS Symposium - NASA SP 1351 1: 309-317.

Stephens, W. (1990). Personal communication on calculation of Degree Days using the Sine Wave method. Cranfield Institute of Technology, Silsoe Campus.

Steven, M.D., Biscoe, P.V., Jaggard, K.W. (1983). Estimation of sugar beet productivity from reflection in the red and infrared spectral bands. International Journal of Remote Sensing. Vol 4, No.2: 325-334.

Steven, M.D., Biscoe, P.V., Jaggard, K.W., Paruntu, J. (1986). Foliage cover and radiation interception. Field Crops Research. 13: 175-87.

Steven, M.D. and Demetriades-Shah, T.H. (1987). Spectral indices of crop productivity under conditions of stress. In Advances in Digital Image Processing. Remote Sensing Society, Nottingham.

Steven, M.D., Malthus, T.J., Danson, F.M., Jaggard, K.W. and Andrieu, B. (1992). Monitoring responses of vegetation to stress. In Proceedings of the 18th Annual Conference of the Remote Sensing Society, From Research to Operation, Eds Cracknell, A.P. and Vaughn, R. The Remote Sensing Society. 369-377.

Steven, M.D., Malthus, T.J. and Clark, J.A. (1992). Achievements and unresolved problems in vegetation monitoring. In Terra-1 Understanding the Terrestrial Environment (Ed. Mather P.M.), Taylor and Francis. 133-145.

Toselli, F., Meyer-Roux, J. (1990) (Eds). The application of remote sensing to agricultural statistics. Joint Research Centre, Commission of the European Communities, Varese, Italy.

Tottman, D.R. (1977). The identification of growth stages in winter wheat with reference to the application of growth-regulator herbicides. Ann. Appl. Biol. 87: 213-224.

Tottman, D. Growth stage identification key, cereals. Long Ashton Research Station.

Tucker, C.J., Holben, B.N., Elgin, J.H., McMurtrey, J.E. (1980). Relationship of spectral data to grain yield variation. Photogrammetric Engineering and Remote Sensing. Vol 46, No.5: 657-666.

Tucker, C.J., Holben, B.N., Elgin, J.H., McMurtrey, J.E. (1980b). Remote sensing of winter wheat total dry matter accumulation. NASA/GSFC Technical Memorandum 80631.

Walker, G.K. (1980). Relations between crop temperature and the growth and yield of kidney beans (Phaseolus vulgaris L). Phd Dissertation, University of California, Davis.

Weir, A.H. Bragg, P.L., Porter, J.R., Rayner, J.H. (1984). A winter wheat crop simulation model without water or nutrient limitations. Journal of Agricultural Science, Cambridge 102: 371-82.

Weir, W.H., Day, W., Sastry, T.G. (1985). Using a whole crop model. In Day, W., Atkin, R.K. (Eds). Wheat Growth and Modelling. Plenum Press, New York.

Zadoks, J.C., Chang, T.T. and Konzak, C.F. (1974). A decimal code for the growth stages of cereals. Weed Research 14: 415-421.

Zmuda, A.D. (1987). The calibration of the MSP 1000 radiometer and the prediction of winter wheat yield by remote sensing. Unpublished MSc thesis, Cranfield Institute of Technology, Silsoe Campus.