DISCRIMINATION OF CROPS, WEEDS AND SOIL BY OPTICAL REFLECTANCE

Federico Hahn

I hereby declare that all the work presented in this thesis is original and has been carried out by the author unless otherwise stated

Federico Hahn

TO MY FATHER, MOTHER AND SISTER

To **Lisa Harrison**
who encourage me
and helped me by
making this work look
simple.

To the **Scottish farmers**
always kind and looking
for progress!

CONTENTS

ACKNOWLEDGEMENTS iv

ABSTRACT v

1. Introduction 1

2. Weed control concepts 4
   2.1 Main weeds in the United Kingdom 5
      2.1.1 Volunteer crops as weeds 8
   2.2 Weed competition in vegetable crops 10
   2.3 Crop weed modelling 14
   2.4 Weed control 15
      2.4.1 Cultural weed control 15
      2.4.2 Mechanical weed control 16
      2.4.3 Biological weed control 17
      2.4.4 Chemical weed control 18

3. Remote sensing for monitoring agricultural crops 20
   3.1 Optical reflection, transmission and absorption 21
   3.2 Biological and optical properties of leaves 23
   3.3 Remote sensing instruments and monitoring crop status 26
      3.3.1 Nitrogen concentration in leaves 28
      3.3.2 Water stress in plants 30
      3.3.3 Crop growth and maturation 32
      3.3.4 Pest and diseases 34

4. Spectral signatures 37
   4.1 Spectrophotometry 37
      4.1.1 Integrating sphere spectrophotometer 38
      4.1.2 Scanning type spectrum analizer 39
   4.2 Spectral signatures used to recognize plant species 44
   4.3 Crop spectra 46
      4.3.1 Brassica crop signatures 46

4.4 Weed spectra 49
4.4.1 Spectral measurements in broad-leaved weeds 54
4.4.2 Spectral measurements in grass weeds 58
4.5 Soil spectra 59
4.5.1 Soil and stone signatures 60

5. Crop weed experiments and discrimination 61
5.1 Discriminant analysis 65
5.2 Cabbage 67
5.2.1 Cabbage cultural techniques 68
5.2.2 Cabbage crops and weed competition 69
5.2.3 Crop/weed/soil discrimination for three cabbage varieties 74
5.2.4 Crop/weed/soil discrimination for spring-sown cabbages 78
5.2.5 Crop/weed/soil discrimination in savoy cabbages 82
5.3 Broccoli 82
5.3.1 Broccoli cultural techniques 83
5.3.2 Weed competition at the different broccoli sites 84
5.3.3 Crop/weed/soil discrimination in mature broccoli 86
5.3.4 Crop/weed/soil discrimination using young broccoli seedlings 91
5.3.5 Effect of straw mulching in crop/weed discrimination 94
5.4 Leek 96
5.4.1 Leek cultural techniques 96
5.4.2 Weed competition in all leek trials 96
5.4.3 Effect of weed population in leek/weed/soil discrimination 102
5.4.4 Leek/weed/soil discrimination 104
5.5 Crop/weed/soil discrimination using wavebands 108
5.5.1 The effect of nitrogen concentration 109
5.5.2 The effect of crop growth 113
5.5.3 The effect of water stress 115
5.5.4 Stressed crops in crop/weed/soil discrimination 119

6. Crop/weed/soil classifiers 121
6.1 Wavelength selection for crop/weed/soil classifiers 121

6.1.1 Cabbage 122
6.1.2 Broccoli 128
6.1.3 Leek 133
6.2 Multivariate analyses and discriminant classifiers 135
6.2.1 Discriminant crop/weed/soil classifier 137
6.3 Neural network classifiers 148
6.3.1 Neural network applications in agriculture 150
6.3.2 Neural networks for crop/weed/soil discrimination 151
6.4 Comparison of discriminant and neural network classifiers 155

7. Weed crop discrimination using spectral signatures 160
7.1 Signatures used in remote sensing 160
7.2 Discriminant integration index 161
7.2.1 Waveband selection 162
7.2.2 Discrimination accuracy from discriminant integration values 163
7.3 Discriminant integration values 168
7.3.1 Discrimination modes in remote sensing algorithms 170

8. Discussion of results 179

9. Conclusions and future work 187

REFERENCES 190

Appendix A Design and measurements of a portable spectroradiometer.
Appendix B Weed species and crop varieties signatures
Appendix C Discriminant analysis
Appendix D Discriminant analysis results
Appendix E Classifier coefficients
Appendix F Discriminant integration index results
Appendix G Remote sensing measurements and analysis
Appendix H Machine vision for crop/weed discrimination
Appendix I Published notes

ACKNOWLEDGEMENTS

To **Professor Brian Witney** and **Andrew Muir** for their overall supervision and time.

To **Nelson Turnbull** for being a real companion during all my work and for his invaluable help in the design of the prototypes.

To all my friends in the Glasshouse Unit including **Jeannete Taylor**, **Brian Pool** and **Donald Mitchell** whose help could not be measured, and to **Paul Partner** who never forgot me in my difficult times.

To **Ken Davies**, **Bill Lamond**, **Martin Parkes, Gail Jackson** and **Bob Graham** for their continuous technical support and guidance during this work.

To **John Fleming** and **Jim Dean** for their continuous support during the elaboration of this document.

To **Rosslyn Allen** and **Wyanette Kean** always helping me in preparing this thesis.

To **CONACYT** and **EL TECNOLOGICO REGIONAL DE LA LAGUNA** for giving me the opportunity of developing this proyect in the **SCOTTISH CENTRE OF AGRICULTURAL ENGINEERING** in order to obtain the degree of Doctor of Philosophy awarded by the **UNIVERSITY OF EDINBURGH**.

Finally, I would like to thank all the **staff** and my **friends** all around Britain that help me to finish this research.

UNIVERSITY OF EDINBURGH

ABSTRACT OF THESIS (Regulation 3.5.10)

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Title of Thesis DISCRIMINATION OF CROPS, WEEDS AND SOIL BY OPTICAL REFLECTANCE.

No. of words in the main text of Thesis

The discrimination of crops, weeds and soil by optical reflectance was tested for broccoli, cabbage and leek crops from several different farms. The effect of crop varieties (in particular cabbage), weed population and type of soil did not affect the discrimination accuracies.

No effects on crop/weed/soil discrimination were noted from the analysis of stressed crop samples (nitrogen concentration and water stress). Crop growth stage also had no influence on crop/weed/soil discrimination.

Crop/weed/soil segregation into their respective groups required the use of classifiers. Two sets of spectral measurements, each comprising three wavelengths, were selected from all the data analyses providing the best overall accuracies. Discriminant analysis provided classification functions which differed greatly between farms. Neural networks provided the final algorithm relating the wavelength sets obtained by discriminant analysis.

The use of a broadband spectral range for discriminating between crop, weed and soil was also considered. This algorithm based on the discriminant integration index, also uses the discriminant analysis results to obtain the spectral range, but requires only one filter for accurate plant recognition.

High discrimination accuracies are achieved with both algorithms and the broadband filter system shows potential for simplification without loss of performance in distinguishing between crops, weeds and soil.

1. INTRODUCTION

Future demands caused by an increased population, with an increased economic wealth will demand food increased quality and quantity. The required production will have to come from increased production per hectare, as good agricultural land area is limited. A maximum potential of 3.2 billion ha could be cropped at the expense of the grasslands and forests, but would have ecological consequences.

Before the introduction of herbicides, weeds were considered to be a major problem in vegetable growing. It was considered that weed control was the key to efficient systems of vegetable production based on optimum plant densities and row spacings.

The outdoor horticultural area in the UK has fallen from 311,000 ha in 1970 to 204,000 ha in 1990, representing less than 4.5 % of the land used for growing crops. Horticultural crops are therefore very much minor crops as far as agrochemical manufacturers are concerned, leading to more severe problems in the availability of herbicides. Horticultural problems caused by herbicides shortage in the UK will increase, partly as a direct consequence of recent UK pesticide legislation, and partly due to a more general increase in the costs of development and registration of pesticides worldwide.

It is becoming increasingly clear that the use of herbicides for the control of weed populations within growing fields of crops has several drawbacks. Economically, chemicals are expensive and the efficiency of application is open to conjecture in that a large proportion of applied chemical does not land on the weeds but on soil or crop plants. The fact that the crop plants are sprayed means that there may be some residual chemicals left on the leaves of the harvested crop, from the food safety point of view this is undesirable. Chemical which lands on the soil or is eventually washed into the soil in time progresses down through the soil until it reaches the water table whereupon it eventually reaches water courses and has the opportunity to affect natural vegetation and animal and human life.

The elimination of the source of contamination would be a major contribution to pollution reduction. The problem might be solved by reducing the amount of chemicals used or by their total elimination. There is a need for weed control from the point of view of producing healthy, high quality produce. But, it is inconceivable that farmers would ever revert to hand methods of weeding. It is therefore necessary that alternative automatic methods of weed control are evolved.

Automatic weeding mechanisms must have the capability of recognising crop plants from weed plants, be able to make a distinction between them and the apply herbicide precisely to the weeds or erradicate them by mechanical means. The sensors and brain are the two essential features of such a device. The aim of the present work described in this thesis is:

to establish if it is possible to use optical spectral reflectance methods as the sensors of a system;

to establish whether there exist spectral differences between several varieties of vegetation;

to investigate whether these differences can be exploited;

to maximize these differences in terms of the discriminant algorithms which might be utilised in a controllling computer processor.

Many of the most serious weed problems arise as a result of the previous years crop, either through the development of volunteers or by creation of a weed population that is difficult to control in the following crop. The effect of weed competition in vegetable crops is mentioned in chapter 2, together with the last weed surveys carried out in the UK.

Vegetable growers are looking for alternative weed control options in the 1990's as herbicide registrations are being cancelled faster than new compounds become available. The use of optimum quantities of herbicides and weed thresholds have been suggested to reduce herbicide usage. Although these thresholds do not reduce crop yield, weeds remaining in the field cause non-uniform maturation, decrease quality and increase costs.

Additionally, concern about pesticide residues in vegetables may force processors to search for zero pesticide residues in the finished products, restricting pesticide usage by their suppliers. At the same time, increased testing of ground water in agricultural areas has revealed detectable levels of several herbicides, making further usage restrictions likely.

Remote sensing carried out by airborne platforms monitors vegetation using optical reflectance detecting crop status (water stress, mineral deficiencies and diseases); these are summarized in chapter 3. Remote sensing techniques using the infrared region are capable of detecting situations not perceived by our eyes. The high cost of these techniques makes them

of limited use to the farmer, but these techniques and equipment need not be mounted on an airframe. It can be land-based and in this form is referred to as ground truth measurements and can be implemented at relatively modest price.

The feasibility of using optical reflectence for discriminating crops from weed species and soil is studied in this report. Weed species and crop signatures were obtained with the use of spectrophotometers, chapter 4, and then analysed. Discriminant analysis was used to obtain the success rate in classifying a sample into its correct category of weed, crop or soil, chapter 5. Samples were taken from different farms growing cabbage, broccoli and leek. The samples were taken during different growth stages, stress conditions and from several crop varieties. Other crops (turnip, cauliflower and potato) were also tested with successful results.

The best discriminant wavelengths for each crop were obtained and used to train a neural network classifier and results are discussed in chapter 6. This classifier had the ability of learning, taking into account different crop varieties, weed species populations in order to generate a final algorithm which could classify succesfully crops and weeds. A group of 500 weed species and 100 crop samples were tested with the algorithm achieving more than 90% accuracy.

Finally, a novel approach used the discriminant integration index as the comparison unit. The index, explained in chapter 7, calculates the area between the sampled spectrum and the reference spectrum limited within a waveband, to discriminate between weed and crop. The results showed high accuracies in discrimination using one broadband filter only, but presented poor results in conventional remote sensing algorithms.

The information provided by this document requires to be tested in a machine vision system with a resolution of 16 bits, and high success rates in crop/weed/soil discrimination are expected, either using a broadband filter or by using the derived wavelength combinations for each crop.

2 WEED CONTROL CONCEPTS

Most of the major crops would not mature as unique species without the help of man, for they are less adapted to the arable environment than certain plants that grow naturally in such conditions. These native plants, known as weeds, invade, compete and as a result reduce crop production. Modern agriculture encourages the invasion of weeds as crops are often sown in rows leaving big spaces for weed colonization.

Weed control has received great attention in recent years. Weeds cause greater losses than either insect or plant diseases and much of the farmer's time is spent controlling them. Some of the main problems caused by weeds are:

- crop yield reduction;
- serious ailments in cattle, horses and sheep;
- alteration in milk flavour;
- interference with harvesting and damage to machinery;
- contamination of seed stocks;
- diseases affecting seed quality.

Nevertheless, in some instances, weeds can be useful for reducing soil erosion, for feeding cattle in semi-arid lands and for feeding insects and other arthropods that are predators or pests that otherwise would feed on the crop. However, studies concerning the presence of weeds in crops have concluded that zero cultivation practices in row crops are more detrimental than beneficial to the interests of the farmer.

Weeds can be classified according to their leaf type or life cycle. According to the leaf type, weeds can be either broad-leaved (dicotyledons) or grasses, rushes and bulb plants (monocotyledons). The life cycle is a function of their reproductive system and can be subdivided into annual, biennial or perennial.

The seed production from each weed plant is often relatively high and gives the weed an advantage in any competitive environment. For example, mayweed (*Matricaria inodora*) produces 3500-4000 fruits per plant. Weed seed populations increase annually, spread by wind, water, birds, animals or man.

The great number of existing seeds do not germinate at the same time, but stay in the land in a dormant state. In order to germinate, water, oxygen, heat energy and light may be required.

The oxygen concentration found in the soil depends widely on the soil porosity and weed populations can be reduced by soil compaction. Unfavourable weather conditions create intermittent germination, causing individual plants with different morphological and physiological characteristics. Chemicals applied to these populations may not achieve the same control.

It is also important to consider that some weeds acquire the ability to regenerate from roots after 10 or 15 weeks. Up to this point, plants can easily be killed by cultivation or contact herbicides.

Germination can be affected by burning and cutting. Burning fields after weed seed maturation is not completely effective as moderate heat breaks seed dormancy and new weeds will appear. Also after burning, more light reaches the soil surface and no competition from other plants exists, leading to further weed germination. Cutting weeds to prevent seed production is a common recommendation. Some weed seeds still show high levels of germination even when the weeds are cut during flowering periods.

Most of the research carried out on weeds relates to the detrimental effects of weeds on crops. Basically three areas are considered:

- competition for light, water and nutrients during and after establishment with crop plants;

- interference with harvesting operations;

- weeds as hosts for pests and diseases.

Weeds compete successfully with crops because they are more aggressive, utilizing the essential elements for growth at the expense of the crop plant and possibly secreting chemicals that affect the growth of the other plants.

2.1 MAIN WEEDS IN THE UNITED KINGDOM

Numerous weed surveys have been carried out in the UK to assess the spread and abundance of weed species. Herbicide choice is governed by the weeds present and these surveys will be a guidance to future herbicide development.

Table 2.1 **Comparison of broad-leaf weed surveys carried out in Great Britain on winter rape and cereal fields.**

Weed species	Percentage incidence of weed species in surveyed crop fields			
	Rape (1)	**Rape (2)**	**Cereal (3)**	**Cereal (4)**
Stellaria media	98	99	94	89
Matricaria spp	81	79	67	53
Veronica persica	71	25	72	55
Lamium purpureum	53	33	47	--
Galium aparine	46	--	58	52
Capsella bursa-pastoris	39	65	23	11
Viola arvensis	38	76	45	14
Sinapsis arvensis	34	16	36	33
Veronica hederifolia	25	--	30	*
Chenopodium album	25	29	13	--
Papaver rhoeas	23	7	18	--
Fumaria officinalis	15	53	17	--
Spergula arvensis	11	62	--	--
Galeopsis spp	10	56	--	--
Geranium dissectum	10	--	11	--
Aphanes arvensis	--	20	12	--
Polygonum aviculare	--	55	--	--
Myosotis arvensis	--	40	--	--

1 Whitehead & Wright (1989)
2 Whytock & Carnegie (1990)
3 Whitehead & Wright (1989)
4 Fisons (1973)
* Veronica spp. not differentiated in Fison cereal survey
- Not included in the survey

Whitehead and Wright (1989a) reported the incidence of weeds in cereal crops after observing 2359 winter cereal fields without herbicide application. The surveys were carried in the spring for broad-leaved weeds ensuring that weed germination had occurred and weed infestation levels were not measured. The disadvantage found was that weeds killed by herbicides during the last crop were not recorded. The results shown in Table 2.1 indicate that although 22 years have passed since Fisons' first survey, the four top weeds were the same and an increase in abundance was noted. Abundance of *Lamium purpureum* and *Viola arvensis* could be attributed to the switching to winter cropping in agriculture and not to herbicide weakness. Weeds have been reduced by herbicide usage in arable lands, but have not been eliminated.

Another survey carried out by Whitehead and Wright (1989b) in 842 fields of winter oilseed rape showed similar weed flora to the cereal survey. They concluded that regardless of the degree of control achieved, the same species re-appear, with the same relative frequency in the subsequent season.

Whytock and Carnegie (1990) surveyed 78 fields of winter oilseed rape in three areas of north-east Scotland in autumn 1989 before herbicide application and found that the more abundant species were *Poa annua*, *Stellaria media*, *Viola arvensis*, *Hordeum vulgare*, *Matricaria spp.*, *Capsella bursa-pastoris* and *Fumaria officinalis*, Table 2.1. The survey repeated in spring 1990 showed a winter-hardened and herbicide tolerant weed population dominated by *Poa annua*, *Viola arvensis* and *Capsella bursa-pastoris*.

Simpson and Carnegie (1989) reported a survey carried out in 113 spring cereal fields in north-east Scotland in 1985. Weed species density were compared with another survey carried out by Carnegie in 1973 in the same districts of Scotland (Carnegie, 1974). The list of species was similar in both surveys although weed abundance decreased in 1985. *Stellaria media* was the most abundant species occurring in 98 %, 86 % and 38 % of the fields at infestation levels higher than 1, 10 and 50 plants per square metre. *Galeopsis spp.* was also abundant and observed in 83 %, 33 % and 10 % of the cereal fields with higher densities than 1, 10 and 50 plants per square metre. *Viola arvensis* increased markedly in most of the districts, while *Capsella bursa-pastoris* and *Lamium purpureum* had a less marked increase. *Spergula arvensis* and *Polygonum persicaria* showed a decline in 1985 compared with 1973.

Poa annua was the predominant grass in cereal and rape fields in Whitehead and Wright (1989a) survey, Table 2.2, and herbicides had problems in controlling it. Volunteer cereals were found in 88 % of rape fields in the spring but by July most of them were eliminated by herbicides.

Gerowitt and Heitefuss (1990) reported the frequency of broad-leaved weed species in three crops (winter barley, winter rye and winter wheat) in Germany. Broad-leaved weed species that appeared frequently in the spring samplings were *Gallium aparine*, *Lamium spp.*, *Matricaria spp.*, *Stellaria media*, *Veronica hederifolia* and *Viola arvensis*.

Table 2.2 Whitehead and Wright surveys on abundance of main grass weeds in winter cereal and rape fields.

Weed species	Percentage incidence of weed species in surveyed crop fields	
	Oilseed rape	Cereals
Volunteer cereals	88	7
Poa annua	80	79
Alopecurus myosuroides	40	38
Avena spp	40	42
Elymus repens	24	21
Bromus sterilis	15	13
Lolium spp	13	14
Poa trivialis	6	7

Surveys on vegetable crops have not been carried out, but similar weed flora is expected as a result of crop rotation. ADAS bulletins recommend farmers not to grow the same vegetable type until after a given rotation of several years to avoid crop pests and diseases and to use cereal crops as a break in the rotation.

2.1.1 VOLUNTEER CROPS AS WEEDS

Talbot (1993) reported a survey of 3201 autumn-sown fields and 2475 spring-sown fields, covering arable areas of Scotland, England and Wales. Field crops without herbicide application were only considered and results are displayed in Tables 2.3 and 2.4.

Table 2.3 Occurrence of volunteers by crop.

Crop	Percentage incidence of volunteers in surveyed crop fields		
	Volunteer oilseed rape	Volunteer cereals	Volunteer potatoes
Winter wheat	26	7	-
Winter barley	18	7	-
Oilseed rape	3	88	-
Spring barley	9	5	5

Table 2.4 Occurrence of volunteers by soil type in the United Kingdom.

		Percentage incidence of volunteers according to soil type and season		
Season	Soil	Volunteer oilseed rape	Volunteer cereals	Volunteer potatoes
Winter	Sandy	11	7	-
	Light	20	7	-
	Medium	18	88	-
	Heavy	22	5	5
Spring	Sandy	10	9	11
	Light	7	13	10
	Medium	12	12	5
	Heavy	13	5	5

Volunteer cereals were the most frequent of all, and found in 88 % of oilseed rape fields. Volunteer cereal reduction was found in fields following potato crops in winter and grass in spring. The type of soil established differences in volunteer crop germination, i.e. volunteer oilseed rape was more common in heavy soils and volunteer potatoes in lighter soils. Previous crop also affected volunteer infestations, i.e. potato volunteers were limited after rape and

grass crops. Volunteer oilseed rape predominated in winter wheat as it is often grown as an entry to wheat.

Lutman (1977) studied why the volunteer potato was becoming an important weed in Britain. Failures in potato harvesting left between 120,000 and 370,000 tubers per ha. Eighty percent of these tubers showed diameters between 1 and 4 cm. Thirty percent were on the surface and 32% deeper than 5 cm. Potato sprouts emerge over a long period during spring, reducing the efficiency of post-emergence herbicides. Early herbicide application controls only a small quantity of tubers. In cereal crops, they interfere with harvesting and in row crops they compete with the main crop, causing serious damages. Drilled leeks competing with potatoes had less foliage and required longer periods to acquire marketable size (Runham *et al.*, 1993). The best control of volunteer potatoes was in a late transplanted crop as late cultivations disturbed the naturally growing potatoes. If leeks and potatoes emerged at the same time, potato control became difficult and dependent on herbicides.

Bowerman (1984) studying volunteer oilseed rape found oilseed rape harvest losses up to 400 kg/ha , corresponding to 80 million seeds. Seeds could persist in the soil for five years and longer when ploughed. Experiments by Garret and Orson (1989) showed that oilseed rape plants could emerge from seeds sown down to 7.5 cm. Cultural control methods include deep ploughing to eliminate rape emergence in the first crop after rape and harrowing which will kill a proportion of seedlings by increasing germination in the autumn (Lutman, 1991). The best strategy is to leave the rape on the surface and kill it by seedbed cultivations. Selective herbicides available to control oilseed rape in vegetable crops are limited, and do not exist for following rape crops, where they reduce seed quality.

2.2 WEED COMPETITION IN VEGETABLE CROPS

Plants growing adjacent to one another compete for soil moisture, soil nutrient and light intensity. Increased fertilizer application enhances the growth of both crop and weed plants. Nitrogen is often the first nutrient to come into short supply as a result of the competition between plants. Experiments have been undertaken in various crops to determine the amount of nutrients consumed by the crop and by the weeds. Figure 2.1. shows the results of a study of corn with five different weeds and it can be seen that each of the weed species contained a higher percentage of nutrients than did corn. As a result, fertilizer application stimulates weed growth to the extent that crop losses actually increase. Therefore, weed control cannot be

achieved with fertilizer. Significant increases in protein content following weed removal can be found in grain fields as nutrient competition disappears.

Competition for light among plants is achieved by the positioning of their leaves. Broad-leaved weeds have an advantage over narrow-leaved plants, and taller plants compete more favourably for light. Plants with less total foliage may be the strongest competitors because they use limited foliage to greater advantage. Heavily shaded plants suffer reduced photosynthesis leading to poorer growth, and as a result, reduced capacity for water or nutrient uptake.

Competition tends to be greater between plants of similar vegetative characteristics. In some instances, root systems tend to be similar, causing greater competition for water and nutrient uptake. For example, grass weeds are more serious in grass crops, as the roots are located at the same depth and tend to absorb the same nutrients.

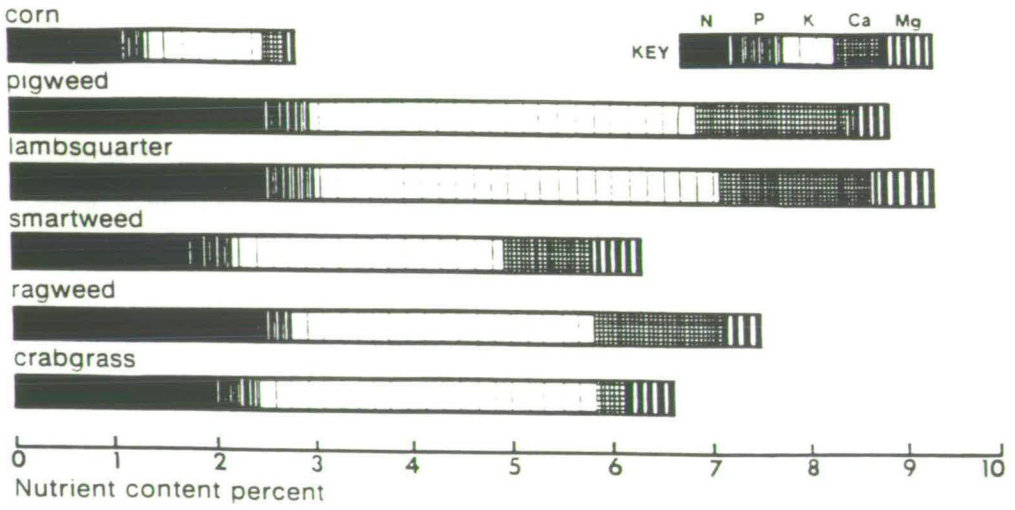

Fig 2.1 Nutrient consumption by different weed species competing with corn (Anderson, 1980).

Chlorotic effects in leaves were also noted. Unweeded plots during the entire growing season did not reduce yield for weed densities of 0.3 weeds/m2. Nevertheless, for weed densities superior to 60 weeds/m2 a complete loss of the marketable hearts was found. The most competitive weed was *C. album* and 2.3 plants/m2 reduced lettuce weight by 55%.

The main effect of weed competition on summer cabbage was plant size reduction and the number of marketable, firm heads (Roberts, Bond and Hewson, 1976). Without weeding the fields during the entire season yields were reduced between 47 and 100%. Hewson (1971) described an experiment with a variable *C. album* population in a cabbage crop and found that three plants per square meter were sufficient to reduce cabbage yield.

Lawson (1972) reported cabbage experiments with spring cabbage planted in early autumn and harvested in late spring in Eastern Scotland. The weed population formed by *Stellaria media*, *Poa annua*, *Capsella bursa-pastoris* and *Senecio vulgaris* reduced cabbage plant and marketable head size during early spring, but no detrimental effect on yield was noted during autumn and winter. *Stellaria media* was the most competitive weed due to its winter hardiness and its ability to make rapid growth in early spring exploiting all ground space.

Experiments carried out in Ontario, Canada studied the effects of row width and weed removal on cabbage yield (Weaver, 1984). The weed population -*Chenopodium album*, *Amaranthus powelli*, *Retroflexus*, *Digitaria sanguinalis*, *Setaria viridis* and *Polygonum persicaria*- did not reduce cabbage yields if the plots were kept free of weeds during the first three weeks after cabbage transplanting. After this period cabbage leaves limited weed seedling growth. Yields were higher, with narrow rows decreasing weed production. It was noted that in narrow rows cabbage weed competition began earlier and weeding had to take place between 3 and 4 weeks after crop emergence.

Weed competition experiments were carried out with carrots sown in single rows in Madison, Wisconsin (Shadbolt and Holm, 1956). Carrot leaf size and root quantity were reduced with weed competition and light intensity transmitted to the carrot leaves after three and a half weeks was also reduced to 15%. The main weed species -*Amaranthus retroflexus*, *Acnida sp.* and *Polygonum persicaria*- reduced yields by 30 to 60% for weed populations ranging between 3 and 20 weeds per square foot. Weeds did not reduce yield when they were removed before three and a half weeks after sowing.

In summary, crops with different growth habits withstand weed competition differently. To establish the effect of weed competition on yield reduction reqires that the results from weedy

and weed free plots are compared. The experiments mentioned here indicate that reduced weed populations need not necessarily guarantee maximum yield and that in most vegetable fields there is a critical time for weeding and if properly timed will not reduce crop yield.

2.3 CROP WEED MODELLING

Weed control decisions based on weed numbers have been considered by a number of researchers (Gerowitt *et al.*,1984, Cussans et al., 1986). However, more recent economic evaluation of the threshold approaches have indicated that it is cheaper and less risky to the farmer to use herbicides at reduced doses (Davies et al.,1993). The main reason for this is the cost in term of man-hours required to assess thresholds.

Models which help in weed control strategies have been developed to assess crop loss. Groenendael (1988) divides the models in two broad categories, one based on the crop and the other based on the weeds. The former predicts crop yields with weeds considered as a yield-reducing factor. The latter studies weed infestations based on the number of weeds predicting long-term damage thresholds. Weeds form time and space patches of different dominance, composition and density. Plant interference studies are required in conjunction with a knowledge on seed dispersal processes and germination conditions.

Regression techniques in static models relate yield loss to weed density at certain times (Kropff, 1988). Linear yield-density regressions are only valid at very low weed densities, but are usually more suited to practical applications since they are easy to use. The hyperbolic yield-density approach presents good results but does not consider date of weed emergence relative to the crop, although it could be achieved by observing crop and weed emergence time and plants density. These data need to be accurate enough to predict plant interaction effectively. Leaf area was introduced as an alternative to account for the degree of weed infestation.

Dynamic modelling is based on the crop and weed species growth limiting factors -water, light and nutrients- and their efficiency to use them in order to calculate the plant's dry matter. The concept of leaf area has evolved from a simulated leaf dry weight to an empirical factor called the specific leaf area. In this new concept, leaf formation is determined by the carbohydrates produced by photosynthesis. Leaf morphological studies indicate that leaf area development early in the growing season is not limited by the carbohydrate supply, but by temperature. When the canopy closes, leaf area can be calculated from the leaves dry matter increment and from the known specific leaf area. Leaf cover measurements are easily performed but are

labour intensive and errors in estimation could provide high yield loss predictions, so leaf cover-yield loss sensitivity should be small.

Leaf area estimation is thus beginning to be used as an important indicator of the degree of infestation and competition.

2.4 WEED CONTROL

Successful weed control is a major contribution to a successful crop. Weed control includes those practices that reduce weed infestations, searching ideally for a total erradication which encounters as main obstacles the presence in the soil of long-lived weed seeds and vegetative reproductive plant parts (Anderson, 1980).

Weed control techniques can be classified in five broad categories:

cultural;
mechanical;
biological;
chemical.

Integrated weed control involves the use of two or more weed control techniques. It is advantageous as one technique rarely achieves an efficient control over all the weeds present in a particular crop. The combined use of herbicides and mechanical weeding can provide a solution for a weed-free crop.

2.4.1 CULTURAL WEED CONTROL

Cultural methods of weed control use highly competitive crops and crop rotations to minimize crop yield loss. Crops considered as good weed competitors (Anderson, 1980) are mainly small and large grains (barley, ensilage, corn, millet, rye and sorghum), legumes (alfalfa, clovers, cowpeas and sweetclover), grasses (crested wheatgrass, sudangrass), and others (buckwheat, sunflower, etc). Any crop well adapted to the area could be used, but care must be taken to avoid it becoming a future problem weed, Anon (1968).

Crop rotations are practised to prevent the buildup of high weed populations common to a particular crop, Leighty (1938). The weeds competing are characteristic of a given crop and will multiply if the crop is grown year after year in the same field. The crops included in the

rotation should have growth and cultural characteristics contrasting with the previous crop. Weeds left by the previous crop should not be able to buildup in the next crop. Crop rotations involve cultivated crops planted in sequence with noncultivated crops.

2.4.2 MECHANICAL WEED CONTROL

Mechanical weed control has been commonly practised throughout the world for many centuries. Hoeing, mowing, flooding, mulching, burning and machine tillage are some mechanical weed control methods.

Hoeing is an effective control method in cotton, soybean and vegetables. The hoe is most effective against weed seedlings and annual and biennial weed species. Hoeing perennial weeds can be successful if practised at intervals of 1 to 2 weeks during the growing season (Anderson, 1980).

Mowing is used basically to reduce seed production and to restrict weed growth. It is mainly used in meadows and pastures, along roadsides and in waste places, Robbins (1942).

Flooding is effective when the roots and/or shoots of the weeds are completely covered by water for a long period of time. Weeds treated in this way die of suffocation, preventing oxygen absorption by the roots and carbon dioxide intake by the leaves. It has been used effectively in paddy fields.

Mulching is the application of a covering layer of material to the soil surface and is used in horticulture to suppress annual weeds, to conserve moisture, to regulate temperature and to protect vegetables during severe frosts (Rowe-Dutton, 1957). Effective weed control depend on the correct choice and use of mulch material. Fresh manure, cereal straw or hay cut may increase the weed problem by introducing weed seeds. Few mulches suppress effectively persistent perennial weeds, and annual weeds reduction by light exclusion is expected when the cover is applied to an adequate depth. Bushnell and Weaver (1930) mentioned that ten tons of straw per acre were required to suppress annual weeds adequately. The straw will give a layer of 8-10 inches deep when freshly applied and of four inches when settled. Other mulches include sawdust, aluminium foil, wet paper pulp and the modern plastic and biodegradable materials.

Burning has been practiced to control weeds in non-cropped areas. Later technologies introduced selective burning applied to the base of tall crop plants to reduce crop damage. The

burners are located near the ground at angles of 30 to 45 degrees with respect to the soil, Colwick (1960). Flaming uses butane and/or propane gas stored under pressure and should not cause combustion of the plant tissue during controlled application (Bainer et al., 1955). Selective burning is most effective for weeds smaller than five centimetres and should be repeated at intervals of 5 to 10 days. Burnt tissue will become apparent some hours after application. Burnt weeds are killed due to cell wall destruction caused by cell sap expansion and by coagulation of cell protoplasm.

Machine tillage or cultivation is similar to hoeing using tractors to move the cultivating tools. It is a quick, efficient and economic weed control method only inefficient with weeds near to or between crop plants in the row. Weed tillage control is achieved by burying small annual weeds and by disruption between the weed plant and soil, killing by dessication. Other cultivators features apart from weed control are soil-surface crusts breakout and land preparation for irrigation. Soil preparation create favorable conditions for weed germination near the surface of the soil. Tillage equipment used for weed control includes various types of harrows, cultivators, brush-weeders, rodweeders, tandem disks and rotary hoes working the soil to depths of less than fifteen centimetres. Disk harrows are used for weed control prior to planting the crop and in orchards. Rotary hoes are operated right over the plant rows at ground speeds of 5 to 6 mph without disturbing well established crop plants (Bainer et al., 1955).

2.4.3 BIOLOGICAL WEED CONTROL

Biological weed control utilizes the natural enemies to reduce and regulate specific weed populations below the level of economic injury. Biological weed control represent a problem for agriculture as there are no absolute guarantees of safety, Huffaker (1964). The agent selected to achieve the control should attack successfully the target weed without harming the valuable crop. Biological control can be achieved directly or indirectly. The former bores into the plant weakening its structure until collapse takes place. Cancelled competitive weed advantage and enhanced conditions for favourable plant pathogens are considered as indirect actions. Three general principles for selecting the biotic agent can be noted.

1. Ensure that the agent only attacks the specific weed and will not modify to attack related species.

2. Obtain agents from areas climatically similar to those in which they are to be introduced.

3. Reduce competition between two or more introduced agents by selecting species with different feeding habits.

The principal biological agents used for controlling terrestial and aquatic plant populations are the insects (Holloway and Huffaker, 1952) and herbivorous fish (Lembi,1980), respectively. Andres (1980), Defago et al. (1983) and Sprenkel et al. (1975) utilized fungi as biotic agent, as these organisms are highly host specific, destructive, persistent and can be easily produced *in vitro*. Biological control of weeds has to be studied seriously when conflicts of plant interest are involved, but many new biotic agents are being introduced around the world.

2.4.4 CHEMICAL WEED CONTROL

Chemical weed control relies on specific substances capable of killing plants or inhibiting their growth. These chemicals called herbicides are available in different physical forms and vary widely in their composition. The use of herbicides in different crops results in increased crop yields, enhanced crop quality and reduction in production and harvesting costs. Herbicide products accounted for 45.1% of the total agrochemicals used in 1992 (British Agrochemicals Association, 1993). Herbicides misuse can cause severe economic losses, so special attention is required in its selection, application mode, timing of application, soil condition and dosage (Klingman and Ashton, 1982). Herbicides can be selective with variable length of activity. However, herbicide utilization depends on availability of water, clods and stones quantity, and its efficiency on water quality as it must be free from contamination by organic mater or clay. Herbicides can be classified according to application time, herbicidal activity and chemical similarity.

Pre-sowing, pre-emergent and post-emergent herbicides are available and applied to the crop fields at different times (Jordan et al., 1963). Pre-sowing herbicides are incorporated into the soil in the area where weed seeds are likely to germinate. Pre-emergent selective herbicides, such, are applied to the soil surface prior to crop emergence and are introduced into the soil by rainfall or irrigation. Post-emergent herbicides are used once the crop and weeds have emerged.

Herbicides that kill plants by contact or are translocated through the foliage are called foliage acting herbicides, while chemicals working by plant root uptake principles are known as soil acting herbicides (Ashton and Crafts, 1980). Soil acting herbicides should be applied to moist soils or when light rain follows the application on weed-free fields. Foliage acting chemicals may be used as pre-emergence treatment when weeds germinate ahead of the crop and as post-emergence treatment where the crop shows enough tolerance.

Herbicides may be inorganic or organic compounds and the great majority are classified within the organic group (Fryer and Makepeace, 1977). Organic herbicides can be classified according to similarities of molecular structure and such groups are referred as chemical families, i.e. aliphatic and aromatic carboxylic herbicides. Another herbicide classification is based on some common chemical characteristic, i.e. phenyl, phenoxy, and benzoic aromatic-carboxylic compounds.

The continued use of one herbicide may induce changes in weed flora, causing resistant weeds to become significant. Herbicide mixtures are often used to control a set of competitive weed species.

When applying chemicals to different crops their effect as residues in the crop, on crop quality and on the soil microflora have to be evaluated. Much of the herbicide applied to a crop reaches the soil surface.

There is evidence in the literature of potential shift effects in the soil microflora. For example, Grossbard (1972) carried out experiments in field plots treated for 8 years with four different herbicides and found that *simazine* and *linuron* reduced carbon dioxide production by 20-30%. Few herbicides tested in the laboratory did not have adverse effects at high concentrations (50 ppm). Herbicide side-effects reduce carbon dioxide production and/or inhibit partial nitrogen mineralization. Experiments carried out at the Weed Research Organization studied the effect on the soil microflora due to herbicide degradation and an increased population of detoxifying herbicides micro-organisms was found. Nitrogen mineralization reduction by herbicides stopped nitrate leaching.

3 REMOTE SENSING FOR MONITORING AGRICULTURAL CROPS.

Remote sensing is used to obtain information of objects by non-contact methods. In vegetation it records all the parts of the plant, i.e. stems, branches, leaves, flowers and fruits, with foliage as the dominant group. The sun is the main source of radiation utilised in remote sensing. The solar source consists of broadband electromagnetic radiation encompassing wavelengths from the ultraviolet (UV) to the far infrared (thermal). Vegetation remote sensing using optical reflectance gathers information from the entire canopy rather than individual leaves,cells or molecules. Optical reflectance equipment used in remote sensing platforms takes measurements in the visible region where pigment-absorption occurs and in the infrared wavebands up to 2500 nm, where water absorption takes place.

The main applications of remote sensing in agriculture are:

land use and crop type classification;
pest, disease, nutrient and water stress monitoring;
assessment of crop photosynthesis and yield prediction.

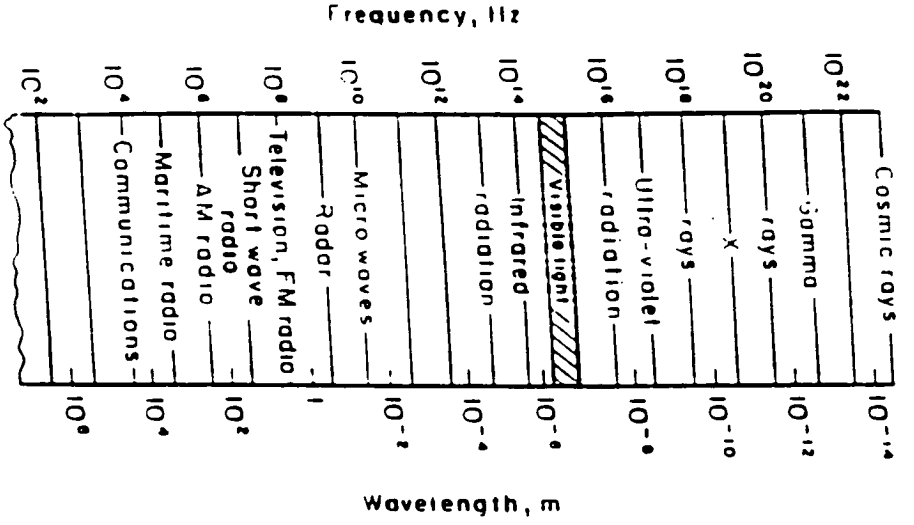

Fig. 3.1 Electromagnetic spectrum.

A short literature review starting with the biological and optical properties of leaves and remote sensing instruments is cited. Finally, a brief review of remote sensing applications in agriculture focuses on plant nitrogen, crop growth, water stress and pest detection.

3.1 OPTICAL REFLECTION, TRANSMISSION AND ABSORPTION

The electromagnetic spectrum can be divided into various wavebands: gamma rays, X rays, ultraviolet, visible, infrared and Hertzian, Fig 3.1. The infrared region can be subdivided in near, medium, thermal and far infrared, while the Hertzian band includes the microwave, high frequency, UHF, VHF and other transmission bands.

When radiation interacts with matter three physical phenomena take place: reflection, absorption and transmission. The incoming radiation hits the matter and some of the radiation is reflected (ρ_λ). Some of the radiation finds its way into the matter, part being absorbed within the object and part crossing the entire section. These phenomena are known as absorption (α_λ) and transmission (τ_λ). The total incoming radiation can be defined as the sum of each one of these components:

$$I_{o\lambda} = \rho_\lambda + \alpha_\lambda + \tau_\lambda \qquad \text{eq. 3.1}$$

Remote sensing measures reflectance exclusively. The two main types of reflectance are the specular reflection, described by Descartes' laws, encountered in smooth surfaces and the diffuse reflection, described by Lambert's laws, typical of rough surfaces, Fig 3.2.

Smooth objects reflect light with the angle of reflectance equal to the angle of incidence. The amount of reflection depends on the angle of incidence and on the refractive indices of the object and surroundings, Fig 3.2A. Fig 3.2B shows a pseudo specular reflection where radiation at small angles close to the angle of reflection is captured by a detector. Perfectly diffuse reflectance would be found at surfaces reflecting radiation over a large variety of reflectance angle, the maximum flux being at an angle of 90 degrees to the surface. Rough surface objects reflect and refract light as a result of the abrupt refraction indices discontinuities present in the optical path reflecting more radiation than smooth surfaces. Fig 3.2D shows a non perfect diffusely reflecting surface where there is a larger specular reflecting component.

Beer-Lambert law (Eq.3.2) obtains the light intensity $I(\lambda)$ at a distance l along the optical path, where the light intensity in the surface at wavelength λ is denoted by $I_{o\lambda}$. The absorption coefficient at this wavelength is denoted by α_λ .

$$I(\lambda) = I_{o\lambda} * e^{-l * \alpha_\lambda} \qquad \text{eq. 3.2}$$

Real objects reflect radiation with a combination of specular and diffuse reflection. Relative reflection variables present dimensionless coefficients as a result of the ratio between two variables of the same kind. The albedo (A) or "whiteness coefficient", expressed as a percentage, is the ratio between the light reflected by the surface and the light incident on the surface. Proper evaluation of this

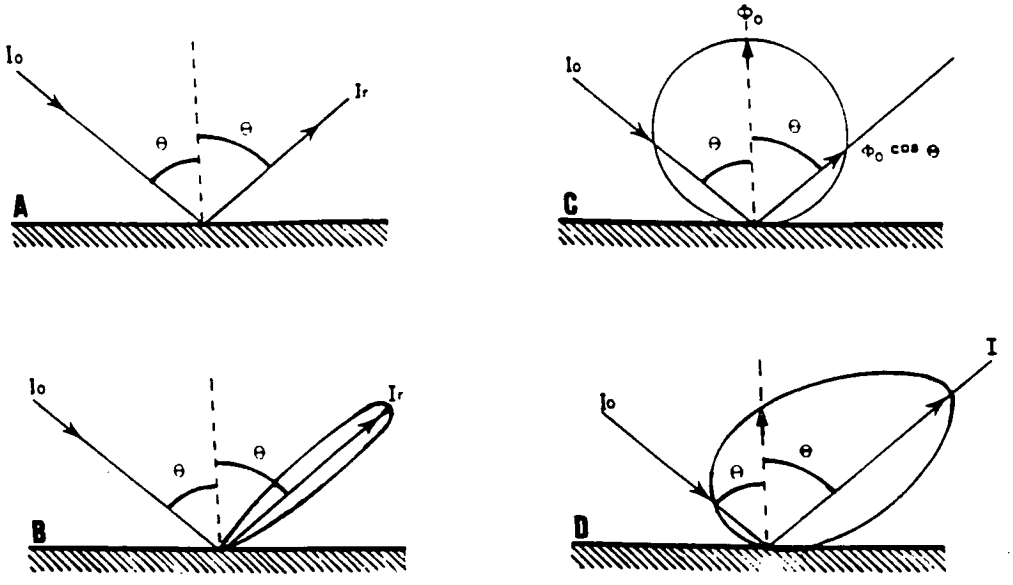

Fig 3.2 Types of reflection: a-perfect specular reflection; b-pseudo specular reflection; c-perfect diffuse reflection; d-diffuse reflection.

coefficient will require an even sensitivity for each wavelength throughout the spectrum. The entire radiation reflected in all directions by the irradiated surface should also be collected. The reflectance coefficient, more commonly used, is the ratio at a given wavelength of the reflected radiation in a specified direction to the incident radiation.

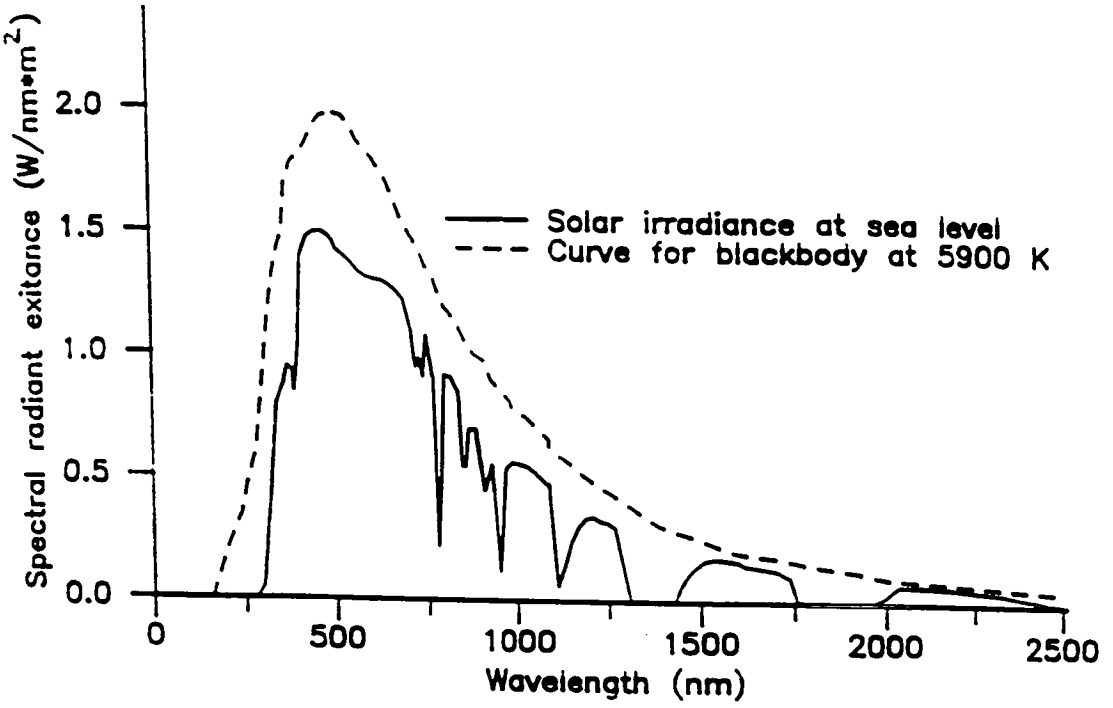

Fig 3.3 Solar irradiance curves.

The use of solar radiation offers useful vegetation reflectance information up to 3000 nm, where the emitted radiation becomes dominant over the reflected radiation. The solar spectrum that reaches the Earth's surface is essentially the spectrum of a blackbody at 6000 K modified by atmospheric absorption and scattering effects. The first absorption is caused by atomic gases present in the Sun's atmosphere. The Earth's atmospheric gases (ozone, oxygen, carbon dioxide and water vapour) absorb the remaining radiation in broad spectral bands. Fig. 3.3 shows the main wavebands available on the Earth's surface. The first waveband corresponds to the entire visible region and several other wavebands are available in the infrared region (770-910 nm, 1000-1120 nm, 1190-1340 nm, 1550-1750 nm and 2050-2400 nm). The first waveband is limited below 300 nm due to ozone absorption and the infrared region contains several oxygen and carbon dioxide absorption bands.

3.2 BIOLOGICAL AND OPTICAL PROPERTIES OF LEAVES

Mature crop and forest leaves are typically 0.2 mm thick. Fig 3.4 shows a leaf cross section with the different cell layers. The top epidermal cells have a cuticular layer on their upper

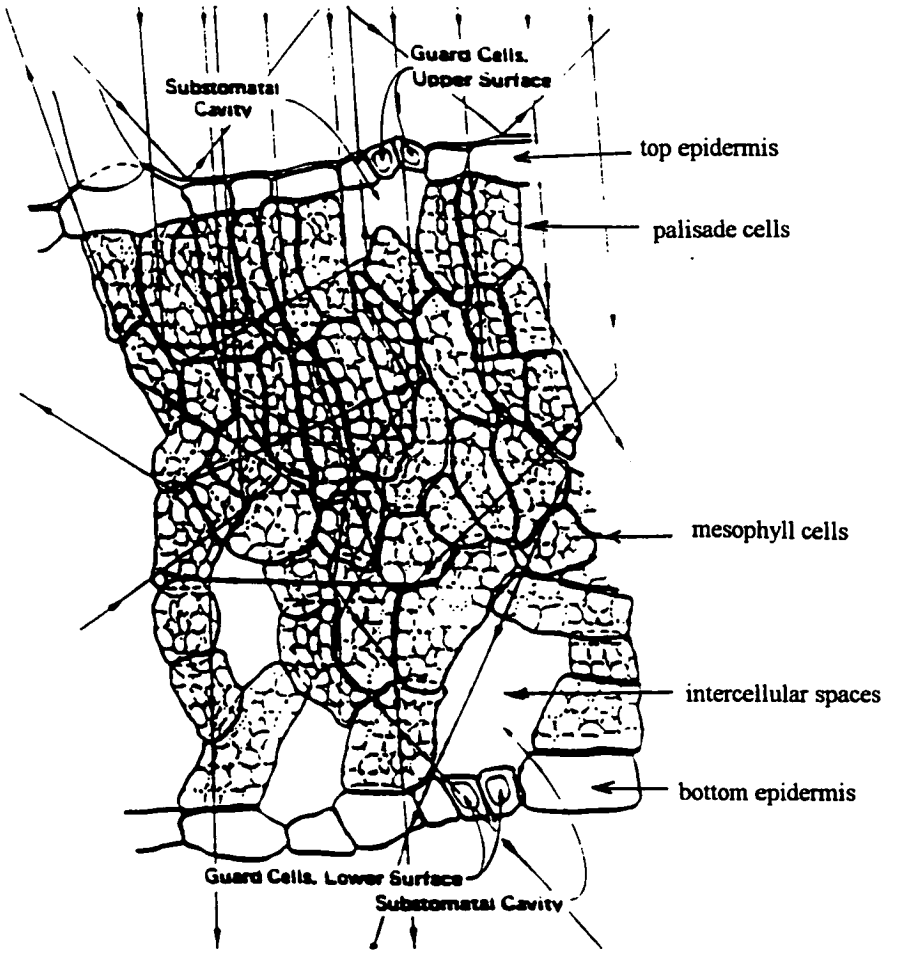

Fig 3.4 Cross section of leaf.

surfaces that diffuses most of the radiation and reflects very little light. Below these cells appear the palisade cells, long and narrow in appearance, enclosing many chloroplasts with chlorophyll pigments. Under the palisade cells are the spongy mesophyll cells where many intercellular spaces are present. In this section, the exchange of carbon dioxide and oxygen takes place during photosynthesis and respiration. The bottom part of the leaf is also composed of epidermal cells with a higher quantity of stomata or ports through which gases come in and go out of the leaf. Stomata can be present sometimes in the top epidermis layer but have a lower quantity of ports than in the bottom epidermis.

Plant tissues have irregular surfaces with diffusion caused by interfaces between air and wet cell walls, Wooley (1971). The refractive index of intercellular spaces is about 1.0 whereas that of the cells with moist cell walls is 1.3-1.5 and this structural association may reflect as much as 96% of the near infrared light (Wooley, 1971). Air filled intercellular spaces cause the incoming radiation to change direction, modifying the final plant spectral response. Wooley comparing transmittance and reflectance measurements in maize leaves reported

sharper peaks in the transmittance spectrum. Reflected radiation scarcely penetrates plant tissue having little chance for interacting with leaf absorption elements. A common leaf spectrum is shown in figure 3.5 showing the visible and near infrared wavebands.

The visible region includes all the wavelengths between 380 nm and 700 nm. Plant pigments are responsible for the spectral reflectance in this region. Chlorophyll presents two absorption bands at 450 and 650 nm. Kleshnin and Shul'gin (1959) found that chlorophyll in green leaves usually absorps from 70% to 90% of the light in the blue and red regions. A healthy leaf is characterized by low reflectance in the blue and red regions and a 20% reflectance peak in the green region (550 nm). Red leaves show low reflectance in the blue and green region and a very high level of reflectance throughout the red region. Other pigments present are the carotenes and xanthophylls. Breakdown of chlorophyll pigments during autumn change the color of leaves from green to yellow due to the presence of the carotenoid pigments. Leaves with lower pigment content have a higher reflectance.

The infrared region embraces wavelengths between 700 and 3000 nm and is divided into the *multidioptric* reflectance zone and the *hydric* zone (Goillot, 1971). A sharp increase in reflectance known as the *red edge* is found at 700 nm in the boundary between the

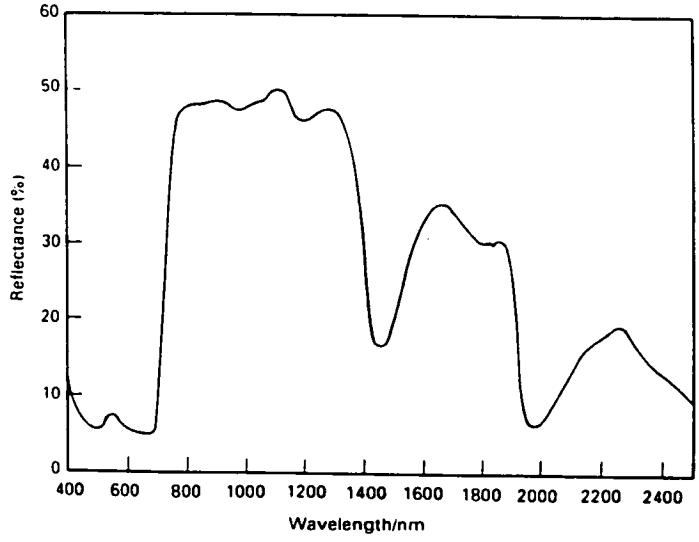

Fig. 3.5 Typical reflectance signature of a leaf.

multidioptric zone and the visible region. High reflectance and weak absorption are characteristic of this zone and may be related to intercellular spaces, where leaf mesophyll and palisade cells scatter near infrared light (Gausman et al., 1969). Reflectance of porous mesophylls in the near infrared region was higher than in compact mesophylls as light passed more often from hydrated cells to air spaces, (Gausman, 1974).

The waxy cuticle of some leaves may affect the reflectance obtained from their internal structure. Gates (1965) considered that the transparency of leaves in this spectral region was necessary for heat dissipation. All the unabsorbed energy is transmitted and varies between plants from 30% to 70%. Wiegand et al. (1972) noted that from the entire near-infrared radiation incident on a mature citrus leaf, 55% is reflected, 40% transmitted and 5% absorbed.

Leaf water content can be studied in the *hydric* spectral band enclosing the wavelengths between 1300 and 2600 nm, where reflectance increases with leaf moisture loss. Reflectance in the hydric zone shows broad absorption peaks due to overtones or combinations of fundamental bands occurring in the mid-infrared (Wetzel, 1983). Palmer and Williams (1974) mentioned absorption bands at 2950, 1940, 1450, 970 and 760 nm due to water pronounced OH bond. The strongest bond is at 2950 nm and becomes weaker as reflectance decreases.

3.3 REMOTE SENSING INSTRUMENTS AND MONITORING CROP STATUS

Remote sensing instruments record reflected or emitted radiation from objects at different wavelengths. The two main instruments -photographic and electro-optical- present collimating, focusing optics, and a filter or spectrometer system which defines the waveband introduced to the film or sensor. While photodetectors require a data acquisition system for processing the information, photographic films act as detector, data recorder and waveband selector. However, photographic systems cannot be used in automated processes, are restricted to wavelengths below 900 nm and need minimum spectral bands of 50 nm for multispectral operations. Photographic systems are compact, relatively simple, cheap, and provide high spatial resolution.

A great variety of photodetectors, providing high spectral resolution in different wavebands, have been developed in the last decade and are commonly used in spectroradiometers and in spectrophotometers. Spectroradiometers are instruments which use an external source, generally the sun to irradiate an object at a desired waveband in order to obtain its reflectance. Spectrophotometers provide a spectral output tailored for the particular application,

incorporating their own light source to minimize illumination variations. Either of these instruments can incorporate a scanning wavelength range or fixed known waveband filters.

The first significant remote sensing spectroradiometric instrument using photodetectors was the geostationary satellite, Landsat MSS (Multiple Spectral Scanner). Lintz and Simonett (1976) described this instrument located at an altitude of 915 km as a spectral scanner provided by four wavebands: 500-600 nm (band 4), 600-700 nm (band 5), 600-700 nm (band 6) and 800-1100 nm (band 7) and with a ground resolution of 79 m by 79 m (one pixel). The Thematic Mapper used in conjunction with the MSS, is a multi-spectral scanner with a 30 mt. ground resolution plus two mid-infrared bands (1550-1750 nm and 2080-2350 nm). The wavebands used by LANDSAT multi-spectral scanner to monitor vegetation, soil and water are shown in Fig 3.6. NASA has agreed for developing LANDSAT-7 with an Enhanced Thematic Mapper plus (ETM+) sensor.

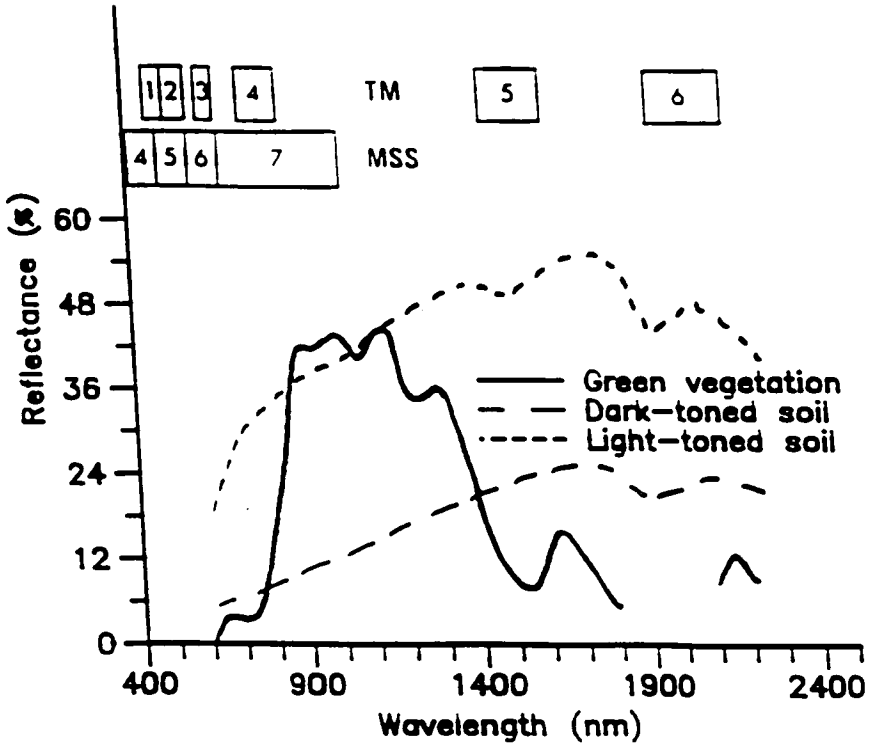

Fig. 3.6 Spectral reflectance curves for vegetation and soil, together with the multispectral scanner (MSS) and thematic mapper (TM) wavebands.

Remote sensing airborne or satellite spectral equipment collect data from the entire crop canopy plus the background soil. Many models have been developed in order to discriminate vegetation from soil under all conditions. Recent studies of transmission and reflection (Myers and Allen, 1968) always depart from the differential equations published by Kubelka and Munk (1931).

The reflectance properties of single leaves are insufficient to explain the reflectance of plant canopies. Additional variables include:

angles of the leaves to sun and detector system;
reflectance of stems, flowers and fruits;
transmittance of canopy elements;
canopy density;
soil reflectance and amount of soil background viewed.

Crop monitoring includes observations on crop growth, nutrient state of the crop, attacks by pests, drought studies and water stress. Other crop remote sensing applications using the vegetation spectral response require to account for these factors.

3.3.1 NITROGEN CONCENTRATION IN LEAVES

Nitrogen is required by plants in greater amounts than other soil-derived nutrients as nitrate tends to leach easily. Nitrogen deficiencies limit crop growth and yield. Chemical analyses of foliage are performed by commercial laboratories to monitor nitrogen status, but costs and time for analysis limit their use by farmers.

Analytical studies in different laboratories and agricultural experimental stations have been carried out to correlate optical transmittance and reflectance with leaf nitrogen concentration, Fig 3.7. Erez and Weinbaum (1985) correlated transmittance and leaf nitrogen in walnut leaves. Walnut samples were taken from fully expanded leaves in mid-summer, when periods of minimal change in leaf nitrogen concentration were present. Leaf nitrogen estimation by optical measurements in deciduous tree fruit species show more accurate results than in herbaceous annuals, as leaf nitrogen levels change more slowly.

Thomas and Oerther (1972) measured diffuse reflectance from sweet pepper leaves in the 500-2500 nm wavelength interval. Reflectance measurements were taken after 10 weeks of growth. The increased reflectance between 700 and 1300 nm with severe nitrogen deficiency

suggested an increase in the intercellular air spaces. The decrease in reflectance of the severely nitrogen-deficient leaves in the 1300 to 2500 nm wavelength interval was associated with their higher water content.

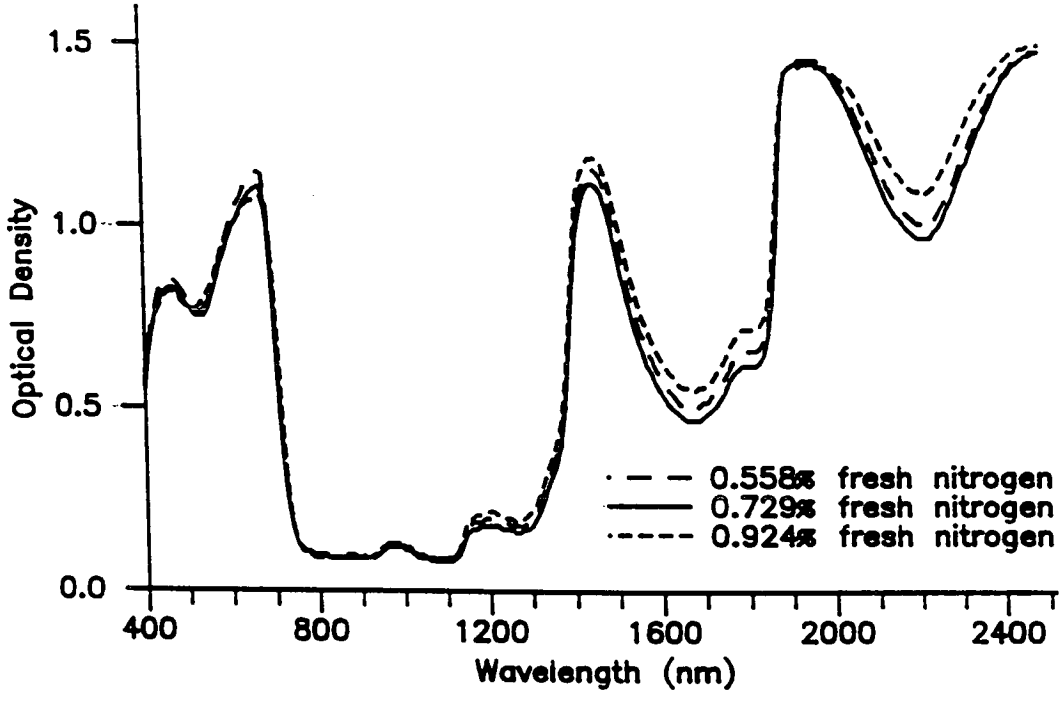

Fig. 3.7 Broccoli transmitance signatures for different nitrogen concentrations (Hahn and Muir, 1993e).

Thomas and Gausman (1976) showed that leaf reflectance was a good estimator of nitrogen content in eight different crops including corn. Reflectance from maize leaves with low-nitrogen concentration increased in the visible region and decreased in the near-infrared range.

Al-Abbas et al. (1974) noted that all nutrient-deficient plants contained less chlorophyll than the control plants. Higher near infrared reflectance was noted with increasing vegetative cover due to increased light scattering and reflectance by multiple layers. Leaf chronological age did not influence the spectra (750 to 2600 nm) of leaves having the same nutrient treatment. Meyer et al. (1992), studying optical reflectance on poinsettia leaves with different nitrogen concentrations, found increments of visible reflectance, but virtually no reflectance differences in the NIR range in nitrogen deficient plants. Walburg et al. (1982) concluded that agronomic changes such as reduced leaf area, plant height, biomass, chlorophyll content and soil cover caused by nitrogen treatments resulted in detectable reflectance variations.

Nilsson and Linner (1987) reported results of wheat and barley field plots affected by nitrogen fertilization and irrigation using a portable radiometer. Four spectral bands of at least 100 nm bandwidth were used. Greatest differences were encountered using the wavelength ratios (800-1100 nm/600-700 nm and 700-800 nm/ 600-700 nm).

3.3.2 WATER STRESS IN PLANTS

Water is essential for plant survival and its limitation can produce crop loss. Irrigation scheduling can be assessed using plant reflectance if good correlations with crop soil water content, stress and yield could be obtained.

Visual observations of stressed plants compared with healthy plants are:

decreased growth rate and biomass;
leaf rolling and wilting;
loss of sheen and development of a pale colour;
increase in angle of the terminal leaf;
increase in canopy and soil temperatures;
shortened green leaf area duration.

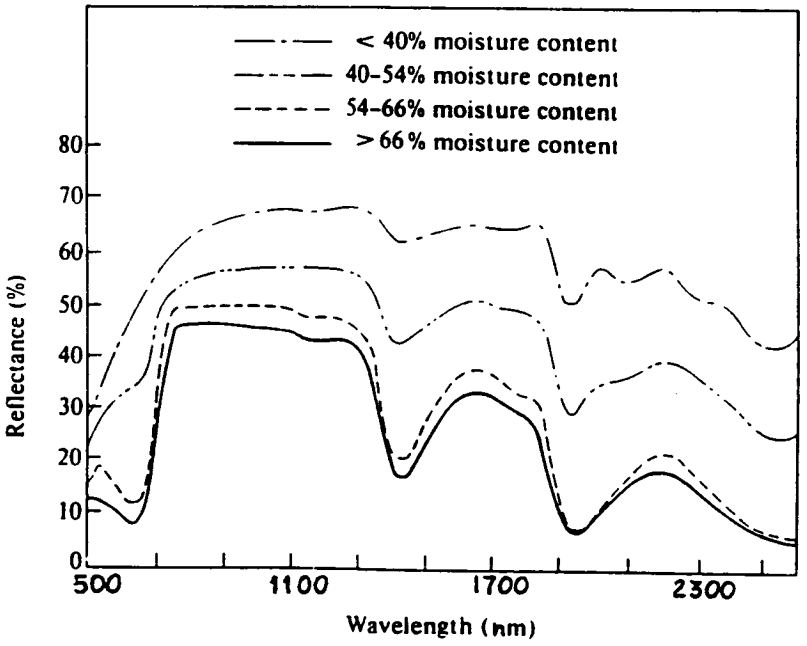

Fig. 3.8 Effect of moisture content on reflectance of corn leaves (Hoffer and Johannsen, 1969).

Biomass production, leaf area index or ground cover could be used to determine the water status of the plant. Reduction in leaf area and vegetative ground cover are of concern as photosynthesis and growth in plants are proportinal to light intercepted by the canopy (Ritchie, 1974). Nutrient and water transport to different plant parts are also limited.

Methods of evaluating crop water stress include leaf water potential, stomatal resistance, leaf temperature and leaf reflectance. Leaf reflectance is used to collect large scale data in a relatively short amount of time and several methods have been proposed. The Idso-Jackson method (Idso et al., 1981) uses the crop water stess index (CWSI) and calculates on a daily basis crop water stress from climate and plant temperature measurements. This index relates canopy air temperature difference with air vapour pressure deficit vpd:

$$Tc-Ta = K1 - K2^* vpd \quad \text{eq. 3.3}$$

where Ta and Tc are the air and surface temperatures, K1 and K2 are constants.
The CWSI index, although presenting a good correlation with crop yield, does not provide a direct indication of the quantity of water required. The index limitations are due to variations caused by wind gusts and cloud cover and soil temperature influence in sparse canopies. Multispectral reflectance (Goward et al., 1985) can use different wavelengths in the visible and infrared regions to detect leaf moisture, Fig 3.8. Plants showing stress change colour and therefore might be screened in the visible region. Lillesand and Keiffer (1987) indicated that measurement of infrared reflected energy allowed detection of plant stress more quickly than other methods as it varied with leaf water content, canopy thickness and leaves internal structure.

Field et al. (1989) tested a reflectance meter with a stressed alfalfa crop. The instrument sensed visible and near infrared radiation at peak wavelengths located at 650 nm and 880 nm. They concluded that this near infrared waveband was a poor indicator of daily water stress. Nevertheless, high correlations were found between infrared reflectance and average plant stress (CWSI). As well, infrared reflectance and soil water content were properly correlated.

Carlson et al. (1971) and Thomas et al. (1971) found significant correlations between relative water content at wilting and reflectance at 1450 and 1950 nm. Field studies failed to identify leaf water content from leaf structure changes during leaf development. Leaf water content was not properly identified with soil background changes as plants wilted. Wiegand et al. (1983) indicated that the strongest correlations, now used in some handheld and remote sensing

of 0.91 using the ratio of canopy reflectances in the near-infrared and red wavelengths. Tucker et al. (1979) used red and near infrared (NIR) wavelengths in a hand-held radiometer to monitor corn and soybean development and defined five distinct and spectrally measurable stages :

emergence up to 20-30% vegetative cover;
rapid foliar growth and development;
full vegetative cover;
onset of senescence, crop maturity and dry-down;
crop maturity, ready for harvest.

Crop growth can be related to the plant cover present in a given area and the amount of radiation reflected from vegetation can be correlated with the fraction of the soil screened by the foliage. Biomass estimation under incomplete ground cover by reflectance indices are only applicable for dry weights lower than 300 g/m2. Arable crops do not achieve their maximum rate of growth until foliage completely covers the ground. Dry weights in arable crops will then range from 500 to 2000 g/m2 making inaccurate biomass estimations by reflectance. Kumar and Monteith (1981) indicated that in many crops the growth rate during vegetative development was proportional to the rate of radiant energy intercepted by the foliage.

Kumar (1981) measured reflectance ratios in a canopy with an experimental radiometer using the 650-670 nm and 750-770 nm wavebands, but could not obtain accurate measurements using filters in these narrowbands. Better results were achieved with the use of broad-band pass filters (400-650 nm and 670-870 nm) as the incoming radiation intensity was not so severely limited. Correlations between reflectance ratio and intercepted radiation gave R-squared values of 0.93 and 0.98 with wheat and sugar beet trials. Dry matter was then estimated using those correlations and the conversion efficiency (typical value 2.6 g/MJ).

Asrar et al. (1984) developed a relationship to calculate leaf area index (LAI) from light interception calculations. He found a linear relationship between the normalised difference vegetation index (ND) and light interception in the visible region with a regression coefficient of 0.97. The reflectances from the infrared (800-1100 nm) and red (600-700 nm) regions denoted by $\rho(IR)$ and $\rho(R)$ respectively, were used to obtain the normalised difference.

$$ND = (\rho(IR) - \rho(R)) / (\rho(IR) + \rho(R)) \qquad \text{eq. 3.4}$$

During early growth stages when leaves are absent the leaf area index is low and ND is equivalent to the ratio of reflectances in the near-infrared and red wavelengths. Increased normalized difference was obtained for higher leaf area index up to a nearly constant value at LAI values above 5. After senescing, the ND values achieved were superior to the ones encountered during the growing period.

Kanemasu et al. (1984) described a winter wheat growth model. Daily data from different plant processes were introduced to the model designed to operate over large areas and using minimum daily weather variables. Two wheat row spacings were analised in Manhattan, Kansas. Yield estimation based on spectrally-derived LAI presented better results than with simulated LAI value. The model was less accurate with wider rows and with plants having larger leaves. Kanemasu concluded that model improvement can be achieved by collecting data bases over wider ranges of cultural and environmental conditions.

3.3.4 PEST AND DISEASES

Remote sensing technology offers a useful tool for detecting the presence of diseases in food and fibre crops. Historical records of disease can be mantained for each orchard tree and solutions for different pest problems presented.

Accurate disease detection is difficult because symptoms may not visibly appear until some time after infection. Diseased plants have different reflectance to healthy ones, Fig 3.10. Healthy foliage is highly reflective in the near-infrared because of the complex association of air spaces and cells. When intercellular spaces are occupied by water or by pathogen cells, the infrared reflectance of the tissue declines.

De Carolis and Amadeo (1980) classified plant diseases that affect spectral response into six different categories: *trophic*, *auxonic*, *necrotic*, *vascular*, *lytic* and *epiphytic*. *Trophic* diseases including mildews and rusts, affect chlorophyll assimilation, increasing respiration and transpiration rates and consequently nutrient and water uptake. A greater reflectance in the visible is expected due to a decrease in pigment content. Variations in the leaf inner structure are minimum as pathogens live on the leaf surface and affect only the epidermis. *Auxonic* diseases decrease the growth capability of the plant and are mainly caused by nutritional stress, chemical agents and viruses. A decrease in chlorophyll content is noted and morphological changes expected.

The characteristic symptoms of *necrotic* diseases including scabs and rice blast are spots on leaves and fruits. The pathogens attack all living tissues in the plant increasing the reflectance in the visible and water absorption bands.

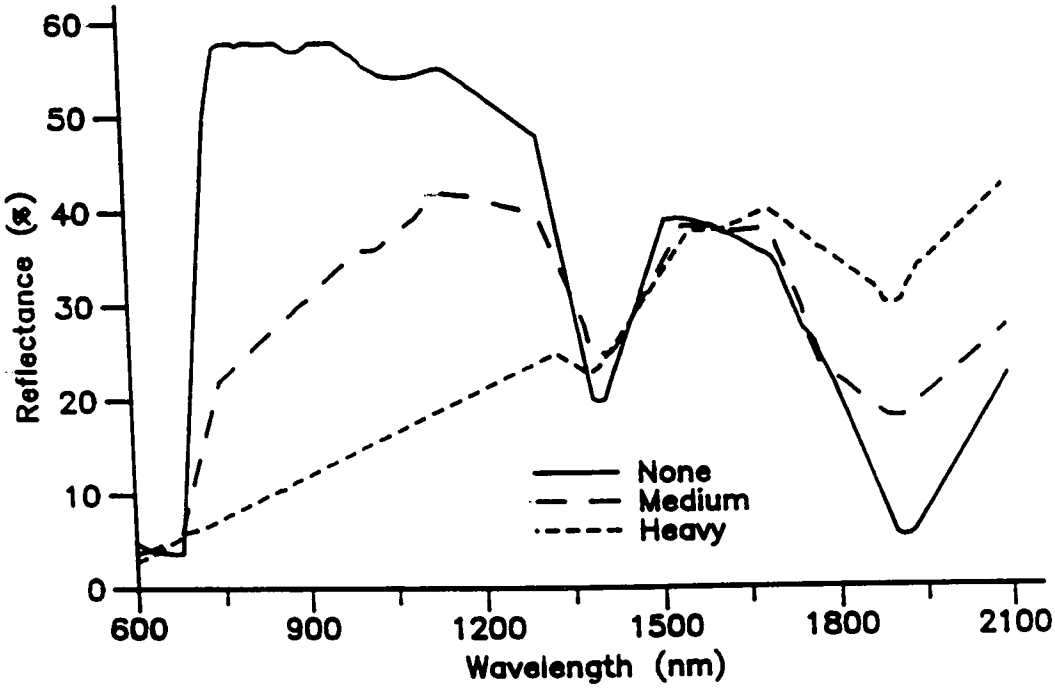

Fig. 3.10 Fungus attack on citrus leaves (after Hart and Myers, 1968).

Vascular diseases produced by pathogens located along the vascular elements affect the water supply system of the plant. Common symptoms are plant wilting and chlorosis, and spectrum variations are observed in the water absorption peaks and in the visible region. Indirectly, leaf inner structure will also change as a result of water stress. *Lytic* diseases disintegrate the tissue structure and the entire spectral response is affected. Finally, *epiphytic* diseases alter functional processes, in particular photosynthesis.

The first remote sensing applications for disease monitoring used photographic equipment and were reported in the late 1920s by Taubenhaus et al. (1929). The potential to detect small amounts of disease in large production areas made aerial photography attractive in disease forecasting. Spectral response of infra-red films caused healthy foliage to show a bright image in infrared photographs, while diseased tissues appear darker. Its use on annual crops was

limited by photographic camera and data acquisition costs and applied only when detection of small amounts of disease was required.

Former photographic studies were substituted by hand-held radiometers and infrared thermometers and nowadays by controlled instruments installed inside airborne platforms.

Nilsson (1984) studied reflectance differences on 6-row barley infected by barley stripe disease (*Pyrenophora graminea*) and concluded that a good correlation existed between reflectance, grain yield and disease intensity. Good results were obtained with a simple ratio between the 800-1100 nm and the 600-700 nm wavebands or between the 700-800 nm and the 600-700 nm wavebands. Canopy temperature was measured with an infrared thermometer which recorded thermal radiation in the spectral range between 8,000 and 14,000 nm. Canopy temperature increased with level of leaf infection. Nilsson (1985) also studied fungal diseases on oil seed rape with a hand held radiometer. A good correlation between the spectral reflectance bands (700-800 nm and 800-1100 nm) and disease incidence caused by Sclerotinia stem rot was reported. Leaf temperature differences ranging from 5 to 8 degrees celsius were noticed between infected and healthy leaves. Leaf temperature is lower in healthy plants.

4 SPECTRAL SIGNATURES

Plant species identification by their signature (spectral reflectance) has been broadly studied using spectrophotometers and/or spectroradiometers (section 4.3). Researchers at the University of Michigan (NASA, 1971) analysed the signature of 2600 plants species and concluded that:

healthy plants at a given stage in their phenological evolution show reflectance signatures specific to the group, the species and even the variety of the plant;

plants present a typical spectral reflectance between 400 and 2600 nm, Fig 3.5;

many internal or external factors to the plant influence its spectral reflectance, i.e. location and age, climatic conditions, biological pathogenic agents and angle of incident radiance.

A Monolite Optical Spectrum Analyzer (OSA) and an integrating sphere spectrophotometer were used during the experiments to obtain the signatures of crops, weed species and soil. A spectroradiometer was designed to measure optical reflectance of plants *on site* at fixed wavelengths.

4.1 SPECTROPHOTOMETRY

Spectrophotometry is the measurement of the spectral characteristics (reflectance or transmittance) of a sample; the former usually referred to the reflectance of a "standard" surface. Standard surfaces exhibiting a continuous high reflectance through the visible are generally of magnesium oxide or calcium carbonate. Measurements including the near infrared region use barium sulphate as their absolute reference.

Spectrophotometers measure different wavebands and are classified into:

fixed filter photometer having filters at specific wavelengths;

abridged monochromator with 3 or 6 tilting filters for scanning segments of the spectrum allowing variable choice of wavelength;

grating monochromator which uses a diffraction grating, scanning a spectral band in narrow intervals, i.e. 2 nm.

4.1.1 INTEGRATING SPHERE SPECTROPHOTOMETER

The integrating sphere is a hollow enclosure which reflects diffuse radiation with high reflecting power. The reflected radiation intensity at any part of the sphere is a measure of the total flux from the light source and does not change with the spatial distribution and location of the source in the sphere.

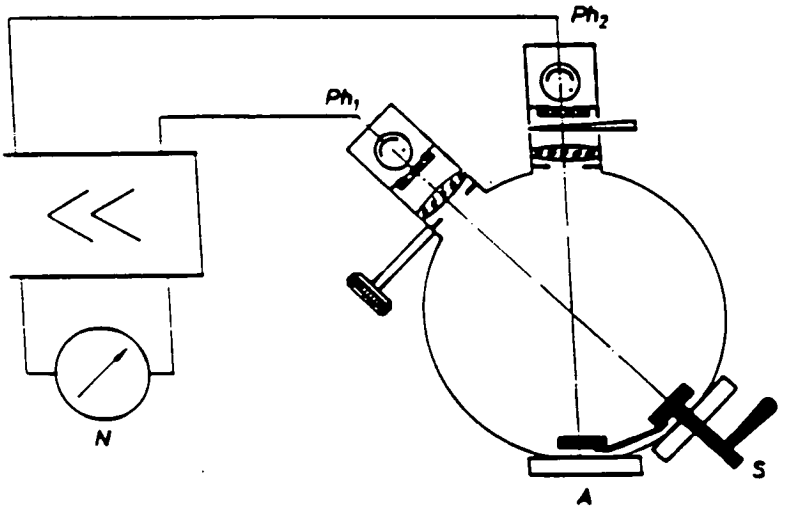

Fig. 4.1 Optical schematic of the Elrepho Photometer based on an integrating sphere design.

Fig. 4.1 shows the principle of operation of a double beam commercial spectrophotometer non-dependent on energy source fluctuations. Sample A placed at the proper opening of the sphere is irradiated diffusely by two incandescent lamps. Light reflected from surfaces A and S strike two photomultipliers Ph1 and Ph2 at angles of 90 degrees from the sample and reference surfaces, respectively. Compensation of the photomultiplier outputs is achieved when the meter arrives to the null position. The spectrophotometer is then ready to measure relative reflectance.

Maximum signal response is obtained when the sphere size, sample and photomultiplier size have been optimized. The sphere should be as small as possible, but large in comparison with the sample to prevent regular reflection from the sample surface. Good compromises include

a sphere having a diameter of five times the maximum sample size and a photomultiplier window of one-tenth the sphere diameter.

4.1.2 SCANNING TYPE SPECTRUM ANALYZER

A monochromator consists of a dispersion system and a continuous light source. Dispersing

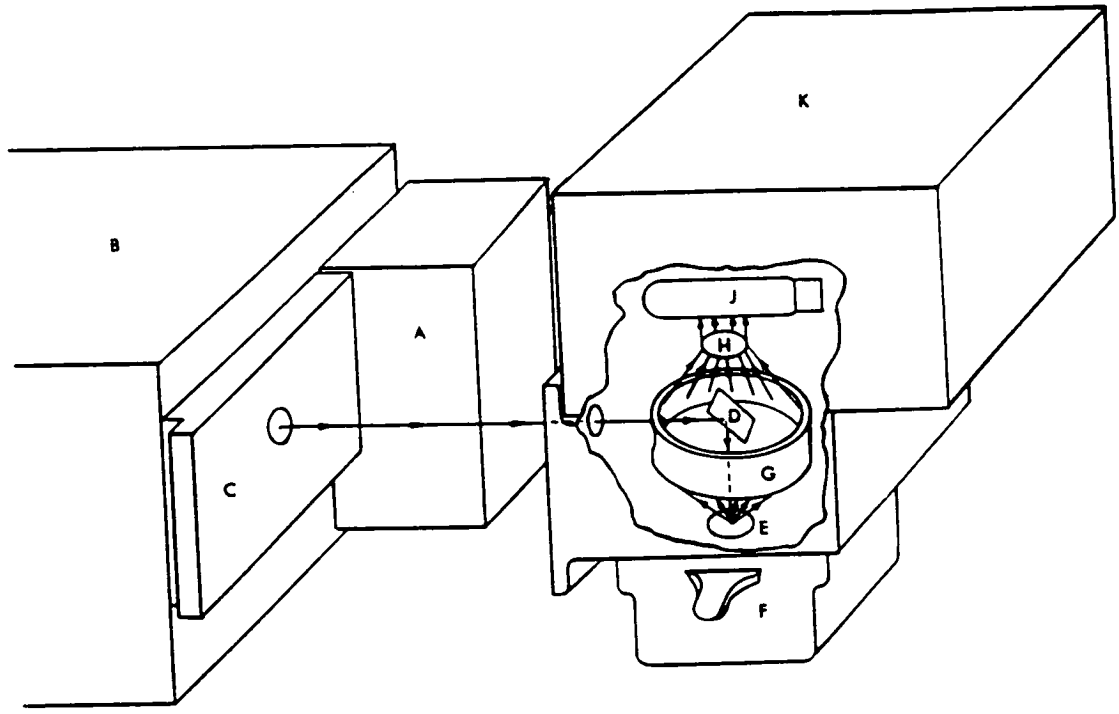

Fig. 4.2 Optical diagram of the Beckman Model DU Spectrophotometer. A, source; B, monochromator; C, mounting block; D, deflection mirror; E, sample surface; F, sample drawer; G, circular ellipsoidal mirror; H, frosted grass diffusing screen; J, phototube; K, phototube housing.

systems use a prism or a diffraction grating to obtain the spectrum from the irradiating source. The spectral resolving power of a dispersing system is described by the ratio $\lambda/d\lambda$, where λ is the wavelength of interest and $d\lambda$ is the minimum wavelength separation that can be resolved by Rayleigh's criterion for two line sources. The spectral resolving power depends on the slit width and on the grating design. The resolving power for a grating corresponds to the distance between grooves and the number of grooves across the grating

width. The width of the entrance slit allowing a wavelength difference $\Delta\lambda$, is also related to the spectral resolving power, and should be infinitesimally small to produce maximum resolving power. The ratio $\lambda/\Delta\lambda$ named "purity" determines the wavelength range present at any given point of the spectrum.

Monochromatic light enters through a slit irradiating the sample or reference surface after being redirected by a mirror, Fig. 4.2. This monochromatic light can be made less divergent by placing a quartz lens before the slit opening. The reflected light from the sample at angles departing up to 25 degrees from the normal strikes the mirror excluding the specular component. Only the diffuse component of the reflected radiation arrives at the photomultiplier.

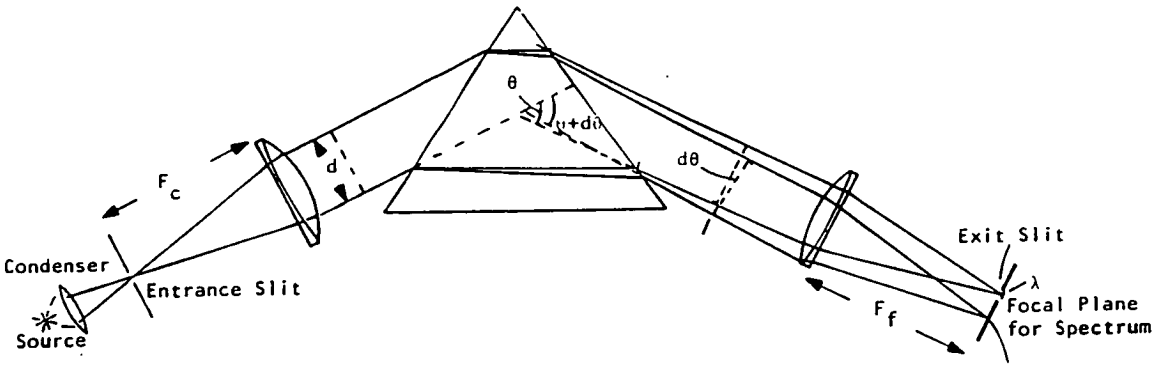

Fig 4.3 Influence of slits in a prismatic system.

The influence of entrance and exit slits for a simple prismatic system are shown in Fig 4.3. Placing a paper in front of the exit slit will allow us to see the outcoming radiation from the prism. Irradiating the entrance slit with a sodium vapour source that emits light at 589 and 589.5 nm produces two sharp well-defined images in the paper, Fig 4.4.b. Widening the entrance slit increases the size of the two images until they overlap, Fig 4.4.a. Reducing the slit size diminishes the image size and increases the spacing between images, Fig 4.4.c. A further reduction will decrease the irradiation level until the images cannot be seen Fig 4.4.d. The output of the instrument is dependent on the size of both slits requiring an optimum combination between resolving power and irradiance level as shown in Fig 4.4.c. Generally both slits are matched, but reduction in the exit slit width decreases the wavelength range in the

output flux. Widening the output slit automatically increases the output flux and wavelength range.

Fig. 4.5 shows the diffraction of a collimated beam of monochromatic flux from a slit source of wavelength λ, incident at angle θ_i on a plane grating. Each slit aperture in the grating acts as a uniformly radiating source. The sum of the contributions from the slits in the grating is maximum when the diffracted waves from all the slits interfere positively. The positions of the maxima are dependent only on the separation "d" between slit apertures and not on the number

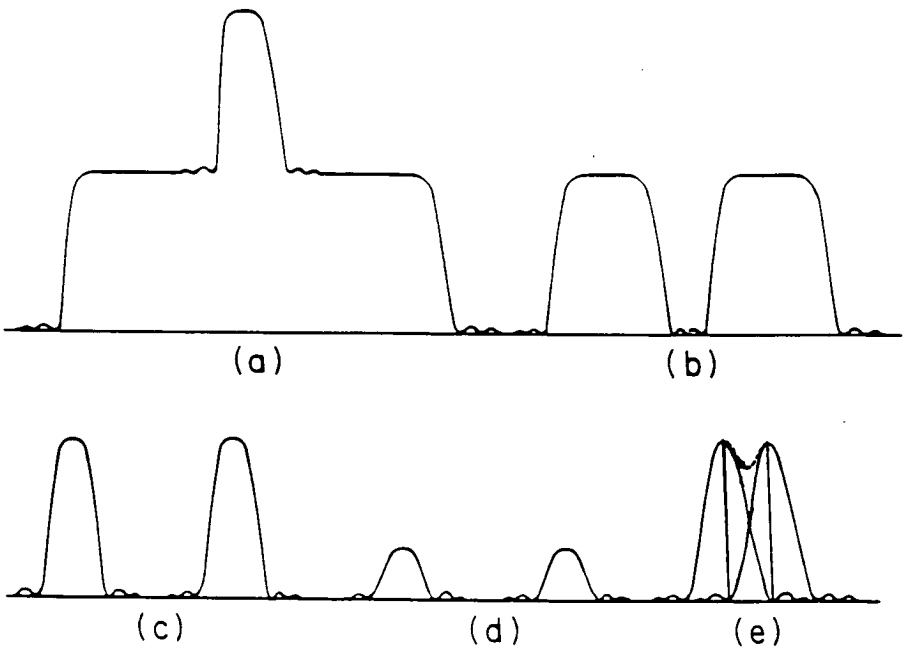

Fig. 4.4 Irradiance distribution in the focal plane of a spectrometer as the entrance slit is reduced in width (a-d). (e) Limit of resolution.

of slits in the grating. As the number of slits are increased the principal maxima becomes narrower and the secondary maxima weaker.

A Monolight Optical Spectrum Analyzer model No. 6800 (OSA) was used to measure relative reflectance in leaf tissues. The OSA scanning monochromator uses a continuously rotating diffraction grating driven by an electronically controlled d.c. motor at approximately 720 rpm,

Fig 4.6. Light incident in the input slit is dispersed into its component wavelengths by the diffraction grating and then sequentially swept past the output slit where a detector converts the optical signal into an electrical signal. The signal is amplified and transmitted to the OSA system controller for processing. The sensitivity of the system is dependent on the optical detector and on the grating selected. The best resolution achieved with UV-visible systems is 1 nm and for infrared systems 2.8 nm.

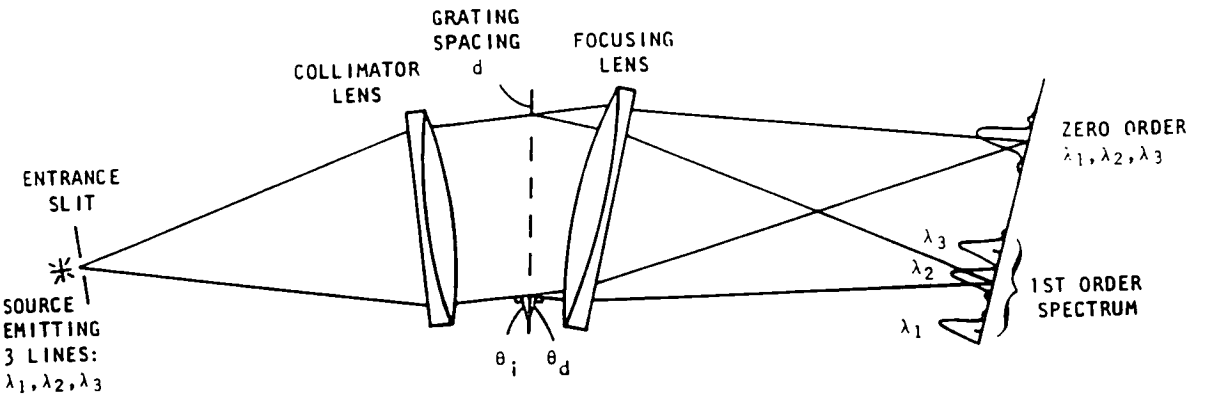

Fig. 4.5 Diffraction by a grating with distance **d** between adjacent slit apertures.

The detector used is chosen depending on the spectral range. A silicon photodiode is used in the 200-850 nm spectral band when the input radiation is high, whereas photomultipliers are preferred for high sensitivity applications working in the same waveband. Germanium and lead selenide photodetectors are used in the 600-1800 nm and 1800-5000 nm spectral ranges, respectively.

The 6800 Series Optical Spectrum Analyzer is a versatile instrument that enables high resolution spectra to be monitored every 80 ms and uses an optical fibre bundle for acquiring the sample radiation. The Optical Spectrum Analyzer comprises a scanning monochromator, a system controller, a module to interface the monochromator, and a computer fitted with a special interface card. The scanning monochromator is connected to the system via the Monochromator Control Module, which controls:

a. the monochromator scanning speed, rotating synchronously or at a predetermined slip frequency with respect to the local a.c. supply frequency;

b. the signal gain which can be amplified up to 1000 times;

c. the signal bandwidth automatically adjusted to optimize the signal-to-noise ratio for any measurement and;

d. the wavelength sampling interval.

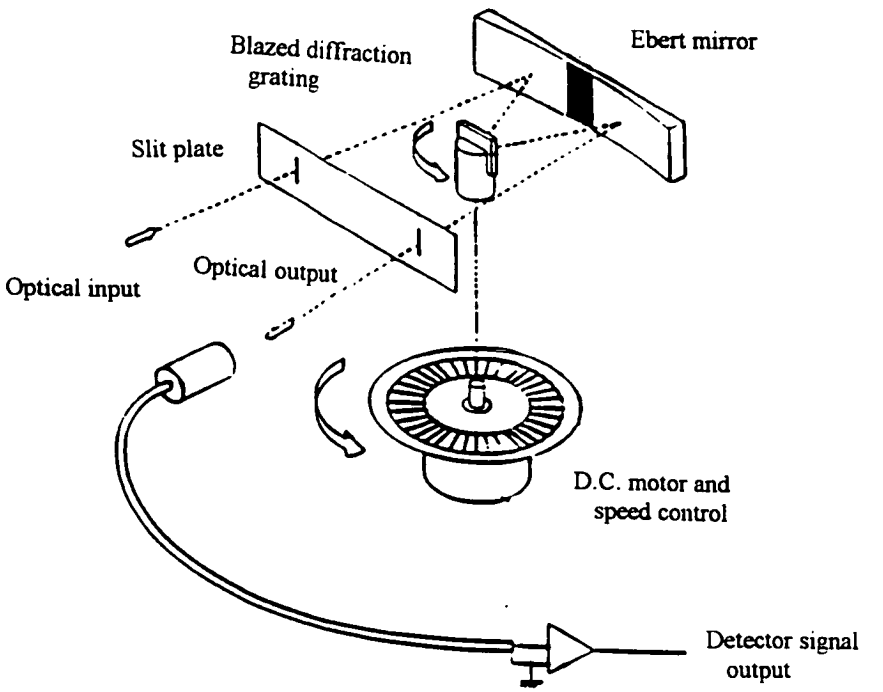

Fig. 4.6 Schematic block diagram of the scanning monochromator.

The sampling pulses vary according to the waveband covered, being closer in the UV/visible region. The wavelength sampling pulses and the signal are then connected to the Adquisition Module via a System Controller. The Adquisition Module with an input multiplexer followed by a high speed analogue to digital converter can acquire spectral signals from up to six monochromators sequentially.

The Wavelength Calibration Module calibrates the scanning monochromator with a low power HeNe laser interfaced through a light guide 1mm thick. Wavelength calibration is required

when a different monochromator is connected to a control module, or after changing the scan speed and/or slit width. Dark level calibration provides accurate compensation for offsets introduced by dark currents generated by photomultipliers or detectors.

4.2 SPECTRAL SIGNATURES USED TO RECOGNIZE PLANT SPECIES

Walter and Koch (1980), Menges (1979), Gausman et al. (1981) have studied plant species spectral signatures in order to identify and classify them. These studies compare diverse plant species signatures to provide:

plant protection requirements from ultraviolet radiation;

crop leaf pigment concentration effects in leaf reflectance;

weed interspecies spectral differences;

reflectance, absorption and scattering coefficients of several plants species.

Plants protect themselves against the potentially damaging ultraviolet radiation (280-320 nm). The epidermal layer from the leaves of many plant species filters the solar radiation, removing much of the UV-B (Cadwell et al.,1983). Gislefoss et al.,(1992) studied the optical properties of the epidermis of leek and cabbage. Leek was found to be more sensitive to UV radiation as cabbage possess protective mechanisms which attenuate UV radiation before reaching the mesophyll cells.

The relation between leaf reflectance and total chlorophyll and carotenoid concentrations was studied for eight crops, including corn, spinach, sorghum, cotton, lettuce, tobacco, cantaloupe and cucumber (Thomas and Gausman, 1977). The best correlation between leaf reflectance and total pigment concentration -chlorophyll or carotenoid- was found at 550 nm. For most crops, chlorophyll was the most important factor affecting reflectance and carotenoid effect on reflectance was best noted during the later growth period of the crops.

Walter and Koch (1980) studied the spectral reflectance in the 500-2500 nm waveband from the top surfaces of 16 plant species leaves in the shooting stage: *Aegopodium podagraria*, *Atriplex Patula*, *Chenopodium album*, *Cirsium arvense*, *Fallopia convolvulus*, *Galeopsis tetrahit*, *Lapsana communis*, *Polygonum amphibium*, *P. lapathifolium*, *Sinapsis arvensis*, *Sonchus arvensis*, *Tussilago farfara*, *Urtica dioica*, maize, potato and sugarbeet. Changes in

leaf properties, mainly dehydration, were avoided by reducing the time of measurement using only a limited number of wavelengths including 500 nm, 550 nm and 660 nm in the visible region and 750 nm, 800 nm, 1100 nm, 1450 nm, 1650 nm, 1850 nm, 1950 nm, 2250 nm and 2500 nm in the infrared region. Walter and Koch (1980) concluded that although green healthy leaves presented similar reflectance signatures, there were qualitative and quantitative interspecies differences in the infrared region. Chlorophyll and water absorption bands largely dependant on environmental conditions were not very useful in inter-species discrimination having the largest inter-species difference and minimum standard deviation at 800 nm. Menges(1979) recognized weed species in an onion field with colour infrared films for optimum herbicide spraying. Richardson et al. (1985) showed that video imagery could be used for distinguishing some weeds from crop plants. Everitt et al.,(1992) reported an experiment to distinguish weeds in rangelands, using three black and white, high resolution, visible/NIR light sensitive cameras (400-1100 nm) and four S-VHS portable video cassete recorders. The S-VHS cameras had filters placed between the camera lenses and the CCD arrays for recording selected wavelengths in the visible and near infrared spectral regions. The filters wavebands used were 644-656 nm, 543-552 nm and 815-827 nm. Video imagery with lower resolution than photography presented limited accuracy in the detection of individual plant species, but provided the users with inexpensive remote sensing data.

The infinite reflectance, the absorption coefficient, and the scattering coefficient of 30 plant species were reported by Gausman et al. (1981) and Gausman and Allen (1973). Discrete reflectance measurements in the 500-2500 nm waveband were taken by a spectrophotometer every 50 nm with seven wavelengths being analyzed: 550 nm, 650 nm, 850 nm, 1450 nm, 1650 nm, 1950 nm and 2200 nm. The 30 plant species exhibited troughs at 1450 nm and 1950 nm corresponding to the water absorption bands followed by reflectance peaks at 1650 nm and 2200 nm. Infinite reflectance calculated by Allen and Richardson equations (1968) was related to the reflectance and the transmittance of a leaf at the desired wavelength, encountering maximum inter-species difference at 850 nm. Short light paths, high infinite reflectance and low light absorption were characteristic of leaves with fine mesophyll structure, having the largest absorption coefficient at 650 nm in the chlorophyll absorption band. The scattering coefficient affected by the leaf structure varied with plant species achieving its highest value at 850 nm. Reflectance and scattering cofficients presented a poor relationship with leaf thickness and water content. Similar internal structures strongly correlated the absorption coefficient with leaf thickness.

4.3 CROP SPECTRA

Spectral data were taken in the laboratory with both spectrophotometers (the integrating sphere spectrophotometer and the Monolite Optical Spectrum Analyzer) after careful collection of the samples in the field. Great diversity of crops were analyzed at first instance, but the importance of broccoli and cabbage crops made them the main subjects of study. Weed leaves in the shooting stage were collected and put in plastic bags after cutting to minimize dehydration. When possible the entire weed plant including the roots was taken to the laboratory and transplanted to a pot. The leaves selected for sampling were the healthier middle aged ones. For the weeds with small leaves such as chickweed, only one measurement was performed per leaf. Several measurements were made on the same leaf of crop and broad-leaved weed species. For most of the work, measurements were taken on the top surface, 1 cm away from the leaf apex.

Each spectrophotometer had different spectral range and sampling intervals. The broader spectral range obtained with the integrating sphere spectrophotometer ranged from 500 nm to 1900 nm taking measurements every 20 nm. A sample of one square inch was required by the integrated sphere spectrophotometer, ideal for big brassica leaves. However, most weed leaves rarely achieved this area with exception of weed species such as *S. arvensis* (charlock), *A. patula* (common orache), *Rumex spp.* (dock) and *U. dioica* (nettle). This disadvantage together with software limitations reduced the application of the integrating sphere spectrophotometer to samples collected in 1991. The Monolite system spectral range was fixed by software from 600 nm up to 1600 nm using 10 nm intervals, including the 700-1350 nm spectral band where plant morphological information is contained. The Monolite Optical Spectrum Analyzer averaged 200 measurements of each sample before storing the result in a floppy disk with an ASCII format easily managed by other software.

4.3.1 BRASSICA CROP SIGNATURES

It was suspected that the large dimensions of mature brassica leaves might present different spectral reflectances in different sections of the leaf blade. Spectra taken from the edge or margin of leaves are referred to as "margin" spectra. The mid part of the leaves include more pronounced veins and spectra from this area are identified as "centre" spectra . Spectra taken from the principal vein forming the midrib of the leaf or the stalk attachment at the base of the leaf are identified as "stalk" spectra.

Ten broccoli leaves and ten cabbage leaves were collected and analysed in the laboratory integrated sphere spectrophotometer. Samples from the upper and lower surfaces of leaves were classified into five different groups, namely, top margin, top centre, underside margin, underside centre and stalk. Twenty spectra were taken from each position of cabbage and broccoli and then averaged.

The average reflectance of cabbage leaf top margin, top centre and stalk are shown in Fig. 4.7. All three spectra show low reflectance in the visible band with similar signature patterns in the 800-1400 nm waveband. The higher reflectance at 650 nm encountered in the stalk indicates a slightly lower chlorophyll content. Maximum reflectance with peak values at 900 nm was found at the margin and centre of the leaf. Above 750 nm, stalk tissues exhibit much lower reflectance values than either the margin or centre. Large reflectance differences between the leaf tissue and the stalk are found from 900 up to 1350 nm, as a result of different cell wall/air space interfaces, diversity in cell structure, stalk thickness and water content.

Fig. 4.8 shows the generally small reflectance difference between top and underside margins of cabbage leaves with maximum differences at 520 nm and 1700 nm. The chlorophyll content is marginally higher in the top surface, which is directed towards the sun.

Broccoli samples were collected randomly from the field and their spectra showed a higher reflectance in the leaf stalk than in the leaf blade in the visible and *red edge* slope wavebands, Fig. 4.9. Leaf margin and centre signatures were similar, while stalk exhibited the highest reflectance up to 820 nm and the lowest reflectance thereafter. Veins contained in the leaf centre increased the reflectance in the visible region and reduced it in the 1100-1400 nm waveband.

Reflectance differences between the upper and lower surfaces of the leaves show higher reflectance in the underside, Fig. 4.10. Chlorophyll and water content are higher in the top surface of the leaf, as shown by values obtained at 650 nm and 1450 nm. In the *red edge* slope, reflectance differences between the top and underside surfaces are larger than those encountered between the top margin and top centre of the leaf, Fig 4.11.

Comparison between the cabbage, broccoli and cauliflower leaf signatures showed reflectance differences in wavelengths above 1100 nm, Fig 4.12. Cauliflower leaves having the highest reflectance in the 1100-1900 nm waveband lose water easily. Thin cauliflower leaves, having a lighter colour presented a different leaf texture with no waxy cuticle. Cabbage leaves presented the lowest reflectance of the three brassicas in this waveband and also the highest

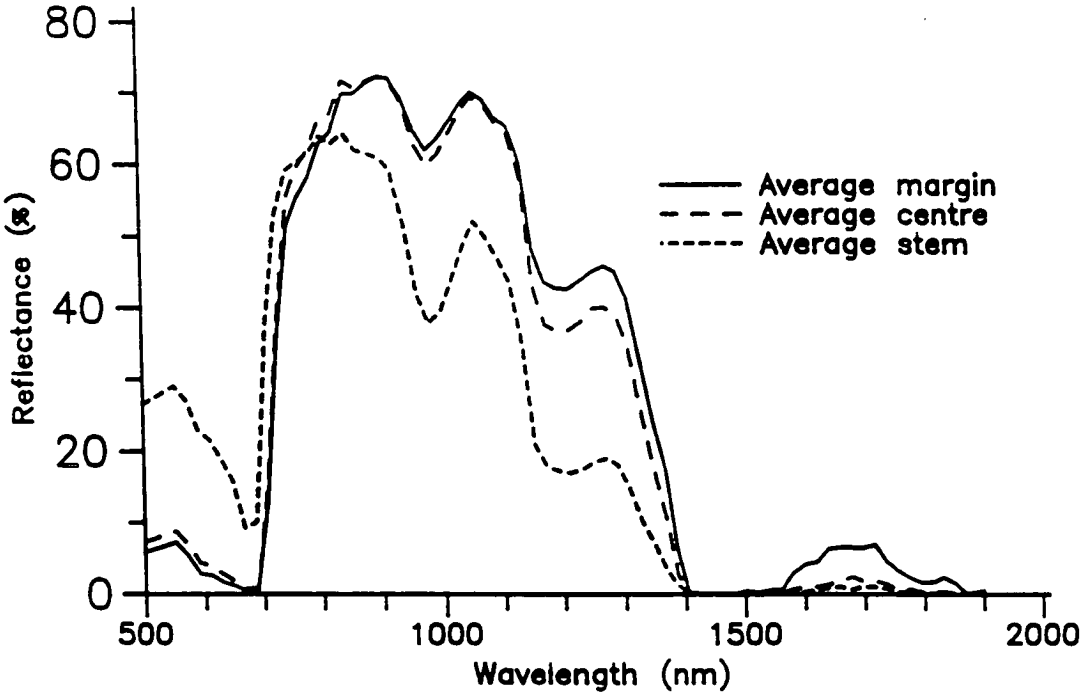

Fig. 4.7 Typical cabbage signatures on the leaf upper surface.

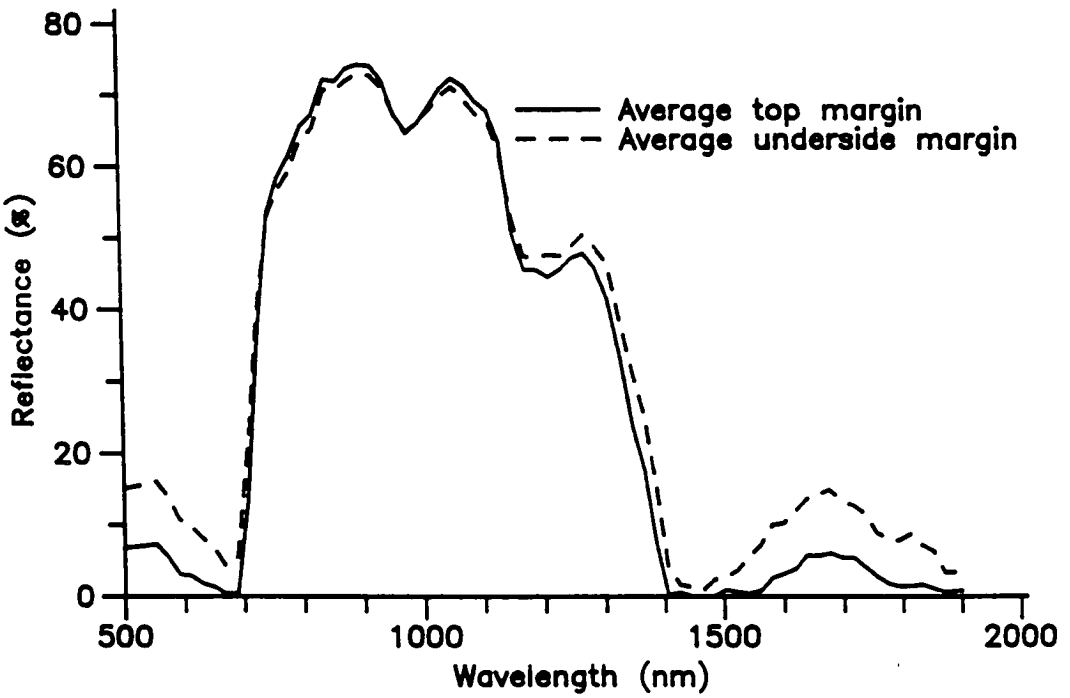

Fig 4.8 Typical cabbage signatures for the upper and lower surfaces margins.

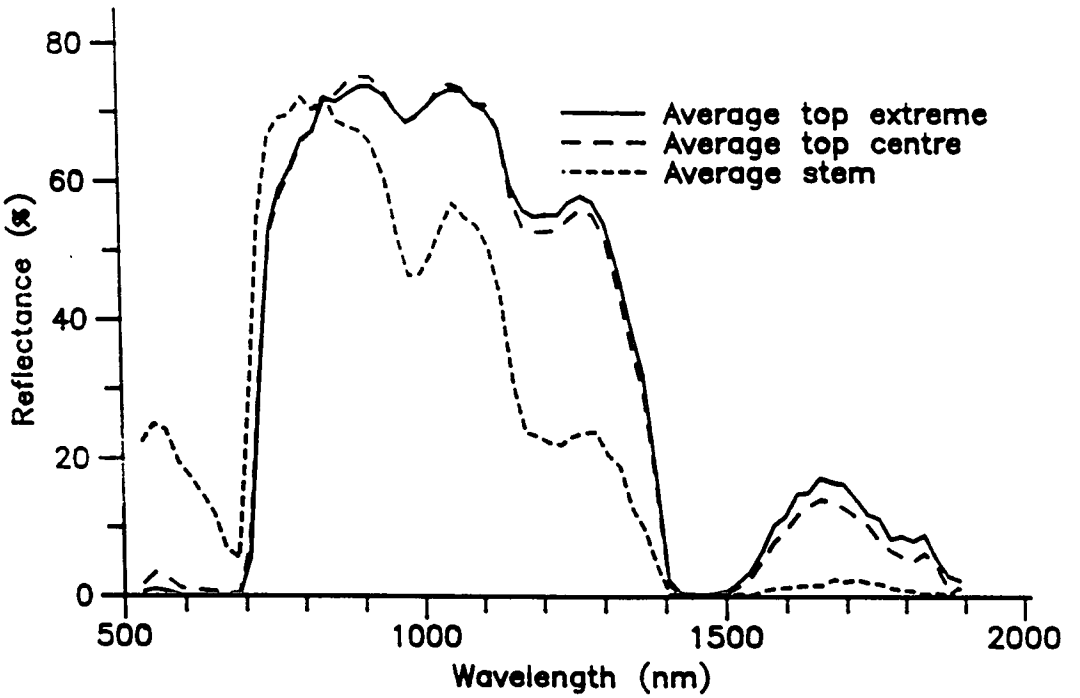

Fig. 4.9 Typical signatures for the upper surface of broccoli leaves.

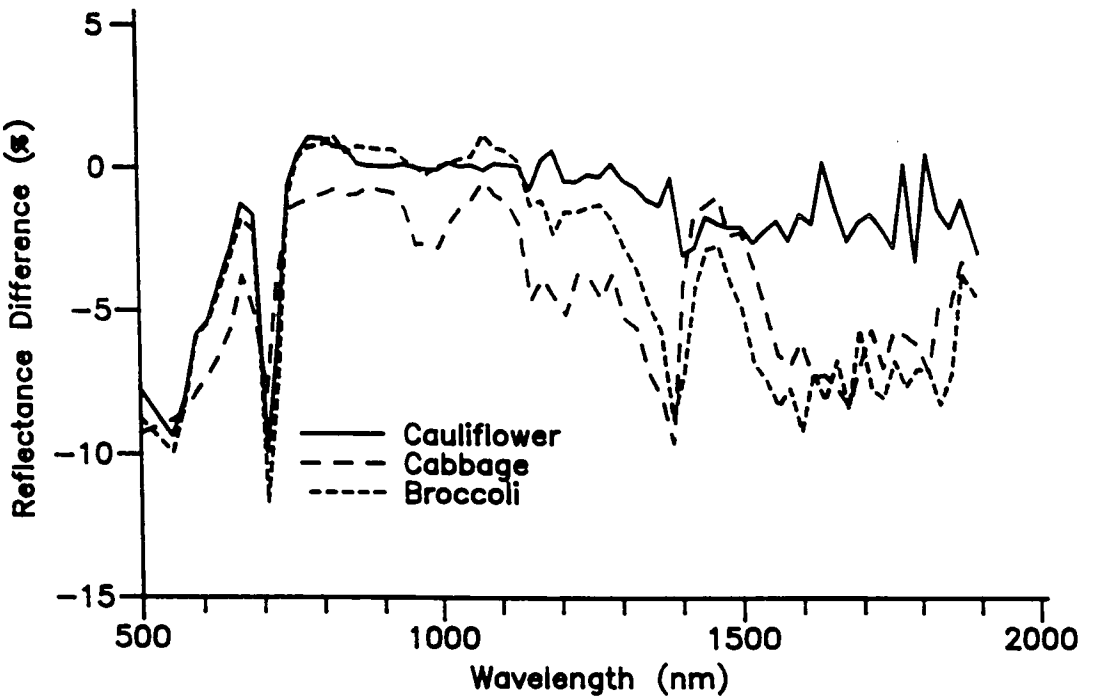

Fig. 4.10 Reflectance differences between upper and lower surface margins in brassicas.

reflectance in the visible region. Reflectance differences between top and underside surfaces for the three crops showed peak values in the *red edge* slope, Fig 4.10. The smallest reflectance difference between both surface signatures was encountered in cauliflower, although presenting maximum reflectance differences between top margin and top centre signatures at 1400 and 1700 nm, Fig. 4.11.

Forty healthy cabbage and broccoli leaves were collected from farms surrounding Bush Estate. Spectral measurements obtained with the Monolite Optical Spectrum Analyzer in the 600-1600 nm waveband from cabbage leaf tissue and stalk were averaged and finally plotted in Fig 4.13. Fig. 4.14 shows the average broccoli leaf tissue and stalk signatures obtained in the 600-1600 nm waveband with the spectrophotometer. All the measurements were taken in the top surface of the leaves and near the apex with an optical fibre. Signatures from ten yellow cabbage and broccoli leaves showed water and clorophyll pigment loss, with higher reflectances at 650 nm and 1450 nm. At the end of the senescing process, the leaf becomes brown and presents a flat spectrum between 600 and 1600 nm. Broccoli and cabbage stalk signatures presented higher chlorophyll content and lowest reflectance throughout all the spectrum compared with their respective yellow leaf signatures. Cabbage leaves presented a greater difference between healthy and stalk signatures than broccoli leaves.

Broccoli and cabbage leaves were also analyzed with the use of a spectroradiometer. The design and operation modes of the portable instrument are presented in Appendix A. Spectral measurements were collected with an optical fibre at 820 nm, a crossover wavelength with high reflectance and small reflectance variance between different leaves, and at 1450 nm which provided an indication of leaf water content. Spectral data was collected from cabbage and broccoli top side surfaces and the reflectance was plotted. Minimum reflectance in cabbage was found near the apex, increasing towards the leaf centre, Fig 4.15. The high reflectance encountered in the leaf centre near the stalk decreases toward the leaf margin. Broccoli presents as well a minimum reflectance at the leaf apex increasing towards the leaf centre, Fig 4.16. Maximum reflectance achieved 3 cm away from the leaf stalk, decreases towards the leaf margin.

4.4 WEED SPECTRA

Twenty six different weed species collected in vegetable fields were analyzed with the spectrophotometer and their signature are shown in appendix B.

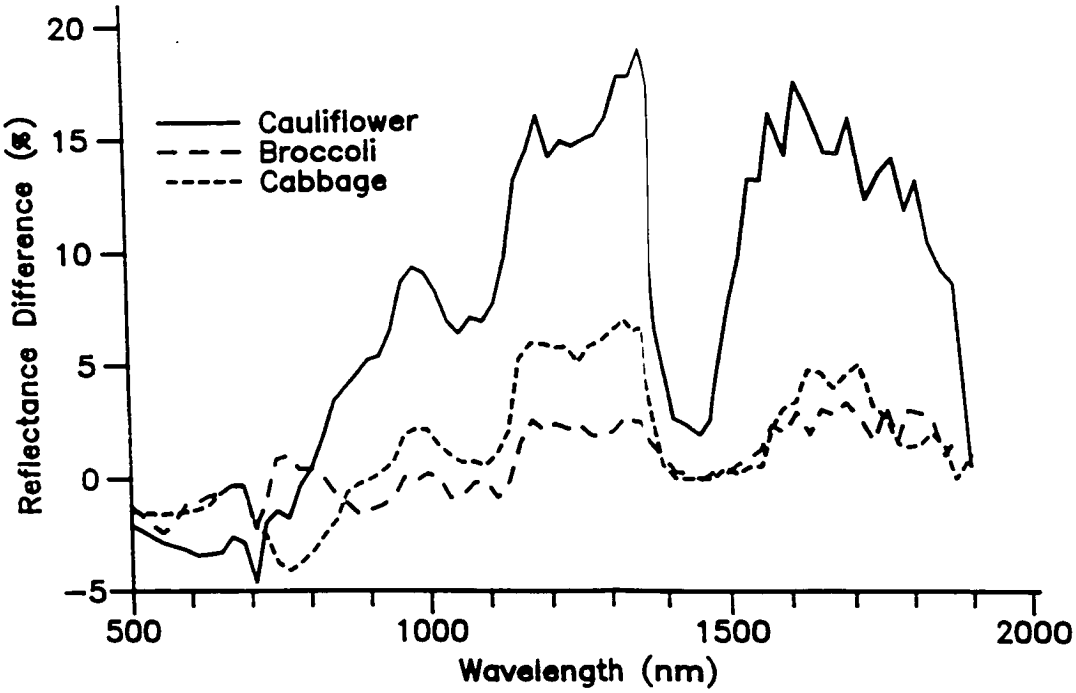

Fig. 4.11 Spectral differences for three brassicas leaves between top margin and centre.

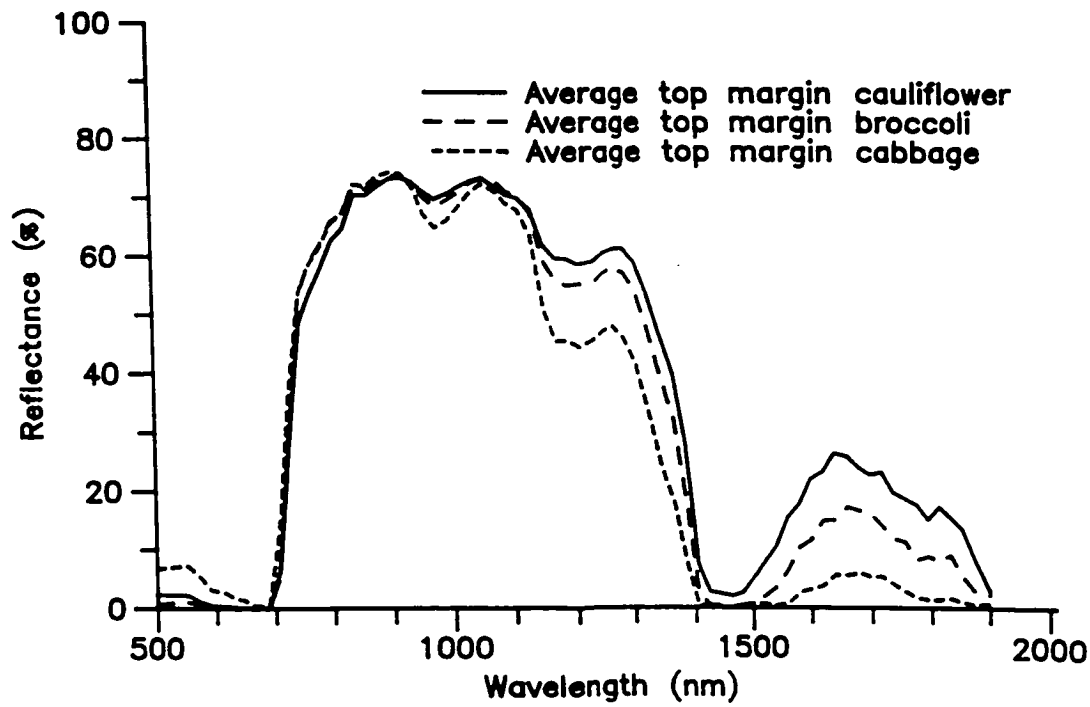

Fig. 4.12 Signature comparison for three brassicas.

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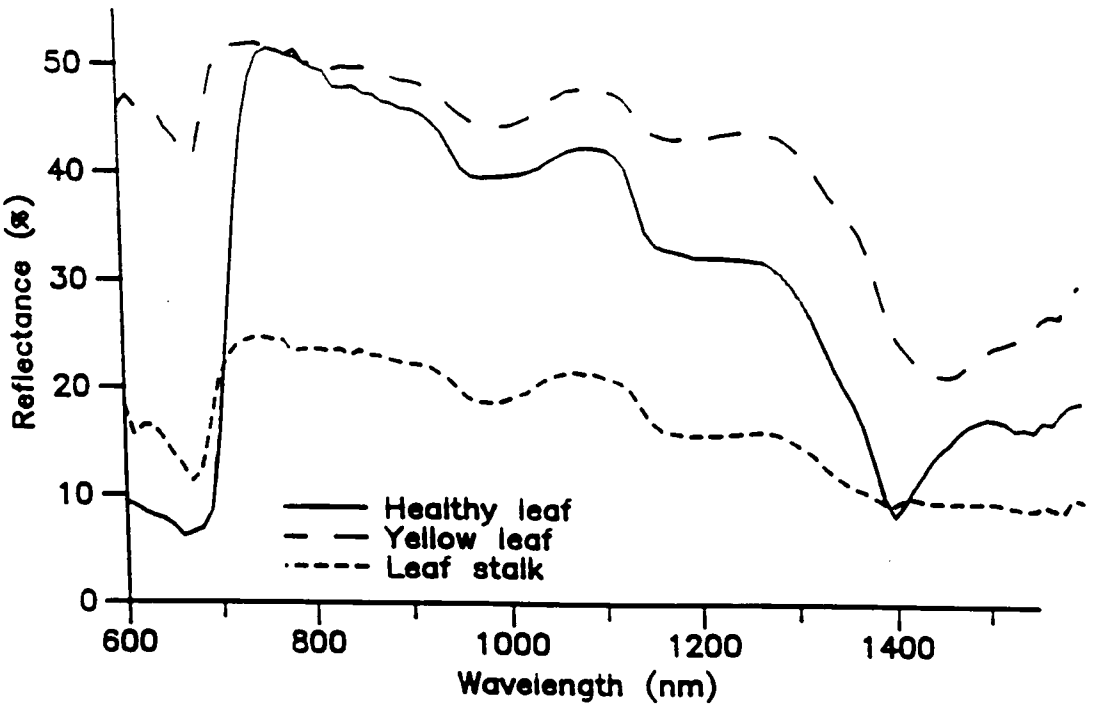

Fig. 4.13 Cabbage signatures measured with an optical fibre probe.

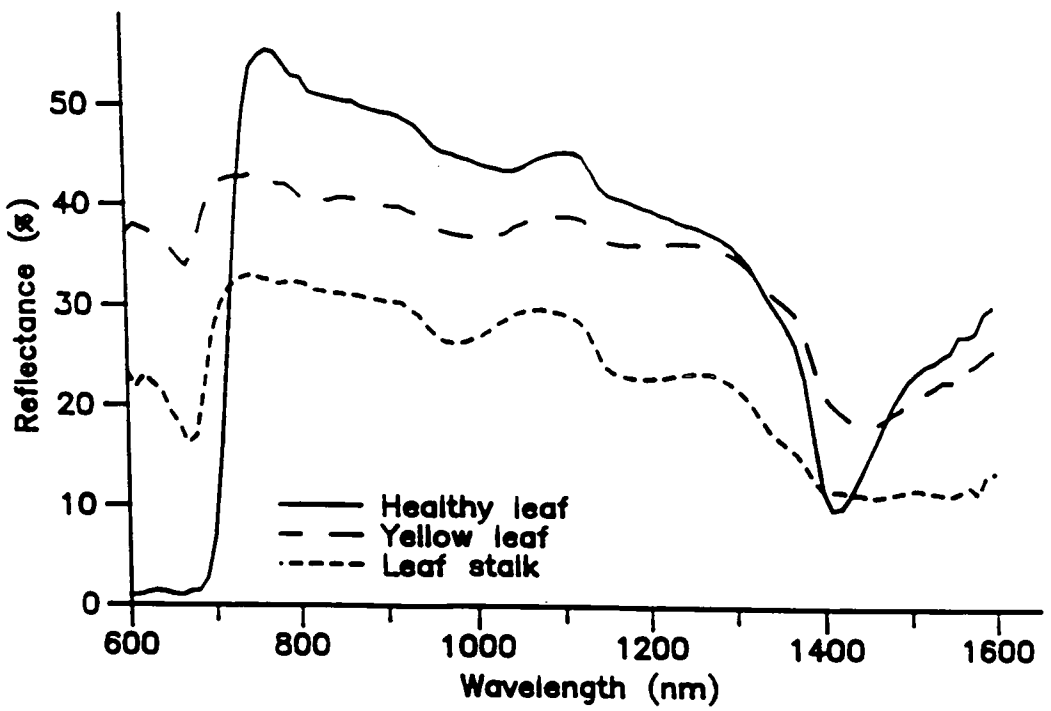

Fig. 4.14 Broccoli signatures measured with an optical fibre probe.

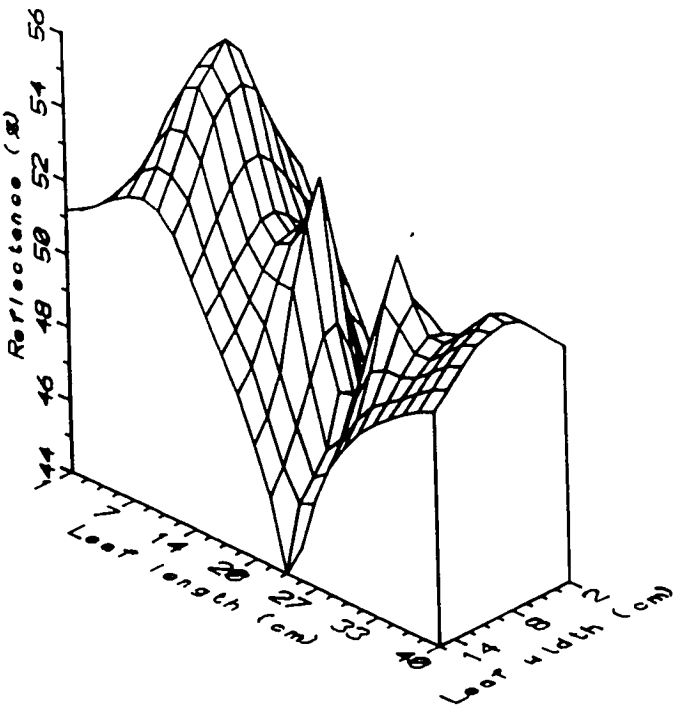

Fig. 4.15 Surface reflectance of a broccoli leaf.

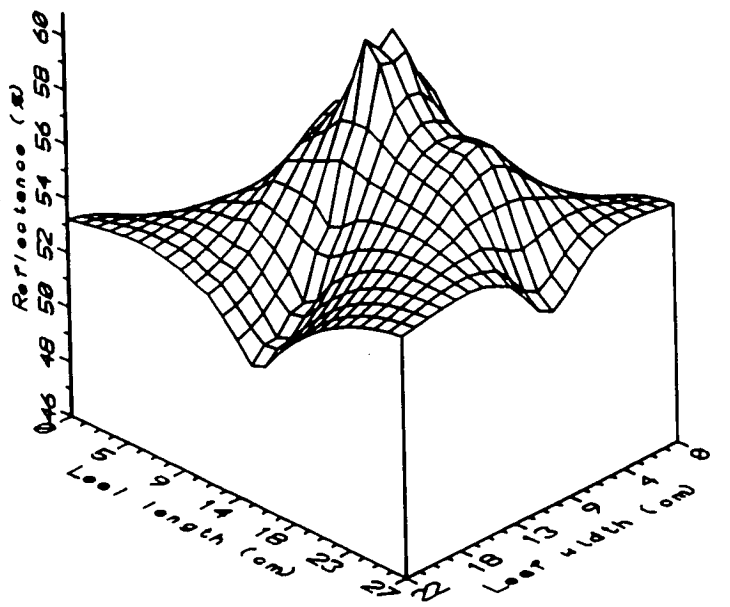

Fig. 4.16 Surface reflectance of a cabbage leaf.

The broad-leaved weeds with highest incidence i.e. *S. media*, *A. patula*, *C. album*, *S. arvensis* and *S. vulgaris* were scanned with the use of the spectrophotometer and also analyzed with the portable radiometer. Additional measurements were taken for some grass weed species as *Holcus lanatus* (yorkshire fog), *Elymus repens* (couchgrass) and *Dactylis glomerata* (cocksfoot).

4.4.1 SPECTRAL MEASUREMENTS IN BROAD-LEAVED WEEDS

A. patula (common orache) an annual weed that postrates in the soil, has the flowering stems upright. Two morphologically different leaves are encountered in this plant: a palmate leaf and a lanceolate leaf. The signature of three different size palmate leaves presented small spectral differences as shown in Fig. 4.17. Lanceolate leaves growing in the flowering stems presented a higher reflectance than palmate leaves, Fig. 4.18.

Spectral signatures accomplished with the Monolite Optical Spectrum Analyzer for 1, 3, 5 and 7 layers of *C. album* leaves show a reflectance increase with the number of layers as shown in Fig. 4.19.

Matricaria spp. presents needle-type leaves with white daisy-like flowers surrounding a composite head. The composite head reflectance is three times higher than the leaf reflectance, with lower chlorophyll concentration and water content in the composite head, Fig. 4.20.

S. vulgaris (groundsel) is an annual weed, presenting leaves with several lobes and yellow "tubular" flowers. Healthy and rusty leaf signatures were plotted in Fig. 4.21, showing highest reflectance the leaf tissues containing rust. Rust attacking groundsel plants decreased the chlorophyll content in the leaves and darkened the colour. Reflectance reduction in the 800-1400 nm waveband can be related to cell damage and leaf dehydration.

Reflectance signatures of *lamium purpureum* (red dead nettle), *Lamium album* (white dead nettle) and *Urtica urens* (common nettle) leaves were scanned with the Monolite Optical Spectrum Analyzer. The results, plotted in Fig. 4.22, show similar signature patterns in white and red dead nettle leaves, the former having a higher reflectance. The chlorophyll and water content found in the three different species are similar.

Spectroradiometer sampling at 820 nm of different weed species (Appendix A) indicated that reflectance:

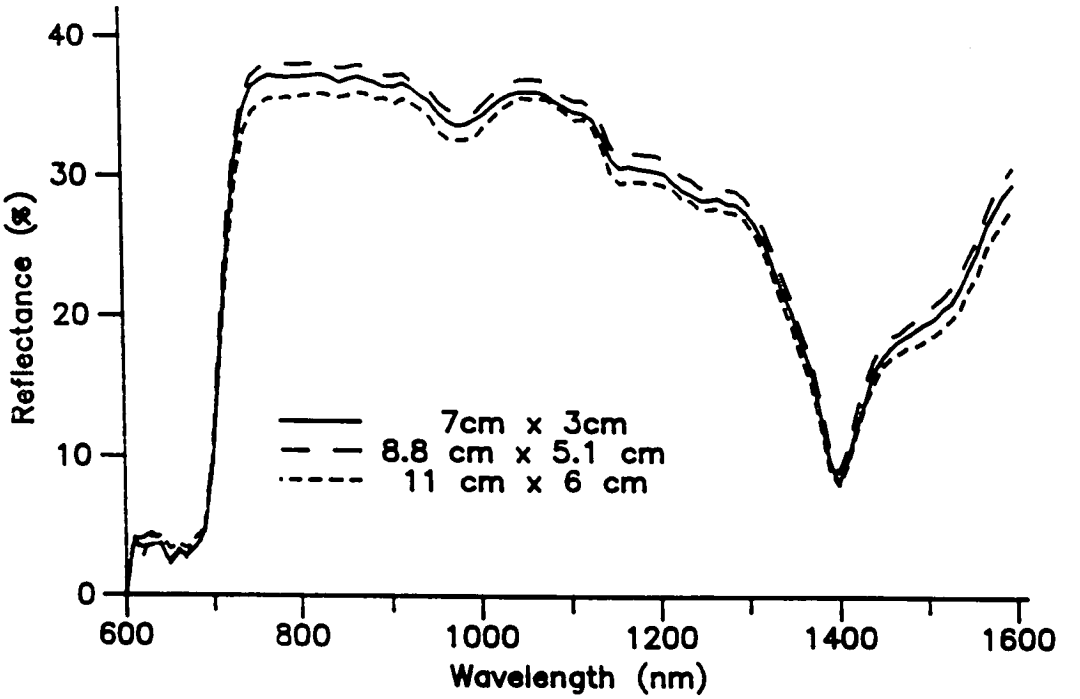

Fig. 4.17 Reflectance signatures of three different size orache leaves.

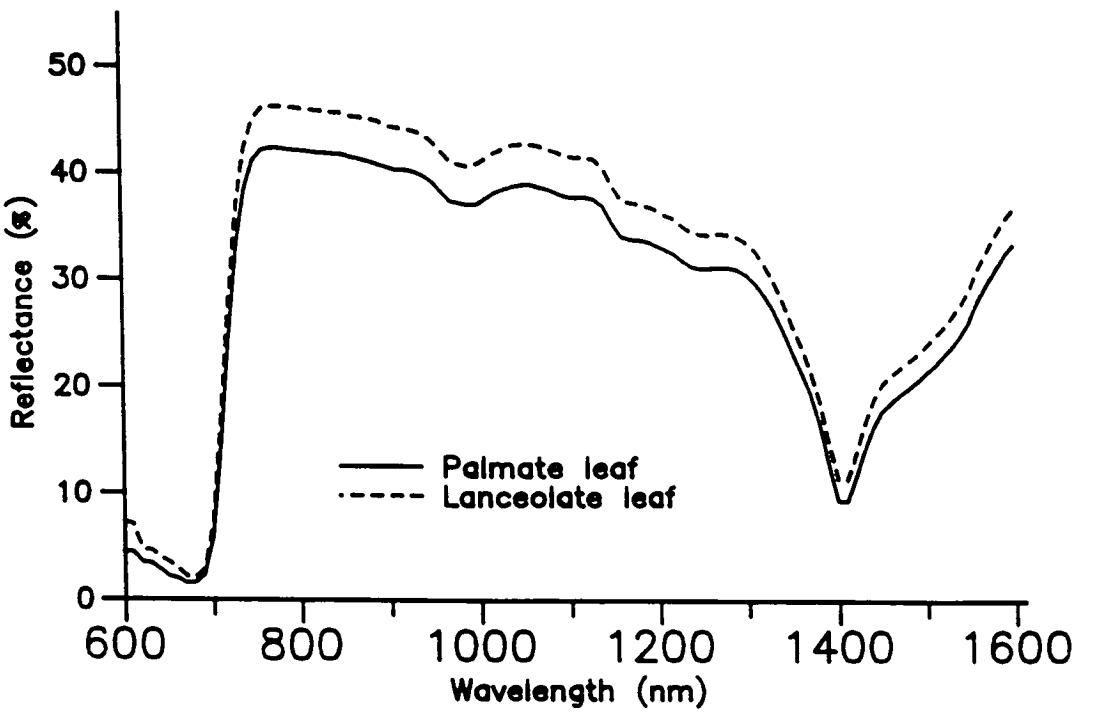

Fig. 4.18 Signatures of two morphologicaly different orache leaves.

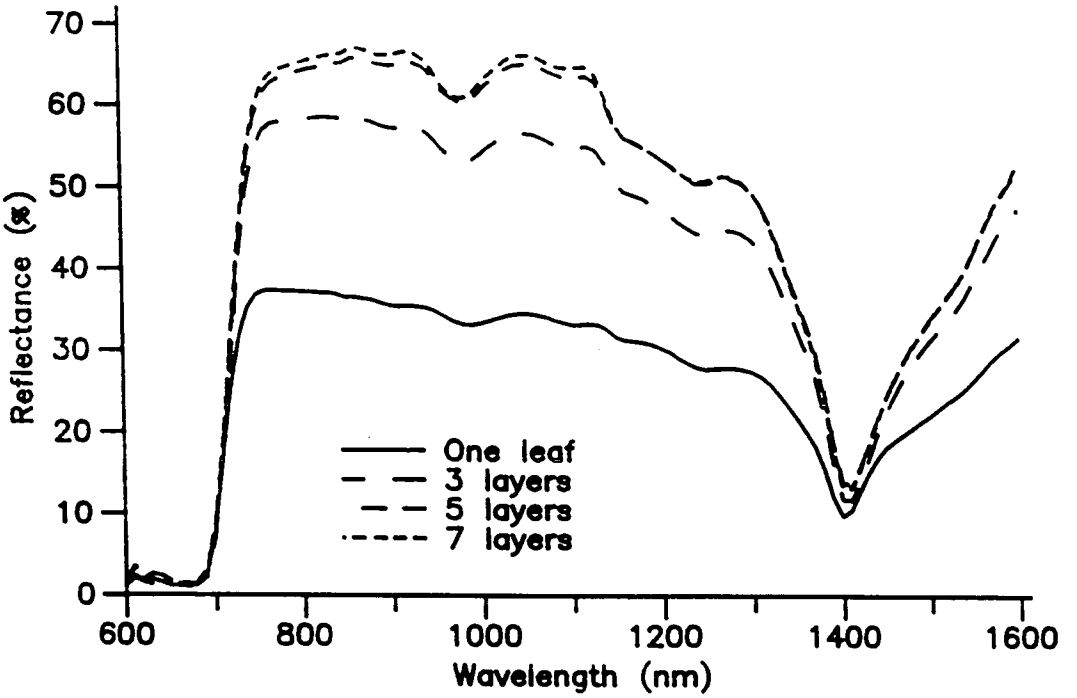

Fig. 4.19 Fathen signatures obtained with different leaf layers.

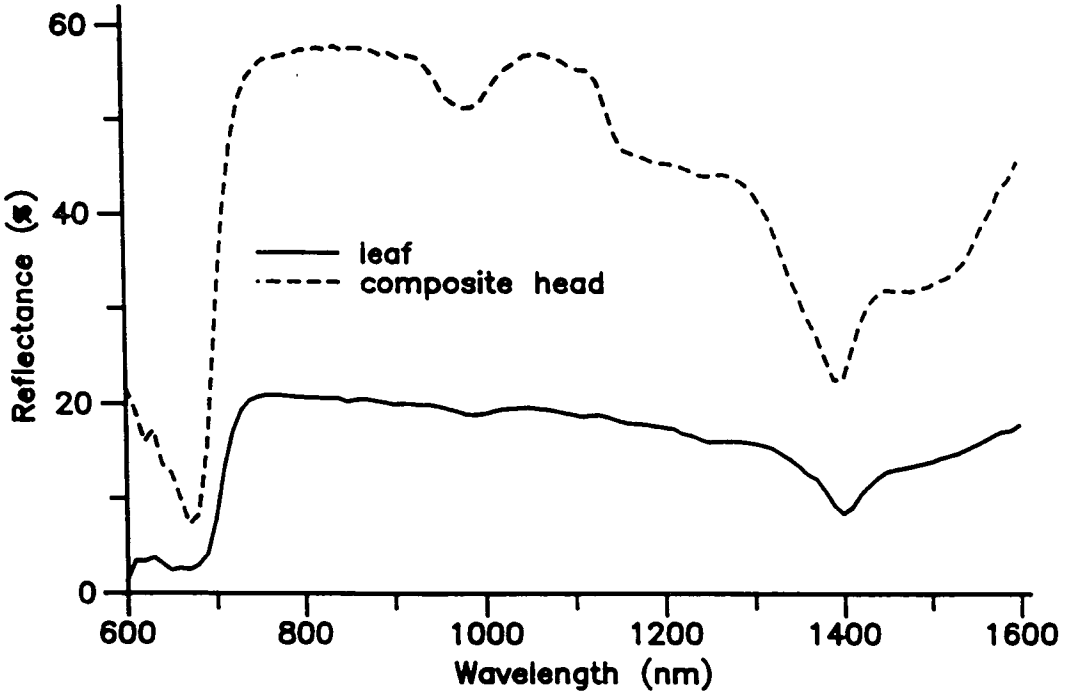

Fig. 4.20 Mayweed leaf and flowering head signatures

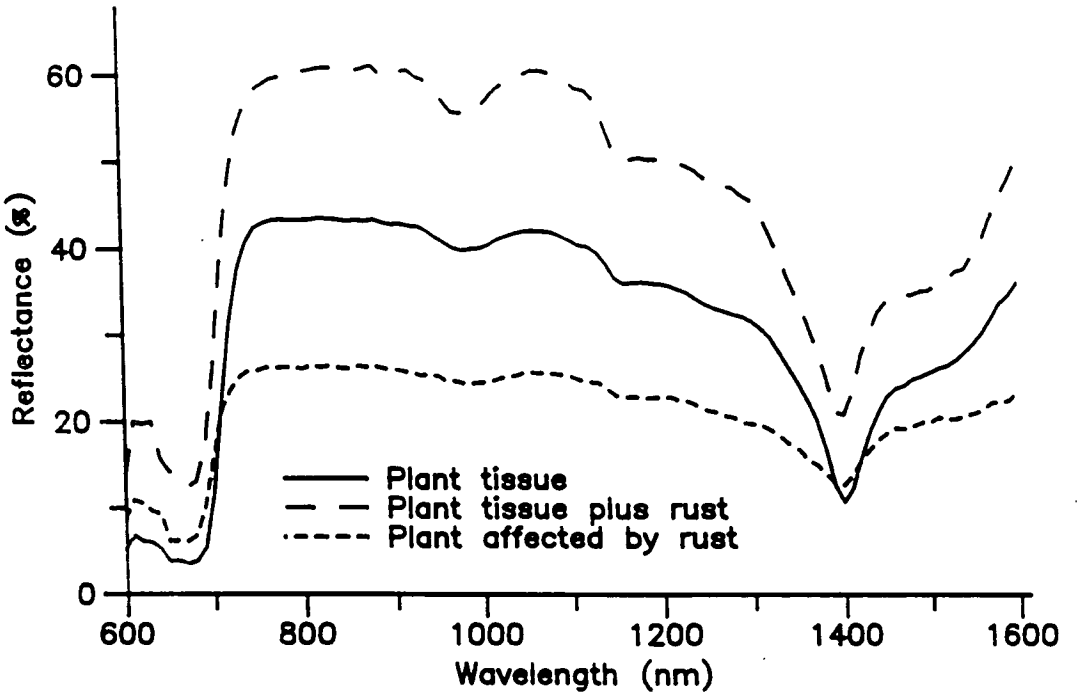

Fig. 4.21 Effect of rust in groundsel reflectance signature.

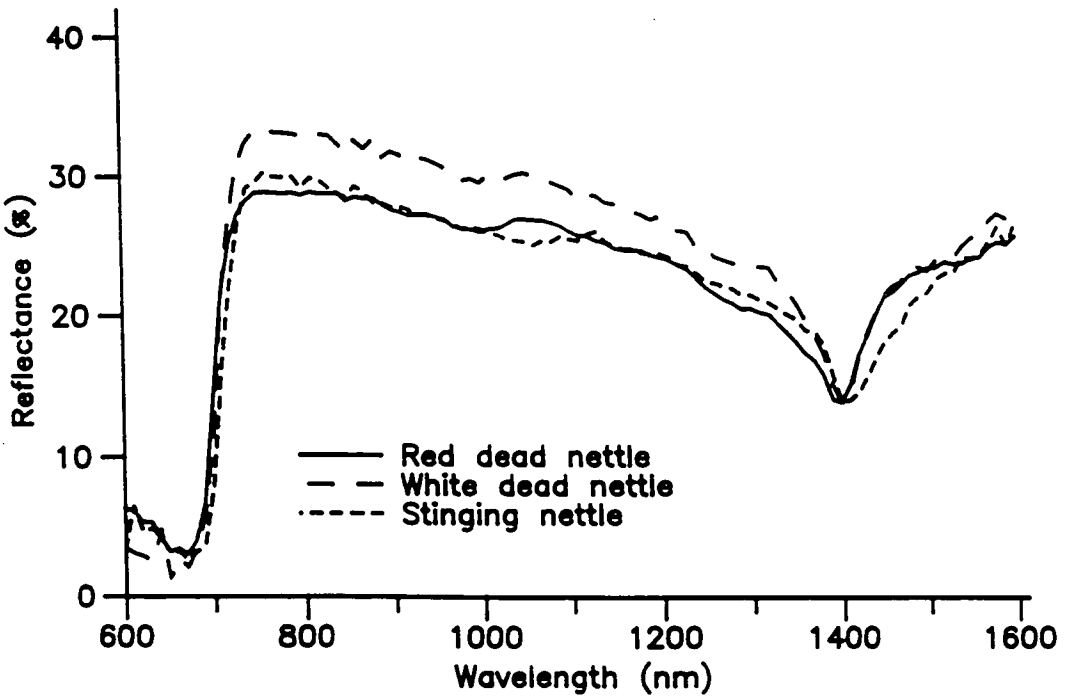

Fig. 4.22 Reflectance signature from three nettle species.

increased with the length and width of *S. media* leaves;

increased in *A. patula* from a minimum at the leaf apex to a maximum at the leaf centre;

decreased in *C. album* from a maximum at the leaf apex to a minimum reflectance in the leaf centre (only four samples could be taken per leaf);

in *A. patula* and was non-dependent on leaf size when the sample was taken two cm away from the apex.

4.4.2 SPECTRAL MEASUREMENTS IN GRASS WEEDS

Reflectance measurements from *H. lanatus* (yorkshire fog), *E. repens* (common couchgrass) and *D. glomerata* (cocksfoot) were obtained with the spectroradiometer and the Monolite Optical Spectrum Analyzer.

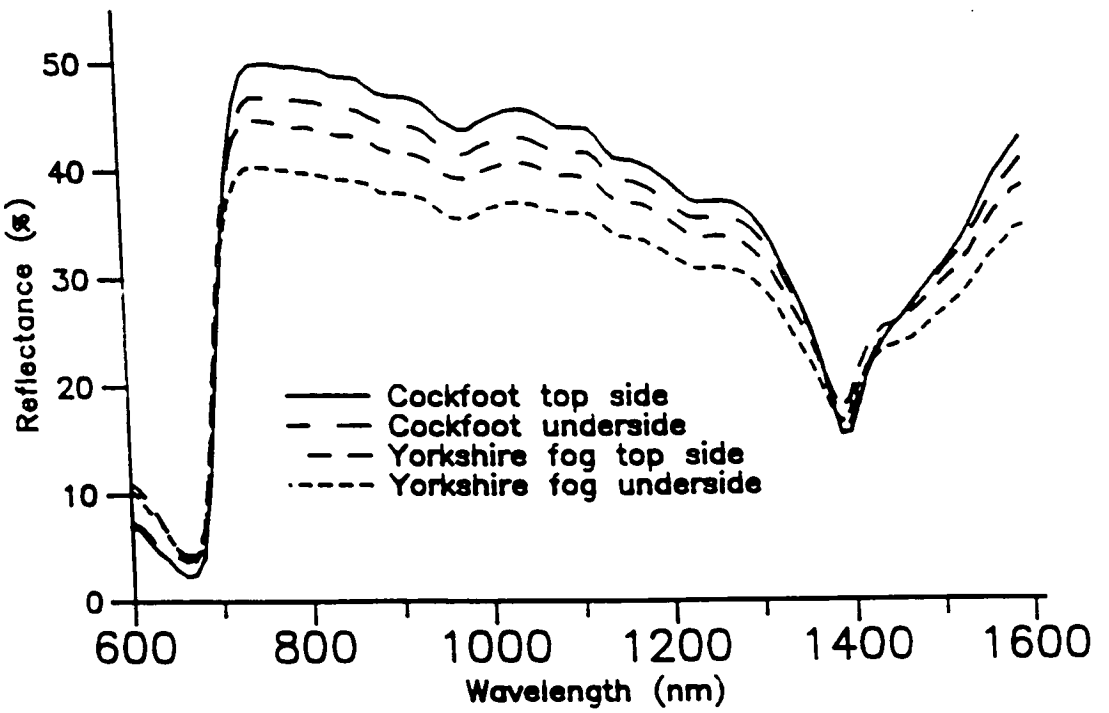

Fig. 4.23 Top and underside signatures of cock foot and yorkshire fog.

Top and underside signatures of *H. lanatus* and *D. glomerata* were obtained with the spectrophotometer, showing higher reflectance values in the top side for both grasses, Fig. 4.23. *D. glomerata* presents a higher reflectance than *H. lanatus* in the 800-1400 nm waveband, with higher chlorophyll and water content encountered at 650 nm and 1450 nm, respectively. Measurement taken with the spectroradiometer indicated maximum reflectance close to the ligule in all the grasses sampled.

4.5 SOIL SPECTRA

Soil reflectance is affected by its particle size, moisture, organic matter content, mineral composition and quantity of soluble salts.

Planet (1970) indicated that wet and dry soil reflectance differences were due to changes in the index of refraction of water due to dissolved soil constituents and to changes in the physical nature of soil particles by the presence of water. Moist soils presented a lower reflectance than drier soils in the 400-2500 nm spectral band, and Beck et al., (1976) suggested that soil moisture could be measured in the 1500-1730 nm waveband.

Increased organic matter content decreased soil reflectance in the 400-2500 nm range (Hoffer and Johannsen, 1969). Organic matter decomposition resembled senesced leaves, increasing infrared reflectance as more air cell interfaces enhanced reflection (Gausman et al., 1975). Regression studies related organic matter content to soil moisture using a curvilinear exponential function (Schreier, 1977).

Soil particle size and shape influence soil reflectance. Coarser particles with irregular shapes formed a surface with a large number of inter-particle spaces, while fine particles give more even surfaces. Most of the light, incident on soils with coarse superficial particles, penetrates the surface before getting scattered. Bowers and Hanks (1965) measured the reflectance of pure kaolinite in diameter size fractions between 0.022 to 2.68 mm, finding a rapid exponential increase in reflectance (for wavelengths between 400 and 1000 nm) as particle sizes decreased. Montgomery (1976) found that silt content was the most important parameter to explain soil spectral variations. Beck et al.,(1976) concluded that the 1500-1730 nm waveband was the best for identifying clay content in surface soils.

The type and amount of iron oxides influence the colours of red and yellow soils. Typically, the ferrous ion produces a band near 1000 nm. The iron absorption band at 870 nm can be seen in fine sandy soils. Soils with a higher iron content reveal broader absorption bands at

870 nm. Obuklov and Orlov (1964) reported that the 500-640 nm waveband was inversely proportional to iron content and Stoner (1979) obtained high correlations between reflectance and iron oxide content in the 1550-2320 nm waveband. Al-Mahawili (1983) studied the reflectance characteristics of saline and non-saline soils in the 500-2300 nm waveband. encountering a lower reflectance in saline soils.

4.5.1 SOIL AND STONE SIGNATURES

Fifty soil samples from different fields were collected and analyzed with the Monolite Spectrum Analyzer in the 600-1600 nm waveband. The sand and clay samples were averaged to produce a representative soil signature including different size particles.

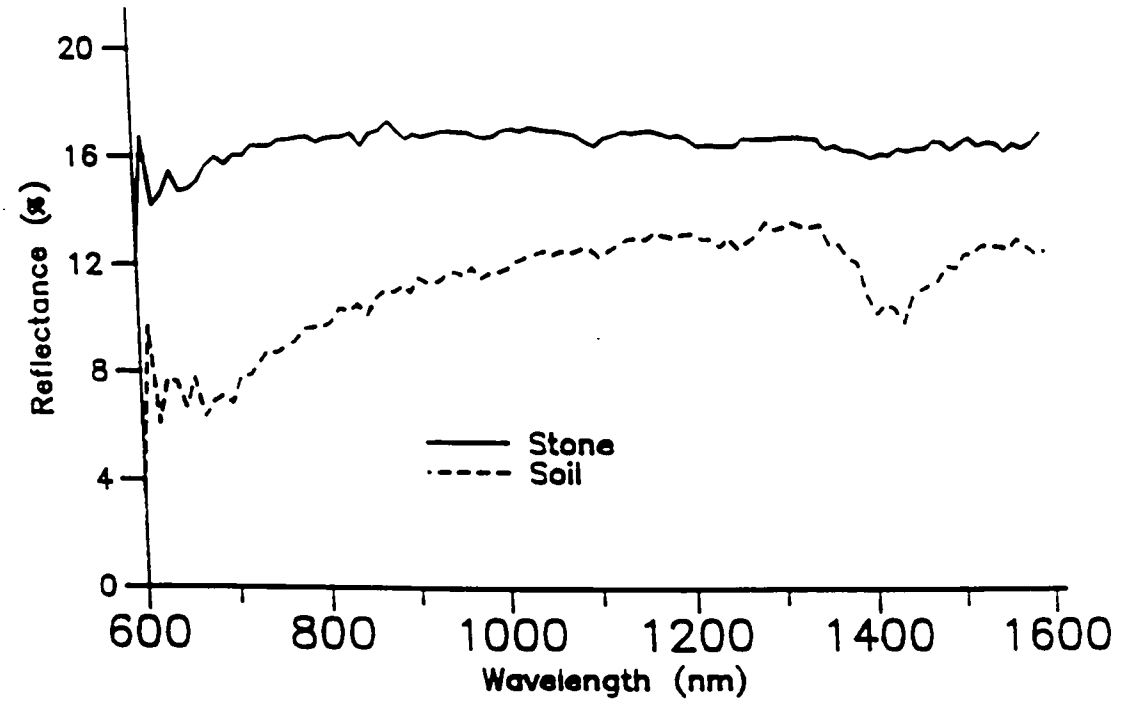

Fig. 4.24 Soil and stone signatures.

Soil and stone signatures shown in Fig. 4.24 have different spectral patterns to leaf signatures. Soil reflectance increases linearly from 600 nm up to 1350 nm, while stone spectra remains flat, with a 15% reflectance throughout all the spectral range (600-1600 nm). The *red edge* slope present in leaves spectra does not appear in soil and stone signatures. Soil and leaf spectra show water absorption bands centered at 1400 nm, having soil spectra lower reflectance in the 800-1300 nm waveband.

5 CROP WEED EXPERIMENTS AND DISCRIMINATION

Three crops of especial horticultural importance were selected to analyse the possibility of using optical reflectance in crop/weed/soil discrimination: cabbage, broccoli and leek. The cropping area, gross production and average farm price of some vegetables in the United Kingdom are shown in Table 5.1 Eleven different sites in Scotland were visited and surveyed during the growing seasons of 1991, 1992 and 1993 and samples collected to form a signature database. Spectral data from trial 1 was obtained using the integrating sphere spectrophotometer while the sampling from the rest of the trials was performed with the Monolite Optical Spectrum Analyzer. The sites included six farms around the Scottish Centre of Agricultural Engineering, 10 km south of Edinburgh and one near St. Andrews. Table 5.2 shows the crops grown in each site and considered as experimental trials for the crop/weed discrimination studies. These trials included several experiments with the purpose of analyzing the effect on crop/weed/soil discrimination of:

crop variety;
weed species;
soil cover.

Ninety five percent or more of the vegetables grown in the United Kingdom are treated with herbicides. The last survey of herbicide usage in vegetable crops in Scotland was carried out in 1991 showing full dependence on the chemicals, Table 5.3. Nevertheless, the choice of herbicides available for horticultural crops is small compared with their counterparts applied in arable crops. The great diversity of broad-leaf weeds in vegetable crops makes chemical weed control difficult to achieve efficiently. Combinations of herbicides are generally utilised and for example, brassicas depend on two for controlling annual weeds: trifluralin and propachlor. Trifluralin a pre-emergence herbicide and propachlor applied after sowing will not control weeds efficiently unless a proper combination is sprayed. Proper decisions must bear in mind the effect of both herbicides on weed populations:

trifluralin does not control mayweeds, groundsel or shepherds' purse;

propachlor does not control fumitory, knotgrass, redshank and fat-hen;

groundsel, mayweeds and shepherd's purse can be troublesome throughout the period of crop sowing while fumitory, knotgrass and redshank are troublesome in early sown crops.

Table 5.2 Crops grown in the different trials.

		TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 6	TRIAL 7	TRIAL 8	TRIAL 9	TRIAL 10	TRIAL 11
LEEK				•	†•	•		†•				
CABBAGE	Spring									•		
	Autumn	•		•	†•		•	•		†•		
	Savoy		•							•		
BROCCOLI	Young					•					•	
	Mature	•	•	•		•			§•			†•

† Soil and stones
§ Straw and soil

Table 5.1 **Field Vegetables grown in the United Kingdom during crop years 1983/84 and 1991/92 (MAFF, 1993).**

Crop	Cropped area (ha)		Gross production ('000 t)		Avg farm gate price(£/t)	
	1983/84	1991/92	1983/84	1991/92	1983/84	1991/92
Asparagus	400	808	0.6	1.9	2,746.32	2,115.62
Beans broad	3,792	5,009	17.0	22.1	216.67	311.51
Beetroot	2,394	2,751	93.5	98.8	139.04	88.09
Brussels sprouts	11,743	8,486	154.3	110.9	257.47	312.32
Cabbage, spring	6,762	6,739	111.7	98.3	212.18	208.00
Cabbage, Summer and Autum	4,611	7,592	144.5	271.9	190.10	107.37
Cabbage, Winter	8,284	8,784	262.1	290.8	161.97	130.77
Calabrese	979	6,252	6.0	37.4	713.94	625.45
Carrots	13,128	17,498	554.5	652.8	133.30	122.82
Cauliflower	15,986	19,711	298.5	345.2	203.85	245.56
Leeks	2,060	3,629	43.7	78.6	375.00	356.39
Lettuce	6,368	8,147	154.5	250.1	307.77	392.60

Table 5.3 Herbicide applications in the United Kingdom.

HERBICIDES	% of crop treated			
	SUMMER / AUTUMN CABBAGE	SPRING / SAVOY CABBAGE	CALABRESE	LEEK
Aziprotryn	18	-	-	-
Chlorbufam / Chloridazon	-	-	-	54
Chlorthal-dimethyl	-	-	29	44
Cycloxydim	38	4	4	-
Glycophosate	-	-	24	20
Ioxynil	-	-	-	78
Metazachlor	8	46	-	-
Paraquat	-	-	2	26
Pendimethalin	-	2	-	32
Prometryn	-	-	-	33
Propachlor	83	51	90	74
Tebutam	3	-	21	-
Trifluralin	87	95	64	-
CROP AREA (acres)	292	174	1260	170

Samples collected from most of the trials were carefully wrapped to reduce imminent water loss and analysed promptly with a spectrophotometer in the laboratory. The spectral band scanned ranged between 600 nm and 1600 nm and the data was stored in floppy disks. Finally, the data was manipulated and presented to the statistical BMDP software for analysis. A complete description of a program run is shown in Appendix C.

5.1.DISCRIMINANT ANALYSIS

Discriminant analysis was used as a tool to determine the best wavelengths that would provide the highest crop/weed/soil and crop/weed species/soil discrimination accuracies. One of the objectives during this study was to account for plant stress differences and different crop growth stages so the spectral data collected presented high dispersion. The experiment was planned for considering some of the variables encountered in the fields. The usefulness of discriminant analysis was questioned and the results analysed using randomly created trial groups. All the results in this chapter were obtained with this analysis without getting into detail of analysing each individual spectrum in the broad spectral conditions that the experiment is covered.

In discriminant analysis, the cases (spectra) are divided into groups (i.e. crop, weed) and the analysis is used to find classification functions that seek to maximize differences between the groups. These classification functions are linear combinations of the variables. In this case, the variables are wavelengths or functions of wavelengths. At each step, the F statistic is computed for each variable to determine which should be added to the function and after entering the variable, the classification functions are recomputed, until group separation stops improving.

Table 5.4 shows the number of spectra used per trial in each of the crop/weed/soil categories. The trial group is a sub group of these spectral cases on which the derived classification functions can be tested. For example, in site 10 there were 33 spectra in this group whereas there were 77 spectra in the analysis from which the classification functions were derived. In the majority of the trials, 60% or more of the spectra were weeds. Generally 30% of the spectra formed the trial group used to validate the analysis.

All groups were presented individually within the discriminant program. The individual groups could then be regrouped according to the philosophy of either a simple 2 group system or several group systems.

Table 5.4 Spectral composition for each trial and their distribution when applied to the discriminant analyses.

		No. of spectra					
		CROP	SOIL	WEEDS	TOTAL	TRIAL GROUP	TRAINING GROUP
TRIAL 1	Broccoli	50	10	82	142	42	100
	Cabbage	50	10	82	142	42	100
TRIAL 2	Cabbage	40	10	70	120	36	84
	Broccoli	30	10	70	110	33	77
TRIAL 3	Cabbage	30	10	100	140	42	98
	Broccoli	30	10	100	140	42	98
	Leek	30	10	100	140	42	98
TRIAL 4	Leek	40	† 20	50	110	33	77
	Cabbage	40	† 20	60	120	36	84
TRIAL 5	Leek	40	10	100	150	45	105
	Broccoli	40	10	100	150	45	105
TRIAL 6	Cabbage	30	10	60	100	30	70
TRIAL 7	Cabbage	40	10	70	120	36	84
	Leek	40	† 20	100	160	48	112
TRIAL 8	Broccoli	40	§ 10	60	110	33	77
TRIAL 9	Cabbage	40	10	70	120	36	84
TRIAL 10	Broccoli	40	10	60	110	33	77
TRIAL 11	Broccoli	40	† 20	50	110	33	77

† Experiments containing both soil and stone spectra.
§ One experiment was carried out with soil and the other with straw.

Data was grouped using one crop in three general categories, i.e. crop, weeds and soil. Another more detailed analysis classified weeds by species into specific categories, in addition to the crop and soil. For example in trial 10 of a total of nine specific categories, seven were weed categories, one was of broccoli and the last one consisted of soil spectra. Trials 4, 7 and

11 included a stone category, which was classified together with the soil general category for analytical purposes. Straw used as a mulch covered all the soil surface in trial 8, and was analyzed within the soil general category.

The success of a particular program run defining wavelengths was determined in two ways:

(i) success in classifying a case from the trial group into its correct *general category* of crop/weed/soil. i.e. redshank in weed and soil in soil;

(ii) success in classifying a case from the trial group into its correct *specific category* defined by crop tissue, weed species, and soil.

The first trial at Gowkly-Moss farm presented a fourth category -crop stalk- spectrally different from the crop leaf tissue. It is worth noting that the brassica and broad-leaf weed spectra in this trial consisted of cases of top and underside leaf spectra in equal numbers.

Two hundred analyses were carried out in each trial to evaluate the success in recognizing brassicas from weeds and soil.

The results of each individual site are shown in Appendix D, where the most relevant program runs are gathered together with their respective number of wavelengths and discrimination efficiencies. At the bottom of each table the wavelengths selected for the program execution are mentioned. The analyses of each site could have more than one experiment, so all are included. Most analyses were carried out for direct wavelengths and wavelength ratios. The wavelength ratios were generated against a common wavelength which could be iteratively changed. In the majority of the cases, this wavelength had the lowest variance within the trial.

5.2 CABBAGE

Cabbage is an important vegetable crop grown in the United Kingdom. Cropping areas for spring, summer-autumn and winter cabbage during 1991/92 were 7784, 7592 and 6739 hectares respectively, with a gross production of 98,300, 271,900 and 290,800 tonnes, respectively. Spring cabbage had an average farm gate value of £208 per tonne, much better than summer-autumn and winter cabbages with average prices of £107.37 and £130.77 per tonne, Table 5.1.

Cabbages that mature during summer or autumn are commonly named after the harvest season. Round or ball headed shapes are common in summer and autumn cabbage varieties. Often grown summer cabbages include Copenhagen Market, Primo and Golden Acre varieties. Autumn Supreme, Autumn Victory and Stanby are some of the better known autumn cabbage varieties. Sowing time for these varieties is between March and May, and for summer crops between February and March. Common winter cabbage varieties such as Polinius, Jupiter and Bartolo, are sown between April and May to be harvested in November. Savoy cabbages mature earlier so later sowing (June) is recommended in order to be harvested at the same time as winter cabbage. Well known varieties of savoy cabbage are Ice Prince, Ice Crown and Wirosa.

Spring cabbage is harvested from October to June. Immature spring greens or 'collards' can be cut in the autumn, but establishment of big cabbage hearts must wait until spring. Cabbage varieties grown as spring greens include First Early Market 218, Dorado and Durham Early. Spring cabbage varieties grown throughout the winter include Offenham, Avon Crest and Compacta.

5.2.1 CABBAGE CULTURAL TECHNIQUES

All cabbages can be grown on well drained soils with a minimum pH of 6.5. Deep and fertile soil with good moisture is required when high yields of large cabbage or good quality cabbage heads are expected. Delayed cabbage harvest results from soils with low fertility and/or little soil depth but overlying moisture retentive chalk. Spring cabbages prefer soils that warm up early in the year and can be grown on sandy soils containing enough organic matter. Cabbage sensitivity to poor rooting conditions makes cultivation necessary to provide a deep firm tilth. Bed systems for cultivation can be used to avoid compaction caused by tractor wheels.

Both transplanting and direct sowing are used with cabbage. A common drilling practice is to deposit in each row, groups of three seeds every 50 cm. Shorter spacings can be used when cabbages will be marketed before achieving maturity, i.e. spring greens cabbages sown with row spacings of 35 cm and every 15 cm in the row. Cabbages that will be harvested when the heads are fully developed are sown with row spacing between 45 and 50 cms. Fields should be singled when plants are 10 cm tall by removing all the unwanted plants. Plant uniformity in a drilled field is achieved only when seeds are placed into a fine tilth.

Weed competition is reduced with transplanting as the plants are well established. Transplanting of cabbage seedlings often takes place when the well developed plant has three

or four true leaves, generally when they are between 15 and 25 cm tall and between 6 and 8 weeks old. The soil can receive a pre-emergent treatment and after transplanting the use of a residual herbicide is recommended.

5.2.2 CABBAGE CROPS AND WEED COMPETITION

Table 5.5 shows the incidence of weeds in the different sites. As can be noted *S. media* (chickweed) and *C. album* (fat-hen) were encountered in almost every field. Weed species competing with the crop, plate 1, varied throughout the whole year and for these analyses only those with the highest incidence at the time of the survey were considered. Only the main weeds encountered in each site or trial are cited and were grouped in three categories according to their relative abundance within the field. The weeds that proliferated throughout the field are marked with three crosses. In contrast, weed species seen in small field patches were marked with only one cross.

A study of weed density in spring cabbages drilled in a sandy loam was carried out at Wallyford farm, near Musselburgh. Weed density was measured at random in the field using a quadrant (100 cm by 100 cm). *S. media* was measured according to relative leaf cover and proved to be the most abundant weed, appearing in 76% of the measurements, Table 5.6. *C. album* was found consistently throughout the field and well identifiable patches of *V. persica*, *C. bursa-pastoris*, *Atriplex patula* and *S. vulgaris* were also encountered. *S. vulgaris* and *C. album* presented the highest densities per square metre. Six or seven cabbages per quadrant were counted in zones free of *S. media* (chickweed) and only two plants were able to subsist in areas covered by 70% of chickweed, Fig 5.1. *S. media- C. album* combination proved to be particularly harmful to the crop.

Gowkly-Moss farm near Bilston (trial 1) cropped several brassicas including autumn cabbage. High incidence of *Matricaria spp* (mayweed) and *P. persicaria* (redshank) in herbicide free areas was the result of the survey carried out in the months of September and October of 1991. *S. media* flourished in between rows with a lower density, while volunteer oilseed rape and *P. annua* (annual meadowgrass) were found in small quantities.

In the organic farm at Damhead (trial2) weed competition with savoy cabbages was dominated by *S. media*, *F. officinalis* (fumitory) and *C. album*, Table 5.5. Many other weed species proliferated in the sandy loam field as no herbicide was applied, the most common

Table 5.5 Weed incidence in each cabbage trial.

Weed	Weed incidence						
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Urtica dioica			+ +				
Malva sylvestris			+				
Phleum pratense			+				
Elymus repens			+ + +		+ +		
Taraxacum officinale			+ +				
E. angustifolium			+		+		
Volunteer oilseed rape	+						
Poa annua	+						
Chenopodium album		+ + +		+ +	+ +	+	+ + +
Fumaria officinalis		+ + +		+		+ +	
C. bursa-pastoris		+ +			+		+ +
Sinapsis arvensis		+ +	+ +		+		
Euphorbia helioscopia		+				+ + +	
Polygonum aviculare		+					
Stellaria media	+ +	+ + +	+ + +			+ + +	+ + +
Senecio vulgaris				+ +		+ +	+ +
Cirsium arvense				+			
Cirsium acaule						+	
Atriplex patula							+ +
Veronica persica							+ +
Polygonum persicaria	+ + +		+ + +		+		
Matricaria spp.	+ + +						
Papaver rhoeas			+				

+ + + Appeared in more than 60% of the sampled quadrants (100cm x 100 cm).
+ + Appeared in more than 30% of the sampled quadrants (100cm x 100cm).
+ Appeared in more than 10% of the sampled quadrants (100cm x 100cm).

Plate 1. Weed competition in cabbage fields.

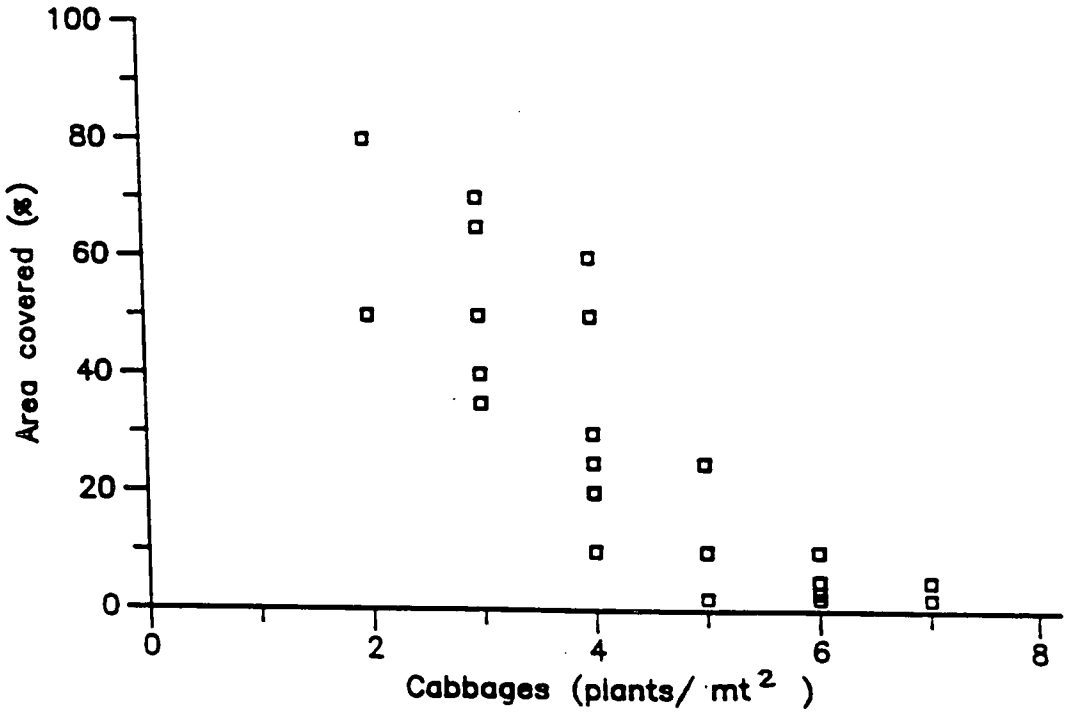

Fig. 5.1 Chickweed coverage versus quantity of cabbages.

were also considered during the analysis. Herbicides were properly applied and only low densities of *S. vulgaris* (groundsel) and *C. album* were encountered. Few seedlings of *F. officinalis* (fumitory) and *C. arvense* (creeping thistle) were also seen.

Cabbages were transplanted to an experimental trial near the Glasshouse Unit during July 1992 when the plants had reached three true leaves. The site was surveyed one month later, finding in *C. album* and *E. repens* the most competitive weeds. Shepherd's purse and *S. arvensis* (charlock) presented lower weed densities, while *P. persicaria* (redshank) and *E. angustifolium* (willowherb) proliferated in the surroundings of the crop field.

Cabbages were drilled during spring at Damhead Farm, trial 7. Both pre-emergence and post emergence herbicide treatments were applied to the field. A visual observation of the weed population was carried out in early August. The weeds with highest density were *S. media* and *E. helioscopia* (sun spurge). The large cabbage cover was responsible for the poor weed competition. *S. vulgaris* and *F. officinalis* were well established in a small section of the field and very few plants of *C. album* and *C. acaule* (dwarf thistle) were seen.

5.2.3 CROP/WEED/SOIL DISCRIMINATION FOR THREE CABBAGE VARIETIES

The farm at Wallyford (trial 9) cultivated two types of cabbages: spring and autumn. Both crops had different weed species and weed density, mainly caused by the different population of cabbages per square metre. Weeds found difficulty in competing with autumn

Table 5.7 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, four, three and two direct wavelengths for spring, autumn and savoy cabbage.**

	TRIAL 2	TRIAL 9		
	Savoy	Autumn	Spring	Savoy
Run No.	1608	1129	1141	1555
No. Wavelengths	**all**	**all**	**all**	**all**
% C/W/S	100	94.4	100	100
% C/Ws/S	100	91.6	100	97.22
Run No.	1617	1131	1143	1557
No. Wavelengths	4	4	4	4
% C/W/S	100	94.4	100	100
% C/Ws/S	97.22	91.6	94.4	91.66
Wavelengths (nm)	680, 840, 1300, 1500	680, 760, 1060, 1480	680, 760, 1060, 1360	680, 760, 1040, 1500
Run No.	1613	1132	1153	1559
No. Wavelengths	3	3	3	3
% C/W/S	100	91.6	100	100
% C/Ws/S	94.44	77.7	83.3	83.3
Wavelengths (nm)	690, 1300, 1500	680, 760, 1060	680, 1060,1360	680, 760, 1040
Run No.	1616	1135	1155	1560
No. Wavelengths	2	2	2	2
% C/W/S	94.44	84.8	100	94.44
% C/Ws/S	69.44	78.7	80.5	77.77
Wavelengths (nm)	680, 1500	760, 1480	720, 840	760, 1040

cabbage and *A. patula* (orache) and *V. persica* (speedwell) were absent. As savoy cabbages were not cultivated at the farm the spectra used were from leaves collected at East Craigs Experimental Station. One hundred and twenty spectra were gathered in nine groups to study the effect of cabbage variety in crop/weed/soil discrimination, Table 5.4.

The best results were obtained with spring cabbage, where a 100% cabbage/weed/soil discrimination was achieved with only two wavelengths, Table 5.7. Program run 1560 using two wavelengths misclassified *S. vulgaris* as savoy, achieving a 94% general discrimination. In the use of all the wavelength ratios the three varieties achieved 100% general discrimination, Table 5.8. With three and two wavelength ratios only, spring cabbage achieved a 100% general classification.

Table 5.8 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, three and two wavelength ratios for spring, autumn and savoy cabbage.**

	TRIAL 2	TRIAL 9		
	Savoy	Autumn	Spring	Savoy
Run No.	1701	1323	1281	1584
No. Wavelengths	**all**	**all**	**all**	**all**
% C/W/S	100	100	100	100
% C/Ws/S	91.66	83.3	100	94.44
Wavelength ratios	÷ 710	÷ 990	÷ 1400	÷ 1400
Run No.	1695	1320	1283	1564
No. Wavelengths	4	4	4	4
% C/W/S	100	97.2	100	91.66
% C/Ws/S	80.55	80.5	91.66	77.77
Wavelength ratios	700/990 740/990 1100/990	680/990 770/990 1400/990	720/1400 1080/1400 1320/1400	680/990 740/990 1380/990
Run No.	1696	1327	1273	1580
No. Wavelengths	3	3	3	3
% C/W/S	100	91.6	100	94.44
% C/Ws/S	83.33	55.5	86.11	69.44
Wavelength ratios	700/990 740/990	680/1400 720/1400	780/710 1320/710	1060/660 1380/660

A 100% spring cabbage/weed species/soil-rock discrimination was obtained using all the wavelengths and wavelength ratios, Tables 5.7 and 5.8. *S. vulgaris* and *C. bursa-pastoris* were not classified properly with four wavelengths reducing cabbage/weed species/soil-rock discrimination to 94%. The use of three ratios in program run 1283, Table 5.8, misclassified *V. persica* and *S. vulgaris* decreasing the specific discrimination to 92%. The best spring cabbage/weed species/soil-rock classification with two ratios was 86%, adding *C. bursa-pastoris* (shepherd's purse) to the weeds not identified properly.

Autumn cabbage/weed/soil and autumn cabbage/weed species/soil-rock using all the direct wavelengths only achieved success rates of 94% and 92%, respectively (Table 5.7). *S. vulgaris* (groundsel) spectra were misclassified as autumn cabbage and *A. patula* (common orache) spectra as groundsel. Program run 1132 using only three wavelengths obtained a 92% general discrimination and *S. vulgaris* (groundsel) interference with cabbage increased. The specific classification decreased to 78% and only *S. media* (chickweed), *A. patula* (orache) and *V. persica* (speedwell) were classified properly. The use of only two wavelengths (760 nm and 1480 nm) decreased autumn cabbage/weed/soil-rock and autumn cabbage/weed species/soil-rock discrimination to 85% and 79%.

In the discriminant analysis carried out for autumn cabbage in trial 9, only program run 1323, Table 5.8, achieved a 100% crop/weed/soil-rock discrimination. This program run used wavelength ratios against a common wavelength of 1400 nm and achieved an 83% efficiency in autumn cabbage/weed species/soil-rock discrimination and *C.album* (fat-hen) and *V. persica* (speedwell) were misclassified. Cabbage was mistaken for *S. vulgaris* (groundsel) when three ratios were used, decreasing the general discrimination to 97%. *C. bursa-pastoris* (shepherd's purse) was difficult to recognize in addition to *C.album* and *V. persica*, resulting in an 81% weed species discrimination.

Savoy cabbage/weed/soil-rock and savoy cabbage/weed species/soil-rock discrimination success rates of 100% and 97% were obtained using all the wavelengths. *S. vulgaris* was the only weed species misclassified. The specific discrimination with four wavelengths decreased to 92% as *C. album* and *S. vulgaris* were not recognized. *C. bursa-pastoris* was added to the misclassified weed species and a weed species discrimination of 83% was achieved with only three wavelengths in program run 1559, Table 5.7. *S vulgaris* (groundsel) interfered with savoy cabbage reducing crop/weed/soil-rock discrimination to 94%. The same weed species were misclassified but the cabbage-groundsel interference also reduced weed species discrimination to 78%.

Savoy/weed/soil discriminant analyses with wavelength ratios performed poorer than with direct wavelengths. The only discriminant analysis that achieved a 100% success rate in classifying the spectral data in their three main categories was program run 1584 using all the wavelength ratios against a common wavelength of 1400 nm, Table 5.8. *S. vulgaris* and

Table 5.9 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, four, three and two direct wavelengths for spring sown cabbage.**

	TRIAL 1	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Run No.	19	35	1027	1301	1121	1129
No. Wavelengths	**all**	**all**	**all**	**all**	**all**	**all**
% C/W/S	100	100	100	100	100	94.4
% C/Ws/S	97.62	95.23	100	100	94.44	91.6
Run No.	156	43	1034	1302	1162	1131
No. Wavelengths	4	4	4	4	4	4
% C/W/S	100	100	100	100	100	94.4
% C/Ws/S	73.81	95.23	100	96.6	86.11	91.6
Wavelengths (nm)	880, 960, 1040,1480	720, 990, 1170,1360	680, 720, 840, 1100	700, 880, 1340,1460	710, 840, 850, 1060	680, 760, 1060,1480
Run No.	158	44	1035	1304	1163	1132
No. Wavelengths	3	3	3	3	3	3
% C/W/S	100	100	100	100	100	91.6
% C/Ws/S	78.57	92.85	100	93.3	83.33	77.7
Wavelengths (nm)	880, 960, 1040	720, 1170, 1360	680, 720, 840	820, 990, 1080	710, 840, 1060	680, 760, 1060
Run No.	159	82	1036	1305	1164	1135
No. Wavelengths	2	2	2	2	2	2
% C/W/S	100	100	100	93.3	100	84.8
% C/Ws/S	73.81	78.57	83.33	76.6	88.88	78.7
Wavelengths (nm)	880, 960	1170, 1360	680, 720	820, 990	840, 1060	760, 1480

V. persica were not properly classified producing a weed species success rate of 94%. Program run 1564 used three ratios to achieve a 92% and 78% general and specific discrimination. The reduction in general classification was caused by *S. vulgaris* and *A.*

patula (common orache) and the only weed species properly classified was *S. media* (chickweed).

A closer look to the best discriminant wavelengths indicates three common wavelengths 680 nm, 760 nm and 1040-1060 nm. The fourth wavelength, always higher, tends to be similar between savoy (1500 nm) and autumn cabbage (1480 nm) but differs in spring cabbage (1360 nm). Sharp decrease in crop/weed species/soil-rock discrimination is noted when the highest wavelength is removed. Savoy/weed/soil-rock discrimination results indicate the importance of 680 nm as a discriminant wavelength. The use of direct wavelengths achieves better discimination results than the use of wavelength ratios. *S.vulgaris* was the weed species most difficult to rcognize.

5.2.4 CROP/WEED/SOIL DISCRIMINATION OF SPRING-SOWN CABBAGES

Autumn cabbage was by far the most common of the region. Table 5.9 depicts the general and specific discrimination accuracies obtained using all the wavelengths for each site where autumn cabbage was cropped. The program runs giving the best discrimination accuracies with four, three and two wavelengths for each site are also included.

Gowkly-Moss (trial 1), Campend (trial 4), and Damhead (trial 7) farms had a 100% cabbage/weed/soil discrimination with four, three and two wavelengths as well as the experiment carried out in SAC fields (trial 3) in 1992. Analyses of the young cabbage plants outside the Glasshouse Unit in Bush Estate (trial 6) failed to produce 100% general discrimination using two wavelengths. General discrimination of 93% was obtained using 820 nm and 990 nm as *C.album* was taken as cabbage. At Wallyford Farm (trial 9) a maximum success rate of 94% in cabbage/weed/soil discrimination was obtained as *S. vulgaris* was misclassified as cabbage.

The best discrimination accuracies achieved with wavelength ratios for all autumn cabbages are summarized in Table 5.10. The ratios were generated against a common wavelength, e.g. 750 nm/ 790 nm, 900 nm/ 790 nm and 1100 nm/ 790 nm. The first row in the Table 5. 10 shows the best program run for each site using all the wavelengths ratios with their respective discriminant success rates and common wavelengths. The second and third rows illustrate the program runs that achieved the best crop/weed/soil discrimination with three and two ratios.

Cabbage/weed/soil discrimination with all the wavelength ratios was 100% accurate in all the sites, Table 5.10. Trial 3 at Bush Estate, trial 4 at Campend Farm and trial 7 at Damhead

Farm achieved 100% crop/weed/soil discrimination with two ratios. At Wallyford Farm (trial 9), *S. vulgaris* interfered with cabbage reducing crop/weed/soil discrimination to 97% and 91% with three and two wavelength ratios, respectively.

Three wavelength ratios and four direct wavelengths were used to compare the crop/weed species/soil discrimination accuracies of the diffemt trials. This number of wavelengths should be increased in order to obtain higher success rates considering the number of weed species involved. In appendix D the weed species that were not properly classified in the main program runs are mentioned. Only the analysis at Campend Farm and outside the Glasshouse unit in Bush Estate (trial 6) provided 100% crop/weed species/soil accuracies with only four wavelengths. The same trials provided 100% success rates using all the wavelength ratios.

The best general and specific weed species discrimination in Gowkly-Moss Farm (trial 1) was obtained using all the wavelengths. All the weeds were successfully classified in their individual groups, except for volunteer oilseed rape where *P. annua* (grass) was misclassified. Wavelength reduction decreased interweed discrimination. Program runs 156 and 159, Table 5.9, have identical success rates of 100% and 74% (individual weeds) using 4 and 2 wavelengths, respectively, the important ones being 880 and 960 nm. *P. persicaria* (redshank) was perfectly recognized, but *Matricaria spp.* (mayweed) was not recognised at all. Volunteer oilseed rape was mistaken for *S. media* (chickweed), and vice versa. The effect of using 1080 nm in addition to 880 nm and 960 nm was to increase cabbage/weed species/soil discrimination to 79%.

Program run 92, Table 5.10, used all the wavelength ratios with a common wavelength of 980 nm to obtain a general and specific discrimination of 100% and 93%. Volunteer oilseed rape was taken as *S. media* and vice versa. The use of only two ratios and three wavelengths reduced discrimination between the four general categories to 95.24%. One of the cabbage spectra was mistaken for *P. persicaria* (redshank) and the redshank for soil. None of the weed groups was completely identified, causing the success rate to fall to 76.19%.

In the experimental trial carried out at Bush Estate field during 1992, *T. officionale* (dandelion) and *S. media* (chickweed) were not correctly classified using all the wavelengths directly (program run 35) and weed species discrimination was 95%, Table 5.9. These weeds were fully recognized with four wavelengths (program run 43) and identical results obtained, however discrimination difficulties were found with *M. sylvestris* (mallow) and *P. persicaria* (redshank).

Table 5.10 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, three and two wavelength ratios for spring sown cabbage.**

	TRIAL 1	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Run No.	92	61	1064	1348	1186	1323
No. wavelengths	**all**	**all**	**all**	**all**	**all**	**all**
% C/W/S	100	100	100	100	100	100
% C/Ws/S	92.86	97.62	100	100	88.88	83.3
Wavelength ratios	÷ 980	÷ 760	÷ 990	÷ 1390	÷ 990	÷990
Run No.	142	126	1071	1366	1191	1320
No. wavelengths	4	4	4	4	4	4
% C/W/S	95.24	100	100	100	100	97.2
% C/Ws/S	71.43	92.85	88.88	96.6	83.33	80.5
Wavelength ratios	940/860 1420/1110	900/710 1400/710 1480/710	690/990 720/990 760/990	1220/990 1320/990 1460/990	710/990 770/990 1060/990	680/990 770/990 1400/990
Run No.	143	137	1083	1351	1199	1327
No. wavelengths	3	3	3	3	3	3
% C/W/S	95.24	100	100	96.6	100	91.6
% C/Ws/S	76.19	88.09	97.22	90	86.11	55.5
Wavelength ratios	940/780 940/860	1360/990 1500/990	1090/710 1300/710	800/1340 1440/1340	740/1380 1060/1380	680/1400 720/1400

A cabbage/weed species/soil discrimination of 98% was encountered using all the wavelength ratios against a common wavelength of 760 nm, Table 5.10. The only weed species misclassified was *T. officionale* (dandelion). Weed species discrimination was reduced to 93% using three wavelengths ratios, program run 126, with the misclassification of *M. sylvestris* (mallow) and *T. officionale* (dandelion).

General and specific discriminations of 100% were obtained at Campend Farm (trial 4) using three direct wavelengths (680, 720 and 840 nm), table 5.9.

Complete discrimination of each category was accomplished with the use of all the wavelength ratios against 990 nm. Specific weed species discrimination of 89% was achieved with three ratios against 1040 nm, Table 5.10, and no weed species was completely identified.

The use of all the direct wavelengths up to 1600 nm in trial 6 outside the Glasshouse Unit at Bush Estate, Table 5.9, provided 100% general and specific discrimination accuracies. Cabbage/weed species/soil discrimination decreased to 97% in program run 1302 using four wavelengths (820 nm, 880 nm, 1340 nm and 1460 nm) as *C.album* was misclassified.

The eight different categories were perfectly classified using all the wavelength ratios against 1390 nm, Table 5.10. General and specific success rates of 100% and 97% were obtained with three ratios (1220 nm/990 nm, 1320 nm/990 nm and 1460 nm/990 nm). The only weed species misclassified was *C. album* (fat hen).

S. vulgaris (groundsel) misclassification was responsible for the 94% cabbage/weed species/soil discrimination achieved using all the direct wavelengths at Damhead Farm. Four wavelengths (710 nm, 840 nm, 850 nm and 1060 nm) were used by program run 1162 to discriminate weed species with an accuracy of 86% and *S. vulgaris* (groundsel), *E. helioscopia* (sun spurge) and *C. acaule* (dwarf thistle) were not recognized properly.

The best cabbage/weed species/soil-rock discrimination had an 89% success rate using all the wavelength ratios against a common wavelength of 990 nm, Table 5.10. *E. helioscopia*, *C. album* and *C. acaule* were classified correctly and of the other three weed species, *F. officinalis* (fumitory), was the most difficult to recognize. With four wavelengths weed species discrimination was reduced to 83%, as *E. helioscopia* (sun spurge) was also misclassified.

It is important to note that three wavelengths are important in weed species classification: 720 nm, 820-840 nm and 1060 nm. When one of them is missing the discriminant accuracy drops drastically. Crop/weed species/soil discriminant accuracies present higher values with direct wavelengths than with wavelength ratios. It is also interesting to note that five from the six cabbage trials had as the three most important discriminant wavelengths, wavelengths below 1100 nm. No conclusion can be made about the weed species most difficult to recognize.

5.2.5 CROP/WEED/SOIL DISCRIMINATION IN SAVOY CABBAGES

Crop/weed species/soil discrimination of 100% was obtained using all the wavelengths up to 1600 nm, Table 5.7 at Damhead Farm. The use of only three wavelengths, program run 1613, maintained a 100% success rate in the general classification, but decreased the cabbage/weed species/soil classification to 94.44%. The discriminant wavelengths were located deep in the near infrared region at 1300 nm and 1500 nm and at 690 nm in the red region. *P. aviculare* (knotgrass) and *C. album* (fat hen) were not classified properly. The use of two wavelengths (1550 nm and 730 nm) reduced crop/weed/soil and crop/weed species/soil discrimination to 94.44% and 69.44%, respectively. Savoy cabbage was misclassified with *P. aviculare*.

Success rates of 100% and 83.33% for cabbage/weed/soil and cabbage/weed species/soil discrimination were obtained using two ratios, Table 5.8. The program run used a common wavelength of 990 nm for each ratio and *P. aviculare*, *S. media* and *E. helioscopia* were properly classified. Program run 1700 used only one ratio (740/990 nm) and a 100% crop/weed/soil discrimination was achieved,although the specific classification decreased to 63.88% with *S. media* the only weed properly classified.

The comparison of the best program runs in trials 2 and 9 shows that in both farms a common wavelength at 680 nm was selected, Table 5.7. Lower wavelength values were encountered in trial 9, without affecting crop/weed/soil discrimination. Discrimination success rates obtained with wavelength ratios in trial 2 are better than in trial 9. The best program runs with three wavelength ratios (1695 and 1564) had common wavelengths at 740 nm and 990 nm, and a notable difference in the highest infrared wavelength being higher in trial 9. Weed species were different in both sites presenting in *P. aviculare* and *S. vulgaris* the hardest seedlings to be recognized in trials 2 and 9, respectively. Wavelengths at 740 nm and 1300 nm are essential for high success rates in crop/weed species/soil discrimination.

5.3 BROCCOLI

Broccoli was introduced to Great Britain in the 1970's and its growing demand increased the cropping area from 979 hectares in 1983/84 to 6,252 in 1991/92. A gross production increase of 626% was obtained with the 37, 400 tonnes produced in 1991/92, Table 5.1. The increase in production reduced the average gate farm price from £713 per tonne in 1883/84 to £625 per tonne in 1991/92.

Broccoli and calabrese have the same cultural techniques and all future recommendations will be equally valid for both brassicas. Calabrese variety selection is based on relative maturity. Experimental trials have shown that relative maturity between variety groups remains consistent throughout the growing season, but not during crop establishment and harvest time. Five calabrese varieties grown extensively by Scottish producers are Cruiser, Greenbelt, Corvet, Skiff and Shogun. Sowing programmes recommend to drill Cruiser in April, while Skiff, Corvet and Shogun can be sown as late as July. For all the varieties, harvesting will take place approximately three months after seed drilling.

5.3.1 BROCCOLI CULTURAL TECHNIQUES

Broccoli requires moist soils with good drainage as the crop is susceptible to drought. However, crop maturity is not dependant on irrigation. Soils having a pH between 6.5 and 7 are preferred. Calabrese can be established by direct sowing or by transplanting, the former being more popular in Scotland. Transplanting has the advantage of making weed control easier, but requires skill in raising the plant. Direct drilling requires a good seedbed preparation making the ground firm, fertile and free of clods. However, excessive cultivation would dry up the tilth and a poor emergence could occur. The correct sequence in preparing soil will start with perennial weed erradication and liming, followed by fertilizer application, cultivation, application of a pre-emergence herbicide and finally rolling. Broccoli raised on beds present higher yield, greater head uniformity, fewer harvests per crop and easier management of harvest operations. Seeds are sown singly at half the theoretical distance between plants and at a depth of 1.2 cm. Sometime after emergence the surplus plants should be chopped out. In the case of high populations, thinning might become difficult as plants grow close together.

Perennial weeds such as couchgrass, dockens and thistles should be erradicated before sowing as there is no satisfactory way to control them. The best control is achieved with glyphosate which is effective in mature and actively growing plants. Grasses are mainly controlled by delapon or TCA application. Annual weeds are controlled by proper applications of trifularin and propachlor, Table 5.3.

The size of broccoli heads is influenced by the plant population, i.e. the denser the population, the smaller the head. Experimental work has shown that the highest yields are obtained with populations averaging 10 plants per square metre. The traditional row spacing for such population is 50 cm. In between the rows, broccoli or calabrese plant spacings vary and are

typically separated by 20 cm (population of 10 plants per square metre). For higher plant populations beds of six rows are recommended with intra-row spacings of 20 cm.

5.3.2 WEED COMPETITION AT THE DIFFERENT BROCCOLI SITES

S. media was the most competitive weed proliferating in all the broccoli sites. Table 5.11 shows the weed incidence for each broccoli site, with *P. persicaria* and *E. repens* being encountered in four of the seven trials.

Broccoli grown beside cabbage at Gowkly- Moss Farm presented similar weed population abundant in *S. media* and *Matricaria spp.*

The organic farm at Damhead, trial 2, presented a different flora in the cabbage and broccoli rows. Weeds abundant in between the rows were *C. album* and *S. media* with *C. arvense* (creeping thistle) showing high incidence. In addition, individual plants of *Matricaria spp.*, *S. vulgaris*, *Rumex spp.* and *T. officinalis* accounted for the rest of the weed population.

The weed population at the SCAE broccoli field in 1992 was similar to the one encountered for cabbage and was also abundant in *S. media*, *E. repens* and *P. persicaria*, as previously mentioned. One year later, broccoli was cropped again in the same field and a different weed flora flourished. The crop was sown in a greenhouse and transplanted when the plants had three true leaves, almost a month later. *S. media* and *E. repens* were the dominant weed species, followed by *S. vulgaris*, *U. dioica* and *C. arvense*. In addition to volunteer oilseed rape, weed species found with very low densities were *C. album*, *C. bursa-pastoris*, *P. aviculare* and *P. persicaria*.

At Claremont Cottage (trial 8) a straw mulch was used to control weeds and proved to be very successful. Only individual plants of *S. media*, *L. purpureum*, *L. albium*, *E. repens* and *M. arvensis* were encountered offering minimum competition to the healthy crop.

Broccoli was transplanted outside the glasshouse unit inside Bush Estate (trial 10) in early June 1993. Weeds were well controlled by herbicides and the few weed seedlings included *C. bursa-pastoris*, *S. media* and *L. purpureum* plus some individual seedlings of *U. dioica*, *Rumex spp.*, *P. aviculare* and *P. persicaria*.

Table 5.11 Weed incidence in each broccoli trial.

Weed	Weed incidence						
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Urtica dioica			+ +			+	
Malva sylvestris			+				
Phleum pratense			+				
Elymus repens			+ + +	+ + +	+		+ +
Taraxacum officinale		+	+				
Rumex spp.		+			+	+	
Vol Oil Seed Rape	+			+			
Poa annua	+						
Chenopodium album		+ + +		+			
Lamium purpureum				+ +		+ +	
C. bursa-pastoris				+		+ +	+
Sinapis arvensis			+ +				
Myosotis arvensis					+		
Polygonum aviculare				+		+	
Stellaria media	+ +	+ + +	+ + +	+ + +	+	+ +	+
Senecio vulgaris		+		+ +			+
Cirsium arvense		+ +		+ +			
E. angustifolium			+				
Papaver rhoeas			+				
Polygonum persicaria	+ + +		+ + +	+		+	
Matricaria spp.	+ + +	+					+ +
Lamium album					+		

+ + + Appeared in more than 60% of the sampled quadrants (100cm x 100 cm).
+ + Appeared in more than 30% of the sampled quadrants (100cm x 100 cm).
+ Appeared in more than 10% of the sampled quadrants (100cm x 100cm).

Broccoli grown in a larger scale farm near St. Andrews had a higher weed incidence of *E. repens* and *Matricaria spp.* In scattered areas of the field *C. bursa-pastoris*, *S media* and *S. vulgaris* were identified.

5.3.3 CROP/WEED/SOIL DISCRIMINATION IN MATURE BROCCOLI

On all the sites a 100% broccoli/weed/soil discrimination was achieved, except for trial 11 where interference of *S. vulgaris* with broccoli reduced the success rate to 97%, using all the direct wavelengths. The best program runs with four, three and two wavelengths are shown in Table 5.12, and trials 3, 5 and 8 obtained 100% general discrimination efficiency in each program run. Trial 2, failed with two wavelengths and identical 84% broccoli/weed/soil and broccoli/weed species/soil discriminations were found. Trial 1 presented a 100% general discrimination in program run 160 using only two wavelengths, whereas programs runs with four and three wavelengths achieved success rates of 95% and 98%, respectively.

The use of all the wavelength ratios also provided 100% general discrimination in every trial, Table 5.13. The best program runs with three and two wavelength ratios for trials 2, 5 and 8 obtained a 100% success rate in broccoli/weed/soil discrimination. Trials 1 and 11 did not achieve a 100% general discrimination efficiency with a reduced number of wavelength ratios, although high success rates were achieved. Program run 807 properly classified the three major groups in trial 3 using three wavelength ratios.

Spectral data collected from Gowlky-Moss Farm (trial 1) indicated that the highest success rate for crop tissue/crop stalk/weed species/soil discrimination was obtained in program run 11 using all the wavelengths, Table 5.12 and *S. media* was mistaken for *Matricaria spp.* (mayweed) and volunteer oilseed rape. It is worth mentioning that 100% general discrimination was obtained with only two wavelengths (1040 nm and 1640 nm) in program run 160, but individual weed classification decreased to 76.19% with *P. persicaria* as the only weed species to be properly identified.

All the wavelength ratios were used by program run 82 and *S. media*, volunteer oilseed rape and *Matricaria spp.* were not identified properly reducing the specific weed species classification to 86%, Table 5.13. The best discrimination accuracy was obtained using four wavelengths in program run 194 which achieved 97.62% and 92.85% success rates for general and weed species classifications, respectively. The wavelengths used were 520, 1040 and 1720 nm and all of them were divided against 700 nm. One of the soil spectra was

mistaken for *P. annua*, but volunteer oilseed rape, *S. media* and *Matricaria spp.* were completely recognized.

Table 5.12 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, four, three and two direct wavelengths for mature broccoli.**

	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 11
Run No.	11	1591	773	1461	1124	1512
No. wavelengths	**all**	**all**	**all**	**all**	**all**	**all**
% C/W/S	100	100	100	100	100	96.96
% C/Ws/S	85.71	100	100	91.11	100	93.93
Run No.	154	1593	775	1463	1125	1514
No. wavelengths	4	4	4	4	4	4
% C/W/S	95.23	100	100	100	100	93.93
% C/Ws/S	78.57	96.96	95.23	88.88	96.96	90.90
Wavelengths (nm)	800, 1000 1040,1640	700, 720 900, 1460	720, 960 1360,1420	720, 1060 1380,1500	700, 820 1380,1480	680, 740 1040,1380
Run No.	164	1595	776	1464	1174	1517
No. wavelengths	3	3	3	3	3	3
% C/W/S	97.62	100	100	100	100	93.93
% C/Ws/S	76.19	96.96	90.47	84.44	90.90	90.90
Wavelengths (nm)	1000,1040 1640	700, 720 1460	720, 960 1420	720, 1060 1380	710, 740 890	790, 1040 1380
Run No.	160	1750	780	1465	1176	1518
No. wavelengths	2	2	2	2	2	2
% C/W/S	100	84.84	100	100	100	93.93
% C/Ws/S	76.19	84.84	90.47	80	84.84	87.87
Wavelengths (nm)	1040,1640	700, 720	740, 990	720, 1380	890, 1380	790, 1380

Perfect crop/weed/soil and crop/weed species/soil discrimination was achieved with spectral data from the organic farm at Damhead (trial 2), using all the wavelengths directly and/or all the wavelength ratios against a common wavelength of 1450 nm, Tables 5.12 and 5.13. Program 1593 ran with four wavelengths (700 nm, 720 nm, 900 nm and 1460 nm) providing

a 97% weed species discrimination where only *C. arvense* was misclassified. The wavelength at 900 nm was not essential and identical discriminations were obtained in program run 1595, with only three wavelengths. Reduction in broccoli/weed/soil discrimination to 85% resulted from using only two wavelengths after *C. album* and *S. vulgaris* interference with broccoli. Crop/weed species/soil discrimination was also 85% as each weed species category was perfectly classified.

Table 5.13 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, four and three wavelength ratios for mature broccoli.**

	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 11
Run No.	82	1905	810	1484	1228	1524
No. wavelengths	**all**	**all**	**all**	**all**	**all**	**all**
% C/W/S	100	100	100	100	100	100
% C/Ws/S	85.71	100	97.62	91.11	96.6	93.93
Wavelength ratios	÷ 700	÷ 710	÷ 990	÷ 990	÷ 710	÷ 990
Run No.	194	1910	807	1487	1253	1525
No. wavelengths	4	4	4	4	4	4
% C/W/S	97.62	100	100	100	100	93.93
% C/Ws/S	92.85	90.90	88.09	88.88	93.93	90.90
Wavelength ratios	520/700 1040/700 1720/700	900/710 1400/710 1460/710	680/1380 740/1380 1500/1380	740/990 1360/990 1480/990	700/1340 960/1340 1480/1340	680/990 760/990 1380/990
Run No.	199	1919	808	1488	1221	1534
No. wavelengths	3	3	3	3	3	3
% C/W/S	90.48	100	97.62	100	100	93.93
% C/Ws/S	71.43	84.84	83.83	80	87.87	87.87
Wavelength ratios	1040/880 1440/880	1360/990 1460/990	740/1380 1500/1380	1360/990 1480/990	1320/990 1460/990	680/710 1400/710

Program run 1910 used three wavelength ratios against a common wavelength of 710 nm and the reduction to 91% in weed species discrimination was caused by *Matricaria Spp.* and *C. arvense* misclassification, Table 5.13. A further reduction to 85% in weed species

discrimination was obtained using two wavelength ratios having additional weed species recognition problems with *T. officinalis* and *Rumex spp.*

In experimental trial 3 at Bush Estate field in 1992 all the weed species were properly classified using wavelengths, Table 5.12. The specific discrimination was reduced to 95% using four wavelengths (720 nm, 960 nm, 1360 nm and 1420 nm); *P. pratense* (timothy) and *E. angustifolium* (willowherb) were misclassified. Program 776 ran without the 1360 nm wavelength and obtained a 90% specific discrimination. *P. pratense*, *E. angustifolium*, *P. persicaria* (redshank) and *E. repens* (couchgrass) were not properly identified.

With the use of all the wavelength ratios against 990 nm in program run 810, a broccoli/weed species/soil discrimination of 98% was achieved encountering difficulties in recognizing *P. rhoeas* (poppy), Table 5.13. Running program 807 with three wavelength ratios decreased the specific discrimination to 88% as *T. officinale* (dandelion), *S. media* and *P.pratense* (timothy) were not classified properly.

From the experiment at the same field one year later (trial 5), general and specific discriminations of 100% and 91% were obtained with all the direct wavelengths and all the wavelength ratios, Tables 5.12 and 5.13. *P. aviculare*, *C. album* and *C. arvense* were not properly classified in both program runs (1461 and 1484). Specific discrimination decreased with the use of four wavelengths to 89% (program run 1463) as *U. dioica* was also misclassified. Three wavelengths (720 nm, 1060 nm and 1380 nm) used in program run 1464 obtained a weed species discrimination of 84% and *C. bursa-pastoris* (shepherds'-purse) was added to the four weed species misclassified in program run 1463. Program run 1487 used three wavelength ratios to obtain an 89% weed species discrimination. *P. aviculare*, *U. dioica*, *C. album* and *C. arvense* were not classified properly. The best 80% weed species discrimination with two wavelengths was achieved using 720 nm and 1380 nm. Similar discrimination accuracy was achieved with two wavelength ratios, Table 5.13.

Program run 1124 used all the wavelengths directly to achieve 100% broccoli/weed/soil and broccoli/weed species/soil discriminations at Claremont Cottage, Table 5.12. Broccoli/weed species/soil discrimination was reduced to 97% using four wavelengths, Table 5.13. *S. media* was the only weed species misclassified. *M. arvensis* (forget-me-not) and *L. album* (white dead nettle) were improperly classified using three wavelengths (710 nm, 740 nm and 890 nm), reducing weed species discrimination to 91%. A further reduction in specific discrimination of 85% with only two wavelengths (program run 1183) resulted as *S. media*, *L. album* and *M. arvensis* were misclassified.

The best program run with all the wavelength ratios achieved a 97% weed species discrimination with *L. album* being misclassified. Three wavelength ratios achieved broccoli/weed/soil and broccoli/weed species/soil discriminations of 100% and 94%. *S. media* and *M. arvensis* (forget-me-not) were the weed species that proved difficult to recognize. Program run 1221 used two wavelength ratios (1320 nm/990 nm and 1460 nm/990 nm) to achieve an efficiency of 88% in weed species discrimination, misclassifying *L. purpureum* (red dead nettle) and *M. arvensis*.

Plants collected at St. Andrews (trial 11) were analyzed by program run 1512 using all the wavelengths directly and failed to classify the three major groups properly, Table 5.12. A 94% broccoli/weed species/soil-rock discrimination was achieved as broccoli was confused with *S. vulgaris*, and *Matricaria spp.* could not be identified properly. Four wavelengths (680 nm, 740 nm, 1040 nm and 1380 nm) used in program run 1514 produced a general discrimination of 94%, with *S. vulgaris* misclassified as broccoli. *Matricaria spp.* could not be identified and the specific discrimination was reduced to 91%. The two lowest wavelengths in program run 1514 were substituted by 790 nm and identical results were obtained with only three wavelengths. It was noted that the wavelength at 1040 did not change the general discrimination (94%), but reduced the specific discrimination to 88% (program run 1518) with the same weed species misclassified.

Of all the analyses carried out in this farm only program run 1524 achieved a 100% broccoli/weed/soil-rock discrimination, Table 5.13, using all the wavelength ratios with a common denominator wavelength of 990 nm. *C. bursa-pastoris* and *Matricaria spp.* were not recognized easily and a specific discrimination of 94% was obtained. The best general and specific discriminations with three wavelength ratios (program run 1525) were of 94% and 91% as *S. vulgaris* was mistaken for broccoli and *S. vulgaris* was the only weed species misclassified. Two wavelength ratios (680 nm/710 nm and 1400 nm/710 nm) provided the same general discrimination, but *S. media* and *S. vulgaris* were not classified properly reducing the specific discrimination to 88%.

Important wavebands for broccoli/weed/soil discrimination include 700-740 nm, and 1380 nm. The only weed species that inerfered with broccoli were *S. vulgaris* and *C. album*. Similar general discrimination accuracies were achieved with wavelength ratios and direct wavelengths, Tables 5.12 and 5.13. Specific discriminations in most of the trials did not present sharp success rate reductions. Minima broccoli/weed species/soil discrimination using only two wavelengths in trials 1 and 8 resulted from a missing wavelength in the 700-800 nm

waveband. Similar weed species misclassification was found between direct wavelength analysis and wavelength ratio analysis for each trial.

5.3.4 CROP/WEED/SOIL DISCRIMINATION USING YOUNG BROCCOLI SEEDLINGS

Weed control should be applied whenever weeds become a problem, but during crop establishment weed problems will delay crop growth by taking away soil nutrients and

Table 5.14 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, four, three and two direct wavelengths for young broccoli seedlings.**

	TRIAL 5	TRIAL 10
Run No.	1382	1086
No. Wavelengths	**all**	**all**
% C/W/S	100	100
% C/Ws/S	95.55	96.96
Run No.	1384	1087
No. Wavelengths	4	4
% C/W/S	100	100
% C/Ws/S	86.66	96.96
WAVELENGTHS	700, 720, 1060, 1380	700, 720, 1380, 1500
Run No.	1385	1088
No. Wavelengths	3	3
% C/W/S	100	100
% C/Ws/S	84.44	96.96
WAVELENGTHS	720, 1060, 1380	700, 720, 1380
Run No.	1386	1090
No. Wavelengths	2	2
% C/W/S	100	100
% C/Ws/S	80.00	100
WAVELENGTHS	720, 1380	700, 720

moisture. Two experiments carried out at Bush Estate were analysed with young broccoli seedlings; the first one, trial 5 used the same weed species and soil samples as the established mature crop covered in section 5.3.3, in order to compare the best discriminant wavelengths selected for both growth stages. In the second experiment at Bush Estate nearby the glasshouses (trial 10) young seedlings were sown and different weed species competed with the crop.

Table 5.15 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, three and two wavelength ratios for young broccoli seedlings.**

	TRIAL 5	TRIAL 10
Run No.	1427	1106
No. Wavelengths	**all**	**all**
% C/W/S	100	100
% C/Ws/S	91.11	100
Wavelength ratios	÷ 1400	÷ 680
Run No.	1408	1101
No. Wavelengths	4	4
% C/W/S	100	100
% C/Ws/S	93.33	96.96
Wavelength ratios	700/990, 1360/990, 1480/990	740/710, 1060/710, 1400/710
Run No.	1409	1102
No. Wavelengths	3	3
% C/W/S	100	100
% C/Ws/S	84.44	78.78
Wavelength ratios	1360/990, 1480/990	740/710, 1400/710

Trial 5 obtained general and specific discriminations of 100% and 96% using all the wavelengths directly and *P. aviculare*, *C. album* and *C. arvense* were not classified properly. With four wavelengths, the specific discrimination decreased to 87% as *C. bursa-pastoris* was poorly recognized. The best specific discrimination with three wavelengths (720 nm, 1060 nm and 1380 nm) was 84% and additional recognition problems were found with *U. dioica*.

Program 1386 was run without 1060 nm and correctly identified *P. persicaria*, *S. media*, *E. repens* and volunteer oilseed rape achieving a specific discrimination of 80%.

The use of all the wavelength ratios against 1400 nm achieved a broccoli/weed/soil and broccoli/weed species/soil discrimination of 100% and 91%, respectively. *P. aviculare*, *C. album* and *C. arvense* were the weed species that showed recognition difficulties. *C. album* was identified properly in program run 1408, as the specific discrimination increased to 93% with three wavelength ratios. Program run 1409 omitted the 750 nm/1040 nm ratio and *P.aviculare*, *C. album*, *C. bursa-pastoris*, *S. media*, *U. dioica* and *P. persicaria* were not identified completely, reducing the discrimination efficiency to 84%.

The best overall discrimination in trial 10 with direct wavelengths used only two wavelengths, 700 nm and 720 nm to perfectly classify all the spectra, Table 5.14. Program runs 1086, 1087 and 1088 had a 97% broccoli/weed species/soil discrimination and the only weed species misclassified was *C. bursa-pastoris* (shepherd's purse).

A 100% general and specific classification was achieved using all the wavelength ratios against a common wavelength of 730 nm, Table 5.15. The specific discrimination decreased with the use of only three wavelength ratios to 97% as *Rumex spp.* (dock) was misclassified. The 70% best weed species discrimination accuracy with only two wavelength ratios was achieved by program run 1102, where *S. media* and *C. bursa-pastoris* were the only weed species to be fully identified.

A comparison between the experiments with both mature and young broccoli in trial 5 indicates that similar wavelengths are used at 720 nm, 1060 nm and 1380 nm. Program runs preferred higher wavelengths for mature broccoli (1500 nm) and wavebands near the water absorption band for young broccoli (1380 nm). Comparable general and specific discrimination accuracies were obtained in both growth satages of trial 5 as a result of proper recognition of similar weed species. The wavelength ratios selected in both analyses were alike and only the wavelength at the low near-infrared waveband was different. Young broccoli seedlings preferred 700 nm, while mature plants 740 nm. Comparison of trials 5 and 10 emphasize the importance of 700 nm and 720 nm, the former being essential together with 1380 nm for crop/weed species/soil discrimination. *C. bursa-pastoris* was the only weed species misclassified in both trials.

5.3.5 EFFECT OF STRAW MULCHING IN CROP/WEED DISCRIMINATION

At Claremont Cottage (trial 8), general and specific discriminations of 100% and 97%, respectively, using a straw background were obtained with all the direct wavelengths and only *L. album* was misclassified, Table 5.16. Program 1601 used four wavelengths (680 nm, 720 nm, 1380 nm and 1480 nm) to obtain similar discriminations, although the only weed

Table 5.16 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, four, three and two direct wavelengths for broccoli sown in soil and in a straw mulch.**

	Claremont Cottage (trial 8)	
	Straw mulch	**Soil**
Run No.	1599	1124
No. Wavelengths	**all**	**all**
% C/W/S	100	100
% C/Ws/S	96.96	100
Run No.	1601	1125
No. Wavelengths	4	4
% C/W/S	100	100
% C/Ws/S	96.96	96.96
Wavelengths (nm)	680, 720, 1380, 1480	700, 820, 1380, 1480
Run No.	1602	1174
No. Wavelengths	3	3
% C/W/S	100	100
% C/Ws/S	87.87	90.90
Wavelengths (nm)	680, 1380, 1480	710, 740, 890
Run No.	1606	1176
No. Wavelengths	2	2
% C/W/S	96.96	100
% C/Ws/S	84.84	84.84
Wavelengths (nm)	680, 890	890, 1380

species misclassified was *M. arvensis* (forget-me-not). *Rumex spp.*(dock) and *L. purpureum* (red-dead nettle) were the only weeds recognized with three wavelengths, resulting in a

broccoli/weed species/hay discrimination of 85%. Broccoli was misclassified with white dead nettle reducing broccoli/weed/straw discrimination to 97% when two wavelengths (680 nm and 890 nm) were used, while weed species discrimination remained in 85%.

Table 5.17 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, three and two wavelength ratios for broccoli sown in soil and on a straw mulch.**

	Claremont Cottage (trial 8)	
	Straw mulch	**Soil**
Run No.	1668	1228
No. Wavelengths	**all**	**all**
% C/W/S	100	100
% C/Ws/S	96.96	96.96
Wavelength ratios	÷ 710	÷ 710
Run No.	1670	1253
No. Wavelengths	4	4
% C/W/S	100	100
% C/Ws/S	96.96	93.93
Wavelength ratios	680/710, 740/710, 1460/710	700/1340, 960/1340, 1480/1340
Run No.	1680	1221
No. Wavelengths	3	3
% C/W/S	100	100
% C/Ws/S	93.93	87.87
Wavelength ratios	680/990, 1460/990	1320/990, 1460/990

Similar results having the straw background were achieved with the use of all and three wavelength ratios against 710 nm, Table 5.17. The general and specific discriminations obtained were 100% and 97% and only *L. album* was misclassified. The best program run (1680)with two wavelength ratios (680 nm/990 nm and 1460 nm/990 nm) achieved a 93% specific discrimination with *M. arvensis* and *L. album* misclassified.

Broccoli/weed/soil and broccoli/weed/straw program runs 1601 and 1125 selected two identical wavelengths at 1380 nm and 1480 nm, Table 5.16. Lower wavelengths showed

differences selecting 680 nm and 720 nm for straw analysis and 700 nm and 820 nm for soil analysis. Higher wavelengths were selected by wavelength ratios used for the soil analyses, and in general provided better discrimination accuracies than direct wavelength analyses. Similarity in discrimination accuracies for direct and wavelength ratios were encountered for soil and straw cover, and *L. album* proved to be difficult to identify. The higher wavelength values obtained from program run 1602, Table 5.16, can be attributed to plant species discrimination between dry and healthy vegetation.

5.4 LEEK

Leek, a popular winter vegetable cultivated in all the United Kingdom, specially in Scotland, was cropped in 3629 hectares during 1991/92 and a gross production of 78,600 tonnes obtained, Table 5.1. This production represented an increase of 80% over the production obtained in 1983/84. The average price paid to farmers was of £356.39 per tonne.

Varieties of leek are available for all seasons. Early leeks, including varieties such as Odin and Colonna, have long stems with pale flag leaves and are usually harvested in September. Swiss giant and Yates Empire can be harvested until the new year and are characterized by medium length stems (15 cm). Winter Reuzen and Siberia are medium stemmed leeks with dark green flags that can be harvested between December and April.

5.4.1 LEEK CULTURAL TECHNIQUES

Leeks prefer deep fertile loams, although they can grow in all kind of soils provided that good drainage and a pH higher than 6.5 is available. Sand particles encountered in leaf sheaths make the leek difficult to market so sandy soils are avoided. Yields are ensured with plant populations between 25 and 50 plants per square metre and a field free of perennial weeds. Row spacings of 25-30 cm are typical, with the distance between plants in the row depending on the leek variety and on the growth stage in which the crop is to be harvested. Typical spacings between two plants in the same row range between 8 and 16 cm according to the plant population desired. Transplanting is not very popular with leeks as considerable labour is required.

5.4.2 WEED COMPETITION IN ALL LEEK TRIALS

Slow germination and seedling growth make leeks susceptible to weed competition. Effective herbicide usage has reduced the need for cultivation. Good weed control programmes include

the use of pre-emergence and post-emergence herbicides. The latter is applied when the leeks have two true leaves (flags) normally four weeks after sowing. Results of the herbicide survey carried out in Scotland during 1991 showed high herbicide diversity with ioxynil and propachlor often used, Table 5.3.

Table 5.18 Weed incidence in different areas of Damhead Farm with and without herbicide application.

Weed species	Weed incidence (%)				
	Without herbicide application			With herbicide	
	Top Hill	Medium Hill	Bottom Hill	Including edges	Not inc. edges
Atriplex patula	100	100	100	87.5	84.62
Chenopodium album	100	33.33	50	37.5	56.15
Senecio vulgaris	92.3	80.95	100	93.75	92.31
Stellaria media	46.15	42.85	75	18.75	7.69
Matricaria spp.	38.46	95.38	66.6	0	0
Voluntary Potato	0	9.52	8.3	12.5	15.38
Polygonum aviculare	7.69	71.43	33.3	31.25	30.77
Taraxacum officinale	53.84	33.33	83.3	12.5	7.69
Viola arvensis	0	9.52	41.6	0	0
Fumaria officinalis	23.07	19.05	0	25	30.77
Sinapsis arvensis	0	19.05	66.6	31.25	7.69
Myosotis arvensis	0	9.52	8.3	0	0
Elymus repens	46.15	9.52	41.6	37.5	30.77
C. bursa-pastoris	23	9.52	0	0	0
Rumex spp.	15.4	9.52	0	0	0

A weed density and incidence survey was carried out at Damhead Farm, trial 7. The sandy farm on a small slope had a vast amount of stones and two field areas were easily identified: one where herbicide application was successful and the other free of herbicides or where they work poorly. Table 5.18 summarizes the weed incidence results after subdividing each area

into well identified patchy-extensions characterized by different weed flora. The herbicide free area showed three different weed flora patches named after the slope zone in which they proliferated: top, middle and bottom. Plate 2 illustrates patch sampling at random with a quadrant (100 cm by 100 cm) and *A. patula* was found in all the ptches.

Table 5.19 Weed density average (plants/m²) of a leek field in different areas of Damhead Farm (trial 7).

Weed species	Average weed density (plants/m²)				
	Without herbicide application			With herbicide	
	Top Hill	Medium Hill	Bottom Hill	Including edges	Not inc edges
Atriplex patula	5..23	7.88	4.33	2.07	1.72
Chenopodium album	11.54	2.4	1	2	2
Senecio vulgaris	3.92	5.08	8.58	5.53	5.58
Stellaria media	4.5	1.67	1.11	1	1
Matricaria spp.	1.33	6.29	4.5	0	0
Volunteer potato	0	1	1	1	1
Polygonum aviculare	1	2.27	1	1.4	1.5
Taraxacum officinale	3	2	1	1	1
Viola arvensis	0	1	1.2	0	0
Fumaria officinalis	1.33	1.67	0	1.25	1.25
Sinapsis arvensis	0	1.67	1.63	1.8	1.5
Myosotis arvensis	0	2	1	0	0
Elymus repens	1.83	3.5	1.6	2	2.5
C. bursa-pastoris	2	1	0	0	0
Rumex spp.	1	1	0	0	0

C. album was found in each quadrant sample at the top of the slope, and *S. vulgaris* was found in all the sampled areas at the bottom, where *S. arvensis* had its highest population. A high incidence of *P. aviculare* in the middle of the slope was encountered. The weeds within

each quadrant sampling were counted and an average value was obtained for each sector. *S. vulgaris* had the highest average densities and a high incidence throughout all the field, Table 5.19. High average densities were also encountered with *A. patula* and *Matricaria spp.*

Herbicide application was not succesful with *A. patula* and *S. vulgaris* but their relative densities were reduced. As expected, weed incidence and density were higher when the edges of the field were included. However, the density of *S. vulgaris* was higher in the cropped area without the edges. Table 5.19 shows the weed species selected for the main analysis: volunteer potato and *C. album*, *A. patula*, *Matricaria spp.*, *S. vulgaris*, *S. arvensis*, *V. arvensis*, *T. officionale*, *F. officinalis* and *S. media*.

Table 5.20 Some typical effects of weed competition in leek.

	Weed dimensions (cm)			**Leek dimensions (cm)**		
	Height	Length	Width	Flag height	Flag width	No.of flags
Sinapsis arvensis	15	10	10	40	2	6
Taraxacum officinale	--	30	24	9.5	0.7	3
Chenopodium album	36	13	13	37	1.7	5
Senecio vulgaris	19	10	16	32	1.7	6
Rumex spp.	5+	14	12	44	1.8	4
Matricaria spp.	5	4.5	4.5	50	2.5	7
Atriplex patula	38	25	25	30	1.2	4
Stellaria media	--	30	30	24	0.8	4
Without weeds				50	3	8

\+ Number of leaves

Competition of weeds and leek was also studied whenever a solitary weed was growing at a distance of 2 cm from the leek. Typical values of flag width and height during crop growth due to weed competition are cited in Table 5.20, *T.officinale* and *S. media* being extremely competitive.

Table 5.21 Weed incidence in each leek trial.

Weed	Weed incidence			
	TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Urtica dioica	+ +		+ + +	
Malva sylvestris	+			
Phleum pratense	+ +			
Elymus repens	+ +		+ + +	
Taraxacum officinale	+ +			+ +
E. angustifolium	+			
Vol. oilseed rape			+	
Chenopodium album			+	+ + +
Fumaria officinalis				+ +
C. bursa-pastoris			+	
Sinapsis arvensis	+ +			+ +
Volunteer potato				+
Polygonum aviculare		+	+	
Stellaria media	+ + +		+ + +	+ +
Senecio vulgaris		+ +	+ +	+ +
Cirsium arvense		+	+ +	
Atriplex patula				+ + +
Viola arvensis		+ +		+
Veronica persica		+		
Polygonum persicaria	+ +		+	
Matricaria spp.				+ +
Papaver rhoeas	+			

+ + + Appeared in more than 60% of the sampled quadrants (100cm x 100cm).
+ + Appeared in more than 30% of the sampled quadrants (100cm x 100cm).
+ Appeared in more than 10% of the sampled quadrants (100cm x 100cm).

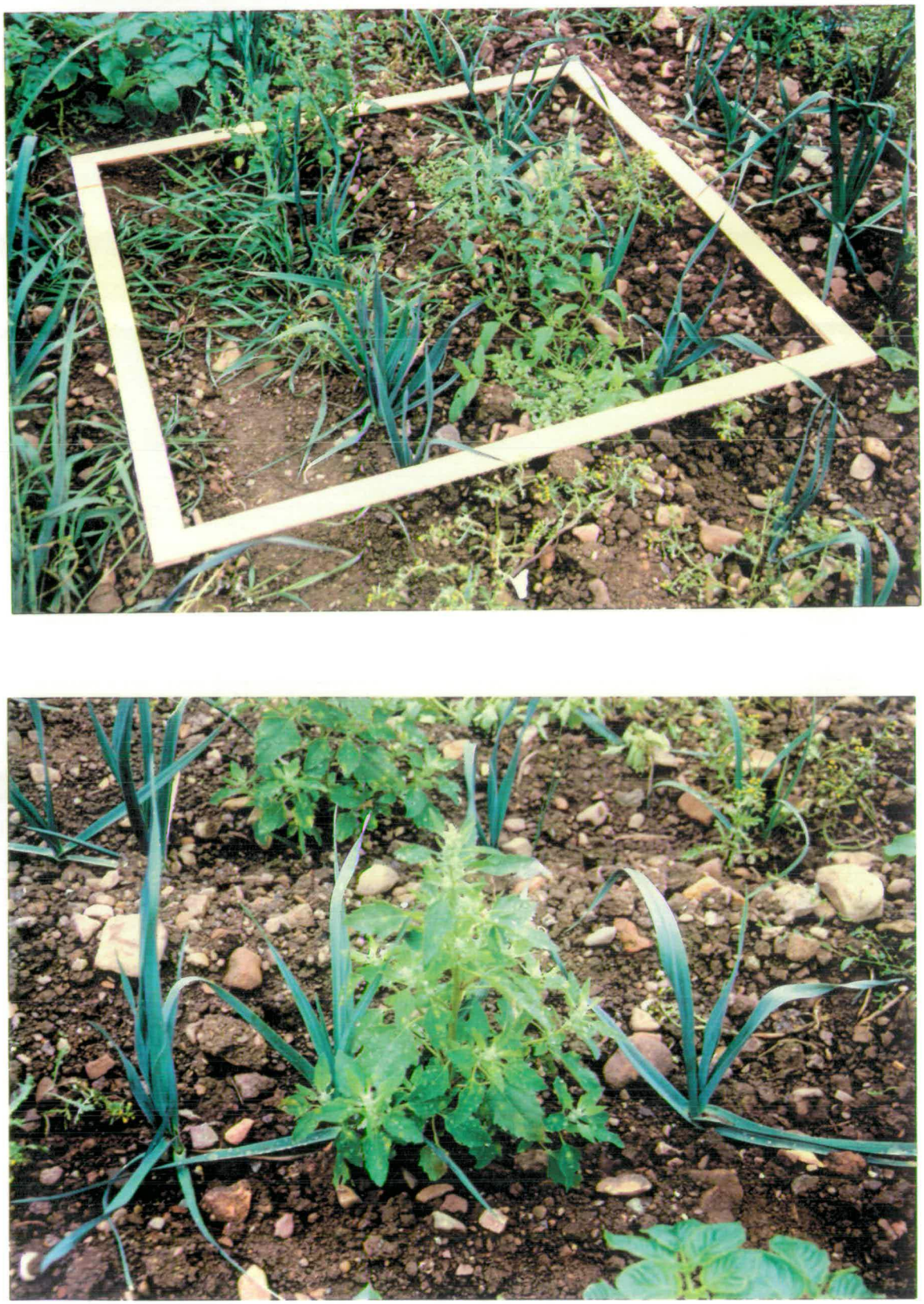

Plate 2. Weed competition in leek fields.

The leek crop was not thinned out and competition between plants did not reduce leek flag size as weeds did. Although in some field patches *C. album* proliferated leek flag size and leaf quantity did not decrease. *A. patula* (common orache), a weed that covers to a vast extent at soil level, proved to be advantageous for leek growth in most of the cases observed. The four or more branches growing at soil level are referred to as arms and together with height were used to characterize common orache. Investigations showed no correlation between leek flag length and width and orache height and arm size.

Weed population surveys were carried out in all the other trials. Leeks were transplanted in early May 1992 to an experimental field at SCAE (trial 3). A high abundance of *S. media* was encountered, together with weed species with a lower incidence: *U. dioica*, *P. pratense*, *E. repens*, *S. arvensis* and *P. persicaria*. *P. rhoeas*, *E. angustifolium* and *M. sylvestris* were only found at the crop field edges, Table 5.21.

In an experiment carried out one year later in the same field it was found that the weed flora had changed (trial 5). The weeds species surveyed were the same as the ones encountered in the broccoli experiment with a high incidence of *E. repens*, *S. media* and *U. dioica,* Table 5.21.

Campend Farm (trial 4) presented a sandy loam fully covered by stones and clods with low weed densities as a result of good herbicide application. The weeds with highest incidence in this site were *S. vulgaris* and *V. arvensis*, and individual specimens of *P. aviculare*, *C. arvensis* and *V. persica* were also encountered, Table 5.21.

5.4.3 EFFECT OF WEED POPULATION IN LEEK/WEED/SOIL DISCRIMINATION

Table 5.19 shows the weed incidence in the top, medium and bottom areas of the sloping farm at Damhead. An analysis was carried out on the effect of weed patches on wavelength selection. Leek, soil and rock spectra remained the same in every analysis carried out and only the broad-leaf weed species with higher incidence than 30% were used for each area. Weeds species selected in the top slope were *A. patula*, *C. album*, *S. vulgaris*, *S. media* and *T. officinale*. In the middle of the slope *Matricaria spp.* was found in 95% of the samplings and replaced *C. album* in the analysis. Some different weed species proliferated in the bottom part of the slope as *S. arvensis* and *V arvensis*, which together with *Matricaria spp.*, *C. album*, *S. media*, *A. patula* and *S vulgaris* formed the weed group used in the crop/weed/soil discriminant analysis.

Only direct wavelengths were used during the entire analysis and leek/weed/soil-rock discriminations of 100% were achieved with all the program runs, Table 5.22. Program runs 1950, 1952 and 1953 used all, four and three wavelengths to achieve a 96% leek/weed species/soil-rock discrimination with only *S. vulgaris* being misclassified. The important wavelengths were 700 nm, 720 nm and 1060 nm. Program run 1956 using two wavelengths (690 nm and 1020 nm) misclassified *C. album*, *S. media*, *S vulgaris* and *A. patula* reducing leek/weed species/soil-rock discrimination to 81%.

Table 5.22 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, four, three and two direct wavelengths for leek.**

	TRIAL 7		
	Bottom of the row	**Middle of the row**	**Top of the row**
Run No.	1623	1632	1950
No. Wavelengths	**all**	**all**	**all**
% C/W/S	100	100	100
% C/Ws/S	94.87	100	96.96
Run No.	1625	1634	1952
No. Wavelengths	4	4	4
% C/W/S	100	100	100
% C/Ws/S	84.61	96.96	96.96
Wavelengths (nm)	700, 720, 780, 1060	700, 720, 1040, 1380	700, 720, 780, 1060
Run No.	1626	1635	1953
No. Wavelengths	3	3	3
% C/W/S	100	100	100
% C/Ws/S	89.74	96.96	96.96
Wavelengths (nm)	700, 720, 1060	700, 720, 1040	700, 720, 1060
Run No.	1629	1639	1956
No. Wavelengths	2	2	2
% C/W/S	100	100	100
% C/Ws/S	79.48	87.87	81.82
Wavelengths (nm)	690, 720	690, 1020	690, 1020

Perfect crop/weed species/soil-rock discrimination was achieved with all the wavelengths using the weed species that proliferated in the middle slope area. This specific discrimination decreased to 96% in program runs 1634 and 1635, where *S. vulgaris* was misclassified. The wavelengths used in program run 1635 were 750 nm, 770 nm and 1090 nm. Reduction in the specific discrimination to 87% was experienced in program run 1639 as *A. patula*, *S. vulgaris* and *S. media* were misclassified.

The specific discrimination in the bottom of the slope was lower than in the higher areas of the slope. Program run 1623 used all the wavelengths and could not recognize *S. vulgaris* obtaining a specific discrimination of 94%. Four wavelengths were unable to properly identify *S. vulgaris*, *V. arvensis* and *C. album* reducing weed species discrimination to 84%. The specific discrimination increased to 89%.with the use of three wavelengths -700 nm, 720 nm and 1060 nm- as *C. album* was properly classified. *A. patula*, *Matricaria spp.* and *S. media* were the only weed species correctly classified by program run 1629 with two wavelengths. The weed species discrimination obtained was 79%.

Comparable wavelength values (700 nm, 720 nm and 1040-1060 nm) were obtained in program runs 1625, 1635 and 1953 for each slope area. The only variation encountered was between 1380 nm in the middle of the row and 780 in the extremes. These six program runs achieved high specific discriminations with a common identification problem: *S. vulgaris*.

5.4.4 LEEK/WEED/SOIL DISCRIMINATION

Analyses of the four leek crops achieved 100% crop/weed/soil discrimination using four and three wavelengths, Table 5.23. The experimental trial at Bush Estate field in 1993 (trial 5) failed to achieve 100% general discrimination with two wavelengths and misclassified *P. persicaria* as leek.

The four sites also achieved 100% general discrimination using all the wavelength ratios, Table 5.24. Trials 3 and 5 carried out at Bush Estate experimental fields achieved 100% success rates with three wavelength ratios, and only the former obtained perfect general identification with two wavelength ratios. The use of two ratios in trial 5 misclassified *P. persicaria* and *E. repens* with leek decreasing leek/weed/soil discrimination to 84%. At Campend farm (trial 4) general discrimination efficiencies of 90% and 87% were obtained with three and two ratios *S. vulgaris* being responsible for those reductions. Damhead farm samples (trial 7) presented a 96% leek/weed/soil-rock discrimination using three ratios as leek

was mistaken for *T. officinale*. With the use of only two ratios, volunteer potato and *T. officinale* were misclassified as leek and a general discrimination of 92% achieved.

Table 5.23 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, four, three and two direct wavelengths for leek.**

	TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Run No.	1	1004	1371	1289
No. wavelengths	**all**	**all**	**all**	**all**
% C/W/S	100	100	100	100
% C/Ws/S	95.23	100	95.5	93.75
Run No.	5	1007	1373	1291
No. wavelengths	4	4	4	4
% C/W/S	100	100	100	100
% C/Ws/S	100	100	86.6	87.5
WAVELENGTHS	720, 1080, 1380, 1500	680, 800, 1080, 1520	760, 1060, 1340, 1480	660, 700, 760, 1060
Run No.	106	1008	1377	1297
No. wavelengths	3	3	3	3
% C/W/S	100	100	100	100
% C/Ws/S	97.62	93.93	86.6	89.5
WAVELENGTHS	720, 1080, 1380	680, 1080, 1520	760, 1340, 1480	710, 770, 1040
Run No.	7	1010	1375	1295
No. wavelengths	2	2	2	2
% C/W/S	100	100	97.7	100
% C/Ws/S	88.09	93.93	73.3	68.7
WAVELENGTHS	1080, 1380	1080, 1520	760, 1340	690, 1060

A 95.23% leek/weed species/soil discrimination using all the wavelengths was the effect of *T. officinale* misclassification in trial 3, Table 5.23. With the use of four wavelengths (720 nm, 1080 nm, 1380 nm and 1500 nm) all the weed species were classified properly. Leek/weed species/soil discriminations of 97.62% and 88.09% were obtained with three and two

wavelengths, respectively. *S. media* was misclassified in the former (program run 106); and *E. angustifolium*, *M. sylvestris* and *S. media* in the latter (program run 7).

Table 5.24 **Best % Crop/Weed/Soil (C/W/S) and % Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for all, three and two wavelength ratios for leek.**

	TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Run No.	68	1048	1445	1477
No. wavelengths	all	all	all	all
% C/W/S	100	100	100	100
% C/Ws/S	97.62	100	88.8	87.5
Wavelength ratios	÷ 710	÷ 1390	÷ 1400	÷ 1400
Run No.	110	1053	1449	1454
No. wavelengths	4	4	4	4
% C/W/S	100	90.90	100	95.83
% C/Ws/S	97.62	72.72	77.7	58.33
Wavelength ratios	720/990 1380/990 1500/990	680/1390 720/1390 810/1390	680/1400 850/1400 1060/1400	660/990 740/990 1380/990
Run No.	113	1023	1405	1475
No. wavelengths	3	3	3	3
% C/W/S	100	87.87	84.4	91.7
% C/Ws/S	85.71	75.75	60	60.4
Wavelength ratios	1380/990 1500/990	1120/710 1400/710	1100/710 1400/710	700/710 760/710

Program run 110 used three ratios against 990 nm to obtain a 97.62% weed species discrimination and only *P. pratense* was not recognised properly. Leek/weed/soil discrimination accuracy of 100% was obtained using two wavelength ratios with a common denominator wavelength of 990 nm (program run 113), Table 5.24. Without the ratio containing 720 nm, weed species discrimination decreased to 85.71% having recognition difficulties with *S. media*, *U. dioica*, *P. persicaria* and *P. pratense*.

Leek/weed/soil-rock and leek/weed species/soil-rock discriminations of 100% were achieved with ratios against 990 nm. By using the main three wavelengths and 990 nm weed species discrimination was reduced to 72% and only *C. acaule* was properly classified. *V. arvensis* was the only weed species properly classified with two ratios and a 75% discrimination efficiency obtained.

In the experiment at Bush Estate field in 1993 (trial 5) a leek/weed species/soil discrimination of 95% was achieved using all the direct wavelengths, the error being due to *C. album* and *P. aviculare* misclassification, Table 5.23. Leek/weed species/soil discrimination accuracy was reduced to 86% in program runs 1373 and 1376 using four and three wavelengths, respectively, showing that the wavelength at 1060 nm was not essential. *L. purpureum* and *C. arvense* were misclassified in addition to *C. album* and *P. aviculare*.

The best discrimination accuracies using all wavelengths were found with ratios against 1400 nm, Table 5.24. *C. arvense*, *C. album* and *P. aviculare* were not recognized achieving 88% leek/weed species/soil discrimination. Weed species discrimination success rate of 77% was obtained with three wavelength ratios (program run 1449) misclassifying *C. album*, *C. arvense*, *C. bursa-pastoris*, *P. persicaria* and *S. media*.

Maximum 100% weed species discrimination was obtained in Campend Farm (trial 4) with the best four wavelengths (680 nm, 800 nm, 1080 nm and 1520 nm), Table 5.23. Without 800 nm, program run 1008 could not properly identify *P. aviculare* and *V. arvensis*, and weed species discrimination decreased to 93%.

Discriminant analyses from spectral data collected at Damnhead Farm (trial 7) misclassified *S. vulgaris* and *F. officinalis* achieving a 93% weed species discrimination using all the wavelengths, Table 5.23. Four wavelengths (660 nm, 700 nm, 760 nm and 1060 nm) were used in program run 1291 and leek/weed species/soil-rock discrimination decreased to 87% as *V. arvensis*, *S. vulgaris* and *F. officinalis* were misclassified *S. arvensis* and *T. officinale* were the only weed species classified correctly, in addition to volunteer potato, when two wavelengths were used and crop/weed species/soil-rock discrimination decreased to 68%.

A leek/weed species/soil-rock discrimination of 87% was obtained with wavelength ratios against a common wavelength of 1400 nm, Table 5.24. The weeds species with more classification problems were *V. arvensis*, *F. officinalis* and *S. vulgaris*. The three ratios of program run 1454 produced a poor 58% weed species discrimination, where no weed species was properly identified.

High discriminant accuracies were achieved in the four trials, but with very different discriminant wavebands. Although an important waveband in the four trials was 1060-1080 nm, high discrepancy was found between the other discriminant wavelengths. High wavelength values between 1480 nm and 1520 nm were also preferred in three of the four trials. Crop/weed species/soil discrimination presented an essential wavelength at 1480 nm in trial 5 and at 770 nm in trial 7. Without these wavelengths the specific discriminations decayed abruptly. None of these wavelengths are used in program run 1010 (trial 3) which achieved a crop/weed species/soil discrimination accuracy of 93%. Direct wavelength program runs achieved better discrimination accuracies than wavelength ratio program runs. Similar weed species were difficult to recognize using either wavelength ratios or direct wavelengths.

5.5 CROP/WEED/SOIL DISCRIMINATION USING WAVEBANDS

Individual studies were carried out to analyse the effect of crop growth, crop water stress and crop leaf nitrogen concentration on reflectance signatures ranging between 600 and 1600 nm.

Two different analyses to discriminate crop/weeds/soil were carried out. The first one obtained the success rates in crop/weed/soil discrimination using specific spectral ranges. The second searched for the minimum discriminant wavelengths that would achieve highest crop/weed/soil discrimination accuracies.

In the waveband analysis, two broad bands (600-1100 nm and 1100-1600 nm) were used and compared with five narrow spectral band of 200 nm each. The five narrow bands that covered the entire 600-1600 nm waveband were 600-800 nm, 800-1000 nm, 1000-1200 nm, 1200-1400 nm and 1400-1600 nm.

Discriminant analysis was used to select and determine the success of various wavelengths in distinguishing broccoli or cabbage from soil and five common weeds encountered in brassica fields:

redshank (*polygonum persicaria*)
chickweed (*stellaria media*)
charlock (*sinapsis arvensis*)
poppy (*papaver rhoeas*)
nettle (*urtica urens*)

The crop categories depended on the experiment carried out, having four and six groups in the stress and nitrogen experiments, respectively.

5.5.1 THE EFFECT OF NITROGEN CONCENTRATION

Broccoli plants were sown in the greenhouse in pots having different nitrogen concentrations. Peat compost was used for root support and different quantities of nitrogen were added to each pot to study the effect of nitrogen concentration on leaf reflectance. Nitrogen applications ranged from nil up to the normal recommendation of 250 kg/ha (Anon,1991) with increments of 25 kg/ha. Phosphate and potassium were added to provide

Table 5.25 Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy with broccoli leaves having different nitrogen concentrations.

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
NIT1	5	3	2
NIT2	5	3	2
NIT3	5	3	2
NIT4	5	3	2
NIT5	5	3	2
NIT6	5	3	2
S. arvensis	10	7	3
P. rhoeas	10	7	3
S. media	10	7	3
U. urens	10	7	3
P. persicaria	10	7	3
Soil	10	7	3
Total	90	60	30

Table 5.26 Discrimination accuracies between six different broccoli nitrogen concentrations, weed species and soil using different wavebands.

Waveband (nm)	Discrimination accuracy (%)		
	Crop/Weed/Soil	Crop/Weed Species/Soil	Nitrogen concentration/Weed Species/Soil
600-1600	100	100	96.6
600-1100	100	96.6	80
1100-1600	100	93.3	76.6
600-800	100	93.3	73.3
800-1000	93.3	80	53.3
1000-1200	90	90	73.3
1200-1400	100	96.6	76.6
1400-1600	100	90	73.3

Table 5.27 Discrimination accuracy between broccoli leaves with different nitrogen concentrations, weed species and soil, using direct wavelengths.

Program run no.	Number of wavelengths	Discrimination accuracy (%)		
		Crop/Weed/ Soil	Crop/Weed Species/Soil	Nitrogen Conc./Weed Species/Soil
N8	13	100	100	96.6
N10	4	100	96.6	90
N12	3	100	96.6	90
N11	3	100	83.3	70
N13	2	100	83.3	70
N15	2	100	83.3	66.6

Program run no.	Selected wavelengths (nm)			
N10	720	1000	1250	1410
N12	720	1000	1410	
N11	720	840	1060	
N13	720	1000		
N15	840	1060		

the typical recommendations. Each seedling was transplanted to its respective pot fifteen days after sowing date. Broccoli leaf spectra were obtained once the plants were well established and the leaf samples sent to the SAC laboratory for chemical analysis by the Kjeldahl method. Spectral signatures of three leaves presenting different nitrogen concentrations were averaged and plotted, Fig. 5.2.

A total of 90 spectra classified into 12 different groups were used to study the effect of nitrogen concentration on broccoli/weed/soil discrimination, Table 5.25. The 30 broccoli spectra were grouped into six different nitrogen concentration categories named NIT1, NIT2,....,NIT6. The remaining spectra consisted of a soil group with ten spectra and five weed species groups of ten spectra each. From the 90 spectra, 60 trained the classifier and the remaining 30 spectra tested it.

Table 5.26 shows the results achieved with different spectral bands. The use of the entire waveband (600-1600 nm) provided 100% success rates in crop/weed/soil and crop/weed species/soil discriminations. The six crop nitrogen concentration categories were identified with a 96.6% success rate as one nitrogen group was misclassified. The 600-1100 nm and 1100-1600 nm wavebands achieved a 100% crop/weed/soil discrimination. Highest crop/weed species/soil and crop nitrogen concentration/weed species/soil discrimination accuracies of 96.6% and 80% were achieved using the 600-1100 nm waveband.

A 100% crop/weed/soil discrimination was achieved with the 600-800 nm, 1200-1400 nm and 1400-1600 nm narrowbands. *U. urens* was misclassified as broccoli in the 800-1000 nm waveband reducing broccoli/weed/discrimination to 93.33%. The lowest general discrimination was encountered in the 1000-1200 nm were *S. arvensis* and *S. media* were taken as broccoli. In the 1200-1400 nm waveband the highest broccoli/weed species/soil and broccoli nitrogen concentration/weed species/soil discriminations were achieved with values of 96.6% and 76.6%, respectively. High specific discrimination was found using the 600-800 nm, 1000-1200 nm and 1400-1600 nm wavebands. Chlorophyll and water absorption bands could be related to leaf nitrogen concentration. Poor cell formation and structure damage may occur with low nitrogen concentrations reducing reflectance signature differences.

Crop/weed/soil discriminations of 100% were obtained with only 2 wavelengths, Table 5.27. Program run N13 used 720 nm and 1000 nm to achieve 83.33% and 70% success rates in broccoli/weed species/soil and broccoli nitrogen concentration/weed species/soil discriminations, respectively. With the use of a third wavelength (1410 nm) in program run N12, specific discriminations of 96.6% and 90% were achieved.

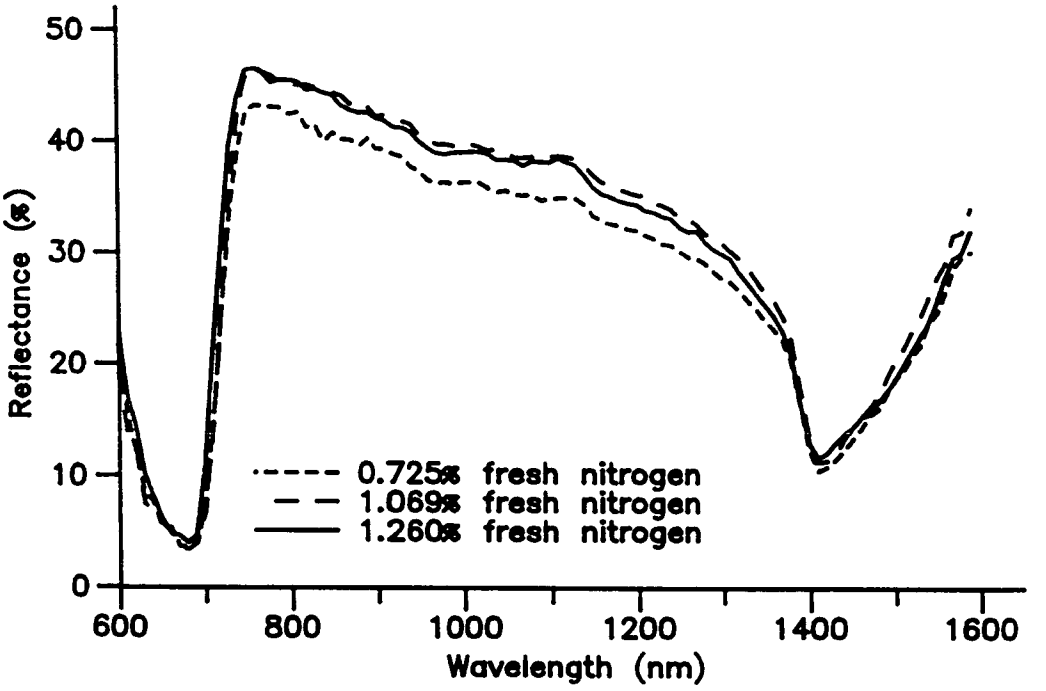

Fig. 5.2 Broccoli spectral signatures for different nitrogen concentrations.

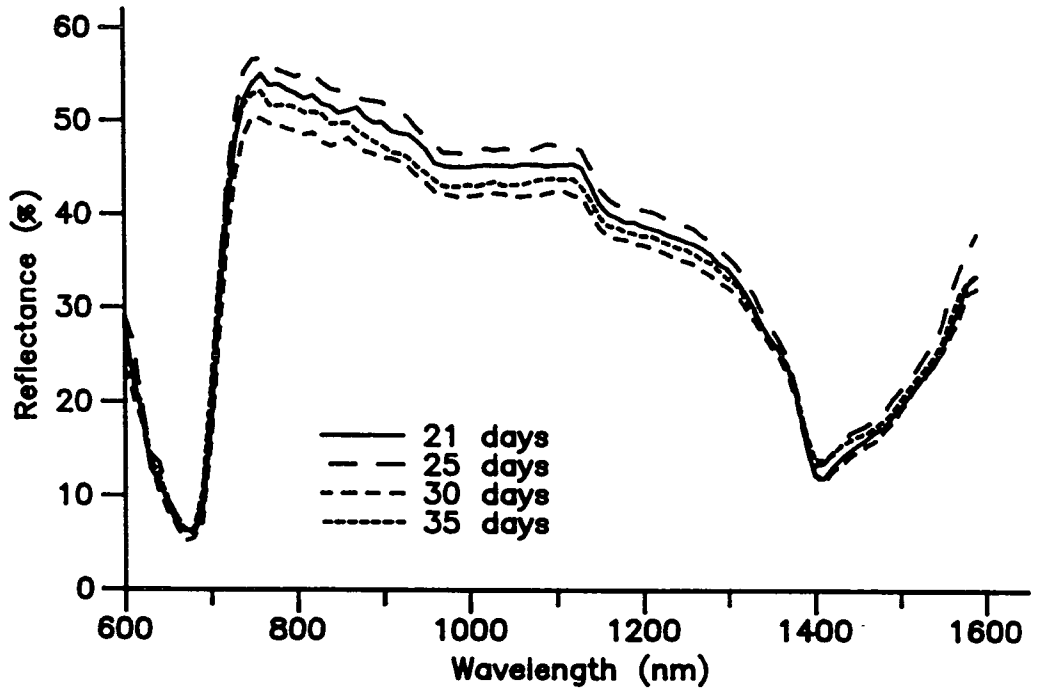

Fig. 5.3 Cabbage reflectance during different growth stages.

5.5.2 THE EFFECT OF CROP GROWTH

Twenty cabbage plants were sown in individual pots in a greenhouse during the months of March and April of 1992 to study their spectral reflectance during the first month of growth. This growth stage is critical as weed competition during this period can greatly affect crop yield. Cabbage growth was referred to the sowing date and to the number of true measurable plant leaves.

Table 5.28 Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy in the cabbage growth stage experiment.

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
CAB-17	10	7	3
CAB-21	10	7	3
CAB-25	10	7	3
CAB-30	10	7	3
CAB-35	10	7	3
S. arvensis	10	7	3
P. rhoeas	10	7	3
S. media	10	7	3
U. urens	10	7	3
P. persicaria	10	7	3
Soil	10	7	3
Total	140	98	42

Table 5.29 Discrimination accuracies between cabbage leaves during different growth stages, weed species and soil, using different spectral bands.

Waveband (nm)	Discrimination accuracy (%)		
	Crop/Weed/Soil	Crop/Weed Species/Soil	Crop Growth/Weed Species/Soil
600-1600	100	100	81.82
600-1100	100	96.97	81.82
1100-1600	100	93.94	75.76
600-800	96.97	90.91	72.73
800-1000	96.97	96.97	78.78
1000-1200	96.97	90.91	75.76
1200-1400	100	96.97	78.78
1400-1600	100	96.97	84.85

Table 5.30 Discrimination accuracies between cabbage during its different growth stages, weed species and soil, using direct wavelengths.

Program run no.	Number of wavelengths	Discrimination accuracy (%)		
		Crop/Weed/ Soil	Crop/Weed Species/Soil	Crop growth/Weed Species/Soil
AG12	22	100	100	81.82
AG13	4	100	96.97	81.82
AG9	4	93.93	78.78	66.66
AG15	3	100	100	81.82
AG10	3	93.93	78.78	66.66
AG17	2	100	96.97	75.76

Program run no.	Selected wavelengths (nm)			
AG13	740	860	1360	1480
AG9	690	740	860	900
AG15	740	1360	1480	
AG10	690	740	900	
AG17	740	1480		

Ten spectra on the top margin of each of the existing leaves were obtained for the first time 17 days after sowing when the plants had three true leaves. With 5 day intervals, four subsequent measurements were taken from the same three leaves. Reflectance increased during the first three spectral measurements until five true leaves were present (25 days after sowing). Leaves grew in size but reflectance began to decrease in the measurements taken 30 and 35 days after the sowing date, Fig. 5.3. In the last sampling, cabbages had seven true leaves and the three leaves measured represented 60% of the total foliage.

Cabbage spectra were grouped into five different growth stage categories: cab-17, cab-21, cab-25, cab-30 and cab-35. The numbers correspond to the period of days that passed after the seeds were sown. A total of 110 spectra were introduced to the discriminant analysis, 77 to obtain the classification function and 33 to form the trial group, Table 5.28.

The 600-1100 nm and 1100-1600 nm spectral ranges discriminated the three general categories with a 100% accuracy, Table 5.29. Weed species discrimination was greatest with the lower wavelengths (96.97%) with only *U. urens* misclassified. *S. media* and *P. persicaria* were not identified properly in the 1100-1600 nm spectral band giving a weed species discrimination of 93.94%. In the 600-800 nm, 800-1000 nm and 1000-1200 nm wavebands cabbage was misclassified as *S. media*, achieving a crop/weed/soil discrimination of 96.97%. The most successful crop growth/weed species/soil discrimination with a success rate 84.85% was obtained in the 1400-1600 nm waveband with *S. media* misclassified.

Crop/weed/soil and crop/weed species/soil discriminations of 100% were achieved with all the wavelengths, Table 5.30. An 81.82% crop growth/weed species/soil discrimination was obtained with all the wavelengths. A 100% cabbage/weed/soil discrimination was achieved with two wavelengths, 740 nm and 1480 nm in program run AG17. All the weeds were correctly classified except *S.media* giving a 96.97% cabbage/weed species/soil discrimination. Adding a third wavelength at 1360 nm, classified each weed species in its respective category. Reduction in number of wavelengths did not decrease drastically specific category classification.

5.5.3 THE EFFECT OF WATER STRESS

Twenty broccoli plants were sown in a greenhouse and transplanted to individual pots after plant emergence. Forty days after, the water applied to the plants was reduced thus stressing the plants. Measurements of water potential and soil volumetric water content were obtained simultaneously with leaf reflectance. Water potential was measured using a pressure chamber

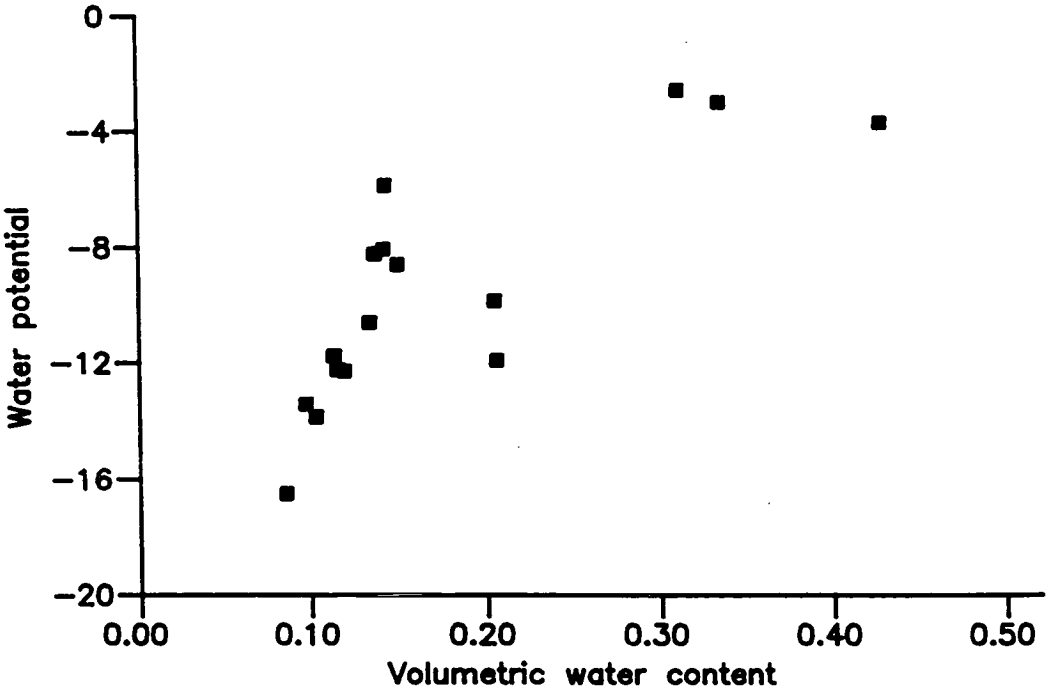

Fig 5.4 Broccoli water potential versus soil volumetric water content.

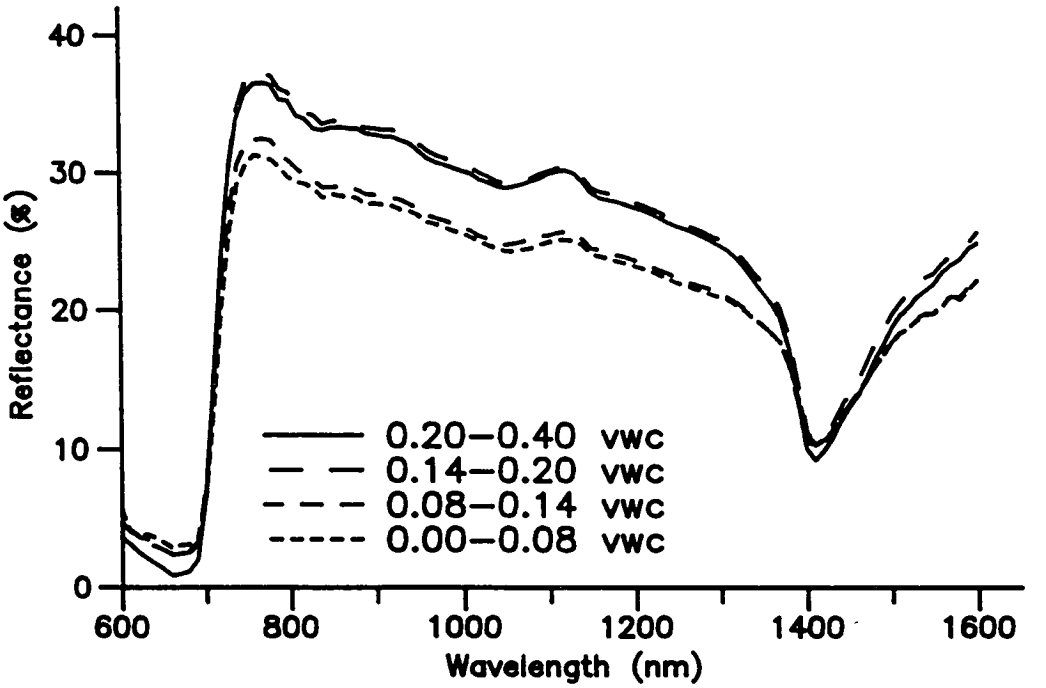

Fig. 5.5 Broccoli signatures for different stress levels.

(Model 1400, Skye Instruments Ltd., Llandrindod Wells, UK) and the soil volumetric water content was calculated from the weights achieved before and after introducing the soil samples into the oven. The third leaf from top to bottom was sampled and five spectra were taken in the top centre of each leaf. Fig. 5.4 shows a good correlation between water potential and soil volumetric water content for soil volumetric water content measurements below 0.2. The leaf spectral signatures were classified into four stress categories: STRESS1, STRESS2, STRESS3 and STRESS4 with soil volumetric water contents ranging between 0.2-0.4, 0.141-0.195, 0.121-0.14 and 0.00-0.12, respectively. Small reflectance differences between STRESS1-STRESS2 and between STRESS3-STRESS4 were encountered and plotted in Fig. 5.5. Stressed plants presented a lower reflectance in the 800-1300 nm waveband with lower chlorophyll and water content. A stress threshold fixed at a soil volumetric water content of 0.14 could identify stressed plants by optical reflectance. Nevertheless, identification difficulties would arise in detecting different stress stages quantitatively.

Table 5.31 Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy in the stress experiment with broccoli.

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
STRESS1	20	15	5
STRESS2	25	17	8
STRESS3	19	13	6
STRESS4	13	9	4
S. arvensis	10	7	3
P. rhoeas	10	7	3
S. media	10	7	3
U. urens	10	7	3
P. persicaria	10	7	3
Soil	10	7	3
Total	137	96	41

Table 5.32 Discrimination accuracies between broccoli under different stress treatments, weed species and soil using different wavebands.

Waveband (nm)	Discriminant accuracy (%)		
	Crop/Weed/Soil	Crop/Weed Species/Soil	Stressed crop/Weed Species/Soil
600-1600	100	100	75.61
600-1100	85.37	80.49	48.78
1100-1600	100	92.68	68.29
600-800	90.24	78.05	39.02
800-1000	87.8	82.93	46.34
1000-1200	90.24	90.24	58.54
1200-1400	97.56	87.8	56.09
1400-1600	100	92.68	60.98

Table 5.33 Discrimination accuracy between broccoli under different stress treatments, weed species and soil using direct wavelengths.

Program run no.	Number of wavelengths	Discrimination accuracy (%)		
		Crop/Weed/ Soil	Crop/Weed Species/Soil	Stressed crop/Weed Species/Soil
ST1	11	100	100	75.61
ST3	4	100	92.68	63.41
ST8	4	100	92.68	63.41
ST4	3	100	90.24	58.54
ST11	3	87.8	87.8	46.34
ST12	3	85.37	82.93	43.9
ST7	2	85.37	68.29	43.9

Program run no.	Selected wavelengths (nm)			
ST3	720	800	1340	1540
ST8	720	1060	1340	1540
ST4	720	1340	1540	
ST11	720	800	1340	
ST12	720	850	1340	
ST7	1340	1540		

From a total of 137 spectra classified into 9 groups, 77 broccoli spectra were classified into four groups, Table 5.31. The five weed species consisted of ten spectra each and the soil category was formed by ten spectra. The classifier was trained by 96 spectra and a trial group of 41 spectra was used to test it.

The 1100-1600 nm broadband presented 100% and 92.68% crop/weed/soil and crop/weed species/soil discriminations with *S. arvensis* and *P. persicaria* misclassified, Table 5.32. The crop stress/weed species/soil discrimination achieved a 68.29% success rate. The lower wavelengths of the 600-1100 nm spectral range misclassified cabbage with *S. arvensis* and *P. persicaria* obtaining a crop/weed/soil discrimination of 85.37%. The only narrowband to achieve a 100% crop/weed/soil discrimination was the 1400-1600 nm waveband. *S. arvensis* and *U. urens* were properly classified obtaining a broccoli/weed species/soil discrimination of 92.68%. The highest broccoli stress/weed species/soil discrimination was achieved with this waveband having a value of 60.98%. The worst discrimination accuracies were obtained in the 600-800 nm and in 800-1000 nm wavebands.

Crop/weed/soil and crop/weed species/soil discriminations of 100% were achieved using all the wavelengths, Table 5.33. With the use of three wavelengths: 720 nm, 1340 nm and 1540 nm in program run ST4, a 100% crop/weed/soil discrimination and a crop/weed species/soil discrimination of 90.24% were achieved as *S. arvensis* and *P. persicaria* were misclassified. Broccoli stress/weed species/soil discriminations with values lower than 60% were achieved using two or three wavelengths. The two wavelengths of program run ST7 misclassified cabbage as soil and soil as *P. rhoeas* decreasing the general discrimination to 85.37%.

Crop/weed/soil discrimination of 100% using wavelength in program run ST4. and a crop/weed species/soil discrimination of 90.24% were achieved as S. arvensis and P. persicaria were missclassified. Broccoli stress/weed species/soil discriminations with values less than 60% were achieved using two or three wavelengths.

5.5.4 STRESSED CROPS IN CROP/WEED/SOIL DISCRIMINATION

Crop status did not affect crop/weed/soil discrimination, and a comparison was valid using the same weed species during the analysis. Crop growth not considered as a crop stress was included only for comparing the three experiments. In the three experiments a 100% crop/weed/soil discrimination was achieved in the 1100-1600 nm broadband, in the 1400-1600 nm broadband and using only three wavelengths. The crop/weed species/soil discrimination accuracy achieved with three wavelengths was higher in the growth and

nitrogen experiments than the one obtained using the 1400-1600 nm waveband, with success rates higher than 90% in all the cases. The three experiments selected a wavelength located at 720-740 nm as one of the three wavelengths, while the other two differed in magnitude. Analyses with the 1400-1600 nm waveband were more efficient in classifying the different crop categories than the three wavelength analyses. Finally, it could be stated that by using only one filter (1400-1600 nm) high discrimination accuracies could be achieved in less time.

6. CROP/WEED/SOIL CLASSIFIERS

A crop/weed/soil classifier algorithm needs to be obtained for sorting an undefined number of different samples into three well defined groups: crop, weed and soil. The algorithm can then be used to classify future samples into one of these three categories, once the proper input data is introduced.

The optimum classifier should take into account computer processing time, the number of mathematical operations and discrimination accuracy considering reflectance differences due to:

crop varieties;
weed species incidence;
crop status, i.e. growth stage and stress condition.

The best discriminant wavelengths and wavebands for each of the three crops (broccoli, cabbage and leek), were presented in previous chapters and showed high crop/weed/soil discrimination accuracies. The selected wavelengths were obtained from discriminant analyses, and for future applications reflectances at these wavelengths will provide the data fed to the classifier. The output of the classifier indicates whether the sample is a crop, a weed or soil.

The two basic classifiers are the discriminant classifier already defined and neural network classifiers.

6.1 WAVELENGTH SELECTION FOR CROP/WEED/SOIL CLASSIFIERS

The process for selecting the best set of wavelengths that will perform efficiently on different crop varieties, crop growth stages and diverse weed species populations requires the integration of the results achieved by each trial.

The integration process consists of selecting the best set of wavelengths for each trial and executing program runs using them in all the other trials. For example, the best three wavelengths obtained from the leek/weed/soil discriminant analysis in trial 3 were applied to trials 4, 5 and 7 and the discriminant accuracies calculated. The analysis was carried out by crop and the results will be discussed.

6.1.1 CABBAGE

Tables 6.1 and 6.2 show the crop/weed/soil and crop/weed species/soil discriminations for each trial, respectively. The columns in both tables depict the success rates achieved with the best three wavelengths of the heading trial. For example, in Table 6.1 the second column heading is trial 2. The best wavelengths for trial 2 -690 nm, 1300 nm and 1500 nm- were run with the spectral data of trial 1 obtaining a crop/weed/soil discrimination of 90.47%. The same wavelengths were used to obtain a 97.61% general discrimination with the spectral data of trial 3. This operation was repeated eight times for each set of wavelengths and a total of 64 program runs executed to cover all the possibilities.

The best wavelengths for trial 1 were 880 nm, 960 nm and 1040 nm and although they presented a different weed population than trials 3 and 7, 100% general discrimination was obtained with their respective spectral data. The lowest success rates achieved with these wavelengths corresponded to autumn cabbage in trial 9 where an 80.5% general discrimination was achieved. The best and worst crop/weed species/soil discriminations corresponded to the spectral data for trials 4 and 9 (autumn cabbage) with success rates of 97.2% and 61.1%, respectively. The average crop/weed/soil and crop/weed species/soil discriminations were 94.34% and 79.55%, Table 6.3.

Trial 2 best wavelengths -690 nm, 1300 nm and 1500 nm- obtained 100% general discrimination with program runs using spectral data for trials 4, 6 and 9 (savoy) and the lowest discrimination of 90.47% with data from trial 1. Maximum and minimum specific discriminations of 92.85% and 61.1% were achieved with data from trial 3 and 7, respectively, Table 6.2. Averaging all the crop/weed/soil and crop/weed species/soil discriminations produces average values of 96.06% and 82.31%, Table 6.3.

The best wavelengths for trial 3 -720 nm, 1170 nm and 1360 nm- were used by program runs with spectral data from trials 1, 2, 6 and 7 and achieved a 100% general discrimination. A minimum general discrimination of 77.7% was obtained with data from trial 9 (autumn cabbage). Average general and specific discriminatios of 97.55% and 82.29%, respectively were obtained, Table 6.3.

Table 6.1 **Cabbage/Weed/Soil discrimination accuracies from each trial using the best three wavelengths obtained in each of the other trials with the same crop.**

Spectral data	Success rates (%) using the best three wavelengths in								
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7 7	TRIAL 9		
							Spring	Autumn	Savoy
TRIAL 1		90.47	100	83.3	95.23	92.85	100	85.71	90.47
TRIAL 2	94.44		100	100	100	91.66	100	100	100
TRIAL 3	100	97.61		97.61	97.61	97.61	100	100	100
TRIAL 4	97.22	100	94.4		91.6	100	100	97.2	97.2
TRIAL 6	96.6	100	100	70		96.6	100	90	86.6
TRIAL 7	100	94.4	100	100	100		100	100	100
TRIAL 9 Spring	97.2	94.4	97.2	100	94.4	100		97.2	97.2
TRIAL 9 Autumn	80.5	91.6	77.7	91.6	86.11	83.3	88.8		91.6
TRIAL 9 Savoy	88.8	100	97.22	97.2	94.4	88.8	97.2	100	

Wavelengths (nm)									
	880	690	720	680	820	710	680	680	680
	960	1300	1170	720	990	840	1060	760	760
	1040	1500	1360	840	1080	1060	1360	1060	1040

Table 6.2 **Cabbage/Weed species/Soil discrimination accuracies from each trial using the best three wavelengths obtained in each of the other trials with the same crop.**

Spectral data	Success rates (%) using the best three wavelengths in								
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9		
							Spring	Autumn	Savoy
TRIAL 1		64.25	83.33	59.52	76.19	78.57	73.8	66.6	71.42
TRIAL 2	80.55		86.11	88.8	94.4	80.55	77.7	94.4	97.2
TRIAL 3	83.3	92.85		80.95	85.71	80.95	88.09	88.09	90.47
TRIAL 4	97.2	88.8	94.4		91.6	100	83.3	97.2	97.2
TRIAL 6	86.6	93.3	90	60		93.3	96.6	80	80
TRIAL 7	77.7	61.1	63	75	77.7		72.2	86.6	91.26
TRIAL 9 Spring	80.5	83.3	80.5	83.3	83.3	83.3		80.5	83.3
TRIAL 9 Autumn	61.1	83.3	72.2	75	75	72.2	75		77.7
TRIAL 9 Savoy	69.4	91.6	88.8	77.7	80.5	88.8	83.3	83.3	

Wavelengths (nm)	880 960 1040	690 1300 1500	720 1170 1360	680 720 840	820 990 1080	710 840 1060	680 1060 1360	680 760 1060	680 760 1040

Table 6.3 **Cabbage relationships between crop/weed/soil and crop/weed species/soil discrimination for all the sites using the best three wavelengths encountered in each site.**

	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9		
							Spring	Autumn	Savoy
AVERAGE % C / W / S	94.34	96.06	97.55	92.46	94.92	93.85	98.25	96.26	95.38
AVERAGE % C / Ws / S	79.55	82.31	82.29	75.03	83.05	82.98	81.25	84.59	86.0
$\frac{\%\ C / Ws / S}{\%\ C / W\ / S}$	84.32	85.69	84.36	81.15	87.49	88.42	82.7	87.8	90.2
$\frac{Avg\ \%\ C / W / S\ -\ avg\ \%\ C / Ws / S}{Avg\ \%\ C / W / S\ +\ avg\ \%\ C / Ws / S}$	8.50	7.71	8.48	10.41	6.67	6.15	9.47	6.45	5.13
$\sqrt{(\%\ C / W / S^2\ +\ \%\ C / Ws / S^2)}$	123.40	126.50	127.62	119.07	126.12	125.27	127.49	128.14	128.47
$\frac{Avg\ \%\ C / W / S + avg\ \%\ C / Ws / S}{2}$	89.94	89.18	89.92	83.74	88.98	88.41	89.75	90.42	90.72
$\frac{\left(\%\ C/W/S + \%\ C /Ws /S\right)\ \left(\%C/W/S\right)}{2}$	82.02	85.67	87.72	77.43	84.46	82.98	88.18	87.04	86.53
WAVELENGTHS (nm)	880 960 1040	690 1300 1500	720 1170 1360	680 720 840	820 990 1080	710 840 1060	680 1060 1360	680 760 1060	680 760 1040

% C / W / S % Crop/Weed/Soil
% C / Ws / S % Crop/Weed species/Soil

Table 6.3 shows average success rates of 92.46% and 75.03% for the general and specific discriminations obtained in trial 4. The three wavelengths selected in this trial were 680 nm, 720 nm and 840 nm and were used to obtain the discrimination efficiencies in each of the other trial sets. A 100% general discrimination was achieved in trials 2, 7 and 9 (spring) and a minimum success rate obtained with trial 6, Table 6.1. Table 6.2 shows low specific discrimination efficiencies in most of the trials. Maximum and minimum specific discriminations were achieved in trials 2 and 6 with values of 88.8% and 60%, respectively.

Trial 6 best wavelengths -820 nm, 990 nm and 1080 nm- were used to study crop/weed/soil and crop/weed species/soil discriminations and after averaging the results from all the trials, success rates of 94.92% and 83.05% were obtained. A maximum 100% general discrimination was achieved in trials 2 and 7 and the minimum in trial 9 (autumn) with a success rate of 86.11%, Table 6.1. Table 5.26 shows that the minimum weed species discrimination was obtained also with trial 9 (autumn) providing 75% success rate. A maximum specific discrimination success rate of 94.4 % was achieved with trial 2.

The best wavelengths of trial 7 -710 nm, 840 nm and 1060 nm- were used by the spectral data of trial 4 to obtain 100% crop/weed/soil and crop/weed species/soil discriminations. Apart from trial 4, only trial 9 (spring) obtained a 100% general discrimination. Minimum general and specific discriminations of 83.3% and 72.2% were achieved in trial 9 (autumn). The average general and specific discriminations of all the trials using these wavelengths were 93.85% and 82.98%, respectively.

Trial 9 used three sets of wavelengths to obtain crop/weed/soil and crop/weed species/soil discriminations. Each set of wavelengths are shown in Table 6.1. The highest average general and specific disrimination of 98.25% and 86% were obtained with spring and savoy cabbage, respectively. Trials 1, 2, 3, 4, 6 and 7 obtained 100% general discrimination using the three wavelengths of trial 9 (spring), i.e. 680 nm, 1060 nm and 1360 nm. The lowest general discrimination was obtained using the autumn cabbage data for trial 9. Specific discriminations obtained with the three wavelength sets are shown in Table 6.2.

The large number of success rates obtained makes the final wavelength selection difficult. The analysis can be simplified by looking at the crop/weed/soil and crop/weed species/soil discrimination average values. The highest average general discrimination corresponded to the program runs using the best three wavelengths for spring cabbage in trial 9. Nevertheless, using the best wavelengths for savoy cabbage in the same trial provided a higher weed species discrimination (86%) than the one achieved with the best wavelengths for spring cabbage

(84.59%). Ratios were obtained between the general and specific average discriminations, but the results did not allow selection of the best set of wavelengths. A multiratio algorithm, equation 6.1, that divided the difference between the general (C\W\S) and specific (C\Ws\S) average discriminations against their sum was tested.

$$O = (C\backslash W\backslash S - C\backslash Ws\backslash S)/(C\backslash W\backslash S + C\backslash Ws\backslash S) \qquad \text{eq. 6.1}$$

The result, O, depends on the discrimination difference and in their magnitudes. Higher difference between general and specific discriminations will increase the ratio output. When similar differences between discriminations are obtained, the ratio will acquire maximum value for small discrimination magnitudes. The optimum wavelength set should provide a minumum ratio value. High values resulted from high differences between both discriminations, indicating poor weed species discrimination. A good example is the comparison of trials 6 and 9 (spring). The latter, having general and specific average discriminations of 98.25% and 81.25% provided a high 9.47 value, while trial 6 with discriminations of 94.92% and 83.05% provided a better 6.67 value. This algorithm indicates which wavelength set performs best considering the difference between general and specific discrimination accuracies. However, the best classifier into the three major categories (crop, weed and soil) not always achieves the minimun value. Small changes are noted also between trials having similar general and specific average discrimination differences but with different general discriminations. General and specific discriminations for each trial were averaged with little success. A weighted algorithm, eq 6.2, was introduced to account for the general discrimination value, so the average value of the general and specific discriminations was multiplied by the general discrimination.

$$O = C\backslash W\backslash S * (C\backslash W\backslash S + C\backslash Ws\backslash S)/2 \qquad \text{eq. 6.2}$$

The best results were achieved with the wavelength sets of trials 9 (spring) and 3. Another weighted algorithm, eq 6.3, evaluated the square root of the sum of the squared specific and general discriminations for each set of wavelengths.

$$O = SQRT\left((C/W/S)^2 + (C/Ws/S)^2 \right) \qquad \text{eq. 6.3}$$

This algorithm achieves highest results with maximium discrimination accuracies. The effect of squaring each discrimination is to accentuate its magnitude. The addition of the squared specific discrimination increases the overall magnitude and the result, O, will also consider

this discrimination. The output selected should be the one with maximum value, and the best results were achieved again in trial 9 (savoy and autumn).

The set of wavelengths selected for application were:

a. 680 nm, 760 nm and 1040-1060 nm due to their low wavelength values, high weed species discrimination and lowest multiratio value -these wavelengths obtaining the best results for both analyses in trial 9 (autumn and savoy) and only differing in the highest wavelength value where a difference of 20 nm existed;

b. 680 nm, 1060 nm and 1360 nm which gave the highest general discrimination.

6.1.2 BROCCOLI

The three best wavelengths -1000 nm, 1040 nm and 1640 nm- for trial 1 provided 100% crop/weed/soil discrimination in trial 2 and 8 and achieved a minimum discrimination of 84.4% in trial 5 (mature), Table 6.4. Perfect weed species discrimination was obtained with trial 2 and a minimum success rate of 55.5% with trial 5 (young), Table 6.5. Average crop/weed/soil and crop/weed species/soil discrimination success rates of 92.68% and 81.59% were obtained, Table 6.6.

Trial 2 best wavelengths included 700 nm, 720 nm and 1460 nm, and 100% general discrimination was obtained in all the trials with exception of trial 1 and trial 11, where a minimum value of 81.8% was encountered. Maximum and minimum weed species discrimination was achieved in trials 8 and 1, respectively. After averaging all the programs run with these wavelengths, 96.83% and 86.92% general and specific average discriminations were obtained.

The use of the best wavelengths for trial 3 achieved crop/weed/soil and crop/weed species/soil average discriminations of 95.83% and 87.11%, respectively. A 100% crop/weed/soil

discrimination was obtained in trials 5 (young), 8 and 10, and a minimum discrimination in trial 11. Minimum and maximum crop/weed species/soil discriminations of 69% and 96.9% are shown in Table 6.5 corresponding to trials 1 and 2, respectively.

The best wavelengths encountered for young and mature broccoli in trial 5 had similar values at 720 nm and 1040-1060 nm. The other wavelength was different, with a value of 760 nm for mature broccoli and 1380 nm for young broccoli. Higher crop/weed/soil and crop/weed species/soil average discriminations of 98.55% and 95.63% were found using the best wavelengths for young broccoli (trial 5). With the use of the best wavelengths for mature broccoli in trial 5 the general and specific average discriminations were 95.63% and 86.4% respectively. With both sets of wavelengths, a 100% general recognition was achieved in trials 8 and 10. Also 100% general discrimination was achieved using the best wavelengths for mature broccoli (trial 5) in the spectral data of young broccoli (trial 5) and vice versa. The minimum general and specific discriminations with the best wavelengths for young broccoli were 93.9% and 84.4%, respectively.

Trial 8 provided two set of wavelengths, one corresponding to the analysis with soil -710 nm, 740 nm and 890 nm- and the other to straw (680 nm, 1380 nm, and 1480 nm). Higher general and specific discriminations were found with the best wavelengths for trial 8 (soil) and crop/weed/soil and crop/weed species/soil average discriminations 96% and 84% achieved. General and specific average discriminations of 94.9% and 80.8% were found with the set of wavelengths obtained from the crop/weed/straw analysis. Trials 10 and 5 (young) achieved 100% general discrimination with both set of wavelengths.

The use of the best wavelengths for trial 10 -700 nm, 720 nm and 1380 nm- in the different trials spectral data provided crop/weed/soil and crop/weed species/soil average discriminations of 96.62% and 87.88%, Table 6.6. A perfect general discrimination was achieved in trials 5 and 8 and a minimum value of 90.9 % obtained in trial 2. Maximum and minimum weed species discrimination of 96.9% and 78.78% were obtained in trials 8 and 11, respectively.

In trial 11 the best wavelengths were 790 nm, 1040 nm and 1380 nm and when applied in program runs for trials 1, 5, 8 and 10 provided 100% general discrimination. The lowest general success rate was 90.9% in trial 2, Table 6.4. Highest and minimum weed species discriminations were encountered in trials 8 and 5 (young) with success rates of 90.9% and 80%, respectively. Table 6.6 shows the average crop/weed/soil and crop/weed species/soil discriminations with values of 98.56% and 86.93%.

Table 6.4 **Broccoli/Weed/Soil discrimination accuracies from each trial using the best three wavelengths obtained in each of the other trials with the same crop.**

Spectral data	Success rates (%) using the best three wavelengths in								
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL		TRIAL 8		TRIAL 10	TRIAL 11
				Young	Mature	Soil	Hay		
TRIAL 1		92.85	90.47	100	83.3	85.71	85.71	95.24	100
TRIAL 2	100		96.9	96.9	96.9	96.96	84.8	90.9	90.9
TRIAL 3	95.24	100		97.6	100	100	95.24	92.85	97.6
TRIAL 5 Young	80	100	100		100	100	100	100	100
TRIAL 5 Mature	84.4	100	97.7	100		97.7	100	100	100
TRIAL 8 Soil	100	100	100	100	100		100	100	100
TRIAL 8 Hay	100	100	100	100	100	100		100	100
TRIAL 10	90.9	100	100	100	100	100	100		100
TRIAL 11	90.9	81.81	81.81	93.9	84.8	87.87	93.93	93.93	

Wavelengths (nm)									
	1000	700	720	720	720	710	680	700	790
	1040	720	960	1060	760	740	1380	720	1040
	1640	1460	1420	1380	1040	890	1480	1380	1380

Table 6.5 **Broccoli/Weed species/Soil discrimination accuracies from each trial using the best three wavelengths obtained in each of the other trials with the same crop.**

Spectral data	Success rates (%) using the best three wavelengths in								
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 5		TRIAL 8		TRIAL 10	TRIAL 11
				Young	Mature	Soil	Hay		
TRIAL 1		69.05	69.04	85.71	61.9	64.29	78.57	83.3	83.3
TRIAL 2	100		96.9	96.9	96.9	96.96	78.7	90.9	90.9
TRIAL 3	90.47	95.24		97.6	90.48	95.3	90.48	88.09	83.3
TRIAL 5 Young	55.5	82.2	91.1		84.4	73.3	68.8	84.4	80
TRIAL 5 Mature	64.4	82.2	86.6	84.4		73.3	66.6	84.4	82.2
TRIAL 8 Soil	87.87	96.96	93.3	90.9	93.93		90.9	96.6	90.9
TRIAL 8 Hay	87.8	96.96	93.3	90.9	90.9	87.87		96.9	90.9
TRIAL 10	81.8	93.93	90.9	93.9	90.9	96.96	84.8		93.9
TRIAL 11	84.84	78.78	75.75	90.9	81.81	87.87	87.8	78.78	

Wavelengths (nm)									
	1000 1040 1640	700 720 1460	720 960 1420	720 1060 1380	720 760 1040	710 740 890	680 1380 1480	700 720 1380	790 1040 1380

Table 6.6 **Broccoli relationships between crop/weed/soil and crop/weed species/soil discrimination for all the sites using the best three wavelengths encountered in each site.**

	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 5		TRIAL 8		TRIAL 10	TRIAL 11
				Young	Mature	Soil	Hay		
AVERAGE % C / W / S	92.68	96.83	95.86	98.55	95.63	96.03	94.96	96.62	98.56
AVERAGE % C / Ws / S	81.59	86.92	87.11	91.4	86.4	84.48	80.83	87.88	86.93
$\frac{\%\ C / Ws / S}{\%\ C / W / S}$	88.03	89.76	90.87	92.74	90.35	87.97	85.12	90.95	88.20
$\frac{Avg\ \%\ C / W / S\ -\ avg\ \%\ C / Ws / S}{Avg\ \%\ C / W / S\ +\ avg\ \%\ C / Ws / S}$	6.36	5.39	4.78	3.76	5.07	6.40	8.04	7.74	6.27
$\sqrt{(\%\ C/W/S^2\ +\ \%\ C/Ws/S^2)}$	123.48	130.12	129.53	134.41	128.88	127.90	124.70	130.61	131.42
$\frac{Avg\ \%\ C / W / S + avg\ \%\ C / Ws / S}{2}$	87.13	91.87	91.48	94.97	91.01	90.25	87.89	92.25	92.74
$\frac{(\%\ C /W /S + \%\ C /Ws /S)}{2}\ (\%\ C/W/S)$	80.76	88.96	87.70	93.60	87.04	86.67	83.46	89.13	91.41
WAVELENGTHS (nm)	1000 1040 1640	700 720 1460	720 960 1420	720 1060 1380	720 760 1040	710 740 890	680 1380 1480	700 720 1380	790 1040 1380

% C / W /S % Crop/Weed/Soil
% C / Ws / S % Crop/Weed species/Soil

The selection of the desired wavelengths used the same algorithms mentioned in section 5.5.1. The square root of the sum of the general and specific average discriminations provided the best choice for selection. The weighted average of both discriminations provided also similar results. The wavelengths selected for application are:

a. 720 nm, 1060 nm and 1380 nm, due to the highest general and specific discriminations and minimum multiratio value (3.76);

b. 710 nm, 740 nm and 890 nm due to the low wavelengths required.

The best wavelengths of trial 11 -790 nm, 1040 nm and 1380 nm- were not considered as the two higher wavelengths are similar to the ones selected in point **a**. Additional tests to point **a** could be carried with a filter at 790 nm. The wavelengths selected in point **b.** corresponded to the best wavelengths for trial 8 (soil) and were selected due to their low wavelength values. However, the results obtained are not as good as the results obtained with the best wavelengths for trial 5 (mature).

6.1.3 LEEK

The discriminant analysis results of trials 4, 5 and 7 are shown in Table 6.7 and Table 6.8 using the best three wavelengths for trial 3 -720 nm, 1080 nm and 1380 nm. Highest 100% and lowest 93.93% general discriminations were achieved in trials 7 and 4. Minimum and maximium weed species discriminations of 77.7% and 87.87% were achieved in trials 5 and 4. The crop/weed/soil and crop/weed species/soil average discriminations shown in Table 6.9 were 97.21% and 81.73%, respectively.

Crop/weed/soil and crop/weed species/soil average discriminations of 97.65% and 84.31% were obtained after running all the trials with the best wavelengths for trial 4: 680 nm, 1080 nm and 1520 nm. Trial 7 achieved the highest success rates of 100% and 93.75% in general and specific discriminations. The lowest general and specific discriminations were 95.24% and 84.31% in trials 3 and 5, respectively.

Table 6.7 Leek/Weed/Soil discrimination accuracies from each trial using the best three wavelengths obtained in each of the other trials with the same crop.

Spectral data	Success rates (%) using the best three wavelengths in			
	TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
TRIAL 3		95.24	97.61	85.71
TRIAL 4	93.93		100	93.93
TRIAL 5	97.7	97.7		97.7
TRIAL 7	100	100	95.83	

Table 6.8 Leek/Weed species/Soil discrimination accuracies from each trial using the best three wavelengths obtained in each of the other trials with the same crop.

Spectral data	Success rates (%) using the best three wavelengths in			
	TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
TRIAL 3		88.09	95.24	76.19
TRIAL 4	87.87		96.96	87.87
TRIAL 5	77.7	71.1		73.3
TRIAL 7	79.6	93.75	87.5	

Table 6.9 Leek relationships between Crop/Weed/Soil and Crop/Weed species/Soil discrimination accuracies for all the sites using the best three wavelengths encountered in each site.

	TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Average % C/W/S	97.21	97.65	97.81	92.44
Average % C/Ws/S	81.73	84.31	93.16	79.12
$\frac{\%\ C/Ws/S}{\%\ C/W/S}$	84.07	86.35	95.25	85.58
$\frac{\text{Avg \% C/W/S - avg \% C/Ws/S}}{\text{Avg \% C/W/S + avg \% C/Ws/S}}$	8.65	7.32	2.43	7.77
$\sqrt{(\%\ C/W/S^2 + \%\ C/Ws/S^2)}$	126.99	129.01	135.08	121.68
$\frac{\text{Avg \% C/W/S + avg \% C/Ws/S}}{2}$	89.47	90.98	95.49	85.78
$\frac{(\%\ C/W/S + \%\ C/Ws/S)}{2}(\%\ C/W/S)$	76.12	76.71	88.96	67.87
Wavelengths (nm)	720, 1080, 1380	680, 1080, 1520	760, 1340, 1480	710, 730 1040

Crop/weed/soil and crop/weed species/soil average discriminations of 97.81% and 93.16% were obtained with the best wavelengths selected of trial 5. The use of these wavelengths (760 nm, 1380 nm and 1480 nm) in trials 4 and 7 provided the best and worst general discriminations with values of 100% and 95.83%, Table 6.7. The same trials also provided the extreme values in weed species discrimination with success rates of 96.96% and 87.50%, respectively.

The best wavelengths for trial 7 were 710 nm, 770 nm and 1040 nm. Crop/weed/soil discriminations obtained with these wavelengths in the different trials failed to classify perfectly the three major groups and the highest and lowest values obtained were of 97.7% and 85.71% in trials 5 and 4, respectively. The lowest weed species discrimination was obtained in trial 5 with a value of 73.3%, while the highest success rate of 87.87% was achieved in trial 4. Crop/weed/soil and crop/weed species/soil discriminations from each trial were averaged resulting in 92.4% and 79.12% accuracies, Table 6.9.

Looking at the general and specific average discriminations in Table 5.33 indicates clearly the best wavelength set. The selection based on the square root, weighted average and multiratio algorithms was:

a. 760 nm, 1340 nm and 1480 nm due to the best general and specific discriminations, and

b. 680 nm, 1080 nm and 1520 nm due to the high crop/weed/soil discrimination and as the first two wavelengths were located in a lower part of the spectrum.

6.2 MULTIVARIATE ANALYSES AND DISCRIMINANT CLASSIFIERS

Statistical dependence and correlation are defined in terms of the probability distributions of the variables. Correlation, a common type of statistical dependence, shows the extent of dependence of one measurement upon the magnitude of the second measurement (Finney, 1962).

Regression analysis provides information on the interrelations between two or more variables, one being the dependent variable and the others the independent variables. The degree of association between the variables is generally represented by the correlation coefficient (r^2).

Several independent variables can be used to predict or estimate the values of a dependent variable. The extent of correlation between several variables can be expressed by multiple correlation coefficients. A multiple regression equation can then be found to relate all the independent variables with a dependent one.

New techniques including principal component analysis, canonical correlation and discriminant analysis were introduced to aid in multivariate analysis when computer programs were able to carry out laborious calculations.

Principal component analysis, useful for one group multivariable analysis, tends to describe the shape of a multivariate distribution by considering selected linear combinations of the independent variables instead of the variables themselves (Bofinger, 1975). The sum of the eigenvalues obtained during the analysis corresponds to the sum of the variances of the independent variables, and their proper interpretation provide successful conclusions. Eigenvalues will determine the components of practical importance for a given data set, and four or five components should account for at least 75% of the variance. In practice it has been found useful to consider those components having eigenvalues greater than unity, and possibly one or two components having eigenvalues ranging between 0.75 and unity (Howard, 1991). Components with eigenvalues lower than unity will account for a smaller proportion of variance than each of the variables separately will achieve.

Principal component analysis can be used together with regression analysis, reducing the number of dependent variables to an optimum and achieving larger correlation coefficients (r^2). Principal component analysis can also be used to examine the possibility of classifying data in groups. The data clustered in each group should be close together, but far apart from the data of other groups.

Canonical correlation analysis searches for the linear functions of two sets of variables which are most closely related (Bofinger, 1975). With one dependent variable, only one canonical correlation will be obtained and the single correlation coefficient squared will be the square of the multiple correlation coefficient. The canonical correlation analysis uses the principal component analysis plus the correlation matrix of the dependent variables. This analysis is used as an aid for multivariate regression prediction analysis in data clustered in a single group.

Discriminant analysis is used with multivariables contained in several groups. The variable distribution in each group population should be known in order to be able to classify any

future observation into the group it suits best. Multivariable discriminant analysis finds linear combinations between independent variables for optimum group discrimination. The analysis calculates the ratio of variance between groups and the variance within groups (F ratio) to determine the best discriminants. The eigenvalues and associated eigenvector weights provide the coefficients for the linear function of the independent variables.

Discriminant analysis should be used with analysis of covariance to determine the associative properties between dependent and independent variables with data classified in groups.

6.2.1. DISCRIMINANT CROP/WEED/SOIL CLASSIFIER

Variable correlations and data groups are often unknown, and therefore should be analysed in order to assess the homogeneity of the data and the possibility of classifying them into groups. Multivariate classifiers contain two stages: the computing for sample matching for each group and the selection of the group with best matching. Data is sequentially entered and processed in order to measure how close the input resembles the most representative pattern of a given group. Probabilistic models are often used and indicate the probability that the input pattern is well classified into each group representative pattern.

The stepwise discriminant analysis so far used finds the subset of variables that maximize group differences. A classification function is obtained during the analysis and it classifies cases into groups. The classification matrix prints the inputs properly classified within the classification function equations. The number of equations depends on the group number and the number of terms on the variables. A classification function can produce optimistic results when it is used to classify the same cases that were used to compute it. Nevertheless, it is expected that new cases can be properly classified into their respective groups.

The F_j variables or groups can be classified by j equations in the form of:

$$F_j = K_j + K_{j1}\lambda_1 + K_{j2}\lambda_2 + ... + K_{jm}\lambda_m \qquad \text{eq. 6.4}$$

where K_j is a constant unique to variable F_j, K_{jm} the gain coefficients for each factor λ, and m defines the factors number.

The discriminant analyses carried out for each trial classified crop, weed species and soil using three or more categories (Appendix D). Three groups were used when all the weed

species were grouped together. A variable quantity of groups was obtained for each trial according to the number of weed species present, plus one crop group and one soil group.

Three equations were required when the weed species were grouped together with the number of factors related to the number of wavelengths used. Two sets of three wavelengths each were selected per crop in chapter 5, and the crop, weed and soil equations are:

$$\text{Crop} = K_c + K_{c1}\lambda_1 + K_{c2}\lambda_2 + K_{c3}\lambda_3; \qquad \text{eq. 6.5}$$

$$\text{Weed} = K_w + K_{w1}\lambda_1 + K_{w2}\lambda_2 + K_{w3}\lambda_3; \qquad \text{eq. 6.6}$$

$$\text{Soil} = K_s + K_{s1}\lambda_1 + K_{s2}\lambda_2 + K_{s3}\lambda_3. \qquad \text{eq. 6.7}$$

Discriminant analysis provides the values of the coefficients K_{c1},....,K_{s3} and K_c,..,K_s. Each case (plant or soil) will present three input data corresponding to wavelengths λ_1, λ_2 and λ_3. Data are introduced to the equations and the case is allocated into the category which achieves the highest value.

Discrimination accuracies from six cabbage trials, six broccoli trials and four leek trials were calculated and compared after classifying all the weeds in one group or by species. In some program runs only two of the three wavelengths were recognized and employed during the analysis. The third wavelength was not taken into account as the variance between the group means was very small, and nil discriminant properties were noted.

The discriminant analysis carried out for each trial provided the classification function coefficients (K_{c1}.....K_{s3} and k_c..K_s). Table 6.10 shows a total of twelve coefficients obtained for each cabbage trial using 680 nm, 1060 nm and 1360 nm as wavelengths. The subscript numbers in the equations are replaced by the wavelength values in order to correlate them easily. It is apparent from Table 6.10. that there are large constant differences encountered between trials. The tables containing the different coefficients for the three crops are shown in appendix E (tables E.1. to E.8.).

Table 6.10 Classification function coefficients for different cabbage trials obtained from programs using 680 nm, 1060 nm and 1360 nm.

Cabbage/ weed/soil	Coefficient name	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Cabbage	Kc-680	5.2188	0.6820	1.1599	0.1748	-0.4584	1.2004
	Kc-1060	1.9025	2.9887	0.7824	0.0716	10.3753	2.5917
	Kc-1360	-0.2500	-3.9936	0.3925	--	-15.4683	-3.2147
	Kc	-64.0383	-51.3986	-25.816	-2.5908	-98.8136	-26.9273
Weed	Kw-680	1.2590	0.1089	-0.3104	0.1385	1.2460	0.0453
	Kw-1060	-0.4270	0.3902	-1.6472	0.1099	0.1747	0.4070
	Kw-1360	3.0496	-0.3758	5.4862	--	0.5196	0.5291
	Kw	-24.9449	-4.8623	-27.3151	-3.9650	-11.6270	-13.9260
Soil	Ks-680	1.0065	0.6364	1.1472	2.3370	2.8982	2.1092
	Ks-1060	-4.9326	-0.9076	-3.9329	-0.1764	-8.0243	-2.2798
	Ks-1360	11.0437	1.2479	9.0727	--	13.3391	4.0548
	Ks	-64.0350	-7.4631	-44.0623	-8.3208	-67.5731	-25.3491

Table 6.11 Cabbage coefficient comparison from programs runs grouping the weeds together or by species in various cabbage trials using 680 nm, 1060 nm and 1360 nm as wavelengths.

Cabbage coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Kc-680	All	5.2188	0.6820	1.1599	0.1748	-0.4584	1.2004
	Species	5.0071	0.7497	3.0284	1.2595	12.7295	4.9565
Kc-1060	All	1.9025	2.9887	0.7824	0.0716	10.3753	2.5917
	Species	7.3939	5.1040	5.2136	4.4203	7.1511	11.2021
Kc-1360	All	-0.2500	-3.9936	0.3925	--	-15.4683	-3.2147
	Species	1.2997	-1.6439	-0.5159	10.4128	-12.3244	-12.1494
Kc	All	-64.0383	-51.3986	-25.816	-2.5908	-98.8136	-26.9273
	Species	-212.814	-162.747	-116.161	-191.956	-405.156	-130.425

Table 6.12 Average and standard deviation of the coefficients used in all the cabbage trials.

Cabbage/ weed/soil	Coefficient name	Classification function av. coefficients and standard deviations			
		Average †	Std deviation †	Average ‡	Std deviation ‡
Cabbage	Kc1	1.4631	1.8957	1.5605	1.9246
	Kc2	0.0179	1.6201	3.7281	3.4068
	Kc3	1.0698	1.8588	-4.5068	5.7308
	Kc	-33.6462	18.0994	-53.3988	26.9861
Weed	Kw1	2.3344	1.1011	1.5595	0.8273
	Kw2	-1.8687	1.3445	-4.0154	2.4327
	Kw3	2.2457	1.4505	7.7516	4.4669
	Kw	-17.9597	6.9321	-41.6965	22.8621
Soil	Ks1	0.6186	0.7061	0.4698	0.6549
	Ks2	0.6928	1.7035	-0.2205	0.7747
	Ks3	0.0981	1.5363	1.8417	2.1508
	Ks	-16.4812	8.1208	-16.5351	8.4153

† for wavelengths: 680 nm, 760 nm and 1040 nm ‡ for wavelengths 680 nm, 1060 nm and 1360 nm.

Table 6.13 Average and standard deviation of the coefficients used in all the broccoli trials.

Cabbage/ weed/soil	Coefficient name	Classification function av. coefficients and standard deviations			
		Average †	Std deviation †	Average ‡	Std deviation ‡
Broccoli	Kc1	0.0032	0.7075	0.5699	1.6689
	Kc2	1.3234	0.0856	-0.6613	1.9929
	Kc3	-1.1905	1.7220	0.9122	1.3355
	Kc	-21.9100	3.6298	-19.1373	9.8786
Weed	Kw1	-1.1356	1.7833	0.8714	0.5526
	Kw2	-0.6934	0.2545	-1.9771	0.6211
	Kw3	4.4000	5.6229	1.6468	0.5048
	Kw	-28.8848	40.4144	-5.5706	1.6334
Soil	Ks1	-0.0853	0.6314	0.3042	0.4781
	Ks2	0.2968	0.1587	-0.0646	0.8102
	Ks3	0.5009	2.0557	0.4204	0.6614
	Ks	-9.8323	4.9858	-11.1440	2.8825

† for wavelengths: 720 nm, 1060 nm and 1380 nm ‡ for wavelengths: 710 nm, 740 nm and 890 nm.

Table 6.14 Average and standard deviation of the coefficients used in all the leek trials.

Leek/ weed/soil	Coefficient name	Classification function av. coefficients and standard deviations			
		Average †	Std deviation †	Average ‡	Std deviation ‡
Leek	Kc1	0.2353	0.8953	0.0123	0.9061
	Kc2	0.5934	0.1641	-0.3762	1.1532
	Kc3	0.5223	0.9058	2.1147	1.9499
	Kc	-28.0979	14.5024	-34.2453	10.3688
Weed	Kw1	0.9411	0.4507	-2.1373	1.5250
	Kw2	-0.4837	0.1746	2.4580	2.0681
	Kw3	1.0834	0.5141	1.9797	1.2855
	Kw	-10.5819	5.2218	-22.4696	11.9188
Soil	Ks1	-0.3248	0.4706	0.4306	0.6254
	Ks2	-0.1572	0.1102	-0.0603	1.5811
	Ks3	1.4299	1.0915	2.2230	1.3762
	Ks	-16.0885	10.7832	-20.7582	10.5974

† for 680 nm, 1080 nm and 1520 nm; ‡ for 760 nm, 1340 nm and 1480 nm.

Table 6.15 Best discriminant wavelength and discrimination accuracies achieved for each trial.

Crop	Wavelen-gth(nm)	Best wavelength (nm) and discrimination accuracies (%) in trial :									
		2	3	4	5 ‡	6	7	8	9 †	10	11
Cabbage	680,1060	680	680	1060		1060	1060		680		
	1360	100	100	100		60	100		100		
	680,760,	760	760	760		760	1040		680		
	1040	97.2	95.2	94.4		60	88.8		91.6		
Broccoli	720,1060	1060	720		720			720		1380	720
	1380	96.9	95.2		95.5			78.7		100	93.9
	710,740,	890	740		710			710		710	740
	890	87.8	69.1		88.8			96.9		93.9	78.7
Leek	680,1080		1080	1080	680		680				
	1520		90.4	90.9	95.5		97.9				
	760,1340		760	760	1480		1340				
	1480		100	87.8	91.1		83.3				

† for spring cabbage; ‡ for mature broccoli.

Table 6.11. summarizes the four constants used to calculate the cabbage crop equation when the weed species are classified individually or in one group using the wavelengths at 680 nm, 1060 nm and 1380 nm as variables. Large differences in the values of K are encountered between both grouping methods. Similar tables are encountered in appendix F for the three crops coefficients and for their soil coefficients using the best two wavelength sets for each crop (tables F.9. to F.20.). Weed coefficients were not compared as each weed species group presented a particular set of coefficients.

The coefficient from each crop trial were averaged and standard deviations calculated. Tables 6.12, 6.13 and 6.14 shows the average coefficients for cabbage, broccoli and leek together with their respective weed and soil coefficients.

Cabbage trial results using the wavelength set of 680 nm, 1060 nm and 1360 nm can be summarized as follows:

100% discrimination accuracy in the six trials when the weeds were grouped by species, Table 6.16;

lower discrimination accuracy in trials 6 and 9 with all the weeds grouped together and an average 92.41% cabbage/weed/soil discrimination accuracy;

discrimination accuracies non-dependent on best discriminant wavelength (or wavelength selection order), Table 6.15;

best discriminant wavelength at 1060 nm in trials 2, 3 and 9 corresponding to savoy, autumn and spring cabbage, respectively, Table 6.15;

best discriminant wavelength at 680 nm in autumn cabbage (trials 4, 6 and 7), Table 6.15;

lowest main eigenvalue and eigenvalue difference (Table E.21) in trial 6, related to minimum success rate;

highest dispersion of the cabbage coefficients than their weed or soil coefficients (Table 6.12).

The results from the cabbage trial analyses using the 680 nm, 760 nm and 1040 nm wavelengths set were as follows:

lower discrimination accuracies with all the weeds grouped together than with the previous subset of wavelengths, having an average discrimination accuracy of 85.91%;

maximum 97.22% crop/weed/soil discrimination accuracy in trial 2 with savoy cabbage, and minimum (60%) in trial 6 with autumn cabbage, where 1040 nm was rejected by the discriminant analysis, Table 6.16;

highest cabbage/weed/soil discrimination accuracies in trials having in 760 nm the main discriminant wavelength, Table 6.15;

misclassification of *S. vulgaris* in trial 4, *C. album* in trial 6 and *A.patula* in trial 9;

reduced eigenvalue differences (Table E.21) in comparison with the previous wavelength set;

smallest main or first eigenvalue in trial 6 related to lowest discriminant accuracy, Table E.21;

lower dispersion of cabbage coefficients with this wavelength set, although still higher than soil and weed coefficients dispersion, Table 6.12.

The effect of cabbage varieties can be reflected in the higher dispersion achieved by cabbage coefficients.

Crop/weed/soil discriminant analysis was carried out with each of the three different cabbage varieties having the same weed species population and soil samples. The two best wavelength sets previously used for the other cabbage trials achieved highest crop/weed/soil discrimination

Table 6.16 **Crop/Weed/Soil (C/W/S) and Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for different cabbage trials using the best two sets of wavelengths after introducing the weed data as one group or in different weed species groups.**

Wave-length (nm)	Weed class. type	Discr. type	Discrimination accuracies (%)					
			TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
680	All	C/W/S	100	100	100	60	100	94.44
1060	Species	C/W/S	100	100	100	100	100	100
1360		C/Ws/S	77.78	88.09	83.33	96.67	72.22	83.33
680	All	C/W/S	97.22	95.24	94.44	60	88.88	91.66
760	Species	C/W/S	100	100	97.22	86.66	100	97.22
1040		C/Ws/S	97.22	90.48	97.22	80	91.66	83.33

C/W/S Crop/Weed/Soil discrimination
C/Ws/S Crop/Weed species/Soil discrimination

Table 6.17 **Crop/Weed/Soil (C/W/S) and Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for different broccoli trials using the best two sets of wavelengths after introducing the weed data as one group or in different weed species groups.**

Wave-length (nm)	Weed class. type	Discr. type	Discrimination accuracies (%)					
			TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
720	All	C/W/S	96.97	95.24	95.55	78.78	100	93.93
1060	Species	C/W/S	96.97	97.62	100	100	100	93.93
1380		C/Ws/S	96.97	97.62	84.44	90.91	93.93	90.91
710	All	C/W/S	87.87	69.05	88.88	96.97	93.93	78.78
740	Species	C/W/S	96.97	100	97.77	100	100	87.87
890		C/Ws/S	96.97	95.23	73.33	90.91	96.96	87.87

C/W/S Crop/Weed/Soil discrimination
C/Ws/S Crop/Weed species/Soil discrimination

Table 6.18 **Crop/Weed/Soil (C/W/S) and Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for different leek trials using the best two sets of wavelengths after introducing the weed data as one group or in different weed species groups.**

Wave-length (nm)	Weed class. type	Discr. type	Discrimination accuracies (%)			
			TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
680	All	C/W/S	90.48	90.91	95.55	97.92
1080	Species	C/W/S	95.24	100	97.7	100
1520		C/Ws/S	88.09	93.94	71.11	93.75
760	All	C/W/S	100	87.87	91.11	83.33
1340	Species	C/W/S	97.62	100	100	95.83
1480		C/Ws/S	95.24	96.96	86.66	87.5

C/W/S Crop/Weed/Soil discrimination
C/Ws/S Crop/Weed species/Soil discrimination

Table 6.19 **Crop/Weed/Soil (C/W/S) and Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for different leek trials using the best two sets of wavelengths after introducing the weed data as one group or in different weed species groups.**

Wave-length (nm)	Weed class. type	Discr. type	Discrimination accuracies (%)		
			SPRING	AUTUMN	SAVOY
680	All	C/W/S	91.66	88.88	94.44
760	Species	C/W/S	97.22	91.66	100
1040		C/Ws/S	83.33	77.77	83.33
680	All	C/W/S	94.44	91.66	94.44
1060	Species	C/W/S	100	88.88	97.22
1360		C/Ws/S	83.33	75	83.33

C/W/S Crop/Weed/Soil discrimination
C/Ws/S Crop/Weed species/Soil discrimination

accuracies when the weeds were grouped by species, Table 6.19. When the weeds were all classified together, highest discrimination accuracies were achieved with the wavelength set of 680 nm, 1060 nm and 1360 nm. *A. patula* was misclassified with spring cabbage while *S. vulgaris* presented problems with autumn and savoy cabbage.

It should be noted that the discrimination accuracy in trial 6 for both wavelength sets decreased to 60% when all the weeds were grouped together.

Broccoli trials were analysed and the use of wavelengths at 710 nm, 740 nm and 890 nm provided the following results:

high discrimination accuracies in all the trials (with exception of trial 11) resulting in a 97.1% average crop/weed/soil discrimination accuracy for weeds grouped by species, Table 6.17;

reduction of discrimination accuracy in trials 3 and 11 as a result of using two wavelengths only;

reduction in the crop/weed/soil discrimination accuracy to 85.91% after averaging all the trials with all the weeds grouped together, Table 6.17;

highest broccoli/weed/soil discrimination in those trials having 710 nm as main discriminant wavelength, Table 6.15;

S. media misclassification in trial 5 and *S. vulgaris* in trials 2 and 11;

lowest main eigenvalues at trials 3 and 11 (Table E.22) corresponded to poor discrimination accuracies;

higher dispersion on broccoli coefficients than with soil and weed coefficients, table 6.13.

The results achieved in the broccoli trials with the wavelength set of 720 nm, 1060 nm and 1380 nm were as follows:

high success rates in all the trials and a 98.09% average crop/weed/soil discriminative accuracy with weeds classified by species, Table 6.17;

grouping the weeds together provided higher discrimination efficiencies in most of the trials and a success rate of 93.41% after averaging all the trials;

use of only two wavelengths in trials 8 and 10 during discriminant analysis decreasing the discrimination accuracy in the former;

maximum discriminative accuracy in trial 10 with 1380 nm as main discriminant wavelength, Table 6.15;

E. angustifolium was misclassified in trial 3 and *S. vulgaris* in trials 2 and 11;

lowest discriminative accuracy coincides with smallest main eigenvalue in trial 8, Table E.22;

Higher dispersion in weed coefficients than in broccoli and soil coefficients, table 6.13;

lower dispersion in broccoli coefficients with this wavelength set, table 6.13.

Discriminant analysis results in leek trials using 680 nm, 1080 nm and 1520 nm as wavelengths showed:

high success rates in each trial and a 98.24% average discriminative accuracy with the weeds grouped by species, Table 6.18;

reduced discrimination accuracy in all the trials grouping the weeds together and an average 93.72% crop/weed/soil discriminative accuracy, Table 6.18;

reduced crop/weed species/soil discrimination accuracy of 71.11% in trial 5 due to discrimination with only two wavelengths, 680 nm and 1080 nm;

best discrimination accuracies in trials having in 680 nm the main discriminant wavelength (trials 5 and 7);

E. angustifolium and *S. media* misclassified in trials 3 and 5, respectively;

the lowest main eigenvalue achieved the maximum discriminant accuracy, Table E.23;

higher dispersion in leek coefficients than in soil and weed coefficients, Table 6.14.

The analysis of the leek trials using 760 nm, 1340 nm and 1480 nm as wavelength set showed:

a 90.58% average crop/weed/soil discrimination accuracy grouping all the weeds together, and a 98.36% success rate for weed classified by species;

best discrimination accuracy achieved in trial 3 (Table 6.18) with all the weeds grouped together and with 760 nm as main discriminant wavelength;

discriminant wavelength selection uncorrelated with discrimination accuracy;

S. media and *T. officinale* misclassification in trials 3 and 7, respectively;

trials 5 and 7 with the highest discriminant accuracies presented the lowest main eigenvalues and eigenvalue differences, Table E.23;

similar dispersion in leek, weed and soil coefficients, Table 6.14;

lower dispersion in leek coefficients with this set of wavelengths, Table 6.14.

6.3 NEURAL NETWORK CLASSIFIERS

Neural networks have become a powerful tool for predicting and correlating variables. It's power is especially due to:

experience-based learning;
generalization;
graceful degradation;
fault tolerance.

Supervised, unsupervised and re-enforcement teaching algorithms allow the network to learn. Supervised **experience-based learning** iteratively adjusts the network to produce the desired output from training input data and is usually used in networks with well known input and

output data. Unsupervised learning is used to classify data when nothing is known about it. This type of learning tries to classify the data into groups set before training and which represent the desired output neurons in the net. Input data is available during re-enforcement learning, having a critical guidance which evaluates the quality of the output.

Neural networks have the ability to **generalise**, giving the correct response to inputs not included in the training set and to extract the central tendency in event of contradictory and noisy inputs (Deck et al., 1991). Network performance decay due to noisy or contradictory training causes **graceful degradation**. Neural networks are insensitive to unit and weight deficiencies (**fault tolerance**) as the information distributed throughout the net has parallel processing characteristics.

Neural networks contain many simple nonlinear computational elements operating in parallel and two elements form the network, the node and its connections. The node, presenting only one output is a processing element similar to the biological neuron and can be connected to several different nodes, using the incoming values to calculate the output based on a threshold. The connections join the node's inputs and outputs presenting a weight capable of modifying the signal traversing it. Learning is achieved by modifying these weights in order to produce a desired output. Network nodes are often organized in groups called layers and two are always present: the input and output layers. The former acquires the information entering the network while the latter transmits the network response. The number of inputs and outputs will depend on the given application. Hidden layers can be found between input and output layers, helping to interconnect them by adding nonlinearity to the mapping.

Neural network nodes generally use the sigmoidal function shown in equations 6.8 and 6.9 , where W_{ij} is the connection weight to the node ,i, in previous layer, θ the bias of the node and O_i is the output from node ,i, in previous layer.

$$f(NET) = 1 / (1 + \exp(-NET)) \qquad \text{eq. 6.8}$$

$$NET = \Sigma O_i * W_{ij} + \theta_i \qquad \text{eq. 6.9}$$

Many other differentiable functions could be used, but the sigmoidal function has the advantage of having a simple derivative and providing a form of automatic gain control. For small signals (NET close to zero) the slope of the input/output curve is steep, producing high gain. The gain decreases as the input increases. This gain control allows the network to

handle large signals without saturation and small signals without excessive attenuation.(Wasserman, 1989).

6.3.1 NEURAL NETWORK APPLICATIONS IN AGRICULTURE

Several applications of neural networks in agriculture have been quoted recently in the literature. Thai (1992) used neural networks to encounter colour differences in the development of two varieties of tomatoes when they change colour from green to red. A Backward-Error-Propagation (BEP) network was employed using 32 input nodes, one of which was the storage temperature and the remaining were reflectance measurements (thirty one wavelengths 10 nm apart in the 400-700 nm waveband). The three outputs corresponded to the constant hue angles for the green and red states and the hue change rate dependent on the storage temperature. Prediction of subsequent rate of colour change seemed possible for only one variety. It was noted that the most important input nodes in the BEP networks presented the highest amplitudes weights.

Murase et al.,(1991) reported the use of neural networks in the growth of radish sprouts in Japan. Radish sprouts growth rate is dependent upon the temperature, the nutrient solution concentration and its growth stage. The network was trained using as inputs the ambient temperature, nutrient concentration (evaluated by electrical conductivity) and time after seeding. The outputs were the rate of growth and the weight of an averaged single sprout. A Kalman filter based neural network provided better results than the BEP algorithm.

Deck et al. (1991) used neural networks to study potato greening caused by sun burn. Normalized hue histograms were obtained from a vision system and used for training with a backpropagation program. The output indicated whether the potato was good or green. A highest 95% green/healthy potato discrimination was achieved with neural network compared with the 90% obtained with conventional linear discriminant method. Deck et al., considers that neural networks outscores the linear discriminant method as the latter assumes incorrect input data, while the neural networks makes no assumptions about the observation vectors.

Bochereau et al., (1992) used a combination of principal components analysis and neural networks to predict apple quality using near infrared spectra. The principal component was first applied to reduce the number of input variables and a multilayer trained the system finally. A total of 350 wavelengths ranging between 1100 nm and 2500 nm were used and were correlated to the refractrometric index (RI) from the juice. To reduce the number of wavelengths used, only the spectral zones related to glucose were considered reducing the

number of variables to 72. Seventeen wavelengths could account for all the samples variance and were selected using principal component analysis. A linear predictor for the refractometric index was then obtained using ten wavelengths with multivariate regression. A backpropagation learning technique was applied to the seventeen variables. The unique output was the refractometric index. Nevertheless, the improvements over the linear model were not significant, and the best performance was obtained by adding an extra hidden layer.

Liu et al. (1992) studied the feasibility of using neural networks for calibration of a soil organic matter sensor in order to overcome nonlinearities, coupling, noise and environmental factors. The input data consisted of soil moisture, soil texture and the reflectance of the soil sensor. The output was the soil organic matter. Supervised training was used to develop the model and the propagation function was used to test the system. The neural network overall accuracy was 94%. The size of the sample data and the methods to represent data are critical for the calibration model.

6.3.2 NEURAL NETWORKS FOR CROP/WEED/DISCRIMINATION

Neural networks were trained to predict crops from weeds and vice versa, using as the network input variables the reflectance of three selected wavelengths. The training data consisted of three inputs, corresponding to the reflectance of the discriminant wavelengths so far selected

Table 6.20 Data sets used to train the neural network for each trial and then to test its performance.

Trial no.	Training and trial data					
	Cabbage		Broccoli		Leek	
	Training	Trial	Training	Trial	Training	Trial
Trial 2	44	120	41	110	--	--
Trial 3	63	140	63	140	63	140
Trial 4	44	120	--	--	41	110
Trial 5	--	--	63	150	63	150
Trial 6	41	100	--	--	--	--
Trial 7	44	120	--	--	76	160
Trial 8	--	--	41	110	--	--
Trial 9	44	120	--	--	--	--
Trial 10	--	--	41	110	--	--
Trial 11	--	--	41	110	--	--

plus a training output. The training output was a zero for weed and soil data and a one for crop data. The output of the network certified whether the sample was a crop or not. A stochastic back propagation algorithm was used to train the neural network using constant alpha and Lrate parameters of 0.9 and 0.1, respectively. The network was trained during 1000 epochs or until the average error measurement approached 0.001. The neural network topology presented three nodes in the input layer, two nodes in one hidden layer and one unique output node, Fig. 6.1. The added hidden neurons improve the predictions of linear regression analysis and it is possible to show that a linear multilayer neural network with one hidden layer corresponds to principal component analysis.

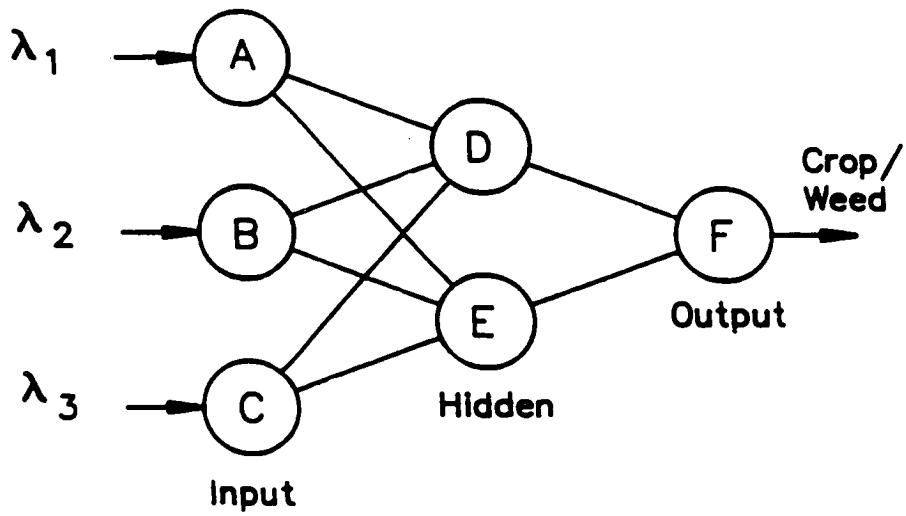

Fig. 6.1 Neural network topology used for crop/weed/soil discrimination.

Each trial group was studied individually during the first attempt. Each network was trained with 30-40% of the total trial data, Table 6.20. The number of crop and weed/soil data used for training had to be similar. As weed/soil data outnumbered crop data, only three data from every ten contained by each weed species were used for training. Crop data was then fixed to the multiple of ten closest to the weed/soil data set. For example, in cabbage trial 2 there were 120 spectra (see Table 5.4), 40 of which were cabbage spectra, 10 soil spectra and 70 weed

spectra (ten for each weed species). The total of 44 training data sets consisted of 24 weeds/soil data sets (three for each weed species plus three of soil) and 20 cabbage data sets for being the closest approximation to 24 as multiple of ten. The trial or test group consisted of the entire crop, weed and soil samples, that in the previous example numbered 120.

After training all the trials from each crop with the best two wavelength sets for each crop the following results were noted.

Best cabbage/weed-soil success rates were achieved with the 680 nm, 1060 nm, and 1360 nm wavelength set, presenting a maximum discrimination accuracy of 99.29% in trial 3, Table 6.21. The maximum 100% cabbage/weed-soil discrimination accuracy was achieved with the wavelength set of 680 nm, 760 nm and 1040 nm. Weed-soil samples presented better recognition than cabbage samples in most of the trials and with both set of wavelengths.

Best broccoli results were obtained having as training inputs the reflectances at 710 nm, 740 nm and 890 nm. A maximum broccoli/weed-soil discrimination of 97.33% was achieved in trial 5 and weed-soil recognition was still better than crop recognition for most of the trials, Table 6.22. The worst problems were encountered with trial 11, specially in recognizing broccoli as weed-soil recognition was 96.66%. The neural

Table 6.21 Crop/weed-soil discrimination accuracies for each cabbage trial using neural networks, and percentage of crop and weed-soil properly classified.

Wavelength set (nm)	Group discri-mination	Discrimination accuracy (%)					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
680,	Total	99.09	99.29	97.50	91	98.33	97.5
1060,	Crop	96.67	100	92.50	90	97.5	95
1360	Weed-soil	100	99.09	100	91.43	98.75	98.75
680,	Total	100	94.29	96.67	86	97.50	90
760,	Crop	100	100	90	90	97.50	70
1360	Weed-soil	100	92.73	100	84.29	97.50	100

Table 6.22 **Crop/weed-soil discrimination accuracies for each broccoli trial using neural networks, and percentage of crop and weed-soil properly classified.**

Wavelength set (nm)	Group discri-mination	Discrimination accuracy (%)					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
720,	Total	97.27	92.72	100	75.45	90.91	74.55
1060,	Crop	96.25	93.57	100	66.25	87.5	78.75
1380	Weed-soil	100	96.96	100	100	100	63.33
710,	Total	96.36	93.57	97.33	90.91	90	80
740,	Crop	96.25	99.09	100	87.50	86.25	73.75
890,	Weed-soil	96.66	73.33	90	100	100	96.66

Table 6.23 **Crop/weed-soil discrimination accuracies for each leek trial using neural networks, and percentage of crop and weed-soil properly classified.**

Wavelength set (nm)	Group discri-mination	Discrimination accuracy (%)			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
760,	Total	96.43	84.55	95.33	93.13
1340,	Crop	100	100	100	100
1480	Weed-soil	95.45	75.71	93.63	90.83
680,	Total	75	94.55	99.33	75.75
1080,	Crop	76.67	100	100	100
1520	Weed-soil	74.54	91.43	99.09	65

networks trained with reflectance data of 720 nm, 1060 nm and 1380 nm presented four nets that worked very well and two that could not learn at all (trials 8 and 11). Trial 11 presented the greatest difficulties as neither the crop or the weed-soil could be properly identified, and only with the use of a bigger training data set could better results be expected. In trial 8, although the crop subset was poorly identified, the weed-soil subset achieved a perfect recognition. Weed-soil recognition was better than crop recognition in most of these broccoli trials.

The best training wavelengths for leek resulted 760 nm, 1340 nm and 1480 nm with a maximum leek/weed-soil discrimination accuracy of 96.43% in trial 3, Table 6.23. A 100% leek recognition was achieved in each trial even in trial 4 having the minimum leek/weed-soil discrimination accuracy. Lower accuracies were found in the networks

trained with reflectance data from 680 nm, 1080 nm and 1520 nm. The highest 99.33% leek/weed-soil discrimination accuracy was achieved in trial 5, while networks from trials 3 and 7 presented difficulties in weed-soil recognition. Crop recognition was better than weed-soil recognition in the four trials.

6.4 COMPARISON OF DISCRIMINANT AND NEURAL NETWORK CLASSIFIERS

Discriminant analysis and neural networks discrimination accuracies from each trial were averaged and compared in Table 6.24. Neural networks worked better in cabbage for both wavelength sets, achieving a 97.12% average discrimination accuracy with the wavelength set of 680 nm, 1060 nm and 1360 nm. Neural networks accuracies trained with broccoli were higher using the lower wavelengths (710 nm, 740 nm and 890 nm), although the best 93.41% average discrimination was achieved with discriminant analysis using the 720 nm, 1060 nm and 1380 nm wavelength set. Leek best average discrimination corresponded to the discriminant analysis using the 680 nm, 1080 nm and 1520 nm wavelength set, although the best accuracies with neural networks was achieved with the 760 nm, 1340 nm and 1480 nm wavelength set.

The validation of this comparison should take into account that:

the trial group of the discriminant analysis is much smaller than the trial group of the neural network;

the training group of the neural network analysis is smaller than that of the discriminant analysis.

Once established that neural networks worked well in each trial, the possibility of creating a general algorithm using data from different trials was studied. This second attempt trained three different networks for cabbage and broccoli. Leek was not studied due to the reduced number of data available. Table 6.25 shows the data sets for training each net, and the trials from which the data was extracted. For easy understanding, the neural networks were numbered from 1 to 6 after the short name of the crop used, e.g. network cab1. The final error measurement obtained during training and the number of epochs required to achieve it are also mentioned in Table 6.25. The neural network final algorithms were tested against a known number of crop and weed-soil samples, Table 6.25. These samples were a collection of weed, soil and crop samples encountered in the trials.

Table 6.24 Average discrimination accuracies of all the trials for each crop using neural network and discriminant analysis.

Crop	Wavelength (nm)	Discrimination accuracy (%)			
		Discriminant analysis	Neural network analysis		
			Crop/Weed-Soil	Crop	Weed-Soil
Cabbage	680, 1060, 1360	92.41	97.12	95.28	98.00
	680, 760, 1040	87.91	94.08	91.25	95.75
Broccoli	720, 1060, 1380	93.41	88.48	87.05	93.38
	710, 740, 890	85.91	91.36	90.47	92.78
Leek	680, 1080, 1520	93.69	86.16	94.17	82.52
	760, 1340, 1480	90.58	92.36	100	88.91

Table 6.25 Principal characteristics used in the neural network analysis of each of the three crops.

Network number	Number of training data	Sites used to extract the training data	Number of epochs for training	Final error measure-ment	Total crop query data	Total weed-soil query data
Network cab1	121	3,7	537	0.00241	190	430
Network cab2	150	3,7,4	1000	0.00747	190	430
Network cab3	238	3,7,4,2,9	651	0.00851	190	430
Network bro4	104	5,2	1221	0.0266	140	370
Network bro5	167	5,2,3	1761	0.1126	140	370
Network bro6	210	5,2,3,10	811	0.0507	140	370

Table 6.26 Accuracy in classificating the crop group, the weed soil group and crop/weed-soil discrimination for each neural netork using all the data collected from the trials.

Network number	Classification accuracy (%)		
	Crop	Weed-soil	Crop/weed-soil
Network cab1	100	70	79.19
Network cab2	100	96.98	97.90
Network cab3	98.95	99.77	99.52
Network bro4	99.29	84.86	88.82
Network bro5	97.85	94.32	95.29
Network bro6	100	95.13	96.47

Crop recognition, weed-soil recognition and crop/weed-soil discrimination accuracies for each neural network are shown in Table 6.26, and in the six networks high crop recognition was noted. Weed-soil recognition and crop/weed-soil discrimination accuracy was poorer in networks cab1 and bro4, where only data from two trials was used. Best weed-soil recognition and crop/weed-soil recognition in cabbage trials was achieved with network cab3 having 99.77% and 99.52% success rates, respectively. Broccoli highest success rates of 95.13% and 96.47% in weed-soil recognition and crop/weed-soil discrimination accuracy were achieved with neural network bro6. Expected increase in crop/weed-soil discrimination resulted from training the network with data containing samples from different trials.

The third and final attempt was to test the neural network algorithms with a completely different data set. The data set was composed of 500 weeds, from 7 different species, 100 crop data and 50 soil data. The weed species involved were *C. album*, *S. media*, *E. repens*, *C. bursa-pastoris*, *S. arvensis*, *A. patula* and *F.officinale* which were encountered in late october in a field growing spring cabbage and broccoli. Neural network results for cabbage and broccoli are shown in Tables 6.27 and 6.28. Crop recognition, weed-soil recognition and crop/weed-soil discrimination accuracies achieved with the six networks are shown in Table 6.29. High crop recognition was achieved in each network, and best weed-soil recognition and crop/weed-soil discrimination accuracy was achieved in networks cab2 and bro6. Reduced discrmination in network 3 was correlated to a higher final error which could be reduced by further training. It is necessary to mention that *A.patula* was not recognized in any of the six networks. After looking at each of the reflectance averages it was found that *A. patula* maximum difference with cabbage was under 20% at 1360 nm and lower than 5% in

the other two wavelengths. In order to better recognize this weed more wavelengths may be required.

Table 6.27 Total number of samples well classified for each group during neural network analyses 1, 2 and 3 using a cabbage crop.

Crop/weed/soil	Total samples per group	Number of samples well classified by:		
		Network cab1	Network cab2	Network cab3
SPRING CABBAGE	100	100	99	100
C. Album	100	82	100	100
S. media	100	99	100	100
E. repens	100	97	99	93
C. bursa-pastoris	50	18	38	34
S. arvensis	50	49	50	50
A. patula	50	0	0	0
F. officinale	50	48	49	50
SOIL	50	50	50	50

Table 6.28 Total number of samples well classified for each group during neural network analyses 4, 5 and 6 using a broccoli crop.

Crop/weed/soil	Total samples per group	Number of samples well classified by:		
		Network bro4	Network bro5	Network bro6
BROCCOLI	100	100	100	100
C. Album	100	100	100	100
S. media	100	100	100	100
E. repens	100	100	100	100
C. bursa-pastoris	50	48	47	50
S. arvensis	50	50	50	50
A. patula	50	0	0	0
F. officinale	50	50	50	50
SOIL	50	50	50	50

Table 6.29 Crop and weed-soil recognition accuracy and crop/weed-soil discrimiation accuracy in the six neural network analyses.

Network number	Classification accuracy (%)		
	Crop	Weed-soil	Crop/weed-soil
Network cab1	100	80.55	83.54
Network cab2	99	88.36	90
Network cab3	100	86.72	88.76
Network bro4	100	90.55	92
Network bro5	100	90.36	91.85
Network bro6	100	90.91	92.31

Table 6.30 Total number of samples well classified by neural networks cab3 and bro6 and discriminant algorithms for cabbage and broccoli.

Crop/weed/soil	Total samples per group	Number of samples well classified by:			
		Network cab3	Discrimi-nant- cab	Network bro6	Discrimi-nant-bro
CAB/BROC	100	100	100	100	100
C. album	100	100	4	100	100
S. media	100	100	97	100	97
E. repens	100	93	2	100	2
C. bursa-pastoris	50	34	6	50	0
S. arvensis	50	50	0	50	0
A. patula	50	0	0	0	0
F. officinale	50	50	40	50	0
SOIL	50	50	50	50	50

The same data was introduced to the discriminant algorithm and the results are shown in Table 6.30. High crop recognition and poor weed-soil recognition were achieved with this algorithm. The advantage of using neural networks can be seen although discriminant analysis needs to be used to provide the best wavelengths required to train the net.

7. WEED CROP DISCRIMINATION USING SPECTRAL SIGNATURES

The discriminant analyses carried out in chapter 5 used very narrow wavebands (10 nm) presenting limitations from a practical point of view. Airborne platforms use broadband filters to measure reflectance from solar radiation, as the transmittance of narrow bandpass filters imply the utilization of artificial illumination systems. A simulation using broadband filters was carried out to evaluate the possibility of using them for crop/weed/soil discrimination.

7.1 SIGNATURES USED IN REMOTE SENSING

Special wavebands are used by satellites to monitor vegetation in the 400-2500 nm spectral band. Plant signatures present important wavebands at 370-500 nm, 630-690 nm, 740-1110 nm and 1350-2500 nm wavebands.

The first generation of satellites (LANDSAT-1, LANDSAT-2 and LANDSAT-3) applied four wavebands to study vegetation:

MSS4 (500-600 nm);
MSS5 (600-700 nm);
MSS6 (700-800 nm);
MSS7 (800-1100 nm);

Improvements carried out in the thematic mapper TM, a second generation sensor were achieved in the areas of spatial, spectral, and radiometric resolution. The field of view was reduced to 30 m, the quantity of bands increased to seven and the resolution increased from six bit data to eight bit data (Tucker, 1978). Each waveband has its particular application:

TM1 (450-520 nm) sensitive to chlorophyll and carotenoid concentrations;
TM2 (520-600 nm) sensitive to the green region;
TM3 (630-690 nm) sensitive to chlorophyll;
TM4 (760-900 nm) sensitive to vegetation density or biomass;
TM5 (1550-1750 nm) sensitive to water in plant leaves;
TM6 (2080-2350 nm) sensitive to water in plant leaves;
TM7 (10400-12500 nm) sensitive to thermal properties.

Infrared and red linear combinations have become common in remote sensing of vegetation biomass and physiological status. The use of the near infrared/red ratio (800 nm/675 nm) for estimating biomass or leaf area index in tropical forests was reported by Jordan (1969). Colwell (1973) concluded that the infrared/red ratio was useful for biomass estimation normalizing soil background reflectance variations.

The difference between infrared and red radiation levels normalized against their sum has been used as a vegetation index (VI), which is a direct function of the ground covered by plants. To avoid negative vegetation index values the transformed vegetation index (TVI) was introduced. A constant of 0.5 was added to the vegetation index and the square root calculated to obtain the TVI index. Rouse et al. (1973) applied the TVI and VI relationships to wheat and rangeland data gathered by LANDSAT and encountered a vegetation index increase with foliage development and a decrease when foliage senesced. The close correlation of biomass to TVI allowed the study of crop development as ground cover, biomass and leaf area index increased. Bands MSS6 and MSS7 were used as the infrared band. It was also found that the ratio between bands MSS6 and MSS5 presented a better correlation with green biomass than the ratio between bands MSS7 and MSS5.

Richardson and Wiegand (1977) proposed the perpendicular vegetation index (PVI). Several other indexes using regression techniques with the four bands produced the soil brightness index (SBI) and the green vegetation index (GVI).

The spectral bands required to discriminate crop from weeds need to provide high success rates independent of leaf water stress, leaf nitrogen concentration and crop growth. If possible, wavelengths below 1100 nm should be used to provide a good compromise in cost.

7.2 DISCRIMINANT INTEGRATION INDEX

Reflectance differences between two different leaf signatures can be quantified using the discriminant integration index, DII, proportional to the area between the two spectra. Plant species present similar signatures shapes non-dependent on water stress, growth stage or nitrogen concentration, as seen in Figs. 5.2, 5.3 and 5.6. An individual spectrum can be classified into the respective plant species after comparing the plant spectrum with the known plant species reference spectrum. When the plant belongs to the plant species the discrimination integration index will tend to zero.

Crop-weed discrimination can be analyzed using this technique, comparing a crop reference spectrum with all the plant spectra. Low DII values characterize crop spectra, while weed and soil spectra exhibit higher values. A threshold is then introduced to discriminate between the two groups, i.e. crop and weed-soil.

Mathematically, the discrimination integration index (DII) for a given waveband can be calculated by performing the following operations:

substracting in each wavelength the reflectance of both signatures;
adding the absolute value of the differences;
dividing the total value by the number of wavelengths;

A formula can be written to express the discriminant integration index over n wavelengths using the reflectance of the sample and the reflectance of the reference spectrum. The operation is performed n times adding the reflectance difference for each wavelength.

$$DII = \left(\sum_{i=0}^{n} abs\left(\rho_S(\lambda_i) - \rho_T(\lambda_i)\right) \right)/n \qquad \text{eq. 7.1}$$

The operation performed corresponds to the normalized integral existing between two spectral signatures in the selected waveband. The absolute operator is used in order to account for all the relative differences encountered between both signatures in the waveband of interest. This technique constitutes effectively a single broadband discriminator.

7.2.1 WAVEBAND SELECTION

Discriminant analysis determined the accuracy in classifying the samples into their correct category providing the best wavelengths for discriminating between groups. The best sets of three wavelengths selected for each crop in chapter 6 provided high discrimination accuracies, but required costly infrared sensors and artificial lightning. The use of artificial illumination can be avoided by increasing the bandwidth of bandpass filters from 10 nm to 100 nm.

Two different histograms helped to select the wavebands for each crop by including the best (first discriminant wavelength) and two general wavelengths (second and third wavelengths in discrimination importance) from each discriminant analysis. The general type histogram considered the best three wavelengths obtained in each discriminant analysis carried out, while

the other high-success type histogram collected the best three wavelengths from each discriminant analysis that achieved 100% crop/weed/soil discrimination accuracy.

Best wavelength repetition was the most important criterion in waveband selection. Although best discriminant wavelengths correspond to the wavelengths that best classify the groups, the word best discriminant (used in the histograms) includes only the first discriminant wavelength of the program run and is marked with a filled square. General wavelengths included in the histograms are marked with blanked squares.

The two broccoli histograms, Fig. 7.1 and Fig. 7.2 show that wavelengths peak within certain wavebands centered at 680 nm and 1380 nm. The best wavelengths of the analyses were encountered at 1380 nm followed by 760 nm and 710 nm. Three wavebands including the most important wavelengths were selected for further study: **680-780 nm, 960-1060 nm and 1320-1420 nm**.

Cabbage histograms, Fig. 7.3 and Fig. 7.4, showed an even wavelength distribution with peak wavelengths at 760 nm and 820 nm. These wavelengths were the most important discriminant wavelengths, but only 820 nm prevailed with the 100% success rate analyses. Another important discriminant wavelengths in the 100% success rate analyses were 1170 nm and 810 nm. The wavebands selected were **680-780 nm, 820-920 nm and 980-1080 nm**.

Leek histograms, Fig. 7.5 and Fig. 7.6, show well distributed wavebands with wavelength peaks at 720 nm and 1060 nm. Neither of them correspond to the best discriminant wavelengths located at 690 nm and 1080 nm. These wavelengths were the best discriminant wavelengths in the 100% success rates analysis and were included inside the selected wavebands: **680-780 nm, 980-1080 nm and 1350-1450 nm**.

An important wavelength will be the most common wavelength in the high-success histogram and in the general histogram, e.g. 1380 nm for broccoli and 820 nm for cabbage.

7.2.2 DISCRIMINATION ACCURACY FROM DISCRIMINANT INTEGRATION INDEX VALUES

Crop/weed-soil discrimination or discrimination accuracy (DA) is defined as the percentage of spectra correctly classified into their respective group i.e. crop as crop and weed as weed. The maximum crop discriminant integration index (DII) was fixed as a threshold to discriminate between both groups. Crop samples present minimum DII's as small differences

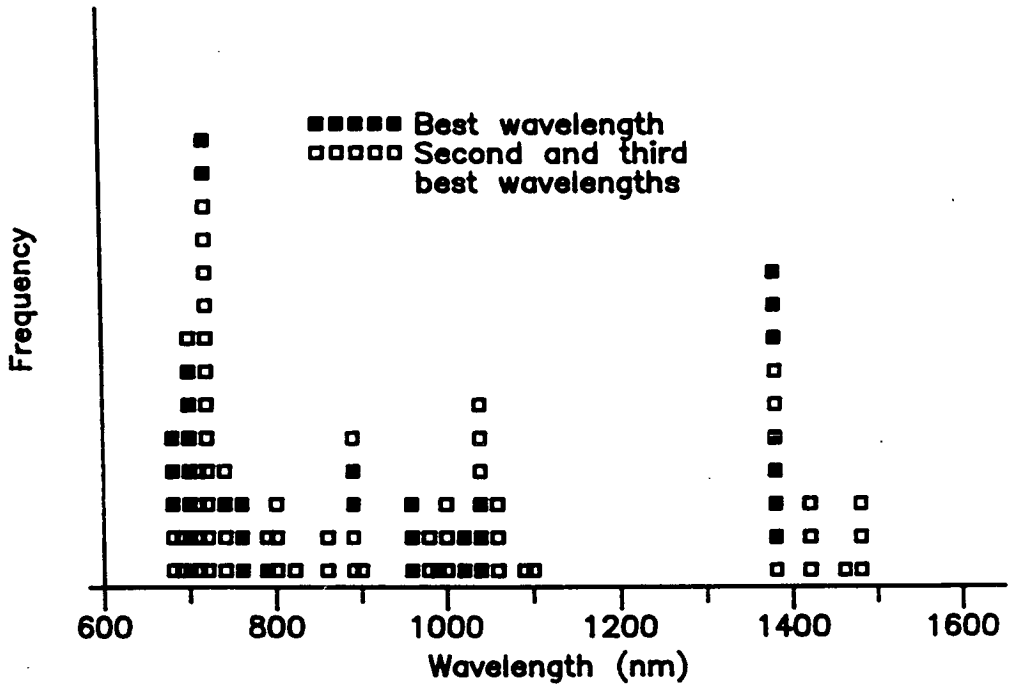

Fig 7.1 Best three wavelengths selected in each broccoli program run.

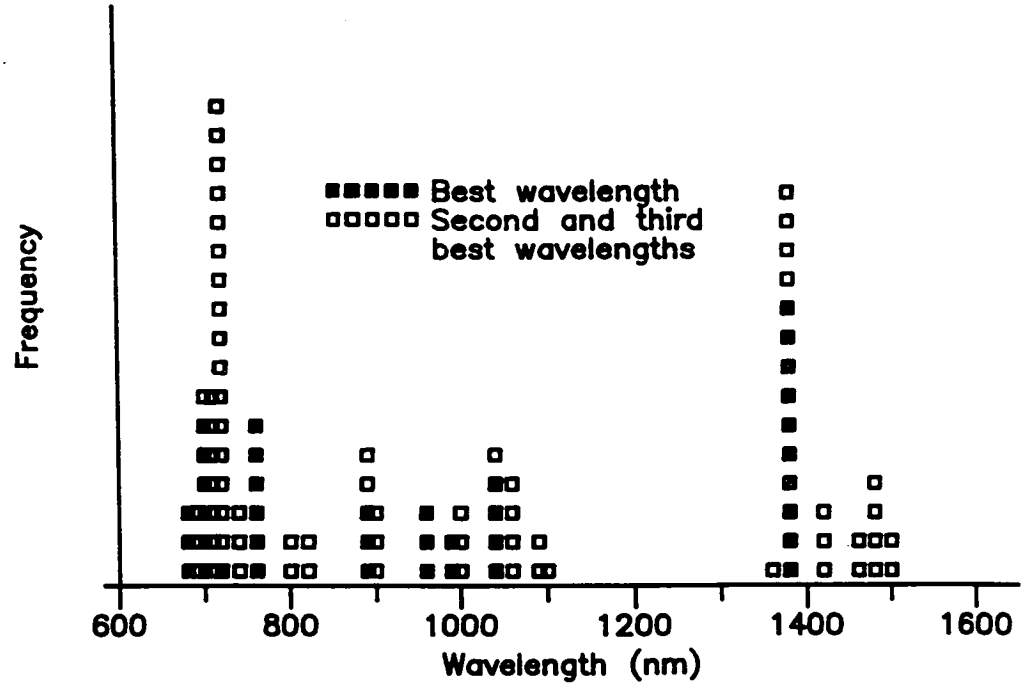

Fig. 7.2 Wavelength distribution using 100% success rate broccoli analysis.

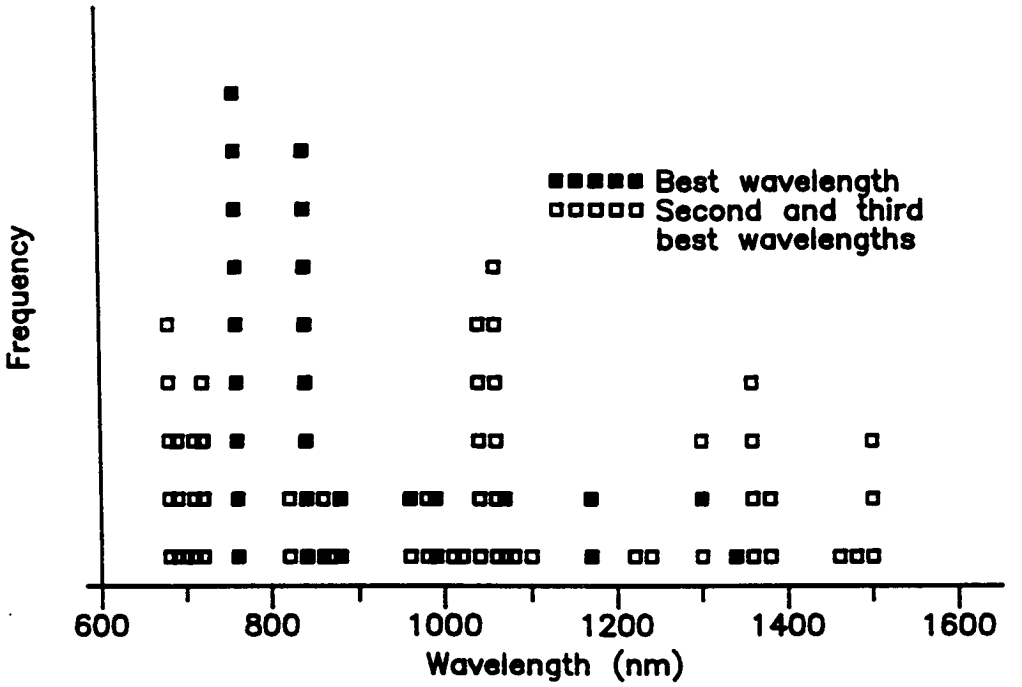

Fig 7.3 Best three wavelengths selected in each cabbage program run.

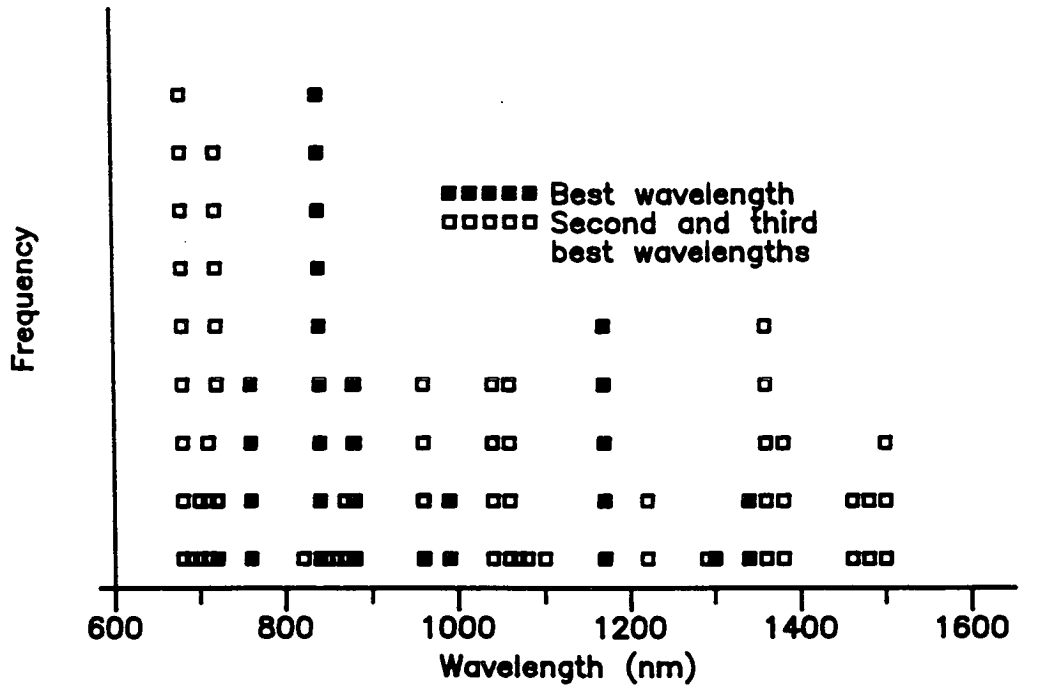

Fig. 7.4 Wavelength distribution using 100% success rate cabbage analysis.

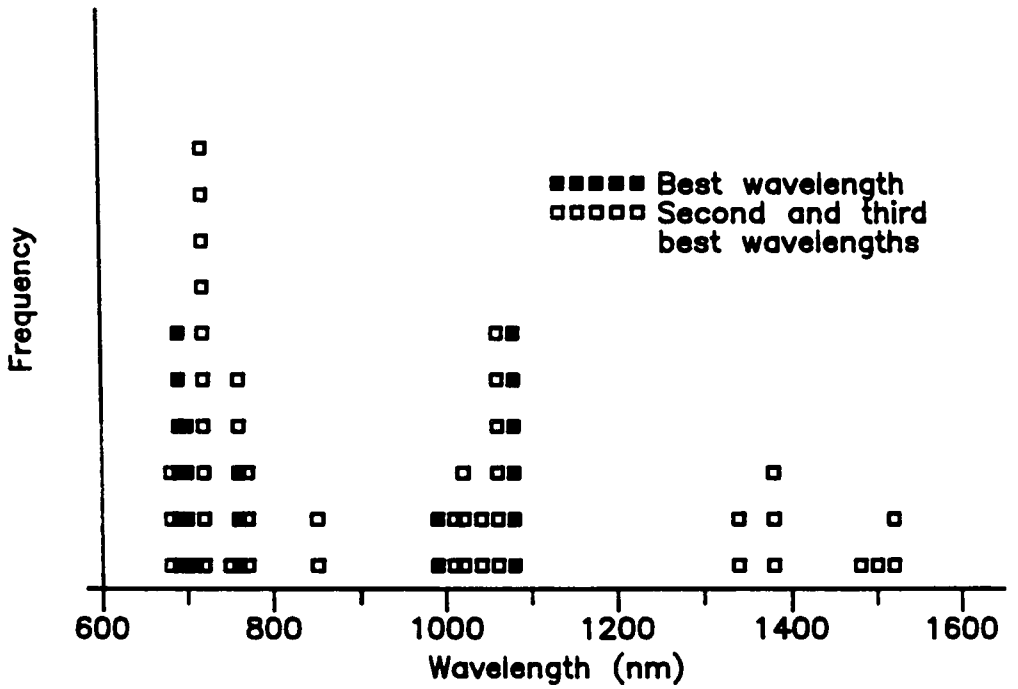

Fig 7.5 Best three wavelengths selected in each leek program run.

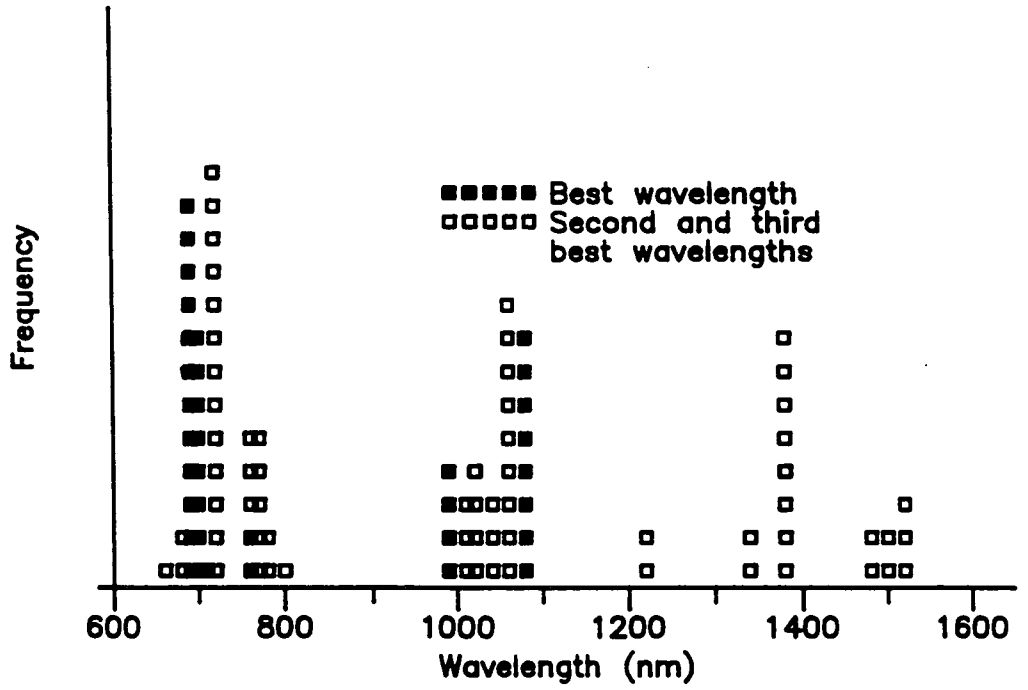

Fig. 7.6 Wavelength distribution using 100% success rate leek analysis.

exist between the crop sample spectrum and crop reference spectrum. The discrimination accuracy involves the determination of the weed-soil samples being well classified and is obtained by:

calculating the DII of each individual crop, soil and weed spectra (DIIs);

finding the maximum crop DII value (DIIt);

counting the number of weed and soil spectra whose DII value is higher than the maximum crop DII;

adding this quantity to the number of crop spectra;

dividing the result by the total number of spectra used.

A logical equation determines whether the sample DII (DIIs) is a crop or not:

IF (DIIs > DIIt); DIIs = WEED-SOIL; eq. 7.2

IF (DIIs <= DIIt); DIIs = CROP; eq. 7.3

A 100% crop/weed/soil discrimination is only possible when each crop DII is lower than each weed and soil DII. Crop DII, weed DII and soil DII group variances provide valuable information about the distribution of individual DII's within each group.

Statistic normal distributions can account for spectral measurements departing from the mean signature. The one sided confidence interval for the population mean (DIIav) is defined at the confidence level of 95% by the equation 7.4 and for the confidence interval of 99% by the equation 7.5, and will correspond to the DIIt crop thresholds.

$$DIIc < DIIav + s\,(t_{0.95}/SQRT(N)) \qquad \text{eq. 7.4}$$

$$DIIc < DIIav + s\,(t_{0.99}/SQRT(N)) \qquad \text{eq. 7.5}$$

Discrimination efficiencies were calculated using the 95% and 99% of the cases within the normalized distribution limits. The maximum DII crop thresholds decreased to values dependent on the crop standard deviation and to the constants ($t_{0.99}$/SQRT(N) and $t_{0.95}$/SQRT(N)) varying with the number of crop spectra, Appendix F. The crop spectra outside these confidence intervals were ignored reducing the total number of spectra. The discrimination efficiency can be obtained by:

calculating the DII crop threshold.

calculating all the crop, weed and soil DII.

comparing the crop DII threshold against each crop DII.

counting the number of crop DII lower than the DII crop threshold, and eliminating the ones with greater DII-the count corresponding to the properly classified crop spectra (CROP-WELL);

counting the weed and soil DII with values higher than the crop DII threshold, this count corresponding to the weed-soil spectra well classified (WEED-WELL);

adding the values of CROP-WELL and WEED-WELL;

dividing this addition by the total number of spectra minus the crop spectra eliminated.

7.3 DISCRIMINANT INTEGRATION MODES

Discriminant integration index values vary according to the form in which they are calculated. Three forms were used and named NATURAL, REFERENCE and COMPENSATED.

In the NATURAL mode the discriminant integration index corresponds to the area beneath the reflectance signature between two limiting wavelengths. It can be calculated by substracting the reflectance spectrum from a null reference spectrum (composed of zeros).

The REFERENCE discriminant integration index is the area between the sampled spectrum and the average crop spectrum of the trial. The crop spectra from each trial were averaged to obtain the crop reference spectrum, and then the DII of each sample either weed, soil or crop evaluated.

The COMPENSATED discriminant integration index is the area between the sampled spectrum and the calculated average crop spectrum obtained after compensating each crop spectrum using the crossover wavelength at 820 nm. It is noticeable that the overall broccoli average signature, obtained after averaging the broccoli spectra from all the trials differs from the average signatures achieved in each individual trial, Fig 7.7, showing similarity in signature patterns, but with magnitude differences. The effect of compensating each individual spectrum using the crossover wavelength at 820 nm will be to normalize all the spectra obtained in different fields, and the average crop trial signature will be closer to the overall signature Fig 7.8.

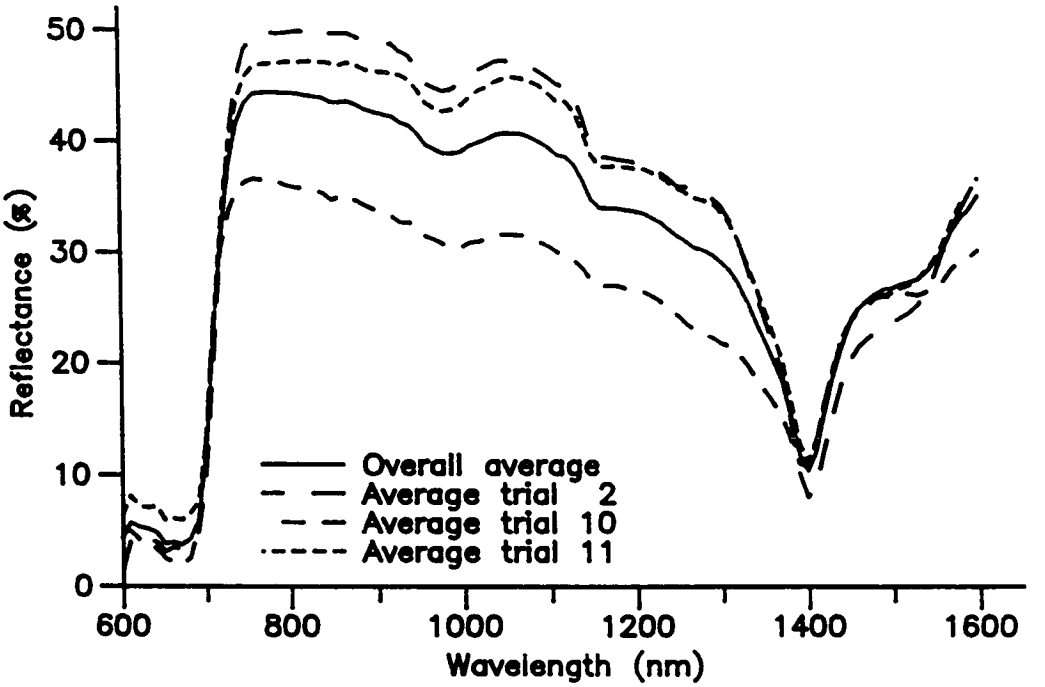

Fig. 7.7 Overall and average signatures from 3 broccoli trials.

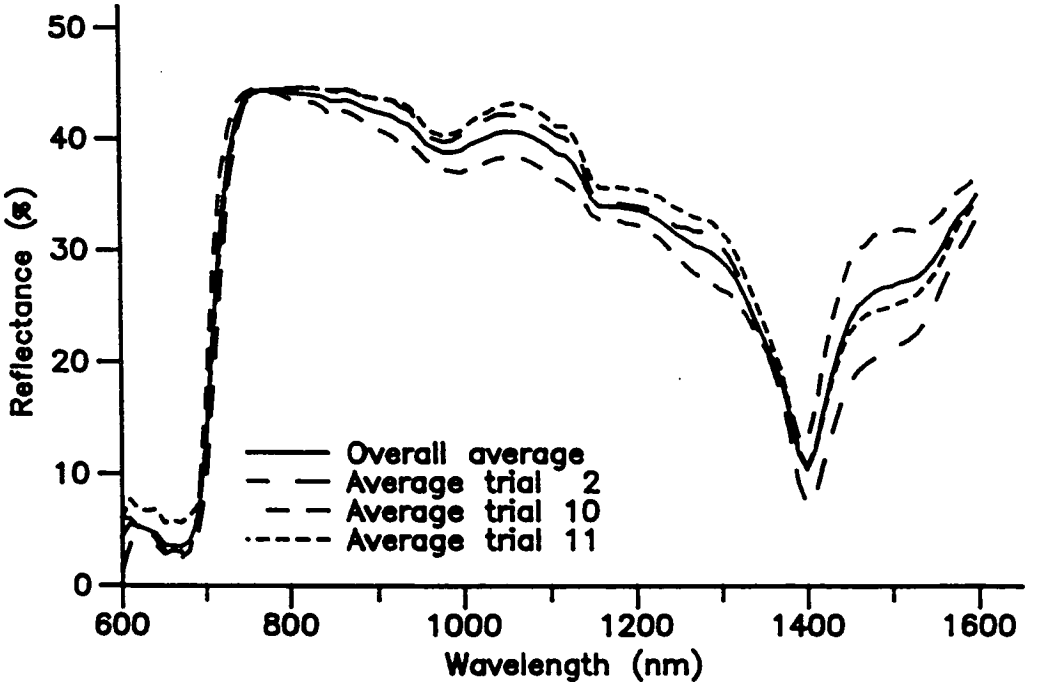

Fig. 7.8 Overall and COMPENSATED average signatures for broccoli

7.3.1 DISCRIMINATION MODES IN REMOTE SENSING ALGORITHMS

Different equations classified in waveband, waveband ratios, multiratio algorithms and complex algorithms were tried to optimize crop/weed/soil discrimination. The wavebands selected in

Table 7.1 NATURAL and REFERENCE average discrimination accuracies of the three crops obtained with a tolerance limit of 99%.

Waveband (nm)	Discrimination accuracies (%)					
	CABBAGE		BROCCOLI		LEEK	
	NAT	REF	NAT	REF	NAT	REF
600 -700	44.61	75.67	60.04	91.15	40.27	76.51
600 - 800	37.91	90.01	49.31	97.95	38.86	98.15
600 -900	42.06	92.13	50.82	97.35	38.01	97.94
600- 1000	42.16	92.44	51.45	96.86	37.63	98.31
600- 1100	42.41	92.68	51.31	96.03	37.14	98.64
600- 1200	43.36	92.95	51.91	96.15	36.97	98.66
600- 1300	44.01	93.98	52.35	96.54	36.97	98.97
600- 1400	44.62	94.92	53.61	98.33	37.15	99.31
600- 1500	45.51	96.06	54.04	98.64	37.33	99.31
600- 1600	45.65	95.96	54.27	98.64	37.17	99.15

section 7.2.1 were used by these equations and the results obtained for several crop trials are summarized in Appendix F. For each equation three different analyses were carried out, calculating the discriminant integration index in different ways.

The results include discrimination accuracies obtained by 100%, 99% and 95% tolerance limits in six cabbage trials, six broccoli trials and four leek trials. The effect of bandwidth in crop/weed/soil discrimination was studied and Table 7.1 shows the average 99% tolerance discrimination accuracies obtained for ten different spectral bands. The smallest bandwidth was 100 nm in the 600-700 nm spectral range and the maximum was 1000 nm in the 600-1600 nm spectral range. NATURAL and REFERENCE discriminant accuracies show best result in the latter, Table 7.1.

Cabbage results indicate a NATURAL discrimination accuracy increase from 37.91% in the 600-800 nm waveband to 45.65% in the 600-1600 nm waveband. Maximum REFERENCE

discrimination accuracy of 96.06% was achieved with the 600-1500 nm waveband, 6.6% higher than the 90.01% achieved in the 600-800 nm waveband.

Table 7.2 NATURAL and REFERENCE average discrimination accuracies of the three crops obtained with a tolerance limit of 99%.

Waveband (nm)	Discrimination accuracies (%)					
	CABBAGE		BROCCOLI		LEEK	
	NAT	DE-REF	NAT	REF	NAT	REF
600 -700	44.61	75.67	60.04	91.15	40.27	76.51
700 - 800	43.88	90.01	49.31	97.95	38.86	98.15
800 -900	41.34	91.51	50.74	92.79	36.73	97.25
900- 1000	42.99	92.28	52.01	94.36	36.97	98.15
1000- 1100	43.27	93.06	51.82	94.41	36.48	99.18
1100- 1200	45.31	93.11	54.21	93.86	36.66	99.15
1200- 1300	45.72	93.23	54.77	93.44	36.84	99.45
1300- 1400	51.16	93.34	61.79	98.64	37.01	99.44
1400- 1500	66.51	91.47	62.34	96.84	41.62	97.46
1500- 1600	56.16	90.55	58.78	94.07	38.32	96.19

Broccoli maximum NATURAL discrimination accuracy of 60.04% was obtained in the 600-700 nm waveband. REFERENCE discrimination accuracies presented higher values with a maximum value of 98.64% obtained in the 600-1500 nm and 600-1600 nm wavebands having a 0.7% increase with respect to the 97.95% achieved in the 600-800 nm waveband.

Leek highest NATURAL discrimination accuracy was 40.27% in the 600-700 waveband. REFERENCE discrimination efficiencies increased from 98.15% in the 600-800 nm waveband to 99.31% in the 600-1400 nm.

Table 7.2 shows the 99% tolerance discriminative efficiencies for the three crops, after averaging the result of six cabbage trials, six broccoli trials and four leek trials. Ten different wavebands having bandwidths of 100 nm were analyzed.

The highest cabbage, broccoli and leek NATURAL discriminative accuracies of 66.51%, 62.34% and 41.62% were obtained in the 1400-1500 nm waveband. Maximum cabbage, broccoli and leek REFERENCE discrimination accuracies in the 1300-1400 nm waveband

were 93.34%, 98.64% and 99.45%, respectively. Minimum REFERENCE discriminant accuracies were encountered in the 600-700 nm waveband for the three crops.

Remote sensing optical instruments provide spectral information which is processed. These instruments provide reflectance from broadband spectral regions and is introduced to algorithms which maximize the difference. Although an algorithm could be developed for each trial in order to relate the discriminant integration index with a constant value (0 for crop, 1 for weed and 2 for soil), the intention of this study was to analize the effect of common remote sensing algorithms in crop/weed/soil discrimination.

The cabbage wavebands selected were used by the different algorithms to obtain the discriminant accuracies for each cabbage trial using 100%, 99% and 95% tolerances. The 99% discriminant accuracies were averaged and showed in Table 7.3. The first, second and third columns show the NATURAL, REFERENCE and COMPENSATED discrimination accuracies, respectively.

The best REFERENCE discriminant accuracy obtained with the selected wavebands corresponded to the third waveband (980-1080 nm) having a value of 93.07%, followed by the second waveband (820-920 nm) with a value of 91.16%. The REFERENCE discriminant accuracies were at least 200% higher than their respective NATURAL discriminant accuracies. COMPENSATED discriminant accuracies presented values of 90.21% and 88.98% in the second and third wavebands, respectively.

REFERENCE discriminant accuracies in broccoli achieved at least 150% higher values than NATURAL discriminant accuracies using the three wavebands selected (algorithms 1-3), Table 7.4. REFERENCE discriminant accuracies of 99.24% and 98.07% were obtained with the third (1320-1420 nm) and first (680-780 nm) wavebands. A COMPENSATED discriminant accuracy of 91.75% was achieved in the 1320-1420 nm waveband.

Leek REFERENCE discriminant accuracies of 98.39%, 98.95% and 97.69% were obtained with the first (680-780 nm), second (980-1080 nm) and third (1350-1450 nm) wavebands, respectively, Table 7.5. These values were 200% higher than the ones encountered with NATURAL discriminant accuracies. The COMPENSATED discriminant accuracies obtained with the first and second wavebands were 91.64% and 93.84%, respectively.

Table 7.3 **Cabbage average discrimination accuracies for each algorithm using NATURAL, REFERENCE or COMPENSATED discriminant integration indices with a tolerance limit of 99%.**

	Algorithm	Discrimination accuracies (%)		
		NAT	REF	COM
1	wav1	44.21	89.34	87.59
2	wav2	41.19	91.16	90.21
3	wav3	43.66	93.07	88.98
4	wav2/wav1	37.38	78.34	73.66
5	wav3/wav1	48.71	83.72	62.66
6	wav1/wav2	79.41	37.29	33.57
7	wav1/wav3	71.21	34.82	35.45
8	(wav2-wav1)/(wav2+wav1)	37.38	79.27	80.81
9	abs((wav2-wav1)/(wav2+wav1)	37.38	60.26	42.29
10	(wav3-wav1)/(wav3+wav1)	49.55	65.13	71.07
11	abs((wav1+wav2)/(wav1-wav2))	37.86	91.04	85.47
12	(wav1+wav2)/(wav1-wav2)	42.26	33.43	34.89
13	(wav3+wav1)/(wav3-wav1)	69.63	47.99	70.63
14	sqrt(((wav2-wav1)/(wav2+wav1))+1)	37.38	72.85	83.36
15	sqrt(((wav3-wav1)/(wav3+wav1))+1)	49.55	87.98	75.11
16	sqrt((wav2-wav1)**2+(wav2+wav1)**2)	42.23	92.36	90.51
17	sqrt((wav3-wav1)**2+(wav3+wav1)**2)	65.24	55.16	55.08

Table 7.4 **Broccoli average discrimination accuracies for each algorithm using NATURAL, REFERENCE or COMPENSATED discriminant integration indices with a tolerance limit of 99%.**

	Algorithm	Discrimination accuracies (%)		
		NAT	REF	COM
1	wav1	49.14	98.07	87.63
2	wav2	51.79	94.32	87.78
3	wav3	65.44	99.24	91.75
4	wav2/wav1	65.79	66.06	58.94
5	wav3/wav1	94.19	49.87	47.89
6	wav1/wav2	59.62	45.21	53.78
7	wav1/wav3	33.46	51.94	71.27
8	(wav2-wav1)/(wav2+wav1)	66.24	72.01	56.78
9	abs((wav2-wav1)/(wav2+wav1)	66.24	46.38	36.41
10	(wav3-wav1)/(wav3+wav1)	94.31	52.52	50.19
11	abs((wav1+wav2)/(wav1-wav2))	61.44	95.43	72.92
12	(wav1+wav2)/(wav1-wav2)	67.03	43.06	38.15
13	(wav3+wav1)/(wav3-wav1)	43.69	39.35	55.09
14	sqrt(((wav2-wav1)/(wav2+wav1))+1)	66.24	72.75	62.99
15	sqrt(((wav3-wav1)/(wav3+wav1))+1)	94.31	53.58	50.98
16	sqrt((wav2-wav1)**2+(wav2+wav1)**2)	51.72	98.79	90.34
17	sqrt((wav3-wav1)**2+(wav3+wav1)**2)	48.46	68.84	64.21

Table 7.5 **Leek average discrimination accuracies for each algorithm using NATURAL, REFERENCE or COMPENSATED discriminant integration indices with a tolerance limit of 99%.**

Algorithm		Discrimination accuracies (%)		
		NAT	REF	COM
1	wav1	38.91	98.39	91.64
2	wav2	36.48	98.95	93.84
3	wav3	41.33	97.69	68.81
4	wav2/wav1	53.21	86.34	91.73
5	wav3/wav1	76.63	37.28	45.68
6	wav1/wav2	69.25	29.48	34.08
7	wav1/wav3	44.08	59.33	79.82
8	(wav2-wav1)/(wav2+wav1)	53.21	89.65	92.07
9	abs((wav2-wav1)/(wav2+wav1)	53.21	37.5	40.65
10	(wav3-wav1)/(wav3+wav1)	76.63	39.03	45.83
11	abs((wav1+wav2)/(wav1-wav2))	40.31	91.46	84.63
12	(wav1+wav2)/(wav1-wav2)	53.39	30.78	31.22
13	(wav3+wav1)/(wav3-wav1)	55.16	29.43	32.18
14	sqrt(((wav2-wav1)/(wav2+wav1))+1)	53.21	89.65	92.07
15	sqrt(((wav3-wav1)/(wav3+wav1))+1)	76.63	40.13	45.99
16	sqrt((wav2-wav1)**2+(wav2+wav1)**2)	36.82	99.24	93.9
17	sqrt((wav3-wav1)**2+(wav3+wav1)**2)	52.07	49.88	49.39

The basic algorithm is the ratio between two wavebands and is used to minimize common changes to both wavebands such as illumination and dust that will have similar effect throughout the spectrum. The ratio between the near infrared and the red wavebands is used to discriminate vegetation from soil. Ratios between the second and first wavebands and between the third and first wavebands were calculated and the results are shown in Appendix F. The inverse of these ratios was also calculated and the results differed substantially.

Waveband ratios using cabbage showed reduced REFERENCE discriminant accuracies with a maximum of 83.72% between the third and first waveband. Natural discriminant accuracies of 79.41% and 71.21% using ratios between first and second wavebands and between first and third wavebands presented higher values than the REFERENCE and COMPENSATED discriminant accuracies.

The best broccoli REFERENCE discriminant accuracy using waveband ratios had a value of 94.19% and was achieved dividing the third waveband by the first waveband, Table 7.4.

The ratio between the second and first wavebands achieved the highest leek REFERENCE discriminant accuracy of 86.34%, Table 7.5. A COMPENSATED discriminant accuracy of 91.73% was achieved with the same ratio. The highest NATURAL discriminant was 76.63% using the third and first wavebands.

The next algorithm considered was the multiratio algorithm, commonly used to monitor biomass. As the difference between the two wavebands increase the value increases, showing that more vegetation is present. When vegetation indexes of weeds and crops are calculated over the same wavebands the existent difference is small, producing low discrimination accuracies. However, multiratio algorithm number 11 presented the highest REFERENCE discriminant accuracy of 91.04% using the first and second wavebands. A COMPENSATED discriminant accuracy of 85.47% was achieved with the same algorithm. This algorithm as such is not used in remote sensing and was applied here to avoid the ratio from taking negative values. The best NATURAL discriminant accuracy in multiratio algorithms was 69.93% in algorithm 13, using the first and third wavebands.

The multiratio algorithm number 10 used the first and third wavebands to achieve a 94.31% NATURAL discriminant accuracy in broccoli trials, Table 7.4. A 95.43% REFERENCE discriminant accuracy was achieved with algorithm 11, using the first and second wavebands.

Multiratio algorithm number 11 using the second and first wavebands in leek trials achieved a 91.46% REFERENCE discriminant accuracy, Table 7.5. COMPENSATED discriminant accuracy of 84.63% was achieved with the same algorithm. Multiratio algorithm number 8 used the same wavebands to obtain 89.65% and 92.65% REFERENCE and COMPENSATED discriminant accuracies.

Typical DII differences between crop and weeds in the 680-780 nm waveband were of 40%, but after applying ratios decreased to only 10-15%. The highest waveband presented small DII differences between plant species, indicating signature similarities in the band. The maximum DII difference encountered was of 10% and decreased with the application of ratios.

The lower reflectance characteristic of the third waveband, provides negative results. The complex algorithm adds a constant of 1 to avoid the vegetation indeces from being negative, but the results achieved were not the highest.

The complex algorithms using square roots obtained high REFERENCE discriminant accuracies. A maximum value of 92.36% was achieved with algorithm number 16. The maximum discriminant accuracy of Table 7.3 was obtained with algorithm 16 having a value of 95.01%.

Complex algorithms presented high discriminant accuracies in the three broccoli analyses, Table 7.4. The NATURAL discriminant accuracies of algorithms 15 and 10 presented similar values. A 98.79% REFERENCE discriminant accuracy was achieved in algorithm 16 using the first and second wavebands. COMPENSATED discriminant accuracy for algorithm 16 was 90.34%

Complex algorithm number 14 achieved 89.65% and 92.07% REFERENCE and COMPENSATED discriminant accuracies using leek as crop, Table 7.5. Complex algorithm number 16 used also the first and second wavebands to achieve REFERENCE and COMPENSATED discriminant accuracies of 99.24% and 93.91%

The square root algorithm (algorithm 16) cannot get a worst result than the one achieved by simple wavebands, but requires more mathematical operations and does not perform the ratio between the wavebands.

Conclusions of the algorithm analysis are as follows.

a. The three wavebands in each crop showed high REFERENCE discrimination accuracies, while waveband ratios showed poor results with REFERENCE discrimination accuracy.

b. Algorithms 11 and 16 presented high REFERENCE discrimination accuracies in the three crops.

c. NATURAL discrimination accuracies rarely achieve 90% values.

d. COMPENSATION discrimination accuracies showed higher values than their respective NATURAL accuracies but smaller than REFERENCE discrimination accuracies.

8. DISCUSSION OF RESULTS.

This chapter gathers the individual achievements obtained during the study, provides a discussion of the results and looks towards the implementation of a practical prototype for identifying crops from weeds and soil.

The feasibility of using optical reflectance in crop/weed/soil discrimination has been studied with success on a great diversity of crops. The constraints affecting crop/weed/soil discrimination were biological variables mainly, including stress vectors, aging, weed incidence and soil cover. Variables such as climate, soil type, solar lighting and leaf inclination should be contemplated in addition to the variables of this first stage to obtain the best non-contacting crop/weed/soil recognition sensor.

This fundamental study provides the wavebands required for designing a crop/weed/soil recognition optical sensor, which indirectly determines the type of sensor required, filter bandwidth and illumination system. Algorithms were also tested to properly classify crop, weeds and soil.

Different farms in Scotland growing broccoli, cabbage and/or leek crops from 1991 to 1993 were visited, and samples of their crops, soils and weed species collected. *S. media* was the most competitive weed species, with *C. album* and *S. vulgaris* proliferating in most cabbage and leek fields, respectively. *S. media* competed strongly with cabbage decreasing its probability of survival when chickweed covered 70% of the growth area. *C. album-S. media* combination proved to be very harmful to cabbage. Leek size was not highly affected as a result of *C. album* and/or *A. patula* competition, and the latter proved to be advantageous for leek growth in most of the cases.

Three instruments were used to collect spectral information from vegetation (crop and weed species), soil and stone samples: an integrated sphere spectrophotometer, a grating type spectrophotometer (the Monolite Optical Spectrum Analyzer) and a spectroradiometer designed to measure optical reflectance on site at fixed wavelengths. All the reflectance measurements were relative to a barium sulphate reference. The different spectral ranges and techniques used by both spectrophotometers complemented the signature measurements. The integrating sphere spectrophotometer collected maximum diffuse reflected radiation without contacting the sample. The Monolite Optical Spectrum Analyzer, which collected the spectral reflectance with an optical fibre, presented versatile software capable of calibrating the spectrophotometer, programming its spectral range and storing the acquired signature.

Large brassica leaves presented signature differences throughout the leaf and three sections - the margin, the centre and the leaf stalk- of brassica leaves were sampled with the integrating sphere spectrophotometer. Stalk and leaf tissue signatures differed greatly, with the former having a slightly higher reflectance at 650 nm as a result of lower chlorophyll content, as well as reflectance differences in the 900-1450 nm waveband, probably caused by different mesophyll structures (Gausman, 1974), cell wall/air interfaces (Wooley, 1971) and water content differences. Central and margin leaf underside reflectance signatures showed higher reflectance than their respective top side signatures with the highest reflectance differences between top and underside in the red slope region (Hahn and Muir, 1993a). Centre and margin top side signatures were similar in the brassica leaves, with reflectance differences above 1100 nm. Senescing yellow leaves presented an apparent red edge displacement in comparison with healthy leaves.

Reflectance measured with the spectroradiometer at 820 nm and 1450 nm on all the surface of cabbage and broccoli leaves showed an increase beside the crop leaf stalk from a minimum value at the leaf apex to a maximum value at the middle of the leaf. Orthogonal measurements to the leaf stalk indicated maximum reflectance in the vicinity of the stalk and minimum reflectance in the leaf margin.

Weed leaves having different shapes and sizes were difficult to sample individually in the integrating sphere spectrophotometer, and spectral differences were noted when leaves were stacked together. Small area leaves could only be sampled with the use of an optical file probe. This fibre could be attached to both the Monolite Optical Spectrum Analyzer and the spectroradiometer. However, signature differences in the 600-1600 nm scanned spectral range were found due to different fibre probe pressures. The spectroradiometer instrument was particularly useful for field sampling, and results showed minimum reflectance near the leaf apex and minimum reflectance variations nearby the same leaf section in different sized broad-leaved weeds. Maximum reflectance was encountered close to the ligule in grass weeds.

Weed species leaves measured with the Monolite spectrophotometer showed different spectral signatures between flower petals, stalk and leaf tissue, and signature similarity between weed species of the same family i.e. *Lamium album* and *Lamium purpureum*. Spectral differences were also encountered between morphologically different leaves within the same species (*A. patula*), and between healthy leaves and leaves affected by rust.

Reflectance signatures of plants in the 600-1600 nm waveband differ between plant species and even between plant varieties. Reflectance differences between plants species in the visible region were small as noted by Walter et al. (1980). The fact that stalk and leaf tissue signatures differ is important for machine vision as leaves can be reconstructed by the their vein structure and shape algorithms could be employed to distinguish crops from weeds. It is apparent from the measurements taken that the best sampling area in the leaf is 2 cm away from the leaf apex. The leaf margin loses water easily and measurements should avoid this section unless stress studies are involved. However, to account for leaf tissue spectral differences, measurements were taken in the top side of the leaf, covering the leaf periphery at a distance of one cm from the leaf margin. High variance values were encountered between brassica signatures as a result of leaf sampling at different growth stages and stress conditions (Hahn and Muir, 1993a).

Discriminant analysis classified signatures into their respective groups, and provided the best discriminant wavelengths. The success of the analysis was determined by the classification of a sample into its correct general category of crop tissue, weed or soil. A more detailed analysis looked for the proper classification of a sample into its correct category of crop tissue, specific weed species or soil.

Discriminant analysis was also used to study the effect of crop stress (i.e. nitrogen and water), crop growth stage, crop variety, weed species population and soil cover on crop/weed/soil discrimination.

Water stressed and nitrogen deficient broccoli plants grown in a greenhouse were analysed, together with five weed species and soil samples. The broccoli leaves were discriminated perfectly from the weed species and soil samples in the 1100-1600 nm broadband and in the 1400-1600 nm narrowband. Nitrogen deficient plants were perfectly discriminated from weeds using only three wavelengths, which were completely different to the wavelengths correlating fresh nitrogen with optical density (Hahn and Muir, 1993e). Crop/weed/soil discrimination was not affected by water stress and three wavelengths were sufficient for performing the discrimination.

Reflectance signatures obtained from cabbage leaves during the first five weeks after sowing and from broccoli leaves between the first and second month after sowing (Hahn and Muir, 1993c) showed a linear reflectance increase with age in broccoli, and a linear reflectance increase in cabbage during the first month only. These signatures analysed together with five weed species and similar soil samples achieved highest crop/weed/soil discrimination accuracy

in the 600-1100 nm and 1100-1600 nm broadbands and the best crop growth stage/weed species/soil discrimination success rate in the 1400-1600 nm narrowband. The wavelength at 1480 nm was found essentialfor good crop/weed/soil discrimination. A similar experiment with different weed species and two completely different broccoli growth stages was carried out, but each crop growth stage was analyzed individually. Crop/weed/soil discrimination accuracies of 100% were achieved for broccoli when it had only four true leaves and for broccoli at the harvest stage having identical wavelengths at 720 nm and 1380 nm.

The performance of three different cabbage varieties (spring, autumn and savoy) grown in the same field was evaluated and although autumn and savoy cabbage signatures were similar, best crop/weed/soil discrimination was achieved with spring cabbage using direct wavelengths and wavelength ratios. As expected, the best discriminant wavelengths for savoy and autumn cabbage but differed from spring cabbage wavelengths.

The use of straw as mulch reduced effectively the weed population. The weeds species growing with this soil cover were used to compare the effect of crop/weed/straw discrimination with crop/weed/soil discrimination. Straw, consisting of dry leaves, was best discriminated from broccoli leaves and weed species using two high discriminant wavelengths located at 1380 nm and 1480 nm differing substantially from the wavelengths selected for sandy soil. Crop/weed/soil and crop/weed/straw discrimination accuracies of 100% were achieved using these sets of wavelengths and obtained better discrimination accuracies with wavelength ratios than with direct wavelengths for both, soil and straw.

Autumn cabbage, broccoli and leek analysis with different weed populations and soil types provided high discrimination accuracies with three direct wavelengths in each site. Direct wavelengths achieved better discrimination accuracy than wavelength ratios. Discriminant wavelengths varied mainly due to weed population and to a smaller extent with crop variety.

Potato, turnip (Hahn and Muir, 1993d) and cauliflower (Hahn and Muir, 1993b) crops were also analyzed to study the feasibility of using optical reflectance in crop/weed/soil discrimination. Cauliflower leaves lost water easily and their texture was similar to weed leaves. A discrimination accuracy of 90.47% using three wavelengths was achieved with cauliflower being the lowest of all the crops (Hahn and Muir, 1993b). Turnip, another brassica, and potato showed a 100% crop/weed/soil discrimination accuracy with three direct wavelengths, (Hahn and Muir, 1993d). Lower success rates were achieved with wavelength ratios for all three crops;

Crop/weed/soil discrimination was studied in a sandy loam leek field with three different and well defined weed patches. The best discriminant wavelengths were similar in the three regions, and non dependent on weed population. The effect of removing or adding three or four weed species within the same crop/weed species/soil environment is not appreciable. A 100% crop/weed/soil discrimination accuracy with only two wavelengths was achieved in each one of the three patches, having a common wavelength of 690 nm. Rust infected *S. vulgaris* was easier to recognize than healthy *S. vulgaris*.

Different algorithms were applied to the spectral information in an attempt to increase reflectance differences between plant species. First derivatives (Hahn and Muir, 1993c) and wavelength ratios were tested, and the latter were used in most of the analyses but achieved lower success rates than the former. Wavelength ratios are useful as they reduce illumination variations common to all wavelengths. The wavelength having the lowest dispersion reflectance within the entire data population was selected as the denominator wavelength of the ratio.

Discriminant wavelengths combinations used by a trial group to provide the best discrimination accuracies could be completely different from than the ones achieved by the entire data set. The result achieved will be optimum for the trial group but not a true representation of the entire data analysed. The wavelengths selected should be the ones representing the entire data set.

Correct grouping of weed species can be achieved using a broader spectral waveband, and more than three wavelengths. Crop/weed species/soil discrimination varied between trials and decreased sharply with the number of wavelengths used. Even using all the 600-1600 nm spectral band perfect interweed discrimination was not achieved.

Further improvements can be made by using three dimensional cameras taking into account heights and leaf stalks, and should be implemented in order to map weeds in the field. This will allow to study their competition effects and will also allow to fix some weed thresholds.

The selection of the best set of wavelengths for each crop considering different crop varieties, crop growth stages and diverse weed species populations was done iteratively, and with the help of weighting algorithms which which took into consideration average crop/weed/soil and crop/weed species/soil discrimination accuracies.

Broccoli and cabbage wavelength sets had one with wavelengths bellow 1100 nm and another with three well dispersed wavelengths in the 600-1600 nm waveband. The 1400-1600 nm narrowband enclosing the water absorption band showed the greatest reflectance difference between the stressed or growing crop and the weed species. The reduction of the higher wavelength value to 1360-1380 nm in the analysis with most crops can be attributed to the "hardiness effect" of plants grown in the field, where leaf tissue gets stronger for surviving against difficult environmental conditions.

Best results were achieved with the wavelength sets which included this 1360-1380 waveband, together with the 1040-1060 nm waveband dependent on the cell structure, and the red waveband (680-720 nm) fundamental for vegetation-soil discrimination.

In the leek analysis, soil discrimination was made using low wavelength and weed species discrimination using higher wavelengths. Leek tissue texture differs from weed species texture, keeping water for days. Leaf moisture can be used to identify leek from different weed species, using wavelengths nearby the water absorption band.

By using the average classification function coefficients obtained from the analysis of each trial, an algorithm capable of sorting weeds, crop and soil was developed. The coefficient value dispersion was high providing an inaccurate general discriminant model.

These wavelengths were then used to train a neural network classifier and high success rates were achieved in each trial. Data from different crop varieties and weed species contained in the trials was used to train the classifier. The classifier was tested with all the data collected from the trials and an increased success rate was achieved when the training data included a higher number of trials.

The final test used 500 weed, 100 broccoli and 100 cabbage leaf samples collected during the last days of October which never trained the neural network. Reflectance data from these samples were introduced to the neural network algorithms providing best 90% and 92.3% success rates in cabbage/weed-soil and broccoli/weed-soil discrimination, respectively. Training nets with the lower wavelengths showed good results and could provide the algorithms for the future as CCD array scanners sensitive up to 1100 nm are relatively cheap. Best accuracies can still be expected from neural networks using a fourth wavelength, or with the use of a second hidden layer.

The use of very narrow spectral bands (5-10 nm) impose limitations in their practical application as not enough radiation is reflected in each band. Crop/weed/soil discrimination using spectral bands require another unit for comparison which was named the discrimination integration index (DII), corresponding to the area between two spectral signatures. The sample spectrum was compared with the average crop spectrum, providing DII values close to zero for crop samples and higher DII values for weed and soil samples. The final DII was compared against a set threshold which varied depending on the tolerance limits. In the worst case (100% tolerance) the threshold corresponded to the maximum crop DII. Within gaussian tolerances the high crop DII's were eliminated and the threshold was reduced in value.

Three wavebands were selected for each crop aided by histograms containing the best discriminant wavelengths. Broccoli and leek histograms showed three well defined spectral wavebands, while cabbage presented a higher wavelength dispersion.

As noted the three crops presented common wavebands at 680-780 nm waveband, and very similar wavebands at 960-1080 nm.

An analysis carried out with incremental spectral ranges indicated maximum discrimination accuracy in the three crops in the 600-1500 nm range. However, the difference between the results of 600-700 nm and the 600-1500 nm waveband was very small for the three crops. Discrimination accuracies for each one of the three crops trials (cabbage, broccoli and leek) were obtained using a 99% tolerance threshold setting and the results averaged. High success rates were achieved in the three crops.

The application of different remote sensing algorithms on the acquired data provided poor discrimination accuracies with waveband ratios as reflectance differences between weed and crop decreased in magnitude. The best discrimination accuracies were provided by the absolute inverted vegetation index (multiratio algorithm) using the two first wavebands for each crop. A square root algorithm provided also high discrimination accuracies using the first and second wavebands, but without ratios.

Remote sensing experiments were carried out in the search for optimum sampling techniques which would minimise signature differences due to probe pressing (Appendix G). The optical fibre was maintained 5 and 10 cm away from the sample, but degradation in signature information was present as a result of diffuse reflectance loss causing reflectance differences within the same crop and weed populations. By the addition of a collector lens a better non-contacting signature was obtained.

Remote sensing measurements of weed species and crops were taken with a camera, but its 8-bit resolution was not sufficient for proper crop/weed recognition (appendix H).

Finally, when comparing the neural network classifier with the waveband analysis, the latter shows improvements by using:

only one filter;
a broadband which eliminates the need of artificial lighting;
minimum mathematical calculations, and;
wavebands below 1100 nm with high accuracy.

Neural networks could be trained using DII as inputs and higher discrimination accuracies might be expected.

9. CONCLUSIONS AND FUTURE WORK.

CONCLUSIONS

The different analyses carried out with different vegetables led to the following conclusions.

1. It is feasible to use optical reflectance in crop/weed/soil discrimination.

2. Crops were discriminated from weeds in the 600-1600 nm spectral band mainly in the 680-1380 nm waveband where plant species mesophyll and cell structure differ.

3. It is feasible to use optical spectral reflectance to distinguish weed species.

4. Wavelengths derived from discriminant analysis can be used as the base variables in a neural network classifier for crop/weed/soil discrimination.

5. Crop/weed/soil discrimination accuracies were not affected by water stress or nitrogen deficient crops.

6. Crop growth stage and crop variety did not affect the efficiency of crop/weed/soil discrimination.

7. Different weed species populations in each trial did not reduce crop/weed/soil discrimination.

8. The best discriminant wavelengths obtained from each farm analysis varied, predominating at 660-680 nm, 1040-1060 nm and 1380 nm.

9. Generally, larger wavelengths were selected by the analysis on data from plants grown inside greenhouses compared to those for crops sown in fields.

10. Best signatures using a fibre optical probe were achieved by adding a condenser lens and samples made 2 cm away from the leaf apex.

11. Similar crop/weed/soil discrimination accuracies are achieved with and without the condenser lens in remote sensing measurements.

12. Broadband filters can be used to distinguish weeds from crop and soil efficiently when the discriminant integration index is used.

13. Discrimination accuracies achieved with the discriminant integration index were high for the three crops studied.

14. Machine vision systems for crop/weed/soil discrimination should include a camera with a higher resolution than 8 bits.

FUTURE WORK

1. This work proved how accurately it is possible for a sensor to distinguish weeds from crop and soil. Weed species can also be discriminated from each other and from crops, making the sensor highly useful for studying crop/weed interactions. To better distinguish weed species, the number of wavelengths used might have to be increased.

2. The neural network classifier and the broadband approach should be tested with waveband ratios to achieve immunity to changes in the illumination source.

3. Several parameters which have not been considered in this thesis have yet to be studied. These include problems due to leaf inclination, fluctuations in lighting and the proximity of plants to each other. It seems inevitable that a weed/crop scanner will have CCD camera in some form at its centre. This would allow the inclusion of scene photography or shape of object information in the discrimination. When plants are in close proximity shape information would seem to be essential for their efficient separation and individual detection.

4. Some initial exploration has indicated that it may be feasible to reconstruct entire infrared signatures with only one or two wavelengths in the near infrared. Signature reconstruction could avoid the use of extremely expensive infrared filters and sensors.

5. Researchers have proposed maximum permissible weed population thresholds and this sensor could be used to gather more information in reduced time in order to provide better assessments in the future for farmers.

6. Two different applications for the sensor can be forecasted: weed killing or detection and removal and crop/weed research. The first one is economically exciting and should be studied

in conjunction with fast precise methods of weed eradication. Sensors based on the above principles can be the eye of an efficient spot spraying machine, reducing the herbicide usage per hectare or the eyes of a mechanical hoe.

The second application is the more interesting one. The efficient operation of a weed killer will provide consequential problems as the complete removal of weeds will cause insects, which normally would use weeds as hosts, to attack the crop directly. This problem can be studied with the sensing system to record crop-weed interactions, to help in the understanding of weeds that protect crops from insects. The sensor sensitivity in the infrared is superior to our eye's capabilities, and may be tuned to monitor crop stress. The interaction between crop and weeds analysed with respect to time may provide important information in the future for the agrochemical industries.

7. An expert system could be developed for the crop/weed erradication system, take into consideration all the ecological variables, store them as historical data base and use them for the forecasting of best care of plants and the environment.

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APPENDIX A

APPENDIX A

DESIGN AND MEASUREMENTS OF A PORTABLE SPECTRORADIOMETER

A spectroradiometer was designed to measure optical reflectance and transmittance in leaves non destructively. The spectroradiometer was characterized by:

reflectance measurements from six different wavelengths;

wide spectral range of operation dependent on the detector used and an;

artificial lighting as the illumination source.

The reflected or transmitted radiation from the leaf, enters the radiometer, Fig. A1, through a condenser lens passes through a filter wheel containing up to six bandpass filters (see top photograph Plate 3) and a shutter before reaching the detector. The shutter fixed to the radiometer assembly, provides blackbody radiation measurements when closed, allowing the light to reach the detectors when open. A mechanism rotates the filter wheel opening the shutter when necessary, Fig. A2, using six screws spaced sixty degrees apart to revolve the wheel manually. When the trigger of the radiometer is pulled, the lever located in the shutter is lifted opening the shutter. Pushing the trigger in the opposite direction turns the filter wheel sixty degrees without opening the shutter. A ball bearing in the radiometer assembly stops the filter wheel rotation precisely.

Three different detectors encapsulated in aluminium housings were adapted to measure the incoming radiation depending on the spectral range desired; only one used at a time. The sensors used were a Hamamatsu visible silicon photodiode (S1226-8BQ) for the 200-1000 nm spectral range, a germanium photodetector (GM5TEC-VHR) for the 650-1800 nm spectral band and an infrared InAs detector (J12TE2-8B6) with a built-in two stage thermoelectric cooler for wavelengths between 1000 nm up to 3600 nm.

A spindle in the back of the spectroradiometer moved the detector axially towards the condenser lense focusing the incoming radiation into the detector until maximum radiation was collected. The detector outputs were soldered to connectors and shielded to avoid noise. Preamplifier and amplifier stages were designed using high input impedance and low input current JFET integrated

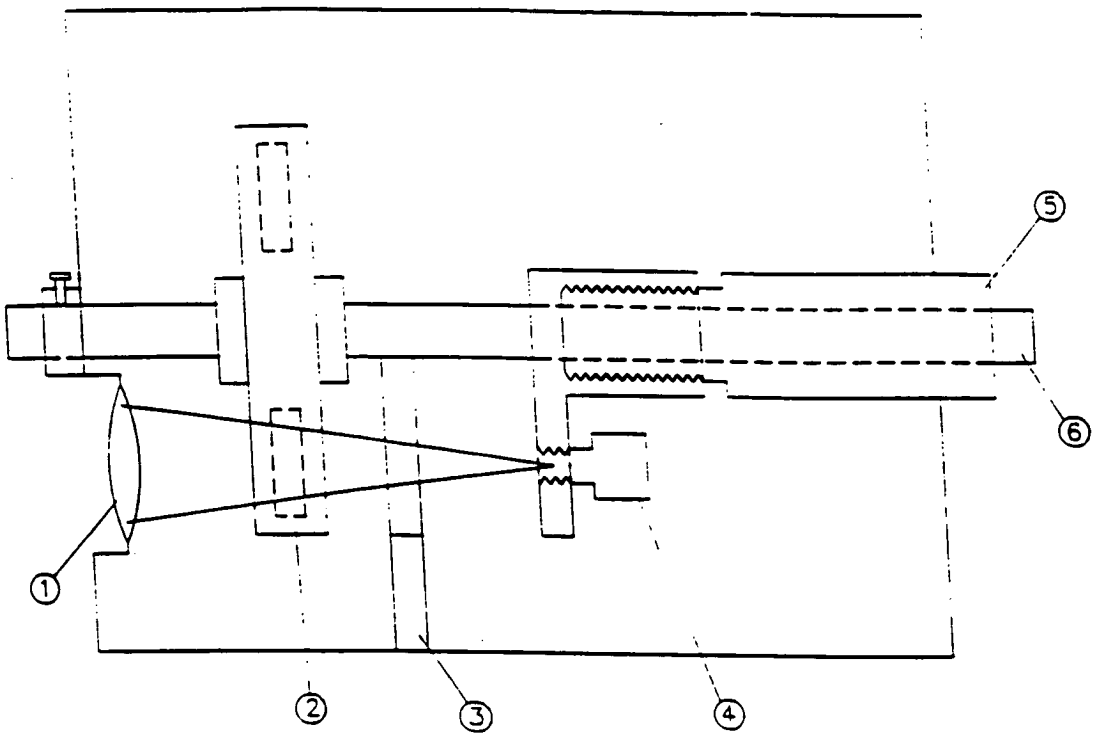


Fig. A1 Components inside the gun assembly; 1 condenser lens; 2 filter wheel; 3 shutter; 4 detector housing; 5 focusing mechanism; 6 shaft.

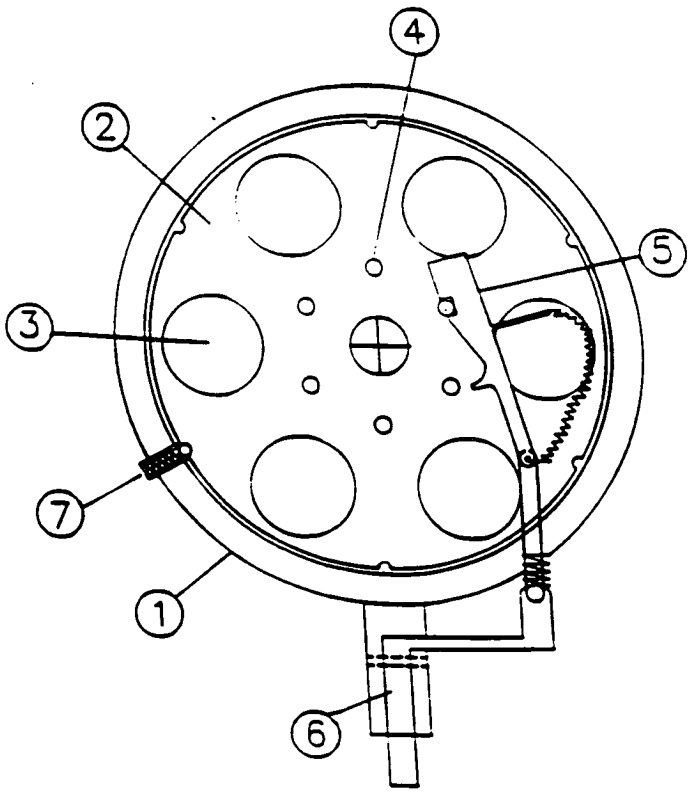


Fig. A2 Filter wheel mechanism; 1 gun assembly; 2 filter wheel; 3 optical filter; 4 filter wheel screws; 5 turning mechanism; 6 trigger; 7 ball bearing.

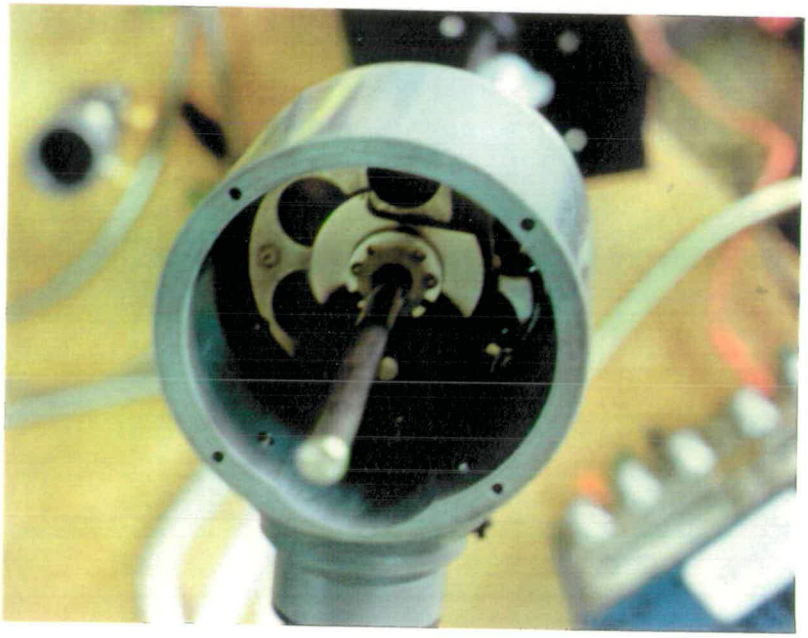


Plate 3. Gun assembly.

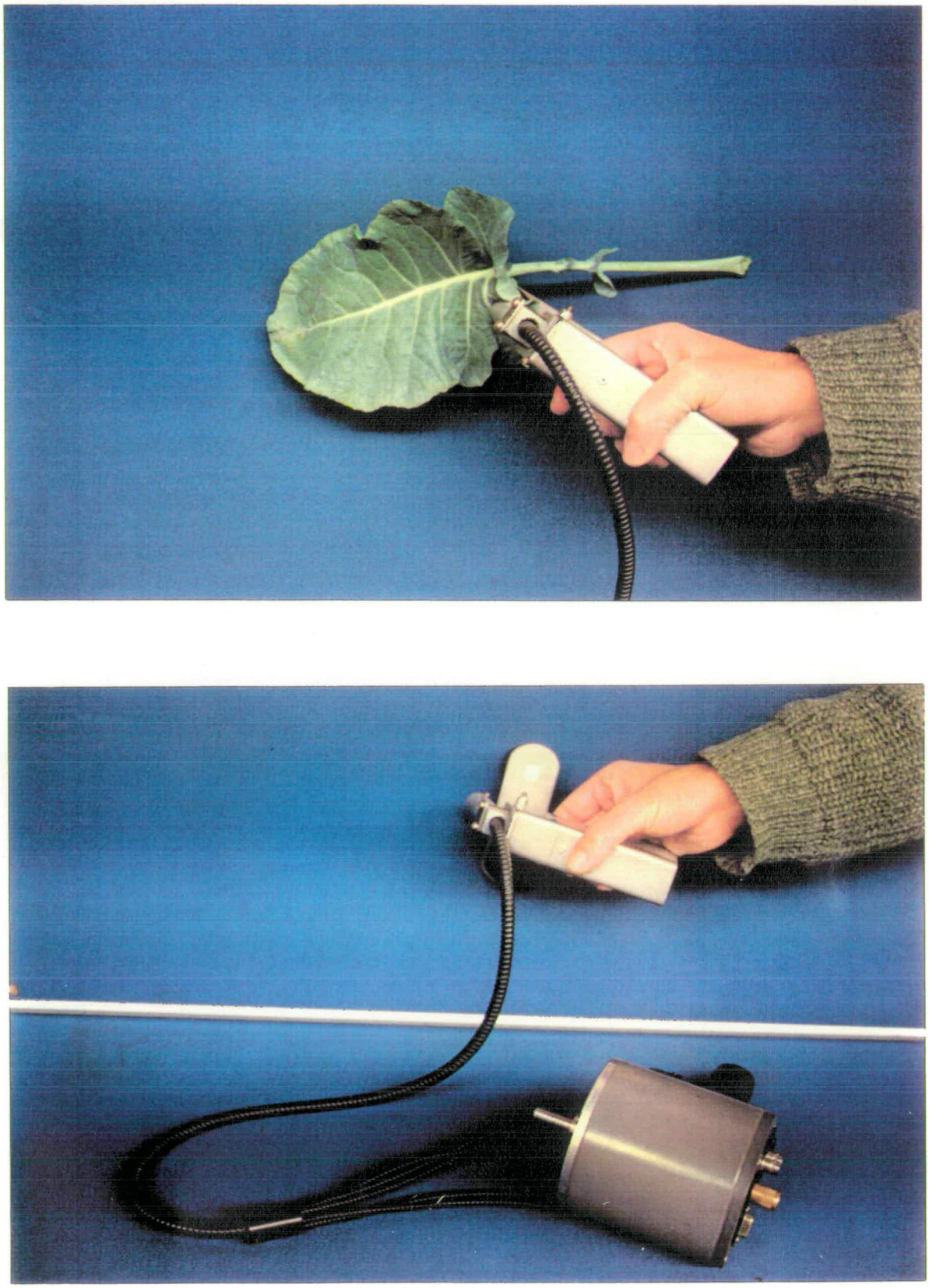


Plate 4. Stapler-like attachment to capture maximum reflectance from leaves.

circuits. The preamplifier, connected as close as possible from the detector output converted the detector current signal to an output voltage. This voltage was then introduced to the amplifier stage and finally fed to a digital meter.

Calibration is essential in every spectral radiometer. Reflectance measurements used a barium sulphate reference, while transmittance measurements used a laser to irradiate the detector at a known wavelength and intensity. In the latter, the detector was moved in parallel to the main shaft towards the condenser lens until properly focused. A special piece containing the laser diode was screwed to the radiometer assembly and presented the laser diode to the condenser lens. In addition dark level calibration was performed after closing the shutter.

A bifurcated randomly combined glass optic fibre bundle was used to collect the reflected radiation. One of the legs of the fibre was connected to an halogen lamp and the other was screwed to the radiometer eliminating any stray radiation. The radiometer was triggered twice during each measurement bringing the common end tip into direct contact with the barium sulphate reference during the first trigger and with the leaf sample during the second operation, obtaining the relative reflectance of the sample (see bottom photograph in Plate 4). The leaf support handled the leaf over a black surface creating enough pressure to avoid reflectance loss at the optic fibre end tip.

For transmittance measurements the illumination source was placed on one side of the sample and the radiometer on the other side. One optical fibre extreme was introduced into the halogen lamp box irradiating the sample through the common end tip which pressed the sample against the radiometer. The transmitted radiation entered the radiometer through the condenser lense.

Wider spectral range transmission measurements (up to 2500 nm) were obtained without the optical fibre, as the optical bundle transmission decayed rapidly after 1500 nm. A tube was fixed to the halogen lamp box with a condenser lens inserted inside the tube (see bottom photograph Plate 3). The radiation collected from the halogen lamp box was collimated and transmitted to the sample pressed between the other extreme of the tube and the radiometer. Sample size and increased bulk of the equipment limited this technique.

The stalk and veins of big brassica leaves caused stray radiation to come in, so a stapler-like grip was designed using a deflecting material that could take the shape of the sample during the

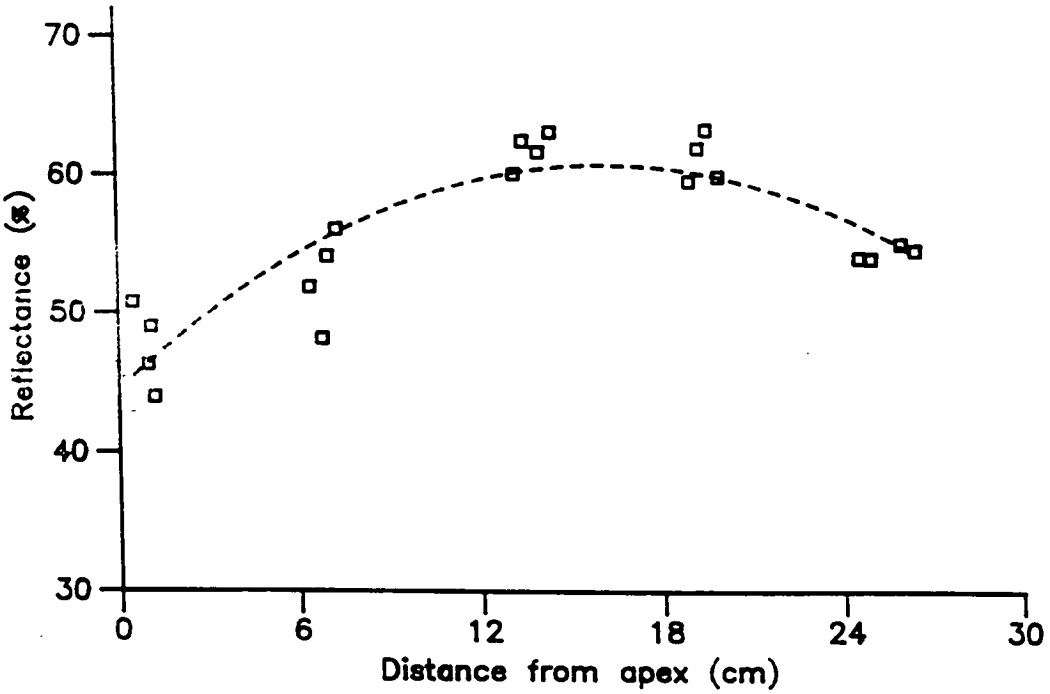


Fig. A3 Cabbage spectral measurements at 820 nm beside the leaf stalk.

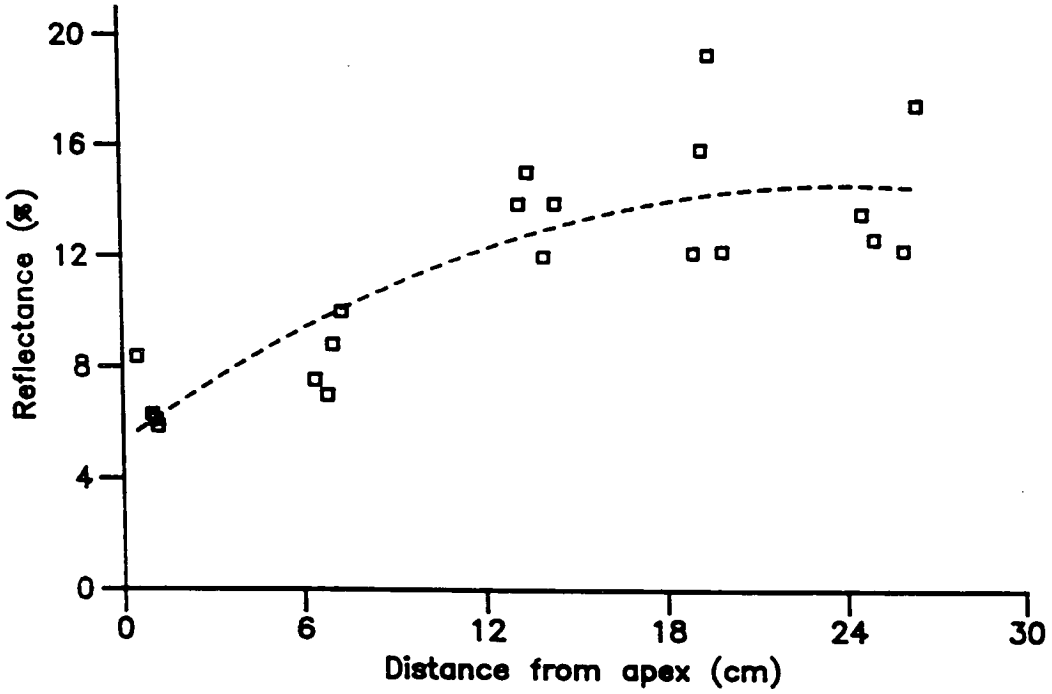


Fig. A4 Cabbage spectral measurements at 1450 nm beside the leaf stalk.

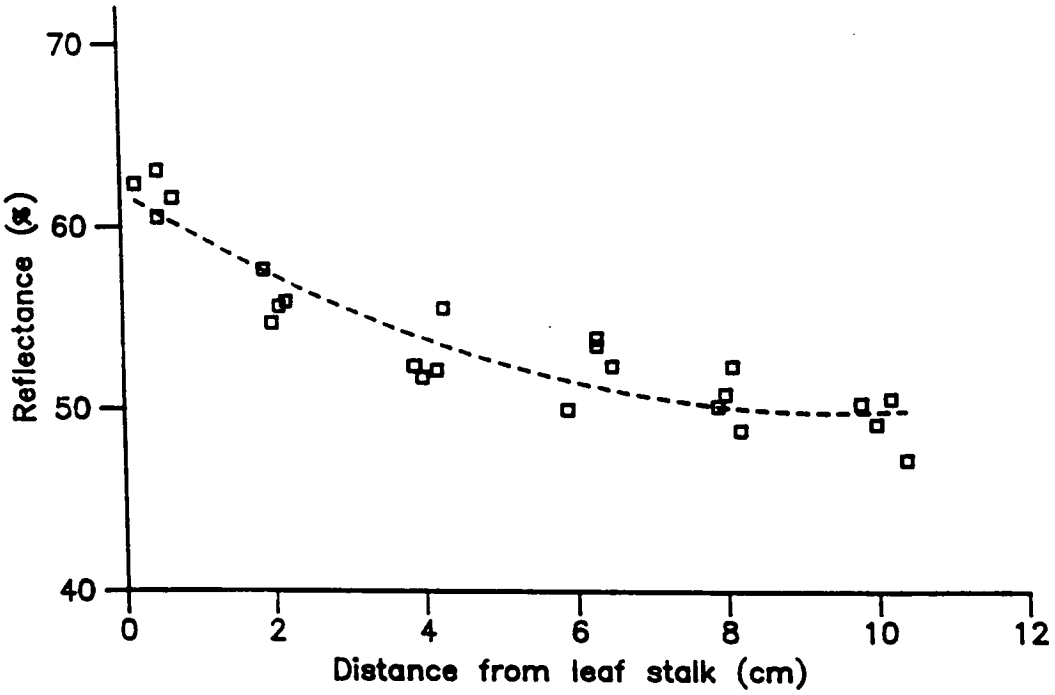


Fig. A5 Transversal cabbage measurements at 820 nm.

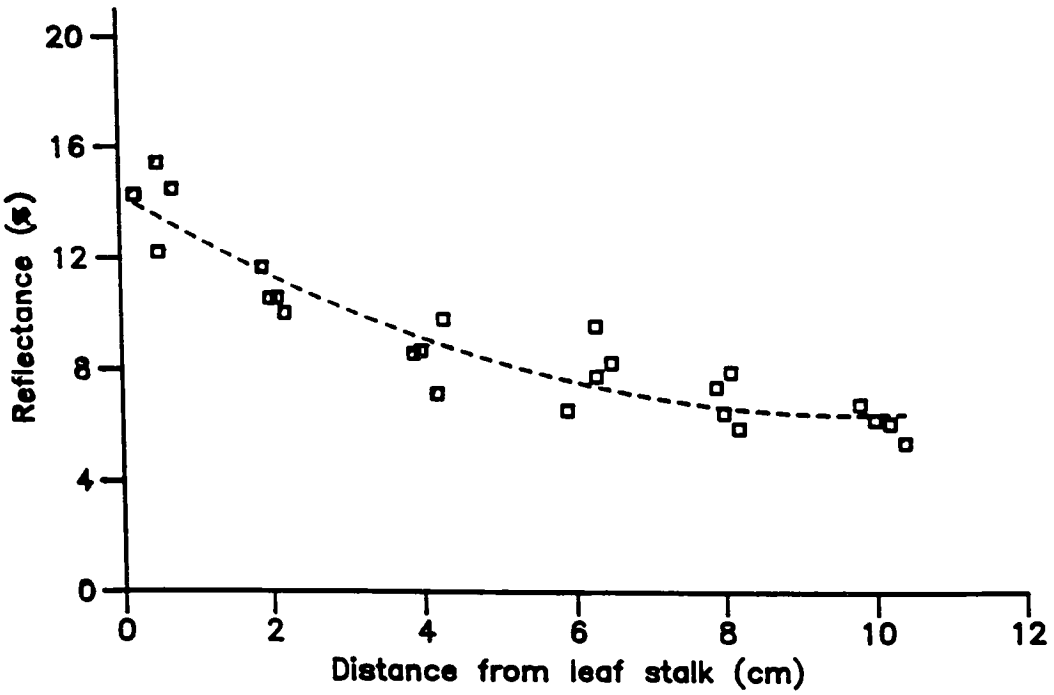


Fig. A6 Transversal cabbage measurements at 1450 nm.

measurement (see top photograph Plate 4). The adecuate pressing of the optical fibre contained in the grip, against the leaf sample was achieved with the use of a spring.

With the optical fibre placed in direct contact with the leaf tissue, reflectance measurements were taken in all the leaf contours of brassicas and different weed species. The wavelengths measured with the optical bandpass filters in the radiometer were 820 nm and 1450 nm, as the former is a crossover wavelength with low variance between leaves, and the latter represents the leaf water content.

Cabbage leaves 30 cm long were sampled beside the leaf stalk, Fig A3; the first measurement obtained at the leaf apex with additional samplings every 7 cm. The lowest reflectance was found at the leaf apex increasing to a maximum on the middle of the leaf. Measurements at 1450 nm indicate minimum reflectance and maximum water content on the leaf apex, Fig A4. Reflectance increased towards the middle of the leaf and even higher thereafter.

Transversal reflectance measurements referred to the leaf stalk were taken in the middle of the leaf every 2 cm. The highest reflectance encountered at 820 nm was near the stalk and decreased to a minimum reflectance at the leaf margin, Fig. A5. Minimum water content was encountered near the leaf stalk increasing to a maximum at the leaf margin, where the lowest reflectance at 1450 nm was recorded, Fig A6.

Fig. A7 shows the recorded reflectances at 820 nm in broccoli leaves 1, 3, 5 and 7 cm away from the leaf stalk, having maximum values at 3 cm. Fig. A8 shows the reflectance on the top side of a 45 cm long broccoli leaf beside the leaf stalk, obtained 1, 10, 20, 30 and 40 cm away from the leaf apex. The minimum reflectance at the leaf apex, increased to a maximum 10 cm away from the leaf apex decreasing thereafter.

A. patula (orache), an annual weed commonly encountered in vegetable crops, has relatively broad true leaves with toothed margins. Spectral measurements at 820 nm beginning at the leaf apex and beside the leaf stalk were carried out, Fig. A9, showing minimum reflectance at the leaf apex and increasing thereafter. Reflectance measurements at 820 nm carried out 1 cm away from the leaf apex were poorly affected by *C. album* leaf size, Fig. A10. Shorter leaves presented a more even reflectance distribution than longer leaves where highest reflectance differences were noted. *A.*

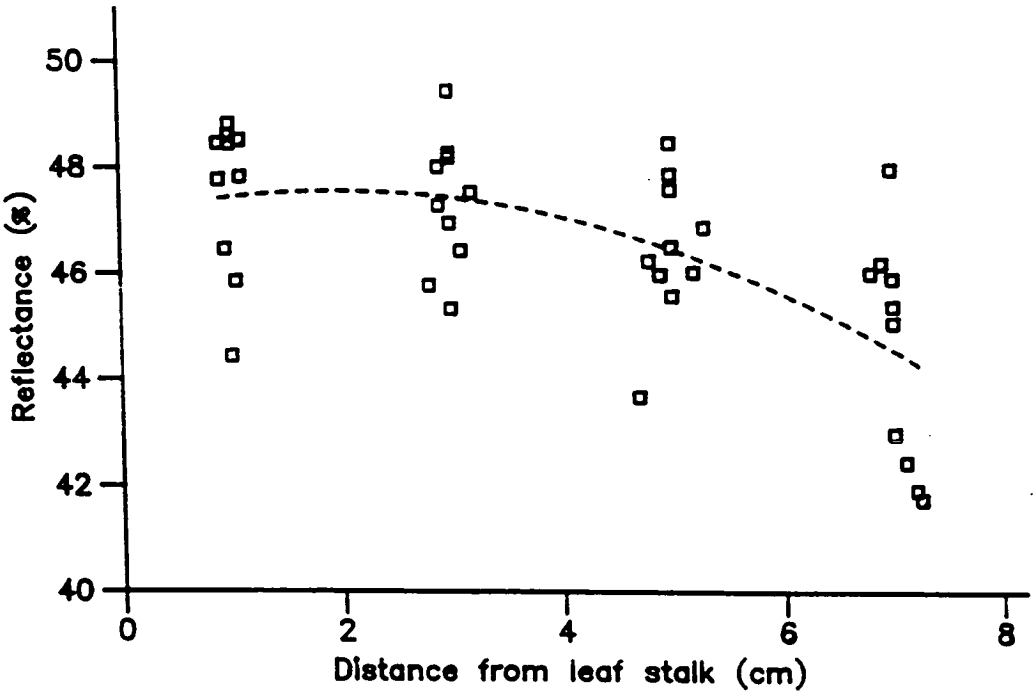


Fig. A7 Transversal broccoli measurements at 820 nm.

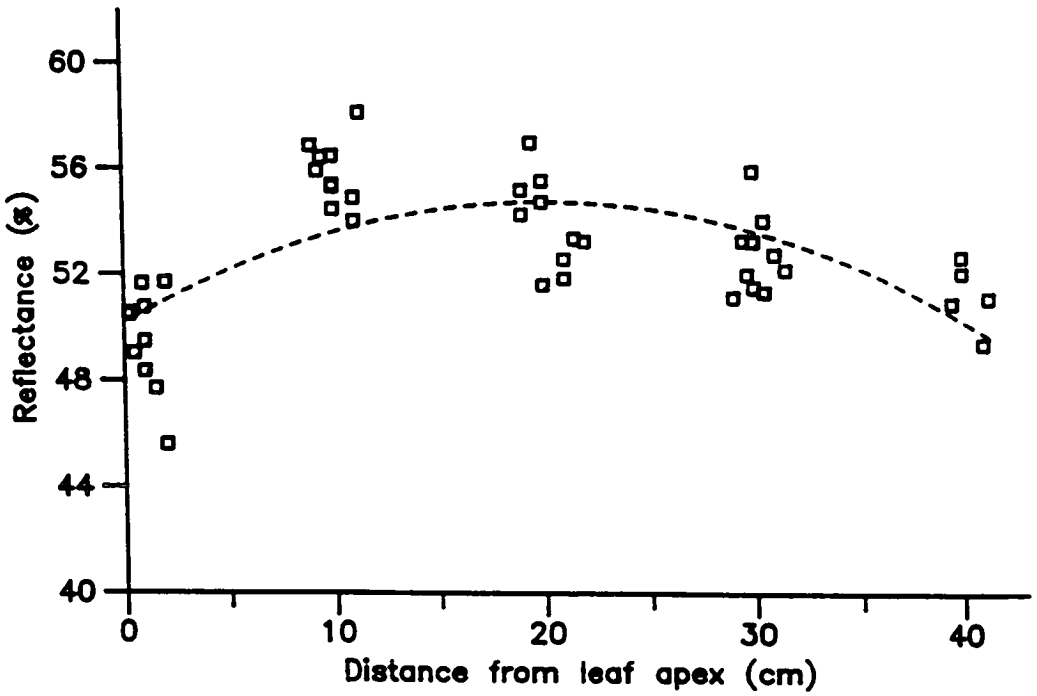


Fig. A8 Broccoli spectral measurements at 820 nm beside the leaf stalk.

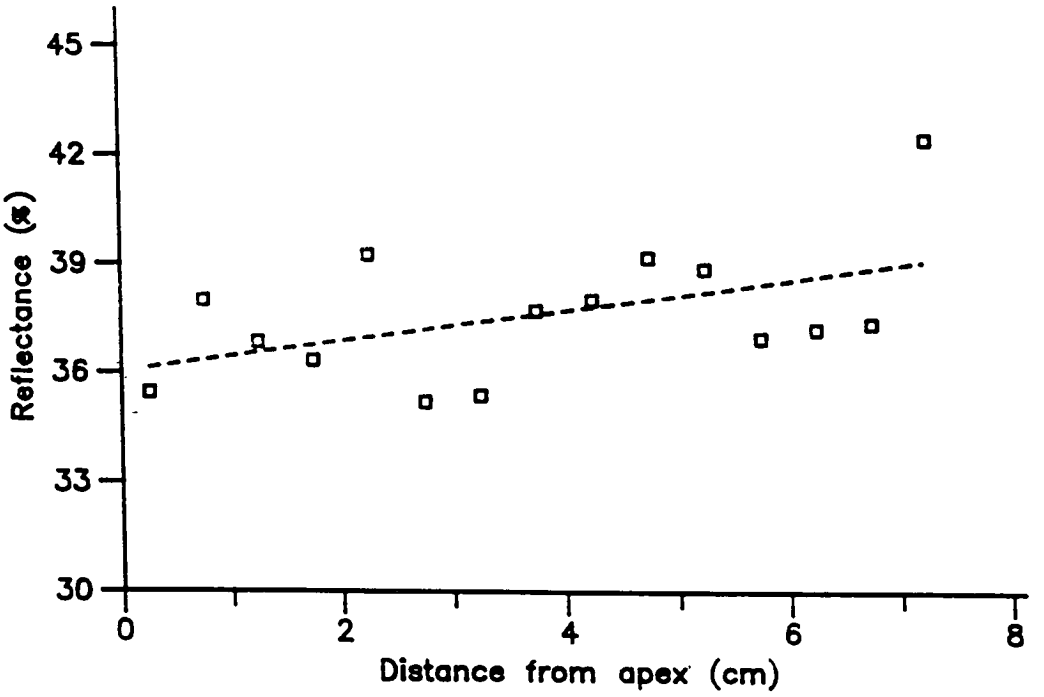


Fig. A9 Orache reflectance at 820 nm measured from the leaf apex.

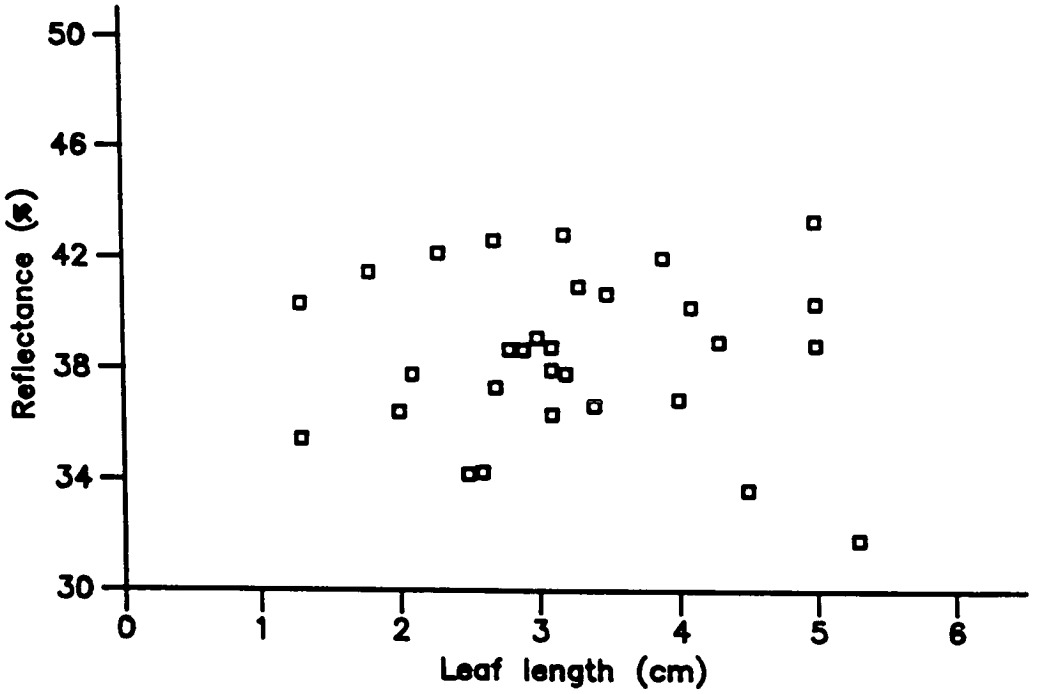


Fig. A10 Spectral measurements at 820 nm of different size fathen leaves.

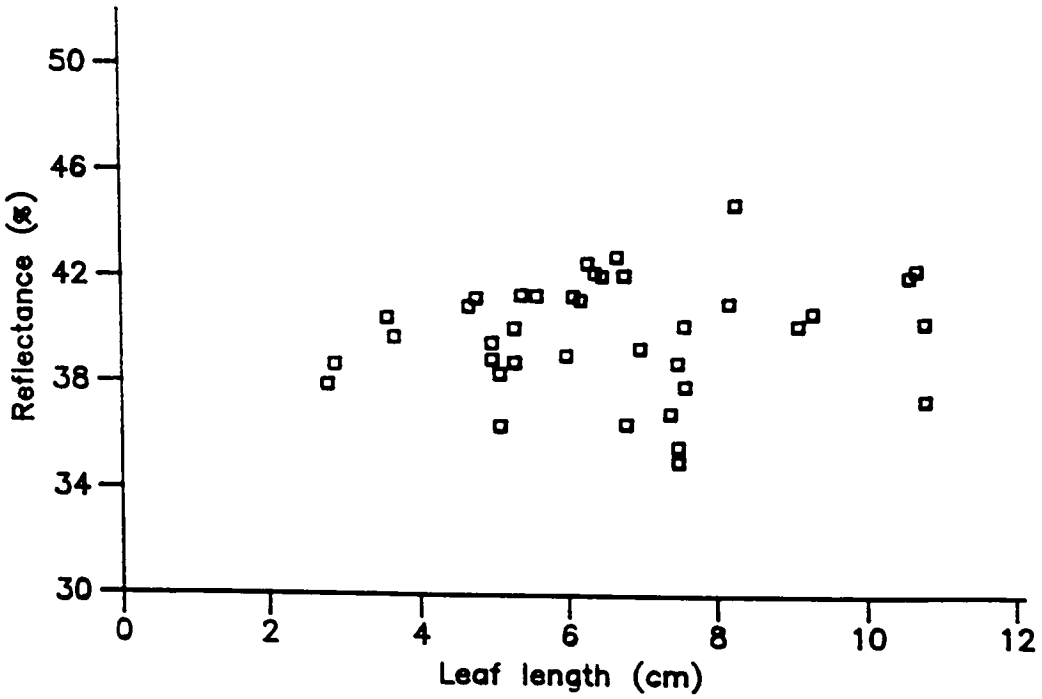


Fig. A11 Spectral measurements at 820 nm for different size orache leaves taken 2 cm from the leaf apex.

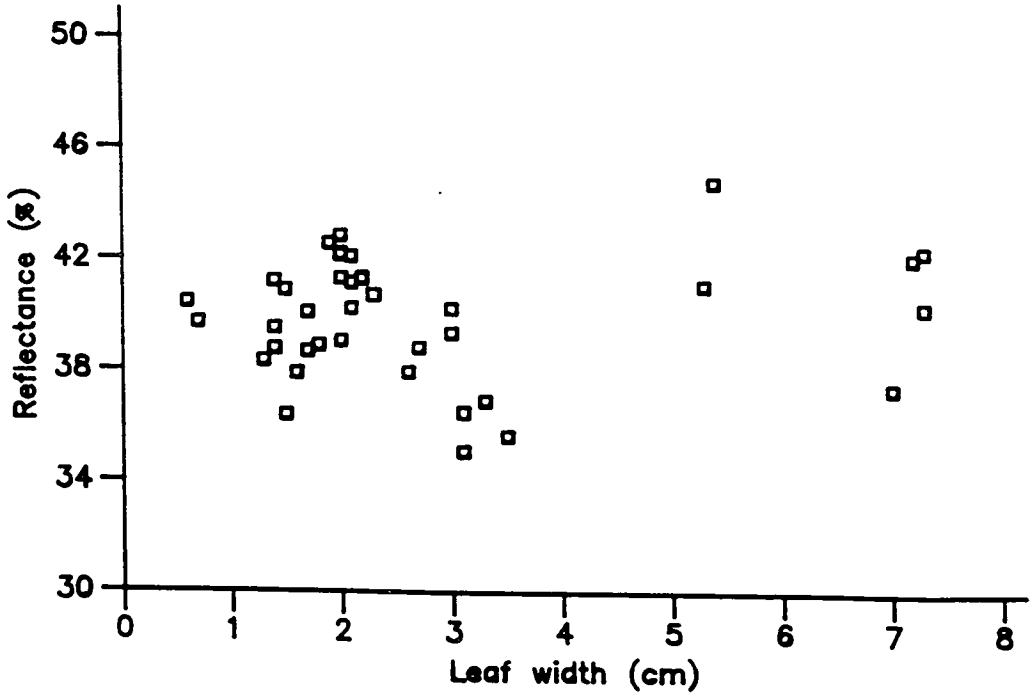


Fig. A12 Spectral measurements at 820 nm of different size orache leaves, taken 2 cm from the leaf apex.

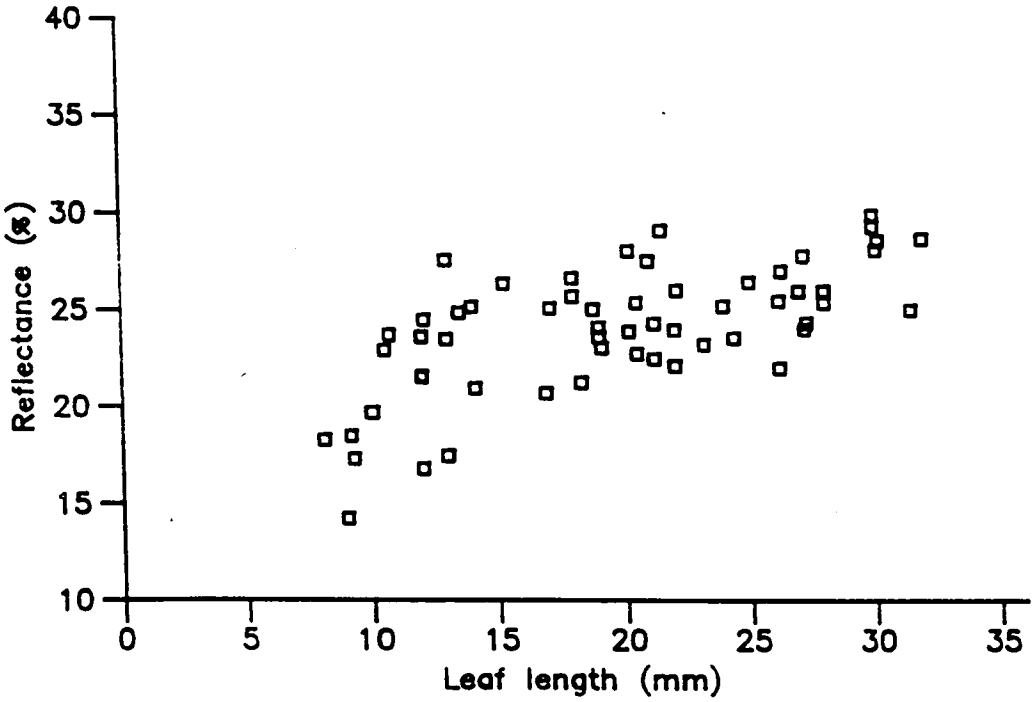


Fig. A13 Spectral measurements at 820 nm for different size chickweed leaves sampled on the leaf centre.

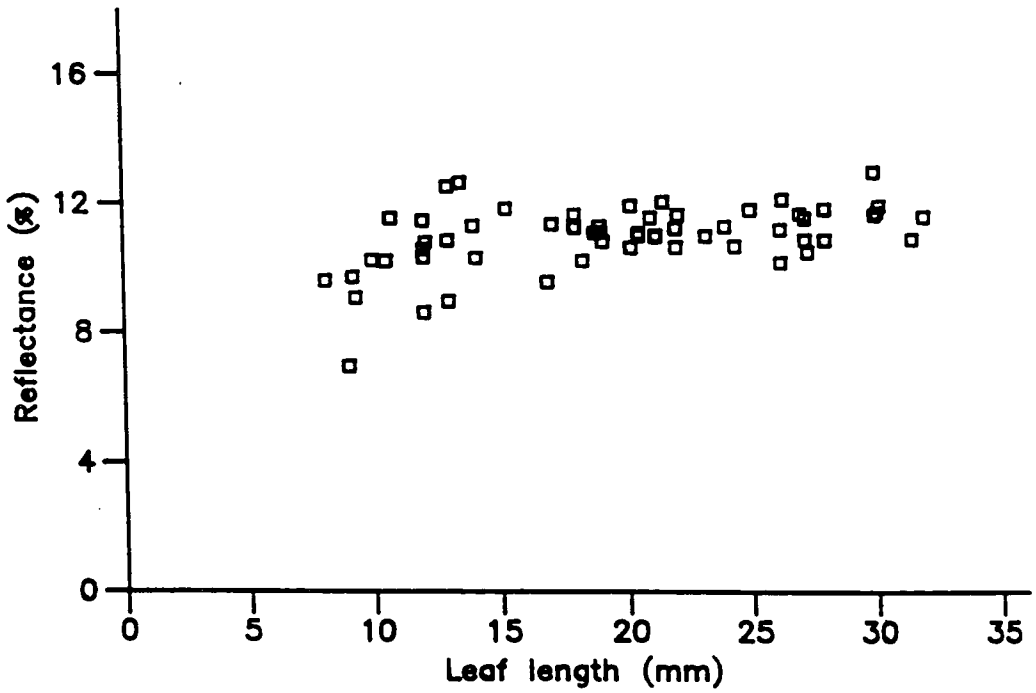


Fig. A14 Spectral measurements at 1450 nm from different size chickweed leaves, sampled on the leaf centre.

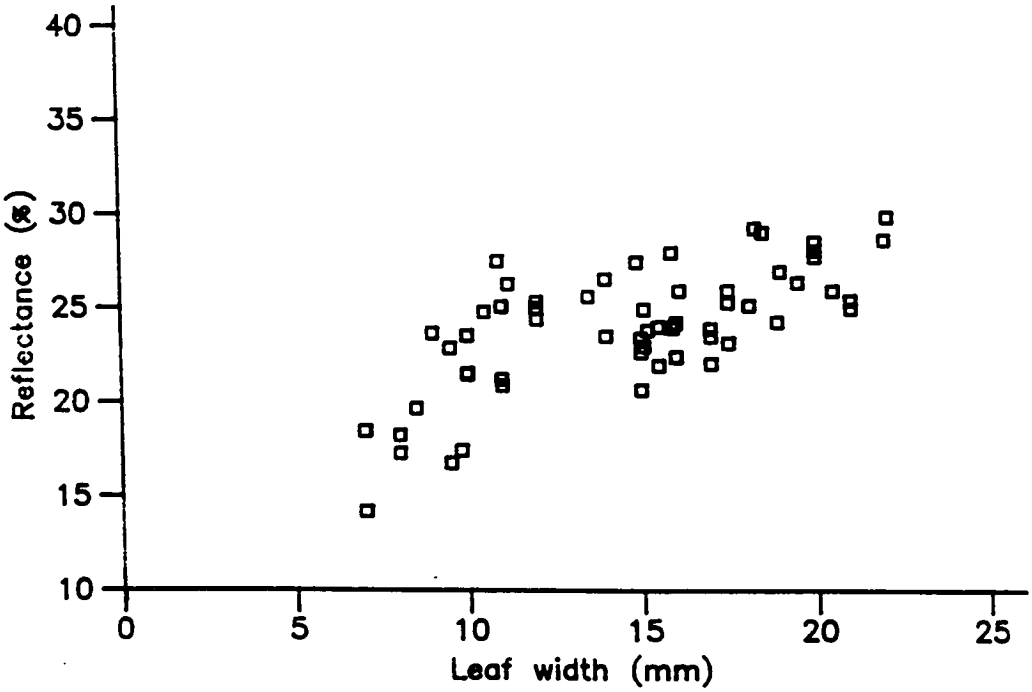


Fig. A15 Spectral measurements at 820 nm from different size chickweed leaves sampled on the leaf centre.

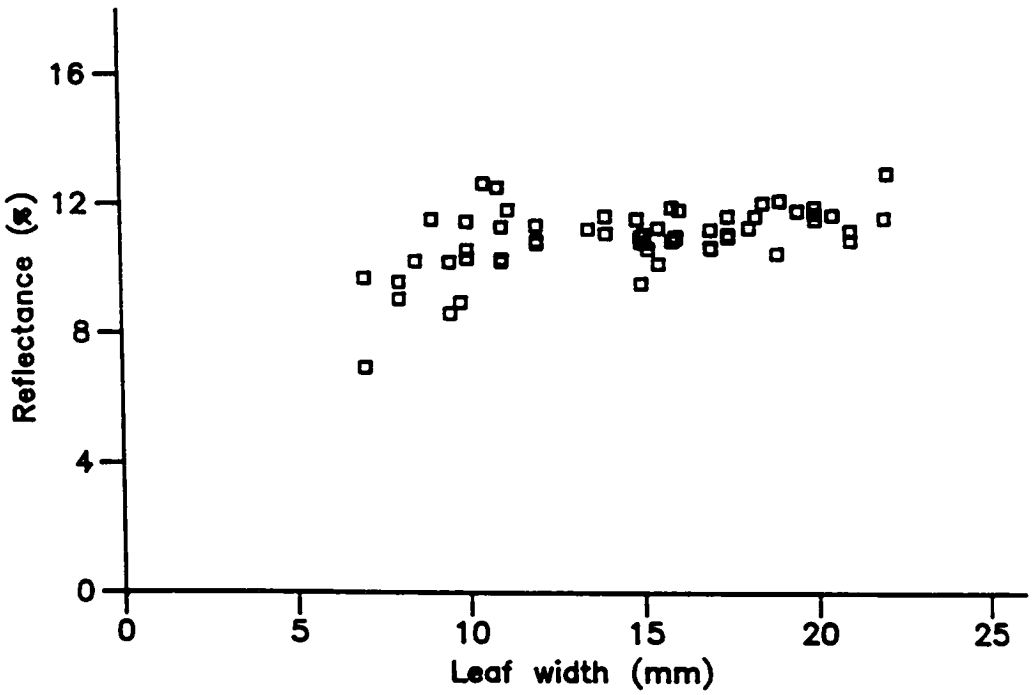


Fig. A16 Spectral measurements at 1450 nm from different size chickweed leaves, sampled on the leaf centre.

patula (common orache) reflectance sampled 2cm away from the apex didnot change substantially with leaf length and width, Figs. A11 and A12.

S. media (chickweed), the most common annual broad-leaved weed postrates on the soil with small oval leaves and white flowers. Good correlation between reflectance at 820 nm and leaf length was achieved, Fig. A13. Reflectance increased also with leaf width at 820 nm, showing broader leaves a higher reflectance, Fig A15. Reflectance at 1450 nm was constant for all the leaves sampled, Figs. A14 and A16.

Spectral measurements at 820 nm were obtained in grass species and plotted in Fig. A17, referred to the ligule. Reflectance decreased as measurements were taken further away from the ligule, with *H. lanatus* presenting the steepest slope.

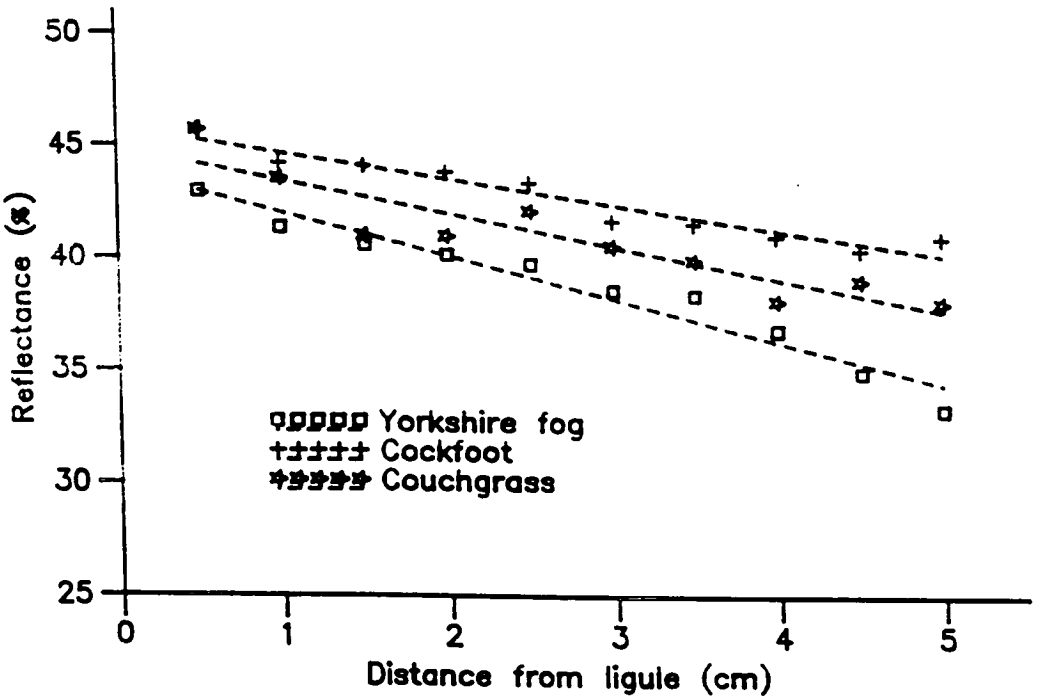


Fig. A17 Reflectance measurements for three grasses at 820 nm.

APPENDIX B

APPENDIX B: WEED SPECIES AND CROP VARIETIES SIGNATURES

Atriplex patula (Orache, Dungle-weed, Iron weed, Spreading Orache.)

This annual plant species, which badly hinders beet harvesting and causes problems in maize, differs from fathen in that it prostrates having only the flowering stems upright. The cotyledons and first true leaves bear a resemblance to those of fathen, but the cotyledons are green beneath and are much much narrower with short stalks. The true leaves are also long and narrow, with two distinct teeth at the base (Fig. B1).

Capsella bursa-pastoris (Shepherd's purse, Pickpocket, Lady's purse.)

This widespread problem weed is an upright annual with small white flowers, followed by seed pods of heart shape, borne along the whole length of the flowering stems. Cotyledons are oval, smooth, with a short stalk (Fig. B4).

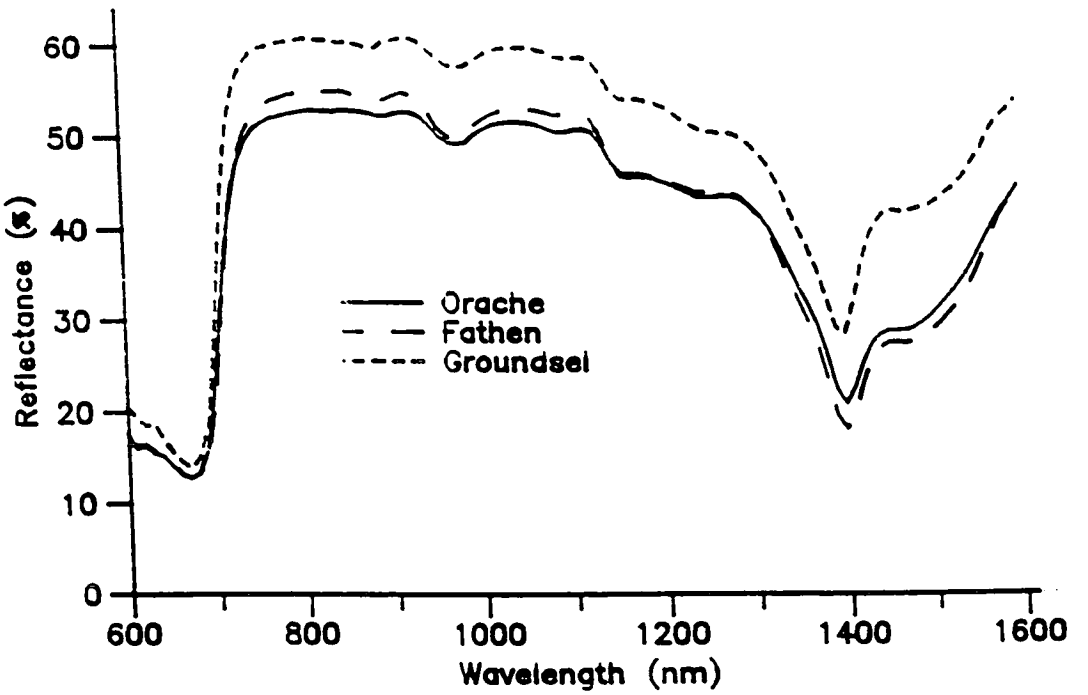


Fig. B1 Weed signatures.

Chenopodium album (Fathen, Dung weed, Goose-foot, Muckweed.)

This weed removes a great quantity of nutrients from the soil in vegetable crops and spring cereals. It is an annual of erect habit, with dense clusters of small green flowers having true leaves with toothed margins. The cotyledons and first leaves are mealy, with a silvery appearance, the former being purplish beneath and borne on a purple stem (Fig B1).

Cirsium arvense (Creeping thistle, Corn thistle, Prickly thistle.)

This last emerging upright perennial has clusters of purple flowers on top of tall stems. These stems generally arise from small pieces of root. Where seedlings occur cotyledons are large and fleshy. First true leaves carry spines along their margins, subsequent leaves are light green, lance shaped and spiny (Fig B6).

Epilobium angustifolium (Rosebay Willow-herb.)

The plant has a bluntly angled stem with alternating narrowly lanceolate leaves, which are bluish-green in colour with prominent lateral veins beneath. The flowers come in long erect racemes, pink to purplish-red, and have shortly clawed petals (Fig B8).

Euphorbia helioscopia (Sun spurge)

This weed species, found in arable fields and nutrient-rich soils, has an obovate shaped, pale green, shortly stalked stem. The flower umbel has five rays, with bracts similar to the stem leaves (Fig. B7).

Fumaria officinalis (Fumitory, Beggary, Smoke, God's fingers and thumbs.)

Fumitory, an annual with pale green feathery leaves and small purple flowers, has long lasting seeds with very long, narrow and light blue-green cotyledons, borne on a tall pinkish stem. The first true leaf is pale green and divided into stalked "leaflets" (Fig. B6).

Lamium album (White Dead-nettle.)

This weed, found in wastelands, is a hairy plant with long-pointed and sharply serrate cotyledons and is sometimes used as a nitrogen indicator. It flowers in whorls and has white, 2-lipped petals. The calyx tube curves upwards, with a ring of oblique hairs inside (Fig. B5).

Lamium purpureum (Red Dead-nettle, Deaf nettle, French nettle.)

This nettle species, found in almost all winter cereals, is encouraged by cultivation techniques. It is an annual weed of erect habit bearing small red flowers. Cotyledons are borne on long stalks with backward directed lobes at the base of the leaf. The first true leaves have shallow teeth, branched veins and are hairy and oval in outline (Fig. B5).

Malva sylvestris (Common mallow)

Mallow, a common weed found in wastelands and dry soils, has cotyledons with 3-5 rounded lobes borne on stalks. The flowers have long, deeply emarginate, purple petals with darker stripes (Fig. B8).

Matricaria inodora (Scentless Mayweed)

The first true leaves of this widespread upright bushy annual with daisy like flowers, are very narrow and generally have several lobes. Cotyledons are very small, oval and stalkless with later leaves very finely divided (Fig. B6).

Myosotis arvensis (Forget-me-not.)

This straggling annual species with small blue flowers, commonly encountered in winter cereals and woodlands, present small and hairy cotyledons slightly pointed when young but becoming rounded as they expand. The first true leaves are hairy and slightly cupped (Fig. B7).

Papaver rhoeas (Common Poppy.)

This weed species is found in cornfields, waysides and waste places and bears a red solitary flower with white milky juice. It has pinnatisect cotyledons with toothed and hairy segments (Fig. B8).

Polygonum aviculare (Knotgrass, Knotweed, Wire-grass, Wire-weed.)

An annual weed species, found in spring cereals and well spaced vegetable crops, presents narrow and long cotyledons borne on a short reddish stem. The first true leaf is broad at the base, long and lance shaped, while the older plant has long leaves which prostrate in the soil (Fig. B7).

Polygonum persicaria (Redshank, Willow weed, Persicaria, Redlegs.)

An annual of upright growth habit is found in all spring crops with heavy damp soils. It has small spikes of pink seed-like flowers and presents lance shaped cotyledons. The first true leaf is broad, smooth, dark green often tinged with red. Later leaves have a black blotch in the centre of the blade (Fig. B3).

Rumex obtusifolius (Broad-leaved Dock.)

Dock, a common weed species in meadows and pasture where it is a real problem, present narrow and long cotyledons often deep purple. First true leaves are broadly lance shaped. Lower leaves are broader and bear thick clusters of brownish green flowers on tough upright stems (Fig. B2).

Senecio vulgaris (Groundsel, Birdseed, Grindsel.)

An annual of upright growth with small yellow "tubular" flowers and a ragged appearance is common on waste and fallow land. It presents characteristic step-like teeth, stalkless and smooth first true leaves with a dark shiny green colour. Cotyledons are oval, narrowing to a stalk and purple beneath (Fig. B1).

Sinapsis arvensis (Charlock, Brassics, Cadlock, Corn mustard.)

An upright annual with characteristic yellow flowers and extensive root system competes strongly for soil nutrients in spring cereals. The cotyledons are kidney shaped and the first true leaf has a broad rounded tip and shallow indentations along its margins (Fig. B2).

Stellaria media (Common Chickweed, White Bird's-eye, Winter-weed.)

This, the most commonly occurring annual broad-leaved weed, chokes plants as it spreads over them. The seedling is light green, tall, has pointed lance shaped leaves and likes water. The older plant has small oval leaves and a prostrate matted habit of growth (Fig. B2).

Taraxacum officinale (Dandelion.)

This plant which has yellow flower heads and a long taproot is found in rich meadows, dryish grassland and waste places. The oblong, deeply lobed, serrate cotyledons are borne on a 1-headed, hollow stalk (Fig. B3).

Urtica urens (Small nettle, Annual nettle, Burning nettle.)

This upright branching annual with clusters of small green flowers is found in vegetables, especially brassicas, preferring friable rich soils. It has small, oval, slightly hairy cotyledons, notched at the apex. First true leaves are coarsely toothed with pointed indentations, yet oval in outline and with stinging hairs (Fig. B5).

Veronica persica (Common Field-speedwell, Large Bird's-eye.)

This prostrate annual with small blue flowers, which die away in mid-summer, is common in winter cereals. It presents a large seedling with "spade" shaped hairy cotyledons. The first true leaf is hairy and regularly toothed (Fig. B4).

Viola arvensis (Field pansy, Field heartsease, Corn pansy, Cat's faces.)

This annual of upright tufted appearance with small yellowish or purple "pansy" flowers has oblong and dark green cotyledons. The blade of the first true leaf has a broadly, rounded tip and toothed margins (Fig. B4).

GRASS WEEDS

Elymus repens (Common couch)

This grass, common in arable and waste land, generally occurrs in localised patches or tufts. It spreads by creeping cord-like rhizomes through the soil. The flower head is spike shaped and variable in length. Seed production is variable and is low compared to annual grasses, but most seeds germinate in the first autumn and can survive for 4-5 years (Fig. B9).

Phleum pratense (Timothy.)

Rather coarse tufted grass, is common in grasslands with many varieties covering a range of growth habits. It is generally light green or greyish-green and the flowering head is a dense cylindrical spike. The spikelets are small, single flowered and tightly packed; green, often tinted pink or white (Fig. B9).

Holcus lanatus (Yorkshire-fog.)

This perennial grass, 20 to 100 cm high, is useful for grazing when young. It has no rhizomes and present compactly tufted stems. Panicles are pale green, pinkish or purple (Fig. B9).

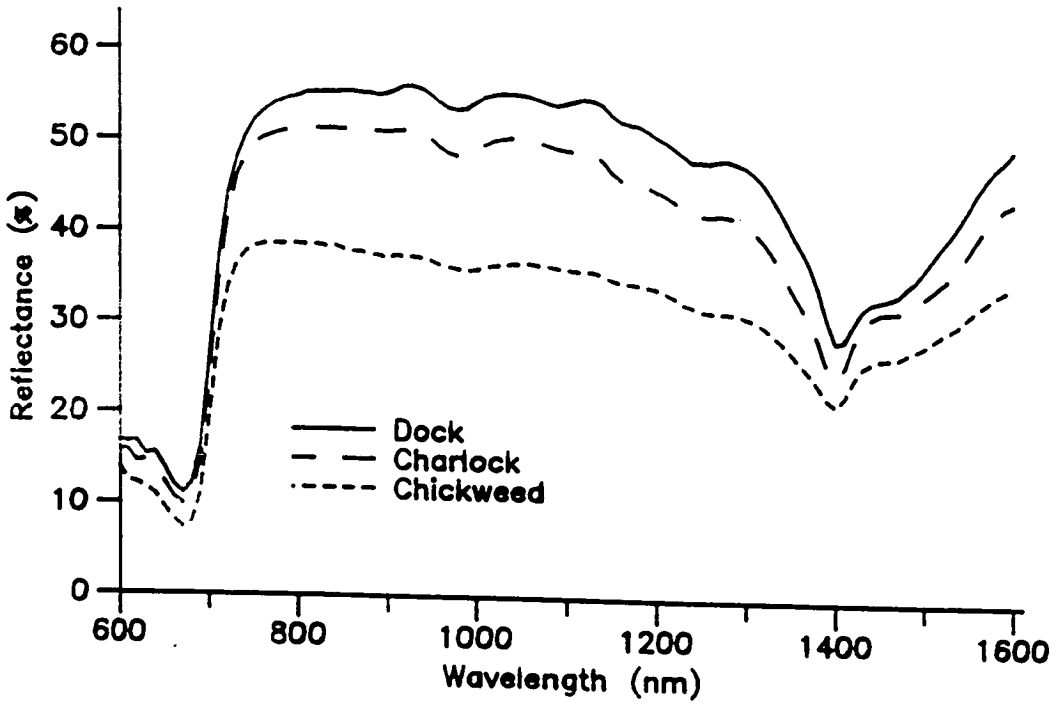


Fig. B2 Weed signatures.

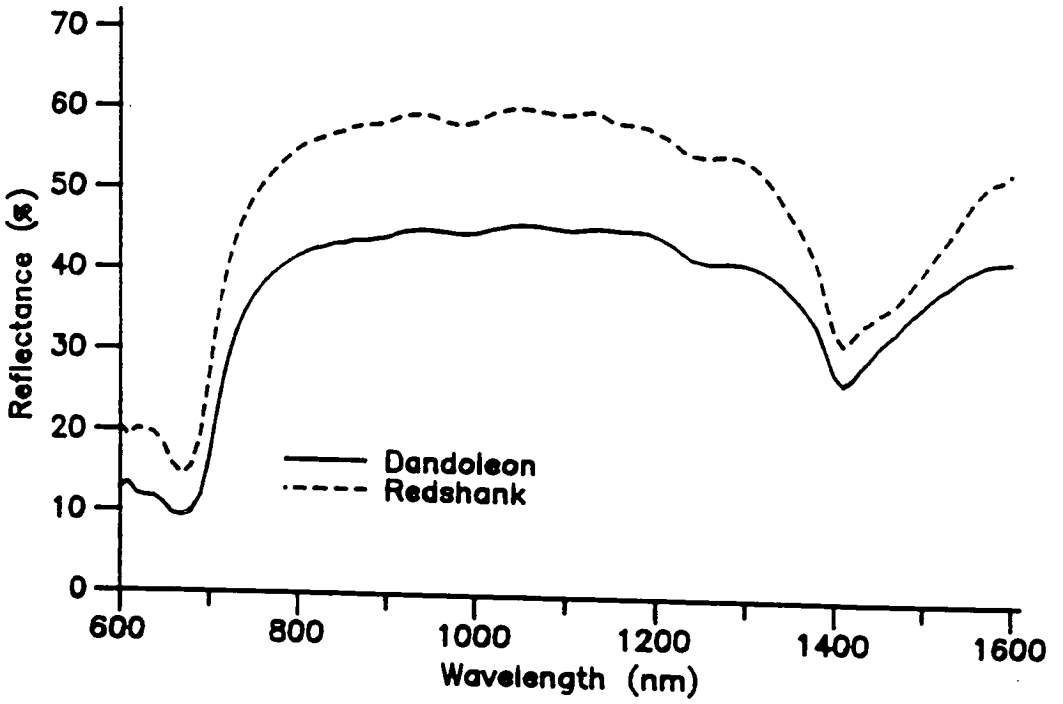


Fig. B3 Weed signatures

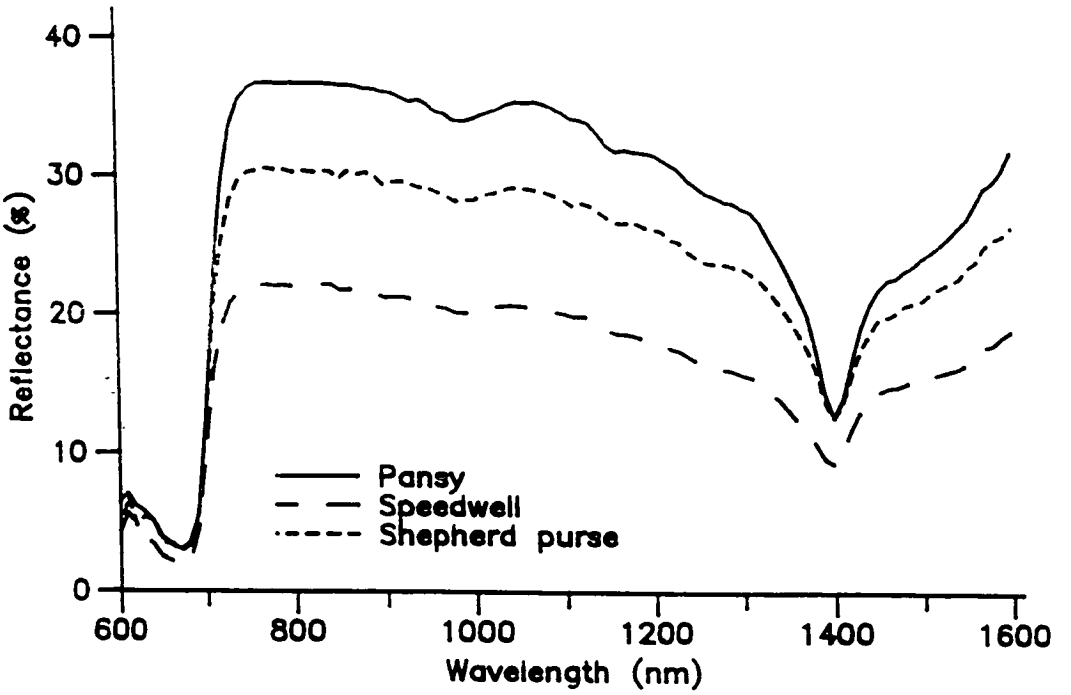


Fig. B4 Weed signatures.

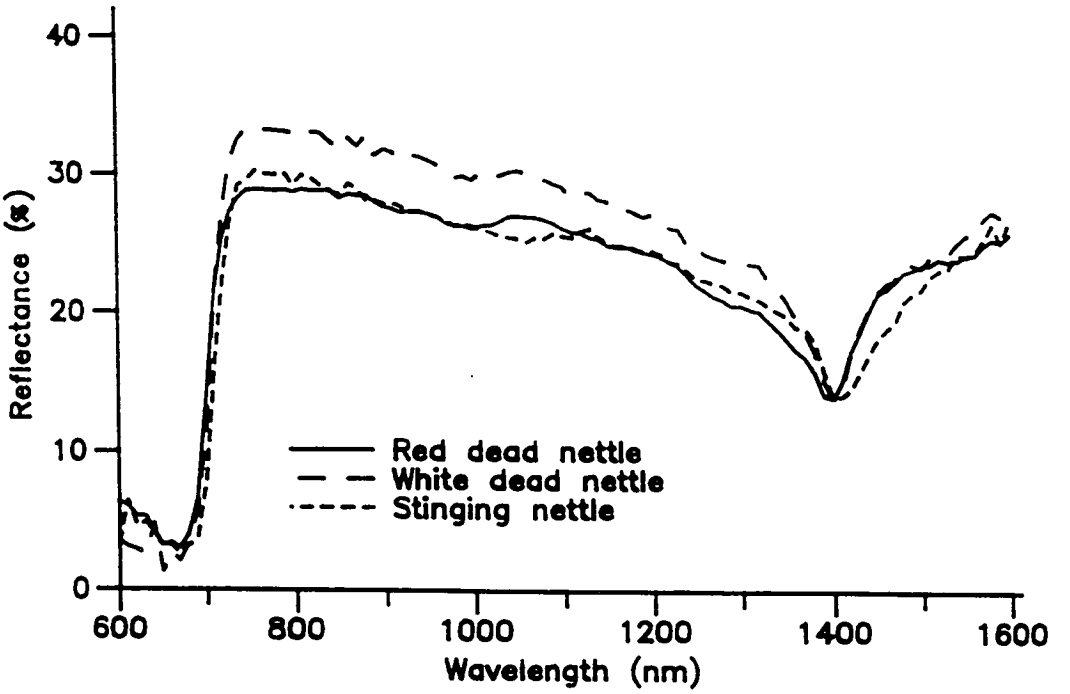
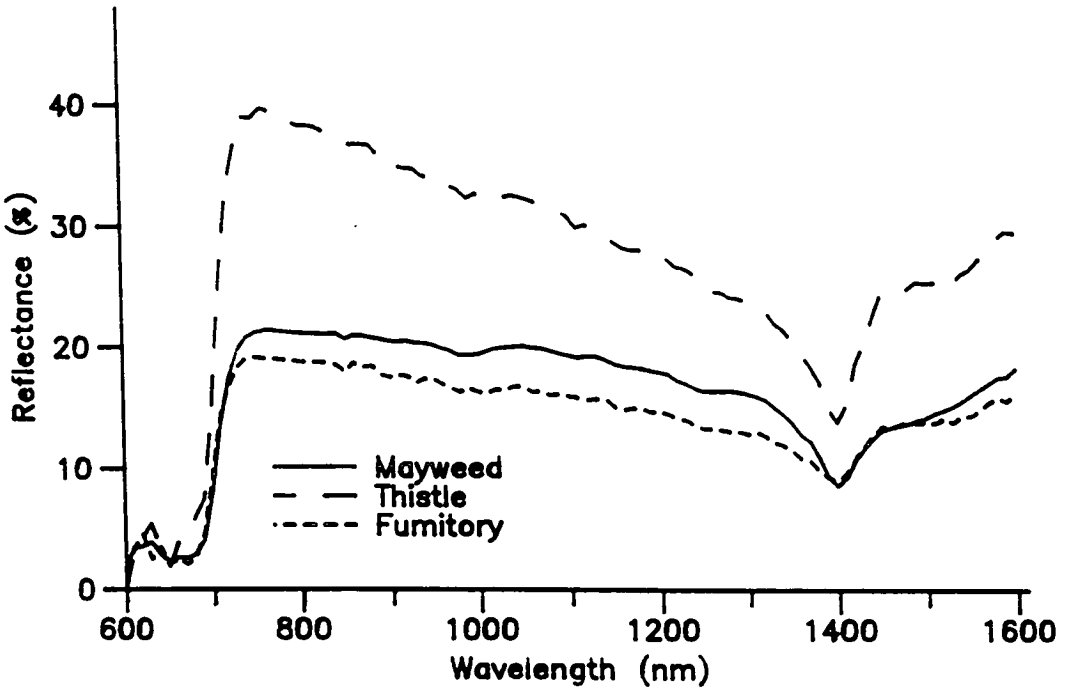


Fig. B5 Weed signatures.



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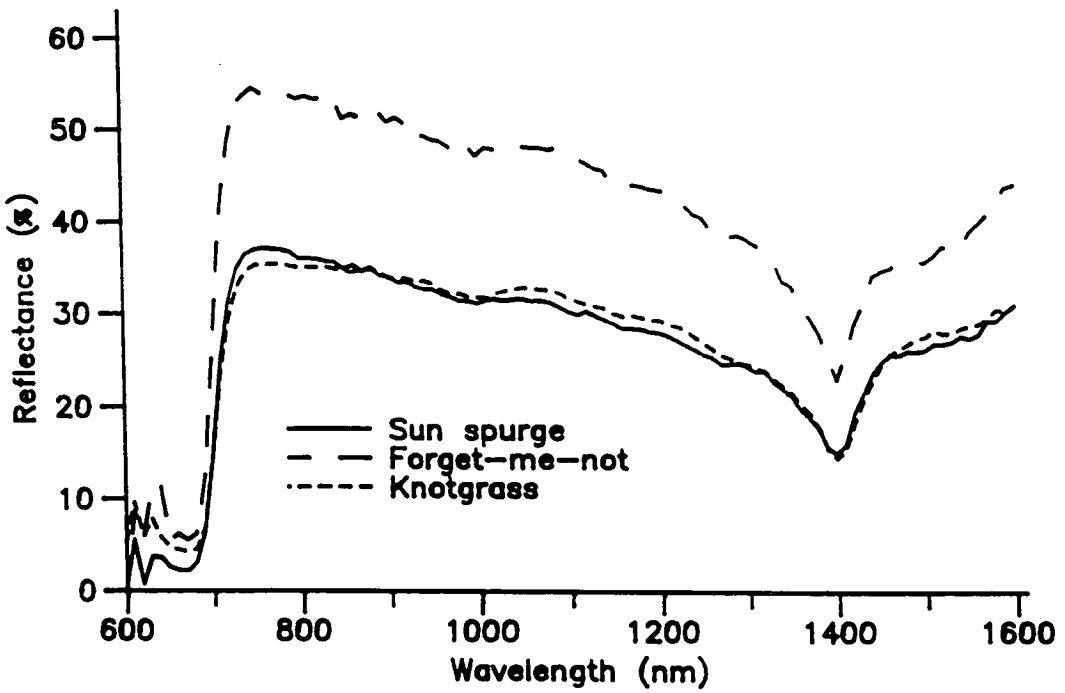


Fig. B7 Weed signatures

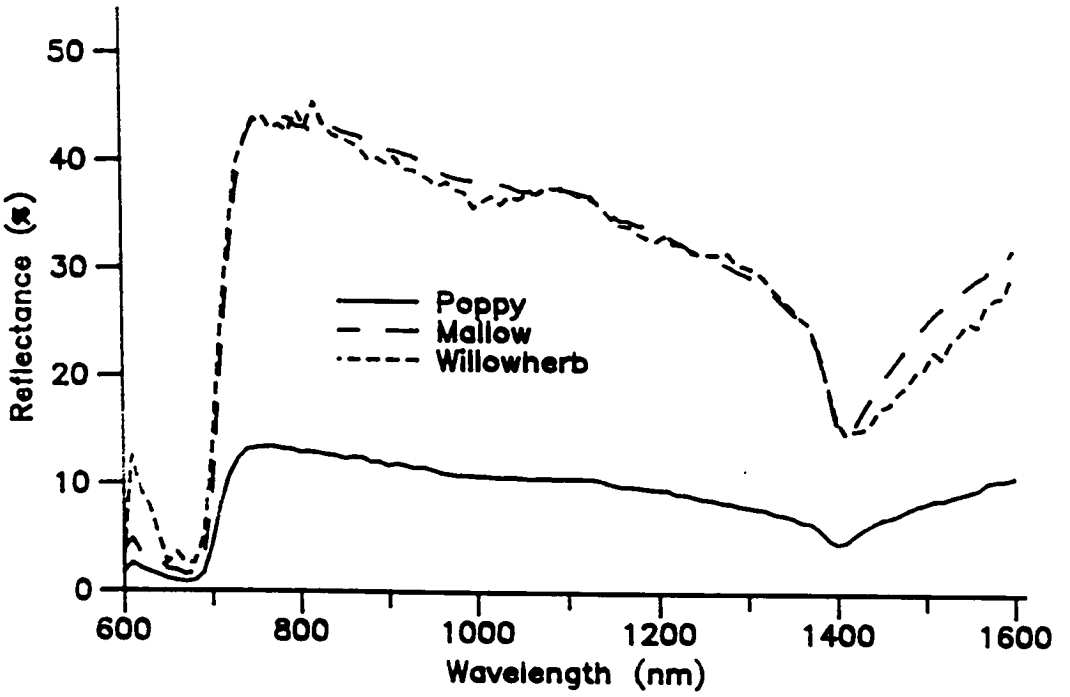


Fig. B8 Weed signatures.

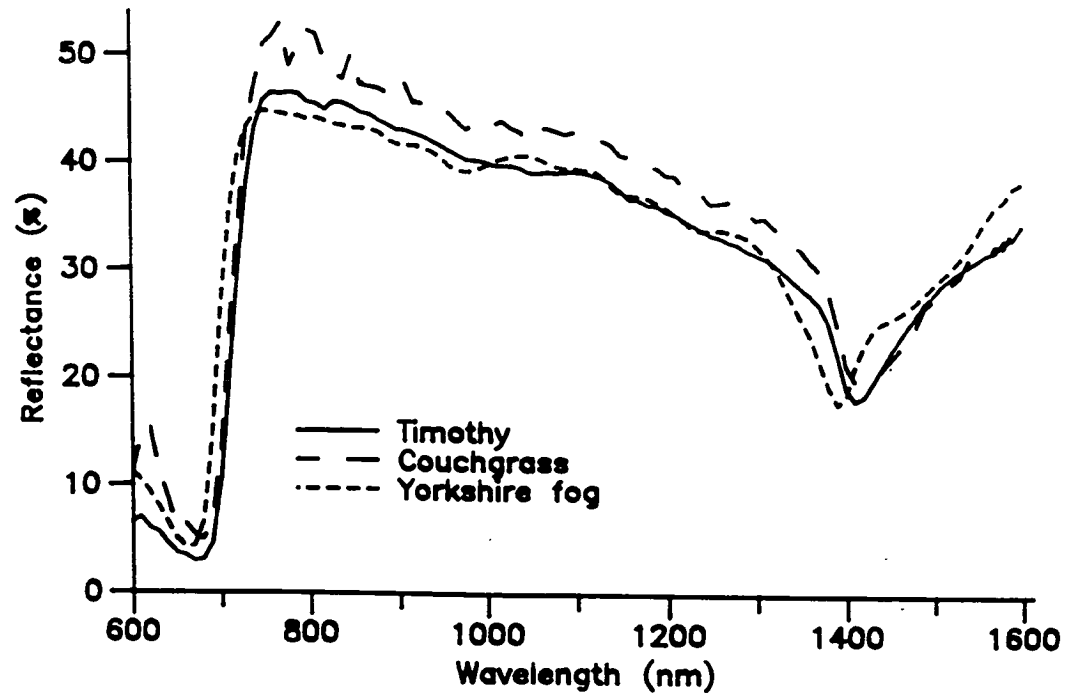


Fig. B9 Weed signatures

BROCCOLI AND CABBAGE VARIETIES.

Reflectance signatures from different cabbage and broccoli leaves are shown in Figs. B10 and B11. Plates 5 and 6 show photographs of this leaves which help to understand the big spectral differences encountered between Autumn pride and Jupiter.

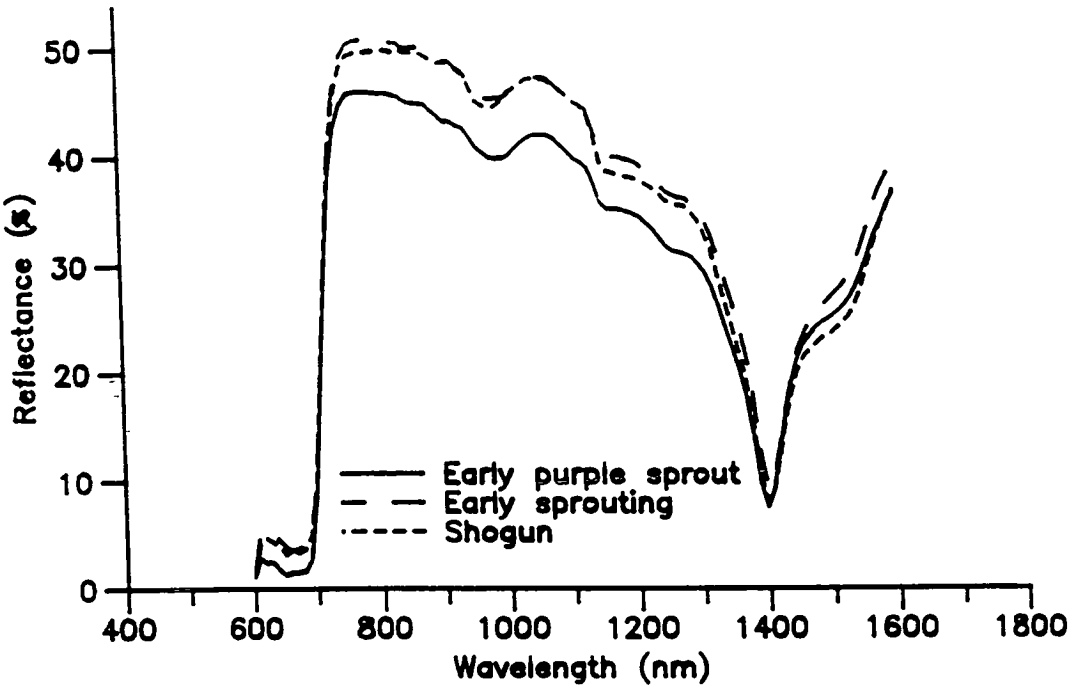


Fig. B10 Broccoli signatures

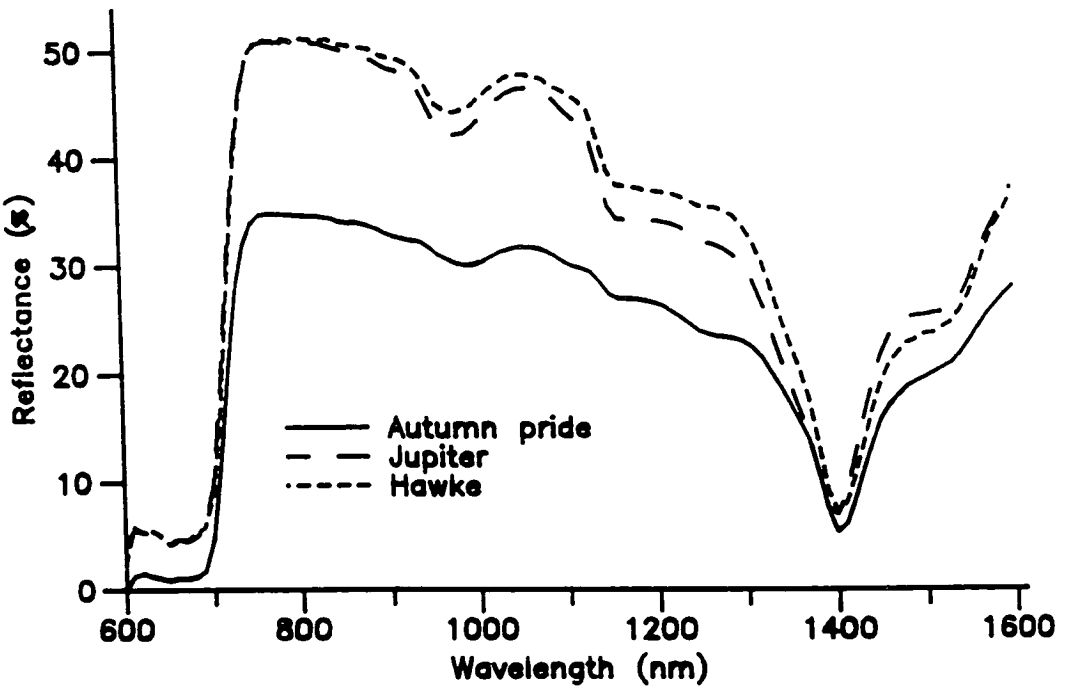
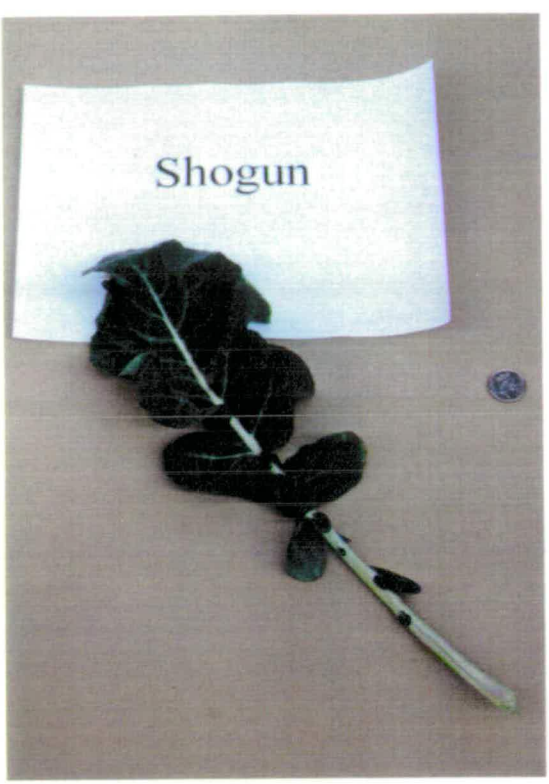


Fig. B11 Cabbage signatures



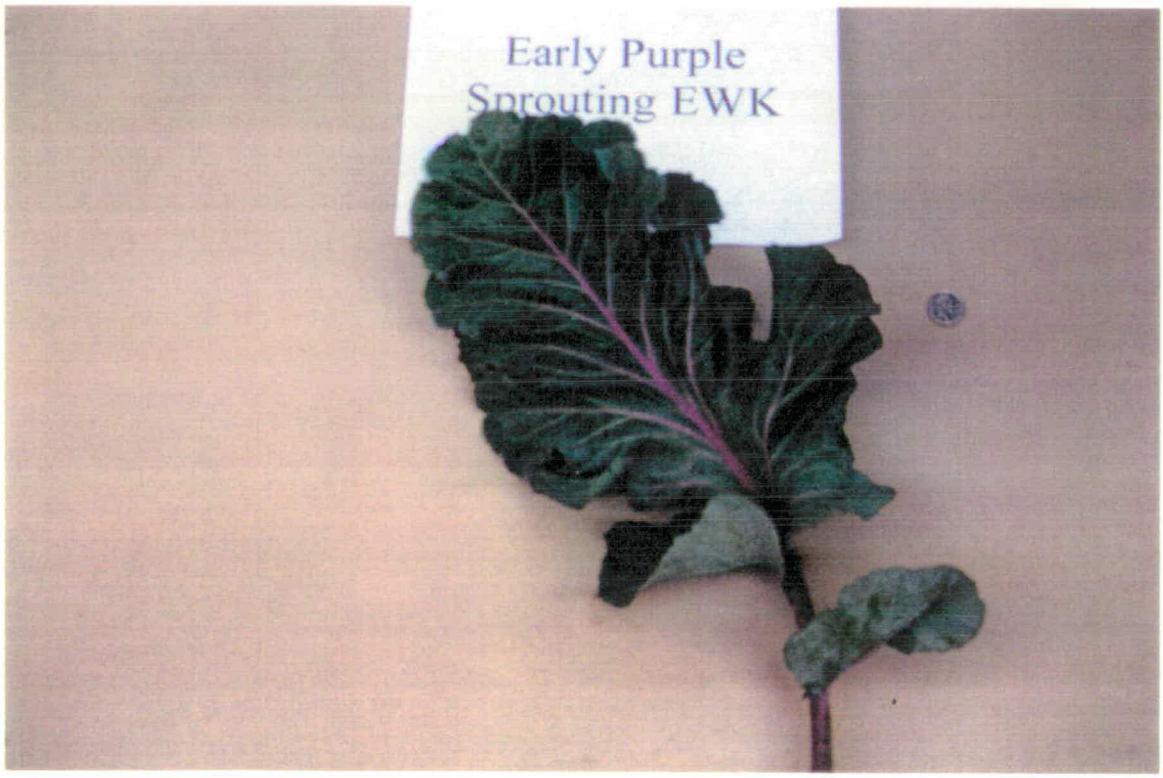


Plate 5. Broccoli varieties.

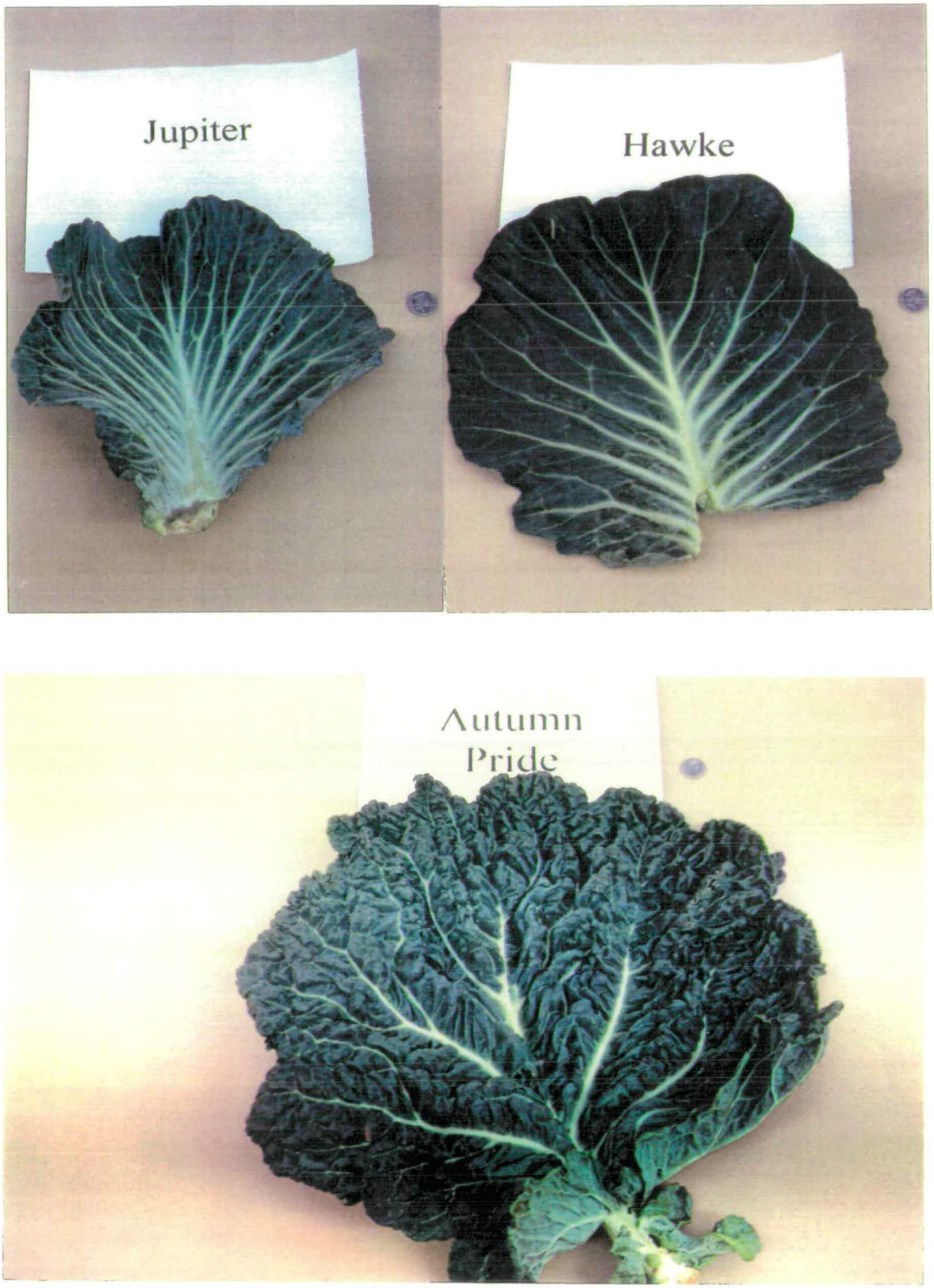


Plate 6. Cabbage varieties.

APPENDIX C

APPENDIX C: DISCRIMINANT ANALYSIS

BMDP (Brown et al., 1988) is a statistical package which uses instructions consisting of paragraphs and commands to introduce and manipulate the data to be analysed. Each paragraph starts with a slash (/) and finishes with a full stop (.). Different programs within the package have some basic set of instructions.

The INPUT paragraph tells how many variables to read per case and how the data is formatted in the file, generally set to **free**.

The VARIABLE paragraph names the variables read per case.

The GROUP paragraph classifies and names group of cases appearing as such in the output.

The END paragraph marks the end of the BMDP instructions.

Discriminant analysis uses these instructions as noted in the following example of an experiment carried out with cabbages in September 1992. A total of 101 variables were used, 100 for the wavelengths and the first one for the group discriminator.

The INPUT paragraph had 110 cases representing the spectra quantity introduced by the file c:\pc90\fede\cab92.prn. The program was acknowledged that only two wavelengths were used: 10 and 18, corresponding to the wavelengths of 680 nm and 760 nm.

The GROUP paragraph included codes and names for each crop/weed/soil category. The code was introduced before each spectrum and referred to as the group discriminator, named **day** in the VARIABLE paragraph. A total of 10 groups were used, having chick (chickweed) a code of 10, clover a code of 11 and cabbage a code of 46. The number of groups used could be controlled, but only 9 were used in this application letting the trial group as a testing unit.

The DISC paragraph is particular to discriminant analysis and can influence the number and order of variables entering the classification function. The limit values of F-to-enter and F-to-remove are used to control the entry or removal of variables. Entering variables must have Fs greater than the enter limit, always higher than the remove limit. The first enter and remove limits are used during forward stepping and the second ones during backward stepping. The JACK command request posterior probabilities and Mahalanobis' D^2 for each case and should

be specified if these statistics are needed. A tolerance limit of 0.01 was used and no variable entered the classification function whose squared multiple correlation (r^2) with the already entered variables exceeded (1-TOL), or whose entry would cause the tolerance of already entered variables to be unacceptable.

The PRINT paragraph is optional. The step command specifies which steps to be printed and with **no step** only step 0 and the last step are printed. When using **no point**, the program does not print the values of the canonical variables used in the plot. The PLOT paragraph is also optional and **no canon** plots the first two canonical variables only.

```
/input
title='cabbage/weed/soil analisis experiment 1992'.
variables=101.
format=free.
cases=110.
file is 'c:\pc90\fede\cab92.prn'.
/variables
names=day,'600','610','620','630','640','650','660','670','680','690','700',
'710','720','730','740','750','760','770','780','790','800','810','820','830','
840','850','860','870','880','890','900','910','920','930','940','950','
960','970','980','990','1000','1010','1020','1030','1040','1050','1060','
1070','1080','1090','1100','1110','1120','1130','1140','1150','1160','1170','
1180','1190','1200','1210','1220','1230','1240','1250','1260','1270','1280',
'1290','1300','1310','1320','1330','1340','1350','1360','1370','1380','1390',
'1400','1410','1420','1430','1440','1450','1460','1470','1480','1490','1500',
'1510','1520','1530','1540','1550','1560','1570','1580','1590'.
group=1.
use=18,10.
/group
codes(1)=10,11,12,13,14,15,16,40,46,17.
names(1)=chick,clover,willow,dock,redshank,couch,nettle,soil,cabbage,
trial.
use=1,2,3,4,5,6,7,8,9.
/disc
enter=2.0,4.0.
remove=1.9,3.9.
jack.
tol=0.01.
/print
no point.
no step.
/plot
no cannon.
/end.
```

The rest of the program includes means, standard deviations, classification functions, the Mahalanobis for each case and eigenvalues. The trial group determined the crop/weed/soil and crop/weed species/soil discrimination accuracies. The variables are printed in the same

order as in the GROUP paragraph. For each 10 spectra collected of each group 7 were used to train the classifier and the remaining three were used as a trial group. Weed species and soil categories had 3 trial spectra each, while cabbage had 9 trial spectra.

GROUP	trial	nettle	soil	cabbage
CASE				
1	chick	276.0 0.000	118.9 0.000	505.7 0.000
2	chick	371.7 0.000	196.2 0.000	592.3 0.000
3	chick	307.1 0.000	147.8 0.000	529.0 0.000
11	clover	581.5 0.000	445.4 0.000	717.3 0.000
12	clover	528.1 0.000	396.6 0.000	669.6 0.000
13	clover	617.6 0.000	488.2 0.000	740.9 0.000
21	willow	6.3 0.234	83.9 0.000	136.3 0.000
22	willow	11.6 0.009	137.2 0.000	83.9 0.000
23	willow	4.8 0.142	137.0 0.000	81.2 0.000
31	dock	350.8 0.000	206.9 0.000	543.6 0.000
32	chick	352.5 0.000	189.7 0.000	564.8 0.000
33	dock	420.0 0.000	247.2 0.000	625.3 0.000
41	redshank	33.4 0.000	281.8 0.000	15.5 0.001
42	redshank	20.6 0.000	242.1 0.000	26.7 0.000
43	redshank	21.5 0.000	247.8 0.000	25.1 0.000
51	couch	1109.8 0.00	1951.8 0.000	563.9 0.000
52	couch	1287.9 0.000	2195.4 0.000	693.1 0.000
53	couch	1113.5 0.000	1970.3 0.000	567.1 0.000
61	nettle	0.6 0.848	140.5 0.000	82.4 0.000
62	nettle	3.2 0.921	176.6 0.000	60.6 0.000
63	nettle	1.7 0.697	106.7 0.000	113.1 0.000
71	soil	124.7 0.000	0.4 1.000	409.0 0.000
72	soil	141.1 0.000	0.1 1.000	439.2 0.000
73	soil	130.5 0.000	0.2 1.000	419.8 0.000
81	cabbage	112.5 0.000	474.6 0.000	1.1 1.000
82	cabbage	110.9 0.000	467.8 0.000	0.9 1.000
83	cabbage	95.4 0.000	432.8 0.000	0.2 1.000
91	cabbage	106.1 0.000	458.4 0.000	0.5 1.000
92	cabbage	81.8 0.000	406.1 0.000	0.3 1.000
93	cabbage	106.1 0.000	469.4 0.000	2.0 1.000
101	cabbage	112.5 0.000	476.2 0.000	1.3 1.000
102	cabbage	122.8 0.000	490.1 0.000	2.3 1.000
103	cabbage	130.0 0.000	505.3 0.000	3.4 1.000

All weed species were classified as weeds, cabbage as cabbage and soil as soil giving a 100% crop/weed/soil discrimination accuracy. The only weed species misclassified was dock in case 32 considered as chick, reducing crop/weed species/soil discrimination accuracy to 32/33 or 96.96%.

APPENDIX D

Table D.1 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
BROCCOLI LEAF	40	28	12
BROCCOLI STALK	10	7	3
Polygonum persicaria	22	16	6
Stellaria media	20	14	6
Matricaria spp.	10	7	3
Poa annua	10	7	3
Volunteer oilseed rape	20	14	6
SOIL	10	7	3
Total	142	100	42

TRIAL 1
Mature Broccoli
Site: Gowkly-Moss Farm
Experiment No. 1
1991

Table D.2 **Discrimination accuracy (%) for mature broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Crop stalk/Weed/Soil	Crop leaf/Crop stalk/Weed species/Soil
11	18	100	85.71
12	5	92.23	71.43
14	5	90.48	66.66
154	4	95.23	78.57
164	3	97.62	76.19
155	3	88.09	69.05
160	2	100	76.19

Program run no.	Selected wavelengths (nm)				
R 12	500	860	900	980	1020
R 14	800	860	1000	1020	1040
R 154	800	1000	1040	1640	
R 164	1000	1040	1640		
R 155	800	1000	1040		
R 160	1040	1640			

Table D.3 **Discrimination accuracy (%) for mature broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Crop stalk/Weed/Soil	Crop leaf/Crop stalk/Weed species/Soil
82	22	100	85.71
84	6	100	88.09
130	6	97.62	80.95
131	5	90.48	69.05
86	5	85.71	66.66
194	4	97.62	92.85
199	3	90.48	71.43

Program run no.	Selected wavelength ratios (nm)				
R 84	520/700	1040/700	1240/700	1440/700	1720/700
R 130	1120/720	1200/880	1440/1040		
R 131	1200/720	1120/720	1440/560		
R 86	520/700	1040/700	1240/700	1440/700	
R 194	520/700	1040/700	1720/700		
R 199	1040/880	1440/880			

TRIAL 1
Site: Gowkly-Moss Farm
Experiment No. 1
1991

Table D.4 **Mature broccoli leaf tissue, broccoli stalk, weed species and soil misclassification for each program run in trial 1 using direct wavelengths.**

Crop leaf/Crop stalk/Weed/Soil	Misclassified Crop leaf/Crop stalk/Weed/Soil in various program runs						
	PROGRAM RUN 11	**PROGRAM RUN 12**	**PROGRAM RUN 14**	**PROGRAM RUN 154**	**PROGRAM RUN 164**	**PROGRAM RUN 155**	**PROGRAM RUN 160**
BROCCOLI LEAF		*P. persicaria*	*P. persicaria*	*P. persicaria*		*P. persicaria*	
BROCCOLI STALK							
P. persicaria			**BROCCOLI LEAF**	**BROCCOLI LEAF**	**BROCCOLI STALK**	**BROCCOLI LEAF**	
S. media	vol. oilseed rape	vol. oilseed rape	vol. oilseed rape *P. annua*	vol. oilseed rape	vol. oilseed rape *Matricaria spp.*	vol. oilseed rape *P. annua*	*Matricaria spp.*
Matricaria spp.	*S. media*	*S. media*	*S. media*	*S. media*	*P. annua*	*S. media*	*P. annua*
P. annua		*S. media*	vol. oilseed rape	*S. media*	*S. media*	vol. oilseed rape	*Matricaria spp.*
Vol. oilseed rape	*S. media*	*S. media*	*S. media*	*S. media*	*S. media*	*S. media*	*S. media*
SOIL							

Table D.5 Mature broccoli leaf tissue, broccoli stalk, weed species and soil misclassification for each program run in trial 1 using wavelength ratios.

Crop leaf/Crop stalk/Weed/Soil	Misclassified Crop leaf/Crop stalk/Weed/Soil in various program runs						
	PROGRAM RUN 82	**PROGRAM RUN 84**	**PROGRAM RUN 130**	**PROGRAM RUN 131**	**PROGRAM RUN 86**	**PROGRAM RUN 194**	**PROGRAM RUN 199**
BROCCOLI LEAF				*P. persicaria*	*Matricaria spp.*		
BROCCOLI STALK							vol. oilseed rape
P. persicaria			*Matricaria spp.*	*Matricaria spp.*		*S. media*	**BROCCOLI LEAF** *Matricaria spp.*
S. media	vol. oilseed rape	vol. oilseed rape *P. annua*	vol. oilseed rape	vol. oilseed rape	vol. oilseed rape **BROCCOLI STALK**		vol. oilseed rape
Matricaria spp.	*S. media*		*S. media*	*S. media*			**BROCCOLI LEAF**
P. annua		*Matricaria spp.*	vol. oilseed rape	*S. media*	**BROCCOLI LEAF**	*Matricaria spp.*	
Vol. oilseed rape	*S. media*	*P. persicaria* *S. media*	*S. media* *P. annua*	*S. media*	*P. persicaria* *S. media*		*S. media* *P. annua*
SOIL				*P. persicaria*		*P. annua*	

Table D.6 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
CABBAGE LEAF	40	28	12
CABBAGE STALK	10	7	3
Polygonum persicaria	22	16	6
Stellaria media	20	14	6
Matricaria spp.	10	7	3
Poa annua	10	7	3
Volunteer oilseed rape	20	14	6
SOIL	10	7	3
Total	142	100	42

TRIAL 1
Autumn Cabbage
Site: Gowkly-Moss Farm
Experiment No. 2
1991

Table D.7 **Discrimination accuracy (%) for autumn cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Crop stalk/Weed/Soil	Crop leaf/Crop stalk/Weed species/Soil
19	14	100	97.62
20	5	100	78.57
17	5	97.61	76.19
156	4	100	73.81
158	3	100	78.57
21	3	95.23	73.81
159	2	100	73.81

Program run no.	Selected wavelengths (nm)				
R 20	640	880	960	1040	1480
R 17	560	640	880	980	1040
R 156	880	960	1040	1480	
R 158	880	960	1040		
R 21	880	980	1040		
R 159	880	960			

Table D.8 **Discrimination accuracy (%) for autumn cabbage using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Crop stalk/Weed/Soil	Crop leaf/Crop stalk/Weed species/Soil
92	17	100	92.86
100	6	100	88.09
135	5	100	80.95
95	5	95.24	76.19
142	4	95.24	71.43
141	4	92.86	78.57
102	4	90.48	76.19
143	3	95.24	76.19

Program run no.	Selected wavelength ratios (nm)				
R 100	520/700	640/700	1080/700	1440/700	1760/700
R 135	840/760	1240/920	1480/840		
R 95	640/980	760/980	1040/980	1440/980	
R 142	940/860	1420/1110			
R 141	1120/720	1200/720	1440/720		
R 102	520/700	1080/700	1440/700		
R 143	940/780	940/860			

TRIAL 1
Site: Gowkly-Moss Farm
Experiment No. 2
1991

Table D.9 **Autumn cabbage leaf tissue, cabbage stalk, weed species and soil misclassification for each program run in trial 1 using direct wavelengths.**

Crop leaf/Crop stalk/Weed/Soil	Misclassified Crop leaf/Crop stalk/Weed/Soil in various program runs						
	PROGRAM RUN 19	**PROGRAM RUN 20**	**PROGRAM RUN 17**	**PROGRAM RUN 156**	**PROGRAM RUN 158**	**PROGRAM RUN 21**	**PROGRAM RUN 159**
CABBAGE LEAF			*P. persicaria*			*P. persicaria*	
CABBAGE STALK							
P. persicaria						**CABBAGE LEAF**	
S. media		Vol. oilseed rape	Vol. oilseed rape	Vol. oilseed rape	Vol. oilseed rape	Vol. oilseed rape *P. annua*	Vol. oilseed rape *P. annua*
Matricaria spp.		*S. media*	*S. media*	*S. media*	*S. media*	*S. media*	*S. media* *P. annua*
P. annua		Vol. oilseed rape	Vol. oilseed rape	Vol. oilseed rape	Vol. oilseed rape	Vol. oilseed rape	Vol. oilseed rape
Vol. oilseed rape	*P. annua*	*S. media*	*S. media*	*S. media*	*S. media*	*S. media*	*S. media*
SOIL							

Table D.10 **Autumn cabbage leaf, cabbage stalk, tissue, weed species and soil misclassification in each program run in trial 1 using wavelength ratios.**

Crop leaf/Crop stalk/Weed/Soil	Misclassified Crop leaf/Crop stalk/Weed/Soil in various program runs						
	PROGRAM RUN 100	**PROGRAM RUN 135**	**PROGRAM RUN 95**	**PROGRAM RUN 142**	**PROGRAM RUN 141**	**PROGRAM RUN 102**	**PROGRAM RUN 143**
CABBAGE LEAF			*Matricaria spp.*	*S. media*	*Matricaria spp.*		*P. persicaria*
CABBAGE STALK							
P. persicaria	*Matricaria spp.* *S. media*		*Matricaria spp.* **CABBAGE LEAF**	vol. oilseed rape *P. annua*	*Matricaria spp.*	*S. media* **CABBAGE LEAF**	**SOIL**
S. media	vol. oilseed rape	vol. oilseed rape	vol. oilseed rape *P. annua*	vol. oilseed rape	vol. oilseed rape *P. annua*	vol. oilseed rape	vol. oilseed rape *P. annua*
Matricaria spp.		*S. media*	*S. media*	vol. oilseed rape			*S. media*
P. annua	*Matricaria spp.*	*S. media*				*P. persicaria*	*S. media*
Vol. oilseed rape	*S. media*	*Matricaria spp.* *P. annua*	*P. annua*	*P. persicaria*	*S. media* *P. annua*	*S. media* **CABBAGE STALK**	*S. media*
SOIL					*P. annua*	*P. annua*	

Table D.11 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
SAVOY CABBAGE	40	28	12
Stellaria media	10	7	3
Fumaria officinalis	10	7	3
Chenopodium album	10	7	3
Capsella bursa-pastoris	10	7	3
Sinapsis arvensis	10	7	3
Euphorbia helioscopia	10	7	3
Polygonum aviculare	10	7	3
SOIL	10	7	3
Total	120	84	36

TRIAL 2
Savoy Cabbage
Site: Damhead Organic Farm
Experiment No. 1
1993

Table D.12 **Discrimination accuracy (%) for savoy cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1608	12	100	100
1617	4	100	97.22
1613	3	100	94.44
1612	3	97.22	80.55
1610	3	97.22	86.11
1616	2	94.44	69.44
1614	2	91.66	83.33

Program run no.	Selected wavelengths (nm)			
R 1617	680	840	1300	1500
R 1613	690	1300	1500	
R 1612	690	1070	1300	
R 1610	840	1300	1500	
R 1616	680	1500		
R 1614	1300	1500		

Table D.13 **Discrimination accuracy (%) for savoy cabbage using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1701	21	100	91.66
1695	4	100	80.55
1684	4	100	77.77
1704	4	100	75.00
1696	3	100	83.33
1698	3	100	77.77
1700	2	100	63.88

Program run no.	Selected wavelength ratios (nm)		
R 1695	700/990	740/990	1100/990
R 1684	690/1400	720/1400	1090/1400
R 1704	680/710	1280/710	1400/710
R 1696	700/990	740/990	
R 1698	740/990	1320/990	
R 1700	740/990		

TRIAL 2
Site: Damhead Organic Farm
Experiment No. 1
1993

Table D.14 Savoy cabbage leaf tissue, weed species and soil misclassification for each program run in trial 2 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1608	PROGRAM RUN 1617	PROGRAM RUN 1613	PROGRAM RUN 1612	PROGRAM RUN 1610	PROGRAM RUN 1616	PROGRAM RUN 1614
CABBAGE LEAF				*C. bursa-pastoris*	*C. bursa-pastoris*	*P. aviculare*	
S. media							
F. officinalis				*S. media*			
C. album		*S. arvensis*	*S. arvensis*	*S. arvensis*	*S. arvensis*	*S. arvensis*	*S. arvensis*
C. bursa-pastoris					***CABBAGE LEAF***	*P. aviculare*	***CABBAGE LEAF***
S. arvensis							
E. helioscopia				*S. media* *P. aviculare*	*P. aviculare*	*C. bursa-pastoris* *P. aviculare* *S. arvensis*	
P. aviculare			*E. helioscopia*	*E. helioscopia*	*E. helioscopia*		*E. helioscopia*
SOIL							*F. officinalis*

Table D.15 Savoy cabbage leaf tissue, weed species and soil misclassification for each program run in trial 2 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1701	PROGRAM RUN 1695	PROGRAM RUN 1684	PROGRAM RUN 1704	PROGRAM RUN 1696	PROGRAM RUN 1698	PROGRAM RUN 1700
CABBAGE LEAF							
S. media							
F. officinalis		*P. aviculare* *E. helioscopia*			*P. aviculare* *E. helioscopia*	*C. album* *E. helioscopia*	*C. album* *E. helioscopia*
C. album		*S. arvensis*			*S. arvensis*	*S. arvensis*	*S. arvensis*
C. bursa-pastoris		*P. aviculare* *S. media*			*P. aviculare* *F. officinalis*	*S. arvensis* *S. media*	*S. arvensis* *S. media*
S. arvensis					*C. album*	*C. album* *C. bursa-pastoris*	*P. aviculare* *C. album*
E. helioscopia		*F. officinalis*				*F. officinalis*	*F. officinalis*
P. aviculare							*S. arvensis* *C. bursa-pastoris*
SOIL							

Table D.16 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
MATURE BROCCOLI	30	21	9
Stellaria media	10	7	3
Taraxacum officinale	10	7	3
Chenopodium album	10	7	3
Matricaria spp.	10	7	3
Cirsium arvense	10	7	3
Rumex spp.	10	7	3
Senecio vulgaris	10	7	3
SOIL	10	7	3
Total	110	77	33

TRIAL 2
Mature Broccoli
Site: Damhead Organic Farm
Experiment No. 2
1993

Table D.17 **Discrimination accuracy (%) for mature broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1591	15	100	100
1593	4	100	96.96
1595	3	100	96.96
1594	3	96.96	96.96
1597	3	96.96	96.96
1596	2	84.84	84.84
1750	2	84.84	84.84

Program run no.	Selected wavelengths (nm)			
R 1593	700	720	900	1460
R 1595	700	720	1460	
R 1594	700	720	900	
R 1597	700	720	890	
R 1596	700	1460		
R 1750	700	720		

Table D.18 **Discrimination accuracy (%) for mature broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1905	17	100	100
1924	4	100	90.90
1910	4	100	90.90
1917	4	100	90.90
1919	3	100	84.84
1925	3	100	78.78
1918	3	96.96	84.84

Program run no.	Selected wavelength ratios (nm)		
R 1924	700/1400	980/1440	1460/1400
R 1910	900/710	1400/710	1460/710
R 1917	700/990	1360/990	1460/990
R 1919	1360/990	1460/990	
R 1925	980/1400	1460/990	
R 1918	700/990	1360/990	

TRIAL 2
Site: Damhead Organic Farm
Experiment No. 2
1993

Table D.19 Mature broccoli leaf tissue, weed species and soil misclassification for each program run in trial 2 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1591	PROGRAM RUN 1593	PROGRAM RUN 1595	PROGRAM RUN 1594	PROGRAM RUN 1597	PROGRAM RUN 1596	PROGRAM RUN 1750
BROCCOLI LEAF				*S. vulgaris*	*S. vulgaris*	*S. vulgaris* *C. album* *Rumex spp.*	*S. vulgaris* *C. album*
S. media							
T. officinale							
C. album							
Matricaria spp.							
C. arvense		*S. media*	*S. media*				
Rumex spp.							
S. vulgaris							
SOIL							

Table D.20 Mature broccoli leaf tissue, weed species and soil misclassification for each program run in trial 2 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1905	PROGRAM RUN 1924	PROGRAM RUN 1910	PROGRAM RUN 1917	PROGRAM RUN 1919	PROGRAM RUN 1925	PROGRAM RUN 1918
BROCCOLI LEAF							*S. vulgaris*
S. media							
T. officinale					*Rumex spp.*	*Matricaria spp.*	
C. album							
Matricaria spp.		*S. media*	*S. media*	*S. media*	*S. media*	*S. media* *T. officinale*	*S. media*
C. arvense		*T. officinale*	*Matricaria spp*	*T. officinale*	*T. officinale* *Rumex spp.*	*Matricaria spp.*	*T. officinale*
Rumex spp.					*T. officinale*	*C. arvense*	
S. vulgaris							
SOIL							

Table D.21 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
AUTUMN CABBAGE	30	21	9
Sinapsis arvensis	10	7	3
Papaver rhoeas	10	7	3
Stellaria media	10	7	3
Urtica dioica	10	7	3
Polygonum persicaria	10	7	3
Malva sylvestris	10	7	3
Phleum pratense	10	7	3
Taraxacum officinale	10	7	3
Elymus repens	10	7	3
Epilobium angustifolium	10	7	3
SOIL	10	7	3
Total	140	98	42

TRIAL 3
Autumn Cabbage
Site: SCAE Fields
Experiment No. 1
1992

Table D.22 **Discrimination accuracy (%) for autumn cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
35	35	100	95.23
43	4	100	95.23
46	4	100	92.85
44	3	100	92.85
82	2	100	78.57
84	2	100	76.91

Program run no.	Selected wavelengths (nm)			
R 43	720	990	1170	1360
R 46	720	1070	1170	1360
R 44	720	1170	1360	
R 82	1170	1360		
R 84	870	990		

Table D.23 **Discrimination accuracy (%) for autumn cabbage using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
61	35	100	97.62
62	5	100	92.85
126	4	100	92.85
63	4	100	80.95
137	3	100	88.09
138	3	100	66.66

Program run no.	Selected wavelength ratios (nm)			
R 62	720/760	1260/760	1380/760	1500/760
R 126	900/710	1400/710	1480/710	
R 63	720/760	1260/760	1380/760	
R 137	1360/990	1500/990		
R 138	750/990	1360/990		

TRIAL 3
Site: SCAE Fields
Experiment No. 1
1992

Table D.24 Autumn cabbage leaf tissue, weed species and soil misclassification for each program run in trial 3 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs					
	PROGRAM RUN 35	PROGRAM RUN 43	PROGRAM RUN 46	PROGRAM RUN 44	PROGRAM RUN 82	PROGRAM RUN 84
CABBAGE LEAF						
S. arvensis						
P. rhoeas						
S. media	*S. arvensis*				*P. persicaria* *T. officinale*	*S. arvensis*
U. dioica					*P. persicaria*	*P. persicaria*
P. persicaria		*U. dioica*	*S. arvensis*	*S. arvensis*	*S. arvensis*	*U. dioica*
M. sylvestris		*P. pratense*	*P. pratense*	*P. pratense*	*E. angustifolium*	*P. pratense* *E. angustifolium*
P. pratense						
T. officinale	*M. sylvestris*				*S. media*	*S. media*
E. repens						*P. pratense*
E. angustifolium					*P. pratense*	*P. pratense*
SOIL						

Table D.25 Autumn cabbage leaf tissue, weed species and soil misclassification for each program run in trial 3 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs					
	PROGRAM RUN 61	PROGRAM RUN 62	PROGRAM RUN 126	PROGRAM RUN 63	PROGRAM RUN 137	PROGRAM RUN 138
CABBAGE LEAF						
S. arvensis						
P. rhoeas					*S. media*	*S. media* *P. persicaria* *S. arvensis*
S. media					*P. persicaria* *S. arvensis*	*P. persicaria*
U. dioica				*P. pratense* *E. repens*	*P. persicaria*	*P. persicaria*
P. persicaria						*M. sylvestris*
M. sylvestris				*T. officinale*		*P. persicaria*
P. pratense			*M. sylvestris*	*E. repens*	*M. sylvestris*	*M. sylvestris*
T. officinale	*E. angustifolium*	*E. angustifolium*	*M. sylvestris*	*M. sylvestris* *P. pratense*		*P. rhoeas*
E. repens						*P. pratense* *U. dioica*
E. angustifolium				*M. sylvestris*		*M. sylvestris* *E. repens*
SOIL						

Table D.26 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
MATURE BROCCOLI	30	21	9
Sinapsis arvensis	10	7	3
Papaver rhoeas	10	7	3
Stellaria media	10	7	3
Urtica dioica	10	7	3
Polygonum persicaria	10	7	3
Malva sylvestris	10	7	3
Phleum pratense	10	7	3
Taraxacum officinale	10	7	3
Elymus repens	10	7	3
Epilobium angustifolium	10	7	3
SOIL	10	7	3
Total	140	98	42

TRIAL 3
Mature Broccoli
Site: SCAE Fields
Experiment No. 2
1992

Table D.27 **Discrimination accuracy (%) for mature broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
773	30	100	100
783	5	100	100
775	4	100	95.23
776	3	100	90.47
780	2	100	90.47
777	2	100	78.57
778	1	92.85	64.28

Program run no.	Selected wavelengths (nm)				
783	720	960	1360	1420	1520
775	720	960	1360	1420	
776	720	960	1420		
780	740	990			
777	960	1420			
778	960				

Table D.28 **Discrimination accuracy (%) for mature broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
810	28	100	97.62
807	4	100	88.09
813	4	100	66.66
826	4	97.62	85.71
819	4	97.62	78.57
808	3	97.62	83.33
815	3	97.62	69.04

Program run no.	Selected wavelength ratios (nm)		
R 807	680/1380	740/1380	1500/1380
R 813	750/990	1360/990	1420/990
R 826	1280/710	1400/710	1480/710
R 819	740/710	1400/710	1480/710
R 808	740/1380	1500/1380	
R 815	1360/990	1420/990	

TRIAL 3
Site: SCAE Fields
Experiment No. 2
1992

Table D.29 **Mature broccoli leaf tissue, weed species and soil misclassification for each program run in trial 3 using direct wavelengths.**

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 773	**PROGRAM RUN 783**	**PROGRAM RUN 775**	**PROGRAM RUN 776**	**PROGRAM RUN 780**	**PROGRAM RUN 777**	**PROGRAM RUN 778**
BROCCOLI LEAF							*M. sylvestris*
S. arvensis							
P. rhoeas							**SOIL**
S. media					*S. arvensis*		*S. arvensis* *T. officinale*
U. dioica					*P. persicaria*	*P. persicaria*	*S. arvensis* *P. persicaria*
P. persicaria				*S. arvensis*	*U. dioica*	*S. arvensis*	*S. arvensis* *U. dioica*
M. sylvestris					*P. pratense*	*E. angustifolium*	*P. pratense* **BROCCOLI LEAF** *E. angustifolium*
P. pratense			*E. repens*	*E. repens*		*E. repens*	
T. officinale							
E. repens				*P. pratense*			*P. pratense*
E. angustifolium			*M. sylvestris*	*M. sylvestris*		*M. sylvestris*	*P. pratense*
SOIL							

Table D.30 Mature broccoli leaf tissue, weed species and soil misclassification for each program run in trial 3 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 810	**PROGRAM RUN 807**	**PROGRAM RUN 813**	**PROGRAM RUN 826**	**PROGRAM RUN 819**	**PROGRAM RUN 808**	**PROGRAM RUN 815**
BROCCOLI LEAF						*T. officinale*	*T. officinale*
S. arvensis			*T. officinale*			*S. media*	
P. rhoeas	*S. arvensis*		*S.media* *P. persicaria*				*S.media* *P. persicaria*
S. media		*P. persicaria*			*P. persicaria*	*P. persicaria*	
U. dioica			*P. persicaria* *P. pratense*	*P. pratense*			*P. persicaria* *P. pratense*
P. persicaria			*M. sylvestris*		*P. rhoeas*		*M. sylvestris*
M. sylvestris			*E. angustifolium*				*E. angustifolium*
P. pratense		*M. sylvestris*	*M. sylvestris*	*M. sylvestris*	*M. sylvestris*	*M. sylvestris*	*M. sylvestris*
T. officinale		*E. angustifolium*	*S. arvensis*	*E. repens* *P. persicaria* **BROCCOLI LEAF**	*E. repens* *M. sylvestris* **BROCCOLI LEAF**	*E. angustifolium*	
E. repens			*M. sylvestris* *E. angustifolium*				*E. angustifolium*
E. angustifolium			*E. repens*				*E. repens*
SOIL							*T. officinale*

Table D.31 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
LEEK	30	21	9
Sinapsis arvensis	10	7	3
Papaver rhoeas	10	7	3
Stellaria media	10	7	3
Urtica dioica	10	7	3
Polygonum persicaria	10	7	3
Malva sylvestris	10	7	3
Phleum pratense	10	7	3
Taraxacum officinale	10	7	3
Elymus repens	10	7	3
Epilobium angustifolium	10	7	3
SOIL	10	7	3
Total	140	98	42

TRIAL 3
Leek
Site: SCAE Fields
Experiment No. 3
1992

Table D.32 Discrimination accuracy (%) for leek using direct wavelengths.

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1	28	100	95.23
5	4	100	100
9	4	100	95.23
6	3	100	97.62
106	3	100	97.62
7	2	100	88.09
104	2	100	88.09

Program run no.	Selected wavelengths (nm)			
R 5	720	1080	1380	1500
R 9	720	990	1220	1380
R 6	1080	1380	1500	
R 106	720	1080	1380	
R 7	1080	1380		
R 104	990	1380		

Table D.33 Discrimination accuracy (%) for leek using wavelength ratios.

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
68	24	100	97.62
110	4	100	97.62
55	4	100	90.47
145	4	97.61	90.47
113	3	100	85.71
112	3	97.61	78.57

Program run no.	Selected wavelength ratios (nm)					
R 110	720/990	1380/990	1500/990			
R 55	720/1080	720/1380	720/1500	1080/1380	1080/1500	1380/1500
R 145	1020/710	1400/710	1480/710			
R 113	1380/990	1500/990				
R 112	720/990	1380/990				

TRIAL 3
Site: SCAE Fields
Experiment No. 3
1992

Table D.34 Leek leaf tissue, weed species and soil misclassification for each program run in trial 3 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1	**PROGRAM RUN 5**	**PROGRAM RUN 9**	**PROGRAM RUN 6**	**PROGRAM RUN 106**	**PROGRAM RUN 7**	**PROGRAM RUN 104**
LEEK LEAF							
S. arvensis							
P. rhoeas							
S. media				*S. arvensis*		*P. persicaria* *T. officinale*	*S. arvensis*
U. dioica							
P. persicaria							
M. sylvestris						*E. angustifolium*	*E. angustifolium*
P. pratense							
T. officinale	*M. sylvestris*						*S. media*
E. repens			*P. pratense*				*P. pratense*
E. angustifolium			*M. sylvestris*		*M. sylvestris*	*P. pratense*	*P. pratense*
SOIL							

Table D.35 Leek leaf tissue, weed species and soil misclassification for each program run in trial 3 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs					
	PROGRAM RUN 68	**PROGRAM RUN 110**	**PROGRAM RUN 55**	**PROGRAM RUN 145**	**PROGRAM RUN 113**	**PROGRAM RUN 112**
LEEK LEAF				*S. arvensis*		
S. arvensis			*P. persicaria*			**LEEK LEAF**
P. rhoeas						
S. media					*P. persicaria*	
U. dioica					*P. pratense*	*P. pratense* *M. sylvestris*
P. persicaria					*S. media*	
M. sylvestris				*T. officinale*		
P. pratense		*M sylvestris*	*M. sylvestris*	*M. sylvestris*	*M. sylvestris*	*M. sylvestris* *E. repens*
T. officinale	*E. angustifolium*		*E. angustifolium*	*M. sylvestris*		*M. sylvestris*
E. repens						*P. pratense*
E. angustifolium						*U. dioica*
SOIL						

Table D.36 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	**Training group**	**Trial group**
LEEK	40	28	12
Senecio vulgaris	10	7	3
Polygonum aviculare	10	7	3
Viola arvensis	10	7	3
Cirsium arvense	10	7	3
Veronica persica	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	110	77	33

TRIAL 4
Leek
Site: Campend Farm
Experiment No. 1
1993

Table D.37 **Discrimination accuracy (%) for leek using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1004	13	100	100
1007	4	100	100
1008	3	100	93.93
1009	3	96.96	96.96
1014	3	93.93	87.87
1010	2	100	93.93
1011	1	100	84.84

Program run no.	Selected wavelengths (nm)			
R 1007	680	800	1080	1520
R 1008	680	1080	1520	
R 1009	850	1080	1520	
R 1014	720	1080	1380	
R 1010	1080	1520		
R 1011	1080			

Table D.38 **Discrimination accuracy (%) for leek using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1048	10	100	100
1017	5	93.93	84.84
1050	5	90.90	90.90
1053	4	90.90	72.72
1025	4	87.87	84.84
1023	3	87.87	75.75
1054	3	84.84	72.72

Program run no.	Selected wavelength ratios (nm)			
R 1017	680/990	720/990	760/990	1070/990
R 1050	810/1390	1080/1390	1120/1390	1500/1390
R 1053	680/1390	720/1390	810/1390	
R 1025	690/710	1090/710	1400/710	
R 1023	1120/710	1400/710		
R 1054	810/1390	1120/1390		

TRIAL 4
Site: Campend Farm
Experiment No. 1
1993

Table D.39 Leek leaf tissue, weed species, stone and soil misclassification for each program run in trial 4 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1084	**PROGRAM RUN 1007**	**PROGRAM RUN 1008**	**PROGRAM RUN 1009**	**PROGRAM RUN 1014**	**PROGRAM RUN 1010**	**PROGRAM RUN 1011**
LEEK LEAF					*S. vulgaris*		
S. vulgaris				**LEEK LEAF**	*V. arvensis*		*V. arvensis*
P. aviculare			*C. arvense*			*C. arvense*	*C. arvense*
V. arvensis							*C. arvense*
C. arvense			*V. arvensis*		*P. aviculare*	*V. arvensis*	*V. arvensis*
V. persica							
STONE							
SOIL							

Table D.40 Leek leaf tissue, weed species, stone and soil misclassification for each program run in trial 4 using wavelength ratios.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf tissue/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1048	**PROGRAM RUN 1017**	**PROGRAM RUN 1050**	**PROGRAM RUN 1053**	**PROGRAM RUN 1025**	**PROGRAM RUN 1023**	**PROGRAM RUN 1054**
LEEK LEAF		*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*
S. vulgaris		**LEEK LEAF**	**LEEK LEAF**	*V. arvensis*	**LEEK LEAF**	**LEEK LEAF**	**LEEK LEAF**
P. aviculare				*C. arvense*		*V. persica*	*V. persica* *V. arvensis*
V. arvensis		*S. vulgaris*		*P. aviculare*			
C. arvense						*P. aviculare*	*P. aviculare*
V. persica		*P. aviculare*		*P. aviculare* *V. arvensis*	*V. arvensis*	*V. arvensis* *C. arvense*	*P. aviculare*
STONE							
SOIL							

Table D.41 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	**Training group**	**Trial group**
AUTUMN CABBAGE	40	28	12
Chenopodium album	20	14	6
Senecio vulgaris	20	14	6
Fumaria officinalis	10	7	3
Cirsium arvense	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	120	84	36

TRIAL 4
Autumn Cabbage
Site: Campend Farm
Experiment No. 2
1993

Table D.42 **Discrimination accuracy (%) for autumn cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1027	16	100	100
1034	4	100	100
1029	4	97.22	97.22
1035	3	100	100
1030	3	97.22	97.22
1036	2	100	83.33
1037	2	97.22	86.11

Program run no.	Selected wavelengths (nm)			
R 1034	680	720	840	1100
R 1029	680	720	840	1240
R 1035	680	720	840	
R 1030	720	840	1240	
R 1036	680	720		
R 1037	680	840		

Table D.43 **Discrimination accuracy (%) for autumn cabbage using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1064	23	100	100
1076	5	100	97.22
1071	4	100	88.88
1083	3	100	97.22
1079	3	100	88.88
1080	2	100	69.44
1084	2	94.44	91.66

Program run no.	Selected wavelength ratios (nm)			
R 1076	680/710	780/710	1300/710	1500/710
R 1071	690/990	720/990	760/990	
R 1083	1090/710	1300/710		
R 1079	680/710	1300/710		
R 1080	680/710			
R 1084	1090/710			

TRIAL 4
Site: Campend Farm
Experiment No. 2
1993

Table D.44 Autumn cabbage leaf tissue, weed species, stone and soil misclassification for each program run in trial 4 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1027	PROGRAM RUN 1034	PROGRAM RUN 1029	PROGRAM RUN 1035	PROGRAM RUN 1030	PROGRAM RUN 1036	PROGRAM RUN 1037
CABBAGE LEAF							
C. album							
S. vulgaris			SOIL		SOIL	*C. album*	*C. arvense*
F. officinalis							
C. arvense						*S. vulgaris*	CABBAGE LEAF *C. album*
STONE							
SOIL							

Table D.45 Autumn cabbage leaf tissue, weed species, stone and soil misclassification for each program run in trial 4 using wavelength ratios.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1064	**PROGRAM RUN 1076**	**PROGRAM RUN 1071**	**PROGRAM RUN 1083**	**PROGRAM RUN 1079**	**PROGRAM RUN 1080**	**PROGRAM RUN 1084**
CABBAGE LEAF							
C. album			*F. officinalis*			*F. officinalis* *S. vulgaris*	
S. vulgaris			*C. album*			*F. officinalis* *C. arvense*	
F. officinalis		*C. album*	*C. album*		*C. arvense*	*C. arvense*	*C. arvense*
C. arvense			*F. officinalis*	*F. officinalis*	*F. officinalis*	*F. officinalis* *C. album*	*F. officinalis* **STONE**
STONE							
SOIL							*S. vulgaris*

Table D.46 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
LEEK	40	28	12
Senecio vulgaris	10	7	3
Polygonum aviculare	10	7	3
Chenopodium album	10	7	3
Volunteer oilseed rape	10	7	3
Cirsium arvense	10	7	3
Capsella bursa-pastoris	10	7	3
Lamium purpureum	10	7	3
Polygonum persicaria	10	7	3
Stellaria media	10	7	3
Elymus repens	10	7	3
SOIL	10	7	3
Total	150	105	45

TRIAL 5
Leek
Site: SCAE Fields
Experiment No. 1
1993

Table D.47 **Discrimination accuracy (%) for leek using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1371	22	100	95.5
1373	4	100	86.6
1377	3	100	86.6
1374	3	97.7	82.2
1376	3	97.7	77.7
1375	2	97.7	73.3
1378	2	97.7	71.1

Program run no.	Selected wavelengths (nm)			
R 1373	760	1060	1340	1480
R 1377	760	1340	1480	
R 1374	760	1060	1340	
R 1376	720	760	1060	
R 1375	760	1340		
R 1378	760	1480		

Table D.48 **Discrimination accuracy (%) for leek using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1445	25	100	88.8
1449	4	100	77.7
1404	4	100	73.3
1395	4	97.7	77.7
1402	4	97.7	71.1
1401	4	97.7	64.4
1405	3	84.4	60.0

Program run no.	Selected wavelength ratios (nm)		
R 1449	680/1400	850/1400	1060/1400
R 1404	690/710	1100/710	1400/710
R 1395	710/990	740/990	1050/990
R 1402	690/710	850/710	1400/710
R 1401	690/710	850/710	1100/710
R 1405	1100/710	1400/710	

TRIAL 5
Site: SCAE Fields
Experiment No. 1
1993

Table D.49 Leek leaf tissue, weed species and soil misclassification for each program run in trial 5 using direct wavelengths.

Crop/Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1371	**PROGRAM RUN 1373**	**PROGRAM RUN 1377**	**PROGRAM RUN 1374**	**PROGRAM RUN 1376**	**PROGRAM RUN 1375**	**PROGRAM RUN 1378**
LEEK LEAF					*P. periscaria*		
S. vulgaris			*C. bursa-pastoris*		*P. persicaria*	*C. album* *P. aviculare*	
P. aviculare	*C. album*	*C. album*	*C. album*	*C. album*		*C. album*	*C. album* *P. persicaria*
C. album	*L. purpureum*	*L. purpureum* *P. aviculare*	*P. aviculare*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare*
Vol. oilseed rape							*C. bursa-pastoris*
C. arvense		*P. aviculare*	*P. aviculare*	*L. purpureum* *P. aviculare*	*L. purpureum*	*L. purpureum* *P. aviculare*	*L. purpureum* *C. album*
C. bursa-pastoris				*P. aviculare* *C. album*	*P. aviculare* *C. album*	*P. aviculare* *C. albume*	
L. pupureum		*C. album*	*C. album*	*C. album*	*P. aviculare*	*C. album*	*C. album*
P. persicaria				**LEEK LEAF**	*S. vulgaris*	**LEEK LEAF**	**LEEK LEAF** *C. album*
S. media							
E. repens							
SOIL							

Table D.50 Leek leaf tissue, weed species and soil misclassification for each program run in trial 5 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1445	**PROGRAM RUN 1449**	**PROGRAM RUN 1404**	**PROGRAM RUN 1395**	**PROGRAM RUN 1402**	**PROGRAM RUN 1401**	**PROGRAM RUN 1405**
LEEK LEAF					*E. repens*	*P. persicaria*	*E. repens* *P. persicaria*
S. vulgaris				**LEEK LEAF**		*P. persicaria*	
P. aviculare	*L. purpureum* *C. album*		*C. bursa-pastoris*	*L. purpureum*	*C. bursa-pastoris*	*L. purpureum*	*C. bursa-pastoris* Vol. oilseed rape
C. album	*L. purpureum* *C. arvense*	*L. purpureum* *P. aviculare*	*P. aviculare*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare* Vol. oilseed rape	*P. aviculare* *C. bursa-pastoris*	*P. aviculare* *C. bursa-pastoris*
Vol. oilseed rape						*S. media*	
C. arvense	*P. aviculare*	*P. aviculare*	*P. aviculare* *S. media*	*P. aviculare*	*P. aviculare* *S. media*	*P. aviculare* *L. purpureum*	*P. aviculare* *S. media*
C. bursa-pastoris		*P. aviculare* *C. album*	*P. aviculare* *C. album*	*P. aviculare* *C. album*	*P. aviculare* *C. album*	*P. aviculare* *C. album*	*C. album*
L. pupureum			*C. arvense*		*C. arvense*	*C. arvense*	
P. persicaria		*L. purpureum*	*E. repens*	*S. vulgaris*	*E. repens*	*S. vulgaris*	**LEEK LEAF** *E. repens*
S. media		*E. repens*	*C. arvense* Vol. oilseed rape		*C. arvense* Vol. oilseed rape	Vol. oilseed rape	Vol. oilseed rape
E. repens						*S. vulgaris*	
SOIL							

Table D.51 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	Training group	Trial group
MATURE BROCCOLI	40	28	12
Senecio vulgaris	10	7	3
Polygonum aviculare	10	7	3
Chenopodium album	10	7	3
Volunteer oilseed rape	10	7	3
Cirsium arvense	10	7	3
Capsella bursa-pastoris	10	7	3
Lamium purpureum	10	7	3
Polygonum persicaria	10	7	3
Stellaria media	10	7	3
Elymus repens	10	7	3
SOIL	10	7	3
Total	150	105	45

TRIAL 5
Mature Broccoli
Site: SCAE Fields
Experiment No. 2
1993

TableD.52 **Discrimination accuracy (%) for mature broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1461	19	100	91.11
1463	4	100	88.88
1467	4	100	75.55
1464	3	100	84.44
1468	3	100	84.44
1465	2	100	80.00
1469	2	100	75.55

Program run no.	Selected wavelengths (nm)			
R 1463	720	1060	1380	1500
R 1467	690	720	760	1040
R 1464	720	1060	1380	
R 1468	720	760	1040	
R 1465	720	1380		
R 1469	760	1040		

Table D.53 **Discrimination accuracy (%) for mature broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1484	37	100	91.11
1486	5	100	95.55
1487	4	100	88.88
1502	4	100	86.66
1488	3	100	80.00
1503	3	100	75.55
1489	2	100	51.11

Program run no.	Selected wavelength ratios (nm)			
R 1486	700/990	740/990	1360/990	1480/990
R 1487	740/990	1360/990	1480/990	
R 1502	700/1400	800/1400	1480/1400	
R 1488	1360/990	1480/990		
R 1503	700/1400	800/1400		
R 1489	1360/990			

TRIAL 5
Site: SCAE Fields
Experiment No. 2
1993

Table D.54 Mature Broccoli leaf tissue, weed species and soil misclassification for each program run in trial 5 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1461	**PROGRAM RUN 1463**	**PROGRAM RUN 1467**	**PROGRAM RUN 1464**	**PROGRAM RUN 1468**	**PROGRAM RUN 1465**	**PROGRAM RUN 1469**
BROCCOLI LEAF							
S. vulgaris			*P. persicaria*		*P. persicaria*	*C. album*	*P. persicaria*
P. aviculare	*C. album*	*C. album*		*C. album*		*C. album*	*C. album*
C. album	*L. pupureum*	*P. aviculare* *L. purpureum*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare* *C. bursa-pastoris*
Vol. oilseed rape							
C. arvense	*P. aviculare*	*P. aviculare*	*P. aviculare*	*L. pupureum*	*P. aviculare*	*L. pupureum* *S. vulgaris*	*P. aviculare* *L. purpureum*
C. bursa-pastoris			*P. aviculare* *C. album*	*P. aviculare* *C. album*	*P. aviculare* *C. album*	*P. aviculare*	*P. aviculare* *C. album*
L. pupureum		*P. aviculare*	*P. aviculare* *C. arvense*	*P. aviculare*		*C. album*	*P. aviculare*
P. persicaria			*S. vulgaris*		*S. vulgaris*		*S. vulgaris*
S. media							
E. repens							
SOIL							

Table D.55 Mature Broccoli leaf tissue, weed species and soil misclassification for each program run in trial 5 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1484	**PROGRAM RUN 1486**	**PROGRAM RUN 1487**	**PROGRAM RUN 1502**	**PROGRAM RUN 1488**	**PROGRAM RUN 1503**	**PROGRAM RUN 1489**
BROCCOLI LEAF							
S. vulgaris					*S. media*		*S. media* Vol. oilseed rape
P. aviculare	*C. arvense* *C. album*		*L. purpureum*	*C. arvense* *C. album*	*L. purpureum* *C. album*	*C. arvense* *C. bursa-pastoris* *S. media*	*S. media* *C. bursa-pastoris*
C. album	*P. aviculare*	*P. aviculare*	*P. aviculare*	*L. purpureum*	*P. aviculare*	*C. bursa-pastoris*	*C. bursa-pastoris* *S. media* *E. repens*
Vol. oilseed rape							*S. vulgaris*
C. arvense	*P. aviculare*	*L. purpureum*	*L. purpureum*	*C. album*		*S. media* *C. bursa-pastoris*	*P. aviculare* *C. bursa-pastoris*
C. bursa-pastoris					*S. media* *P. persicaria*	*C. album*	*S. media* *L. purpureum* *E. repens*
L. pupureum			*P. aviculare*	*C. arvense*	*C. arvense*	*C. arvense*	*P. aviculare* *E. repens*
P. persicaria			*L. purpureum*		*L. purpureum*		*E. repens*
S. media					*C. bursa-pastoris*		*P. aviculare* *C. arvense*
E. repens							*P. persicaria*
SOIL							

Table D.56 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
YOUNG BROCCOLI	40	28	12
Senecio vulgaris	10	7	3
Polygonum aviculare	10	7	3
Chenopodium album	10	7	3
Volunteer oilseed rape	10	7	3
Cirsium arvense	10	7	3
Capsella bursa-pastoris	10	7	3
Lamium purpureum	10	7	3
Polygonum persicaria	10	7	3
Stellaria media	10	7	3
Elymus repens	10	7	3
SOIL	10	7	3
Total	150	105	45

TRIAL 5
Young Broccoli
Site: SCAE Fields
Experiment No. 3
1993

Table D.57 **Discrimination accuracy (%) for young broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1382	15	100	95.55
1384	4	100	86.66
1388	4	100	75.55
1385	3	100	84.44
1389	3	100	82.22
1386	2	100	80.00
1390	2	100	64.44

Program run no.	Selected wavelengths (nm)			
R 1384	700	720	1060	1380
R 1388	690	710	760	1040
R 1385	720	1060	1380	
R 1389	720	760	1040	
R 1386	720	1380		
R 1390	710	760		

Table D.58 **Discrimination accuracy (%) for young broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1427	21	100	91.11
1408	4	100	93.33
1429	4	100	84.44
1409	3	100	84.44
1430	3	100	75.55
1421	3	100	73.33
1410	2	100	51.11

Program run no.	Selected wavelength ratios (nm)		
R 1408	700/990	1360/990	1480/990
R 1429	700/1450	760/1450	1480/1450
R 1409	1360/990	1480/990	
R 1430	700/1450	760/1450	
R 1421	700/990	740/990	
R 1410	1360/990		

TRIAL 5
Site: SCAE Fields
Experiment No. 3
1993

Table D.59 Young broccoli leaf tissue, weed species and soil misclassification for each program run in trial 5 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1382	**PROGRAM RUN 1384**	**PROGRAM RUN 1388**	**PROGRAM RUN 1385**	**PROGRAM RUN 1389**	**PROGRAM RUN 1386**	**PROGRAM RUN 1390**
BROCCOLI LEAF							
S. vulgaris			*P. persicaria*		*P. persicaria*	*C. album*	*P. persicaria*
P. aviculare	*C. album*	*C. album*	*C. album*	*C. album*	*C. album*	*C. album*	*C. album*
C. album	*L. purpureum*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare*	*P. aviculare* *L. purpureum*		*P. aviculare* *C. bursa-pastoris*	*P. aviculare*
Vol. oilseed rape							*C. bursa-pastoris*
C. arvense	*P. aviculare*	*L. purpureum*	*P. aviculare*	*L. purpureum*	*P. aviculare*	*L. purpureum* *S. vulgaris*	*P. aviculare* *L. purpureum* *C. bursa-pastoris*
C. bursa-pastoris		*P. aviculare* *C. album*	*C. album*	*P. aviculare* *C. album*	*P. aviculare* *C. album*	*P. aviculare*	*P. aviculare* *C. album*
L. pupureum			*C. arvense*	*P. aviculare*		*C. album*	*C. arvense*
P. persicaria			*S. vulgaris*		*S. vulgaris*		*S. vulgaris*
S. media							
E. repens							
SOIL							

Table D.60 Young broccoli leaf tissue, weed species and soil misclassification for each program run in trial 5 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1427	**PROGRAM RUN 1408**	**PROGRAM RUN 1429**	**PROGRAM RUN 1409**	**PROGRAM RUN 1430**	**PROGRAM RUN 1421**	**PROGRAM RUN 1410**
BROCCOLI LEAF							
S. vulgaris						*P. persicaria*	Vol. oilseed rape *S. media*
P. aviculare	*C. album* *L. purpureum*	*C. album*	*C. album* *C. arvense*	*L. purpureum*	*C. bursa-pastoris* *C. arvense*	*L. purpureum*	*C. bursa-pastoris* *S. media*
C. album	*P. aviculare*		*C. bursa-pastoris*	*P. aviculare*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris* *S. media* *E. repens*
Vol. oilseed rape							*S. vulgaris*
C. arvense	*L. purpureum*	*P. aviculare*	*P. aviculare* *C. album*		*P. aviculare*	*P. aviculare*	*P. aviculare* *C. bursa-pastoris*
C. bursa-pastoris				*S. media* *P. persicaria*	*C. album*	*C. album* *P. aviculare*	*S. media* *L. purpureum* *E. repens*
L. pupureum		*C. arvense*	*C. arvense*	*C. arvense*	*C. arvense*	*C. arvense*	*P. aviculare* *E. repens*
P. persicaria				*L. purpureum*		*S. vulgaris*	*E. repens*
S. media				*C. bursa-pastoris*	Vol. oilseed rape	Vol. oilseed rape	*P. aviculare* *C. arvense*
E. repens							*P. persicaria*
SOIL							

Table D.61 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
AUTUMN CABBAGE	30	21	9
Epilobium angustifolium	10	7	3
Sinapsis arvensis	10	7	3
Polygonum persicaria	10	7	3
Elymus repens	10	7	3
Chenopodium album	10	7	3
Capsella bursa-pastoris	10	7	3
SOIL	10	7	3
Total	100	70	30

TRIAL 6
Autumn Cabbage
Site: SCAE Glasshouse Unit
Experiment No. 1
1993

Table D.62 **Discrimination accuracy (%) for autumn cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1301	31	100	100
1302	4	100	96.6
1303	3	100	93.3
1304	3	100	93.3
1305	2	93.3	76.6
1308	2	86.6	76.6
1307	2	80.0	76.6

Program run no.	Selected wavelengths (nm)			
R 1302	700	880	1340	1460
R 1303	880	1340	1460	
R 1304	820	990	1080	
R 1305	820	990		
R 1308	880	1340		
R 1307	990	1340		

Table D.63 **Discrimination accuracy (%) for autumn cabbage using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1348	27	100	100
1366	4	100	96.6
1345	4	96.6	90.0
1354	4	96.6	90.0
1362	4	96.6	90.0
1351	3	96.6	90.0
1367	3	93.3	93.3

Program run no.	Selected wavelength ratios (nm)		
R 1366	1220/990	1320/990	1460/990
R 1345	760/710	800/710	1480/710
R 1354	800/1340	850/1340	1440/1340
R 1362	800/1440	1200/1440	1320/1440
R 1351	800/1340	1440/1340	
R 1367	1320/990	1460/990	

TRIAL 6
Site: SCAE Glasshouse
Experiment No. 1
1993

Table D.64 Autumn cabbage leaf tissue, weed species and soil misclassification for each program run in trial 6 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/ Soil in various program runs						
	PROGRAM RUN 1301	**PROGRAM RUN 1302**	**PROGRAM RUN 1303**	**PROGRAM RUN 1304**	**PROGRAM RUN 1305**	**PROGRAM RUN 1308**	**PROGRAM RUN 1307**
CABBAGE LEAF					*C. album*	*C. album*	*C. album*
E. angustifolium							
S. arvensis			*P. persicaria*		*C. album*	*P. persicaria*	
P. persicaria							
E. repens							
C. album		*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*P. persicaria* *S. arvensis*	*P. persicaria* **CABBAGE LEAF**	*S. arvensis* **CABBAGE LEAF**
C. bursa-pastoris				*P. persicaria*	*P. persicaria*		
SOIL							

Table D.65 Autumn cabbage leaf tissue, weed species and soil misclassification for each program run in trial 6 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/ Soil in various program runs						
	PROGRAM RUN 1348	**PROGRAM RUN 1366**	**PROGRAM RUN 1345**	**PROGRAM RUN 1354**	**PROGRAM RUN 1362**	**PROGRAM RUN 1351**	**PROGRAM RUN 1367**
CABBAGE LEAF			*E. angustifolium*		*E. repens*		*E. angustifolium* *E. repens*
E. angustifolium				**CABBAGE LEAF**	*E. repens*	**CABBAGE LEAF**	
S. arvensis			*E. repens*				
P. persicaria							
E. repens				*E. angustifolium*		*E. angustifolium*	
C. album		*C. bursa-pastoris*					
C. bursa-pastoris							
SOIL							

Table D.66 **Number of spectra in each of the Cop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
AUTUMN CABBAGE	40	28	12
Senecio vulgaris	20	14	6
Chenopodium album	10	7	3
Stellaria media	10	7	3
Cirsium arvense	10	7	3
Fumaria officinalis	10	7	3
Euphorbia helioscopia	10	7	3
SOIL	10	7	3
Total	120	84	36

TRIAL 7
Autumn Cabbage
Site: Damhead Farm
Experiment No. 1
1993

Table D.67 **Discrimination accuracy (%) for autumn cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1121	11	100	94.44
1162	4	100	86.11
1122	4	100	86.11
1163	3	100	83.33
1123	3	100	80.50
1164	2	100	88.88
1160	2	100	63.88

Program run no.	Selected wavelengths (nm)			
R 1162	710	840	850	1060
R 1122	700	840	1220	1380
R 1163	710	840	1060	
R 1123	840	1220	1380	
R 1164	840	1060		
R 1160	840	1380		

Table D.68 **Discrimination accuracy (%) for autumn cabbage using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1186	45	100	88.88
1210	5	100	94.44
1189	5	100	83.33
1191	4	100	83.33
1199	3	100	86.11
1200	2	100	69.44
1213	2	100	58.33

Program run no.	Selected wavelength ratios (nm)			
R 1210	740/710	1100/710	1400/710	1440/710
R 1189	700/990	740/990	1380/990	1460/990
R 1191	710/990	770/990	1060/990	
R 1199	740/1380	1060/1380		
R 1200	740/1380			
R 1213	1400/710			

TRIAL 7
Site: Damhead Farm
Experiment No. 1
1993

Table D.69 Autumn cabbage leaf tissue, weed species and soil misclassification for each program run in trial 7 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/ Soil in various program runs						
	PROGRAM RUN 1121	**PROGRAM RUN 1162**	**PROGRAM RUN 1122**	**PROGRAM RUN 1163**	**PROGRAM RUN 1123**	**PROGRAM RUN 1164**	**PROGRAM RUN 1160**
CABBAGE LEAF							
S. vulgaris	*C. album* *C. arvense*	*C. album*	*E. helioscopia*	*C. album*	*C. album* *E. helioscopia*		*E. helioscopia*
C. album					*S. vulgaris*		*E. helioscopia*
S. media			*C. arvense*				*C. arvense* *C. album*
C. arvense		*E. helioscopia*	*E. helioscopia*	*E. helioscopia*	*E. helioscopia*	*E. helioscopia*	*E. helioscopia*
F. officinalis		*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*
E. helioscopia		*C. arvense* *C. album*	*C. arvense*	*C. arvense*	*C. arvense*	*C. arvense*	*S. vulgaris* *C. album*
SOIL							

Table D.71 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	**Training group**	**Trial group**
LEEK	40	28	12
Sinapsis arvense	10	7	3
Chenopodium album	10	7	3
Atriplex patula	10	7	3
Volunteer Potato	10	7	3
Taraxacum officinale	10	7	3
Viola arvensis	10	7	3
Matricaria spp.	10	7	3
Stellaria media	10	7	3
Fumaria officinalis	10	7	3
Senecio vulgaris	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	160	112	48

TRIAL 7
Leek
Site: Damhead Farm
Experiment No. 2
1993

Table D.72 **Discrimination accuracy (%) for leek using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1289	20	100	93.75
1291	4	100	87.5
1297	3	100	89.5
1292	3	100	87.5
1293	3	100	83.3
1295	2	100	68.7
1294	2	95.8	66.6

Program run no.	Selected wavelengths (nm)			
R 1291	660	700	760	1060
R 1297	710	770	1040	
R 1292	700	760	1060	
R 1293	690	760	1060	
R 1295	690	1060		
R 1294	690	760		

Table D.73 **Discrimination accuracy (%) for leek using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1477	20	100	87.5
1454	4	95.8	58.3
1474	4	91.6	70.8
1472	4	89.6	66.7
1475	3	91.7	60.4
1482	3	89.6	72.9
1455	3	87.5	52.1

Program run no.	Selected wavelength ratios (nm)		
R 1454	660/990	740/990	1380/990
R 1474	700/710	760/710	1220/710
R 1472	660/710	760/710	1220/710
R 1475	700/710	760/710	
R 1482	760/1400	1060/1400	
R 1455	660/990	740/990	

TRIAL 7
Site:Damhead Farm
Experiment No. 2
1993

Table D.74 Leek leaf tissue, weed species, stone and soil misclassification for each program run in trial 7 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1289	**PROGRAM RUN 1291**	**PROGRAM RUN 1297**	**PROGRAM RUN 1292**	**PROGRAM RUN 1293**	**PROGRAM RUN 1295**	**PROGRAM RUN 1294**
LEEK LEAF							*T. officinale*
S. arvensis							
C. album		*V. arvensis*			*V. arvensis*	*V. arvensis*	*V. arvensis* *A. patula*
A. patula						*C. album* *S. media*	*C. album*
Vol. potato							
T. officinale							**LEEK LEAF**
V. arvensis		*C. album*	*C. album*	*C. album*	*C. album*	*C. album*	*C. album*
Matricaria spp						*F. officinalis*	*F. officinalis*
S.media						*S. vulgaris*	
F. officinalis	*Matricaria spp*	*Matricaria spp*		*Matricaria spp*	*Matricaria spp*	*Matricaria spp*	*Matricaria spp*
S. vulgaris	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*
STONE							
SOIL							

Table D.75 Leek leaf tissue, weed species, stone and soil misclassification for each program run in trial 7 using wavelength ratios.

Cropleaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1477	**PROGRAM RUN 1454**	**PROGRAM RUN 1474**	**PROGRAM RUN 1472**	**PROGRAM RUN 1475**	**PROGRAM RUN 1482**	**PROGRAM RUN 1455**
LEEK LEAF		*T. officinale* Vol. potato	*T. officinale* Vol. potato	Vol. potato	*T. officinale*	*T. officinale* *V. arvensis* *A. patula*	**Vol. potato** *A. patula*
S. arvensis		*S. media*			*A. patula*		*S. media*
C. album		*Matricaria spp* *A. patula*		**LEEK LEAF**	*Matricaria spp* *S. media*	*Matricaria spp*	**LEEK LEAF** *V. arvensis* **Vol. potato**
A. patula		*S. vulgaris*	*V. arvensis*	*C. album*			
Vol. potato		*T. officinale*	*T. officinale*	*T. officinale*	**LEEK LEAF**		**LEEK LEAF** *A. patula* *F. officinalis*
T. officinale		Vol. potato	Vol. potato	Vol. potato		**LEEK LEAF** *Matricaria spp*	**LEEK LEAF** *A. patula* *F. officinalis*
V. arvensis	*Matricaria spp*	*Matricaria spp* *C. album*	*Matricaria spp* *C. album*	*Matricaria spp* *C. album*	*F. officinalis*	*Matricaria spp* *T. officinale*	*T. officinale*
Matricaria spp		*F. officinalis* *C. album*	*V. arvensis* *C. album*	*F. officinalis* Vol. potato	*V. arvensis*	Vol. potato	*A. patula*
S.media		*S. arvensis* *S. vulgaris*			*V. arvensis* *Matricaria spp* *C. album*		*V. arvensis* *F. officinalis*
F. officinalis	*Matricaria spp*	*Matricaria spp* *V. arvensis*	*Matricaria spp*	*Matricaria spp*	*S. media*	*Matricaria spp*	*Matricaria spp* *V. arvensis* *S. media*
S. vulgaris	*A. patula*	*A. patula* *T. officinale*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula* *C. album*
STONE							
SOIL							

Table D.76 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	**Training group**	**Trial group**
LEEK	40	28	12
Sinapsis arvensis	10	7	3
Chenopodium album	10	7	3
Atriplex patula	10	7	3
Viola arvensis	10	7	3
Matricaria spp.	10	7	3
Stellaria media	10	7	3
Senecio vulgaris	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	130	91	39

TRIAL 7
Leek
(Bottom of the row)
Site: Damhead Farm
Experiment No. 3
1993

Table D.77 Discrimination accuracy (%) for leek using direct wavelengths. (Bottom of the row)

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1623	16	100	94.87
1625	4	100	84.61
1626	3	100	89.74
1628	3	100	84.61
1627	3	100	82.05
1629	2	100	79.48
1630	2	100	71.79

Program run no.	Selected wavelengths (nm)			
R 1625	700	720	780	1060
R 1626	700	720	1060	
R 1628	690	720	1010	
R 1627	690	770	1010	
R 1629	690	720		
R 1630	690	1010		

TRIAL 7
Site: Damhead Farm
Experiment No. 3
1993

Table D.78 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	Training group	Trial group
LEEK	40	28	12
Atriplex patula	10	7	3
Taraxacum officinale	10	7	3
Matricaria spp.	10	7	3
Stellaria media	10	7	3
Senecio vulgaris	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	110	77	33

Table D.79 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	Training group	Trial group
LEEK	40	28	12
Chenopodium album	10	7	3
Atriplex patula	10	7	3
Taraxacum officinale	10	7	3
Stellaria media	10	7	3
Senecio vulgaris	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	110	77	33

TRIAL 7
Leek
(Middle and top of the row)
Site: Damhead Farm
Experiment Nos.: 4 and 5
1993

Table D.80 **Discrimination accuracy (%) for leek using direct wavelengths. (Middle of the row)**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1632	15	100	100
1634	4	100	96.96
1635	3	100	96.96
1637	3	100	96.96
1636	3	100	93.93
1639	2	100	87.87
1638	2	93.93	90.90

Program run no.	Selected wavelength ratios (nm)			
R 1634	700	720	1040	1380
R 1635	700	720	1040	
R 1637	690	720	1020	
R 1636	690	770	1020	
R 1639	690	1020		
R 1638	690	720		

Table D.81 **Discrimination accuracy (%) for leek using direct wavelengths. (Top of the row)**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1950	16	100	96.96
1951	9	100	96.96
1952	4	100	96.96
1953	3	100	96.96
1954	3	100	93.93
1956	2	100	81.82
1955	2	93.93	75.75

Program run no.	Selected wavelengths (nm)			
R 1952	700	720	780	1060
R 1953	700	720	1060	
R 1954	690	770	1020	
R 1956	690	1020		
R 1955	690	770		

TRIAL 7
Site: Damhead Farm
Experiment No. 4 & 5
1993

Table D.82 Leek leaf tissue, weed species, stone and soil misclassification for each program run in trial 7 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs (Bottom row)						
	PROGRAM RUN 1623	PROGRAM RUN 1625	PROGRAM RUN 1626	PROGRAM RUN 1628	PROGRAM RUN 1627	PROGRAM RUN 1629	PROGRAM RUN 1630
LEEK LEAF							
S. arvensis				*V. arvensis*		*V. arvensis*	*V. arvensis*
C. album		*V. arvensis*		*V. arvensis*	*V. arvensis*	*V. arvensis* *A. patula*	*V. arvensis*
A. patula							*C. album* *S. media*
V. arvensis		*C. album*	*C. album*	*C. album*	*C. album*	*C. album*	*C. album*
Matricaria spp							
S. media					*S.arvensis*		*S. vulgaris*
S. vulgaris	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*V. arvensis*	*A. patula*
STONE							
SOIL							

Table D.83 Leek leaf tissue, weed species, stone and soil misclassification for each program run in trial 7 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs (Middle row)						
	PROGRAM RUN 1632	**PROGRAM RUN 1634**	**PROGRAM RUN 1635**	**PROGRAM RUN 1637**	**PROGRAM RUN 1636**	**PROGRAM RUN 1639**	**PROGRAM RUN 1638**
LEEK LEAF							*T. officinale*
A. patula						*S. media*	
T. officinale							**LEEK LEAF**
Matricaria spp.							
S. media						*S. vulgaris*	
S. vulgaris		*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*
STONE							
SOIL							

Table D.84 Leek leaf tissue, weed species, stone and soil misclassification for each program run in trial 7 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs (Top row)						
	PROGRAM RUN 1950	PROGRAM RUN 1951	PROGRAM RUN 1952	PROGRAM RUN 1953	PROGRAM RUN 1954	PROGRAM RUN 1956	PROGRAM RUN 1955
LEEK LEAF							*T. officinale*
C. album						*A. patula*	*A. patula*
A. patula						*C. album* *S. media*	*C. album*
T. officinale							**LEEK LEAF**
S. media						*S. vulgaris*	
S. vulgaris	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*
STONE							
SOIL							

Table D.85 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
MATURE BROCCOLI	40	28	12
Lamium album	10	7	3
Lamium purpureum	10	7	3
Rumex spp.	10	7	3
Myosotis arvensis	10	7	3
Stellaria media	10	7	3
Elymus repens	10	7	3
SOIL	10	7	3
Total	110	77	33

TRIAL 8
Mature Broccoli
Site: Claremont Cottage
Experiment No. 1
1993

Table D.86 **Discrimination accuracy (%) for mature broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1124	24	100	100
1125	4	100	96.96
1126	3	100	90.90
1174	3	100	90.90
1183	2	100	84.84
1176	2	100	84.84
1184	1	100	78.78

Program run no.	Selected wavelengths (nm)			
R 1125	700	820	1380	1480
R 1126	820	1380	1480	
R 1174	710	740	890	
R 1183	960	1380		
R 1176	890	1380		
R 1184	890			

Table D.87 **Discrimination accuracy (%) for mature broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1228	17	100	96.66
1253	4	100	93.93
1220	4	100	90.90
1221	3	100	87.87
1254	3	100	87.87
1232	3	100	81.81
1223	2	100	90.90

Program run no.	Selected wavelength ratios (nm)		
R 1253	700/1340	960/1340	1480/1340
R 1220	740/990	1320/990	1460/990
R 1221	1320/990	1460/990	
R 1254	960/1340	1480/1340	
R 1232	1380/710	1420/710	
R 1223	1460/990		

TRIAL 8
Site: Claremont Cottage
Experiment No. 1
1993

Table D.88 **Mature broccoli leaf tissue, weed species and soil misclassification for each program run in trial 8 using direct wavelengths.**

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/ Soil in various program runs						
	PROGRAM RUN 1124	**PROGRAM RUN 1125**	**PROGRAM RUN 1126**	**PROGRAM RUN 1174**	**PROGRAM RUN 1183**	**PROGRAM RUN 1176**	**PROGRAM RUN 1184**
BROCCOLI LEAF							
L. album			*L. purpureum*	*L. purpureum*	*L. purpureum*	*L. purpureum*	*L. purpureum*
L. purpureum							
Rumex spp.							*L. purpureum*
M. arvensis			*L. album*	*S. media*	*S. media*	*S. media*	*S. media*
S. media		*M. arvensis*	*M. arvensis*		*M. arvensis*	*M. arvensis*	*M. arvensis*
E. repens							
SOIL							

Table D.89 Mature broccoli leaf tissue, weed species and soil misclassification for each program run in trial 8 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/ Soil in various program runs						
	PROGRAM RUN 1228	**PROGRAM RUN 1253**	**PROGRAM RUN 1220**	**PROGRAM RUN 1221**	**PROGRAM RUN 1254**	**PROGRAM RUN 1232**	**PROGRAM RUN 1223**
BROCCOLI LEAF							
L. album	*M. arvensis*					*S. media*	*M. arvensis*
L. purpureum				*Rumex spp.*		*Rumex spp.*	*Rumex spp.*
Rumex spp.						*L. purpureum*	
M. arvensis		*L. putpureum*	*Rumex spp.* *L. album*	*Rumex spp.* *L. album*	*Rumex spp.* *L. album*	*Rumex spp.* *L. album* *S. media*	*Rumex spp.*
S. media		*M. arvensis*			*M. arvensis*		
E. repens							
SOIL							

Table D.90 **Number of spectra in each of the Crop/Weed/Straw categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Straw	Number of spectra		
	Total	**Training group**	**Trial group**
MATURE BROCCOLI	40	28	12
Lamium album	10	7	3
Lamium purpureum	10	7	3
Rumex spp.	10	7	3
Myosotis arvensis	10	7	3
Stellaria media	10	7	3
Elymus repens	10	7	3
STRAW	10	7	3
Total	110	77	33

TRIAL 8
Mature Broccoli
Site : Claremont Cottage
Experiment No. 2
1993

Table D.91 **Discrimination accuracy (%) for mature broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Straw	Crop leaf/Weed species/ Straw
1599	20	100	96.96
1601	4	100	96.96
1602	3	100	87.87
1605	3	100	81.81
1606	2	96.96	84.84
1604	2	93.93	78.78
1607	1	96.96	72.72

Program run no.	Selected wavelengths (nm)			
R 1601	680	720	1380	1480
R 1602	680	1380	1480	
R 1605	680	710	890	
R 1606	680	890		
R 1604	680	1380		
R 1607	680			

Table D.92 **Discrimination accuracy (%) for mature broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Straw	Crop leaf/Weed species/ Straw
1668	20	100	96.96
1670	4	100	96.96
1658	4	100	93.93
1676	4	100	93.93
1680	3	100	93.93
1663	3	100	90.90
1662	2	100	81.81

Program run no.	Selected wavelength ratios (nm)		
R 1670	680/710	740/710	1460/710
R 1658	680/1340	740/1340	1480/1340
R 1676	680/990	760/990	1460/990
R 1680	680/990	1460/990	
R 1663	710/1340	1480/1340	
R 1662	1480/1340		

TRIAL 8
Site: Claremont Cottage
Experiment No. 2
1993

Table D.93 Mature broccoli leaf tissue, weed species and straw misclassification for each program run in trial 8 using direct wavelengths.

Crop leaf/ Weed/Straw	Misclassified Crop leaf/Weed/Straw in various program runs						
	PROGRAM RUN 1599	**PROGRAM RUN 1601**	**PROGRAM RUN 1602**	**PROGRAM RUN 1605**	**PROGRAM RUN 1606**	**PROGRAM RUN 1604**	**PROGRAM RUN 1607**
BROCCOLI LEAF							
L. album	*M. arvensis*		*S. media*	*L. purpureum*	**BROCCOLI LEAF**	**BROCCOLI LEAF** *S. media*	**BROCCOLI LEAF** *M. arvensis*
L. purpureum							*S. media* *L. album*
Rumex spp.							
M. arvensis		*S. media*	*L. album*	*S. media*	*S. media*	*S. media*	*Rumex spp.* *E. repens*
S. media			*M. arvensis*	*M. arvensis*	*M. arvensis*	*M. arvensis*	*M. arvensis*
E. repens							
STRAW							

Table D.94 Mature broccoli leaf tissue, weed species and straw misclassification for each program run in trial 8 using wavelength ratios.

Crop leaf/ Weed/Straw	Misclassified Crop leaf/Weed/Straw in various program runs						
	PROGRAM RUN 1668	PROGRAM RUN 1670	PROGRAM RUN 1658	PROGRAM RUN 1676	PROGRAM RUN 1680	PROGRAM RUN 1663	PROGRAM RUN 1662
BROCCOLI LEAF							
L. album	*M. arvensis*	*M. arvensis*	*M. arvensis*	*M. arvensis*	*M. arvensis*		*M. arvensis* *S. media*
L. purpureum						*Rumex spp.*	*Rumex spp.*
Rumex spp.							
M. arvensis			*Rumex spp.*	*Rumex spp.*	*Rumex spp.*	*L. album*	*Rumex spp* *S. media.*
S. media						*M. arvensis*	
E. repens							
STRAW							

Table D.96 **Discrimination accuracy (%) for savoy cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1555	12	100	97.22
1556	12	100	80.55
1557	4	100	91.66
1558	4	100	83.33
1559	3	100	83.33
1560	2	94.44	77.77
1561	1	83.33	58.33

Program run no.	Selected wavelengths (nm)			
R 1557	680	760	1040	1500
R 1558	680	710	760	1040
R 1559	680	760	1040	
R 1560	760	1040		
R 1561	760			

Table D.97 **Discrimination accuracy (%) for savoy cabbage using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1584	12	100	94.44
1585	10	100	88.88
1564	4	91.66	77.77
1588	4	91.66	63.88
1580	3	94.44	69.44
1589	3	91.66	55.55
1582	2	86.11	50.00

Program run no.	Selected wavelength ratios (nm)		
R 1564	680/990	740/990	1380/990
R 1588	680/1400	720/1400	770/1400
R 1580	1060/660	1380/660	
R 1589	680/1400	720/1400	
R 1582	1380/660		

TRIAL 9
Site: Wallyford Farm
Experiment No. 1
1993

Table D.98 Savoy cabbage leaf tissue, weed species, stone and soil misclassification for each program run in trial 9 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1555	**PROGRAM RUN 1556**	**PROGRAM RUN 1557**	**PROGRAM RUN 1558**	**PROGRAM RUN 1559**	**PROGRAM RUN 1560**	**PROGRAM RUN 1561**
CABBAGE LEAF						*S. vulgaris*	*S. vulgaris*
C. album		*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris* *A. patula*
S. media							**CABBAGE LEAF**
S. vulgaris	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*C. album*
C. bursa-pastoris		*C. album*		*C. album*	*C. album*	*C. album*	*C. album* *A. patula*
A. patula							*C. album*
V. persica		*C. bursa-pastoris*					
STONE							
SOIL							

Table D.99 Savoy cabbage leaf tissue, weed species, stone and soil misclassification for each program run in trial 9 using wavelength ratios.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1584	**PROGRAM RUN 1585**	**PROGRAM RUN 1564**	**PROGRAM RUN 1588**	**PROGRAM RUN 1580**	**PROGRAM RUN 1589**	**PROGRAM RUN 1582**
CABBAGE LEAF			*S. vulgaris*	*C. album* *A. patula*	*S. vulgaris*	*S. vulgaris* *A. patula*	**SOIL** *A. patula*
C. album		*C. bursa-pastoris*	*V. persica*	*V. persica*	*V. persica*	*C. bursa-pastoris* *A. patula*	*C. bursa-pastoris* *A. patula* **CABBAGE LEAF**
S. media				*C. album*	*V. persica*	*C. album* *A. patula*	*V. persica* *A. patula*
S. vulgaris	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*S. media*	*A. patula* *C. bursa-pastoris*
C. bursa-pastoris			*V. persica*	*C. album* *S. media*	*V. persica* *C. album*	*V. persica* *C. album* *S. media*	*V. persica* *A. patula*
A. patula			**CABBAGE LEAF**	**CABBAGE LEAF** *C. bursa-pastoris*	**CABBAGE LEAF**	**CABBAGE LEAF** *C. album* *V. persica*	**CABBAGE LEAF**
V. persica	*C. album*	*C. bursa-pastoris*	*C. album*	*C. bursa-pastoris* *S. media*	*C. album* *A. patula*	*C. bursa-pastoris* *S. media*	*C. bursa-pastoris* *A. patula* *S. media*
STONE							
SOIL							

Table D.100 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	**Training group**	**Trial group**
SPRING CABBAGE	40	28	12
Chenopodium album	10	7	3
Stellaria media	10	7	3
Senecio vulgaris	10	7	3
Capsella bursa-pastoris	10	7	3
Atriplex patula	10	7	3
Veronica persica	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	120	84	36

TRIAL 9
Spring Cabbage
Site: Wallyford Farm
Experiment No. 2
1993

Table D.101 **Discrimination accuracy (%) for spring cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1141	15	100	100
1143	4	100	94.4
1153	3	100	83.3
1145	3	97.2	83.3
1151	3	94.4	91.6
1155	2	100	80.5
1154	2	97.2	83.3

Program run no.	Selected wavelengths (nm)			
R 1143	680	760	1060	1360
R 1153	680	1060	1360	
R 1145	680	760	1060	
R 1151	760	1060	1500	
R 1155	720	840		
R 1154	1060	1360		

Table D.102 **Discrimination accuracy (%) for spring cabbage using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1281	15	100	100
1283	4	100	91.66
1263	4	100	86.11
1273	3	100	86.11
1284	3	100	86.11
1276	3	100	80.55
1277	2	100	75.00

Program run no.	Selected wavelength ratios (nm)		
R 1283	720/1400	1080/1400	1320/1400
R 1263	680/990	720/990	1400/990
R 1273	780/710	1320/710	
R 1284	720/1400	1080/1400	
R 1276	750/710	1050/710	
R 1277	750/710		

TRIAL 9
Site: Wallyford Farm
Experiment No. 2
1993

Table D.103 Spring cabbage leaf tissue, weed species, stone and soil misclassification for each program run in trial 9 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1141	**PROGRAM RUN 1143**	**PROGRAM RUN 1153**	**PROGRAM RUN 1145**	**PROGRAM RUN 1151**	**PROGRAM RUN 1155**	**PROGRAM RUN 1154**
CABBAGE LEAF					*S. vulgaris*		*S. vulgaris*
C. album			*C. bursa-pastoris* *A. patula*	*C. bursa-pastoris*		*C. bursa-pastoris*	*C. bursa-pastoris*
S. media			*C. album*				*C. album* *C. bursa-pastoris*
S. vulgaris		*A. patula*		*A. patula*	*A. patula* **CABBAGE LEAF**	*A. patula*	
C. bursa-pastoris		*C. album*	*C. album*	*C. album*		*C. album*	*C. album*
A. patula			*C. album*	**CABBAGE LEAF**			
V. persica						*C. bursa-pastoris*	
STONE							
SOIL							

Table D.104 Spring cabbage leaf tissue, weed species, stone and soil misclassification for each program run in trial 9 using wavelength ratios.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1281	**PROGRAM RUN 1283**	**PROGRAM RUN 1263**	**PROGRAM RUN 1273**	**PROGRAM RUN 1284**	**PROGRAM RUN 1276**	**PROGRAM RUN 1277**
CABBAGE LEAF							
C. album			*C. bursa-pastoris*		*C. bursa-pastoris*		
S. media							*C. album* *V. persica*
S. vulgaris		*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*	*A. patula*
C. bursa-pastoris		*C. album*	*C. album*	*C. album*	*C. album*	*C. album*	*S. media*
A. patula							*S. vulgaris*
V. persica		*C. album*	*C. album* *C. bursa-pastoris*	*C. album* *S. vulgaris*	*C. album*	*C. album* *S. vulgaris*	*S. vulgaris* *C. bursa-pastoris*
STONE							
SOIL							

Table D.105 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	**Training group**	**Trial group**
AUTUMN CABBAGE	40	28	12
Chenopodium album	10	7	3
Stellaria media	10	7	3
Senecio vulgaris	10	7	3
Capsella bursa-pastoris	10	7	3
Atriplex patula	10	7	3
Veronica persica	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	120	84	36

TRIAL 9
Autumn Cabbage
Site: Wallyford Farm
Experiment No. 3
1993

TableD.106 Discrimination accuracy (%) for autumn cabbage using direct wavelengths.

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1129	12	94.4	91.6
1131	4	94.4	91.6
1132	3	91.6	77.7
1140	3	88.8	80.5
1135	2	84.8	78.7
1133	2	83.3	69.4
1134	2	83.3	61.1

Program run no.	Selected wavelengths (nm)			
R 1131	680	760	1060	1480
R 1132	680	760	1060	
R 1140	680	1060	1480	
R 1135	760	1480		
R 1133	760	1060		
R 1134	680	1060		

Table D.107 Discrimination accuracy (%) for autumn cabbage using wavelength ratios.

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1323	11	100	83.3
1320	4	97.2	80.5
1317	4	94.4	77.7
1329	4	94.4	77.7
1324	4	94.4	66.6
1341	4	91.6	63.8
1327	3	91.6	55.5

Program run no.	Selected wavelength ratios (nm)		
R 1320	680/990	770/990	1400/990
R 1317	680/990	740/990	1400/990
R 1329	680/1400	770/1400	1440/1400
R 1324	680/1400	720/1400	1440/1400
R 1341	720/680	900/680	1400/680
R 1327	680/1400	720/1400	

TRIAL 9
Site: Wallyford Farm
Experiment No. 3
1993

Table D.108 Autumn cabbage leaf tissue, weed species, stone and soil misclassification for each program run in trial 9 using direct wavelengths.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1129	**PROGRAM RUN 1131**	**PROGRAM RUN 1132**	**PROGRAM RUN 1140**	**PROGRAM RUN 1135**	**PROGRAM RUN 1133**	**PROGRAM RUN 1134**
CABBAGE LEAF	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*
C. album			*C. bursa-pastoris*			*C.bursa-pastoris*	*C. bursa-pastoris* *A. patula*
S. media				*C. bursa-pastoris* *A. patula*	**CABBAGE LEAF**		*C. album*
S. vulgaris	*A. patula*	*A. patula*	*A. patula*	**CABBAGE LEAF**	*A. patula*	*A. patula*	*A. patula* **CABBAGE LEAF**
C. bursa-pastoris			*C. album*		*A. patula*	*C. album*	*C. album*
A. patula							*C. album*
V. persica	*C. bursa-pastoris*						
STONE							
SOIL							

Table D.109 **Autumn cabbage leaf tissue, weed species, stone and soil misclassification for each program run in trial 9 using wavelength ratios.**

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1323	**PROGRAM RUN 1320**	**PROGRAM RUN 1317**	**PROGRAM RUN 1329**	**PROGRAM RUN 1324**	**PROGRAM RUN 1341**	**PROGRAM RUN 1327**
CABBAGE LEAF			*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*
C. album	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*V. persica* *A. patula*	*V. persica*	*C. bursa-pastoris* *A. patula*
S. media						*C. album*	*C. album* *A. patula*
S. vulgaris	*A. patula*	**CABBAGE LEAF** *A. patula*	**CABBAGE LEAF** *A. patula*	**CABBAGE LEAF**	*C. album*	*A. patula*	**CABBAGE LEAF** *S. media*
C. bursa-pastoris	*C. album*	*C. album* *V. persica*	*C. album*	*C. album* *V. persica*	*C. album* *V. persica*	*C. album*	*C. album* *V. persica* *S. media*
A. patula					*C. album* *V. persica*	*C. album* *C. bursa-pastoris*	*C. album* *V. persica*
V. persica	*C. bursa-pastoris* *S. vulgaris*	*C. bursa-pastoris* *C. album*	*C. bursa-pastoris* *C. album*	*C. bursa-pastoris* *C. album*	*C. bursa-pastoris* *C. album*	*C. bursa-pastoris* *S. vulgaris*	*C. bursa-pastoris* *S. media*
STONE							
SOIL							

Table D.110 **Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Soil	Number of spectra		
	Total	**Training group**	**Trial group**
YOUNG BROCCOLI	40	28	12
Stellaria media	10	7	3
Urtica dioica	10	7	3
Polygonum persicaria	10	7	3
Capsella bursa-pastoris	10	7	3
Polygonum aviculare	10	7	3
Rumex spp.	10	7	3
SOIL	10	7	3
Total	110	77	33

TRIAL 10
Young Broccoli
Site: SCAE Glasshouse Unit
Experiment No. 1
1993

Table D.111 **Discrimination accuracy (%) for young broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1086	10	100	96.96
1087	4	100	96.96
1092	4	100	87.87
1088	3	100	96.96
1093	3	100	90.90
1090	2	100	100
1097	2	100	87.87

Program run no.	Selected wavelengths (nm)			
R 1087	700	720	1380	1500
R 1092	700	720	900	1090
R 1088	700	720	1380	
R 1093	700	720	1090	
R 1090	700	720		
R 1097	720	900		

Table D.112 **Discrimination accuracy (%) for young broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1106	9	100	100
1108	5	100	93.93
1101	4	100	96.96
1116	4	100	96.96
1102	3	100	78.78
1103	2	100	75.75
1118	2	100	69.69

Program run no.	Selected wavelength ratios (nm)			
R 1108	720/680	1340/680	1420/680	1480/680
R 1101	740/710	1060/710	1400/710	
R 1116	700/990	740/990	1320/990	
R 1102	740/710	1400/710		
R 1103	1400/710			
R 1118	1320/990			

TRIAL 10
Site: SCAE Glasshouse Unit
Experiment No. 1
1993

Table D.113 Young broccoli leaf tissue, weed species and soil misclassification for each program run in trial 10 using direct wavelengths.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1086	**PROGRAM RUN 1087**	**PROGRAM RUN 1092**	**PROGRAM RUN 1088**	**PROGRAM RUN 1093**	**PROGRAM RUN 1090**	**PROGRAM RUN 1097**
BROCCOLI LEAF							
S. media							
U. dioica			*Rumex spp.* *P. aviculare*		*Rumex spp.*		*Rumex spp.* *C. bursa-pastoris*
P. persicaria							
C. bursa-pastoris	*Rumex spp.*	*Rumex spp.*	*Rumex spp.*	*Rumex spp.*	*Rumex spp.*		*Rumex spp.*
P. aviculare			*C. bursa-pastoris*		*C. bursa-pastoris*		*C. bursa-pastoris*
Rumex spp.							
SOIL							

Table D.114 Young broccoli leaf tissue, weed species and soil misclassification for each program run in trial 10 using wavelength ratios.

Crop leaf/ Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1106	**PROGRAM RUN 1108**	**PROGRAM RUN 1101**	**PROGRAM RUN 1116**	**PROGRAM RUN 1102**	**PROGRAM RUN 1103**	**PROGRAM RUN 1118**
BROCCOLI LEAF							
S. media							*P. aviculare*
U. dioica					*P. persicaria*	*C. bursa-pastoris*	*P. persicaria*
P. persicaria		*U. dioica*			*U. dioica*	*U. dioica*	*U. dioica*
C. bursa-pastoris						*P. aviculare* *Rumex spp.*	*P. aviculare* *S. media*
P. aviculare					*Rumex spp.*		*S. media*
Rumex spp.			*P. aviculare*	*U. dioica*	*P. aviculare*	*P. aviculare* *C. bursa-pastoris*	*U. dioica* *C. bursa-pastoris*
SOIL							

Table D.115 **Number of spectra in each of the Crop/Weed/Stone-Soil categories, in the training group and in the trial group used to test discrimination accuracy.**

Crop/Weed/Stone-Soil	Number of spectra		
	Total	**Training group**	**Trial group**
MATURE BROCCOLI	40	28	12
Matricaria spp.	10	7	3
Elymus repens	10	7	3
Capsella bursa-pastoris	10	7	3
Stellaria media	10	7	3
Senecio vulgaris	10	7	3
STONE	10	7	3
SOIL	10	7	3
Total	110	77	33

TRIAL 11
Mature Broccoli
Site: Nr. St. Andrews
Experiment No. 1
1993

Table D.116 **Discrimination accuracy (%) for mature broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/ Stone-Soil	Crop leaf/Weed species/ Stone-Soil
1512	13	96.96	93.93
1514	4	93.93	90.90
1517	3	93.93	90.90
1513	3	87.87	84.84
1515	3	87.87	84.84
1516	3	87.87	84.84
1518	2	93.93	87.87

Program run no.	Selected wavelengths (nm)			
R 1514	680	740	1040	1380
R 1517	790	1040	1380	
R 1513	680	790	1060	
R 1515	740	1040	1380	
R 1516	680	740	1040	
R 1518	790	1380		

Table D.117 **Discrimination accuracy (%) for mature broccoli using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		Crop leaf/Weed/Soil	Crop leaf/Weed species/ Soil
1524	31	100	93.93
1525	4	93.93	90.90
1533	4	93.93	90.90
1534	3	93.93	87.87
1545	3	93.93	69.69
1553	3	90.90	84.84
1526	3	90.90	81.81

Program run no.	Selected wavelength ratios (nm)		
R 1525	680/990	760/990	1380/990
R 1533	680/710	1320/710	1400/710
R 1534	680/710	1400/710	
R 1545	1120/680	1400/680	
R 1553	690/1400	730/1400	
R 1526	760/990	1380/990	

TRIAL 11
Site: Nr St Andrews
Experiment No. 1
1993

Table D.118 **Mature broccoli leaf tissue, weed species, stone and soil misclassification for each program run in trial 11 using direct wavelengths.**

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1512	**PROGRAM RUN 1514**	**PROGRAM RUN 1517**	**PROGRAM RUN 1513**	**PROGRAM RUN 1515**	**PROGRAM RUN 1516**	**PROGRAM RUN 1518**
BROCCOLI LEAF	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*
Matricaria spp.	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*	*C. bursa-pastoris*
E. repens							
C. bursa-pastoris							
S. media							
S. vulgaris			**BROCCOLI LEAF**	**BROCCOLI LEAF**	**BROCCOLI LEAF**	**BROCCOLI LEAF**	**BROCCOLI LEAF** *C. bursa-pastoris*
STONE							
SOIL							

Table D.119 Mature broccoli leaf tissue, weed species, stone and soil misclassification for each program run in trial 11 using wavelength ratios.

Crop leaf/ Weed/Stone-Soil	Misclassified Crop leaf/Weed/Stone-Soil in various program runs						
	PROGRAM RUN 1524	**PROGRAM RUN 1525**	**PROGRAM RUN 1533**	**PROGRAM RUN 1534**	**PROGRAM RUN 1545**	**PROGRAM RUN 1553**	**PROGRAM RUN 1526**
BROCCOLI LEAF		*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*	*S. vulgaris*
Matricaria spp.	*S. vulgaris*						
E. repens					*C. bursa-pastoris*		
C. bursa-pastoris	*Matricaria spp.*				*E. repens*	*E. repens*	*Matricaria spp.*
S. media				*S. vulgaris*	*Matricaria spp* *C. bursa-pastoris*		
S. vulgaris		*C. bursa-pastoris*	*Matricaria spp.*	*C. bursa-pastoris*	*Matricaria spp.*	**BROCCOLI LEAF** *C. bursa-pastoris*	**BROCCOLI LEAF** *C. bursa-pastoris*
STONE							
SOIL							

APPENDIX E

Table E.1 Classification function coefficients for different cabbage trials obtained from programs using wavelengths at 680 nm, 760 nm and 1040 nm.

Cabbage weed/soil	Coefficient name	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Cabbage	Kc-680	5.0948	0.3719	1.1947	0.2833	-0.3570	1.0110
	Kc-760	2.2099	1.3277	-0.0121	0.0464	-2.2543	-1.1816
	Kc-1040	-0.3306	-1.4168	1.0026	--	3.8564	2.2374
	Kc	-67.7033	-14.5341	-26.1018	-2.4874	-33.7199	-26.1717
Weed	Kw-680	1.8901	0.0756	0.1311	0.2937	0.8945	0.1016
	Kw-760	3.8700	0.1993	0.8843	0.0729	-0.7778	-0.7115
	Kw-1040	-2.6088	-0.1098	0.0381	--	1.5536	1.6175
	Kw	-29.6856	-4.6822	-18.8017	-3.7562	-13.2324	-16.0039
Soil	Ks-680	4.1513	0.9731	2.6763	2.2433	1.4496	2.4217
	Ks-760	-4.5069	-1.4921	-1.3198	-0.1392	-1.3030	-0.7218
	Ks-1040	5.0707	1.7239	1.4986	--	1.9663	0.9690
	Ks	-30.4168	-9.6590	-18.5721	-8.6285	-14.0849	-17.0657

Table E.2 Classification function coefficients obtained from different cabbage trials using 680 nm, 1060 nm and 1360 nm .

Cabbage/ weed/soil	Coefficient name	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Cabbage	Kc-680	5.2188	0.6820	1.1599	0.1748	-0.4584	1.2004
	Kc-1060	1.9025	2.9887	0.7824	0.0716	10.3753	2.5917
	Kc-1360	-0.2500	-3.9936	0.3925	--	-15.4683	-3.2147
	Kc	-64.0383	-51.3986	-25.816	-2.5908	-98.8136	-26.9273
Weed	Kw-680	1.2590	0.1089	-0.3104	0.1385	1.2460	0.0453
	Kw-1060	-0.4270	0.3902	-1.6472	0.1099	0.1747	0.4070
	Kw-1360	3.0496	-0.3758	5.4862	--	0.5196	0.5291
	Kw	-24.9449	-4.8623	-27.3151	-3.9650	-11.6270	-13.9260
Soil	Ks-680	1.0065	0.6364	1.1472	2.3370	2.8982	2.1092
	Ks-1060	-4.9326	-0.9076	-3.9329	-0.1764	-8.0243	-2.2798
	Ks-1360	11.0437	1.2479	9.0727	--	13.3391	4.0548
	Ks	-64.0350	-7.4631	-44.0623	-8.3208	-67.5731	-25.3491

Table E.3 **Classification function coefficients obtained from programs runs for different broccoli trials with 720 nm, 1060 nm and 1380 nm as wavelengths.**

Broccoli/ weed/soil	Coefficient name	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Broccoli	Kc-720	-1.1114	0.0471	0.8426	0.3576	--	0.2343
	Kc-1060	1.2340	1.4297	1.2447	--	1.9910	1.3851
	Kc-1380	1.7601	-1.9625	-2.5857	-0.2387	-2.3950	-1.9739
	Kc	-26.1814	-17.0327	-24.5019	-3.5525	-19.4079	-19.9238
Weed	Kw-720	-1.0879	0.2758	0.3451	0.6201	--	0.4649
	Kw-1060	0.1542	0.1262	0.4873	--	0.3354	0.4193
	Kw-1380	4.0398	-0.3092	-0.8777	-0.4363	0.7649	-0.8494
	Kw	-18.2942	-5.6656	-6.8959	-7.8650	-13.9299	-8.4734
Soil	Ks-720	-4.2175	0.0095	-0.2998	-0.4520	--	-0.0346
	Ks-1060	-0.8594	-0.9484	-0.6804	--	-1.6841	-0.2855
	Ks-1380	14.1165	1.4935	1.4556	0.6129	3.8195	0.5345
	Ks	-98.8140	-6.8535	-7.2497	-4.4839	-21.3469	-2.6220

Table E.4 **Classification function coefficients obtained from programs runs for different broccoli trials with 710 nm, 740 nm and 890 nm as wavelengths.**

Broccoli/ weed/soil	Coefficient name	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Broccoli	Kc-710	-0.7633	-0.3668	1.9333	-0.4501	2.9233	--
	Kc-740	0.3247	0.3651	-0.7967	1.1324	-3.4409	-0.6642
	Kc-890	1.0757	--	--	-0.7992	2.4600	0.8404
	Kc	-27.4272	-9.6073	-16.4045	-5.2539	-24.7309	-6.0277
Weed	Kw-710	-0.3667	0.3059	0.9066	0.7123	0.5669	--
	Kw-740	1.0263	-0.0206	-0.3041	-0.3067	-0.9135	0.0523
	Kw-890	-0.1905	--	--	0.1125	1.3394	0.1078
	Kw	-11.4501	-5.5120	-6.6455	-7.4706	-14.5114	-4.8018
Soil	Ks-710	0.4677	0.2769	0.5153	0.4938	1.6528	--
	Ks-740	-2.1970	-0.1161	-0.2201	-1.1307	-2.6035	-0.3452
	Ks-890	2.0579	--	--	0.9357	1.9468	0.4018
	Ks	-5.5129	-1.6493	-2.1046	-3.5996	-7.5994	-1.7642

Table E.5 **Classification function coefficients obtained for different leek trials from programs runs using 760 nm, 1340 nm and 1480 nm as wavelengths.**

Leek/ weed/soil	Coefficient name	Value of classification function coefficients			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Leek	Kc-760	1.2784	-0.4500	-0.7916	-0.3333
	Kc-1340	-1.8666	2.0850	-1.3469	2.1089
	Kc-1480	0.1189	1.4646	4.7607	--
	Kc	-19.6485	-40.3317	-42.7558	-28.9623
Weed	Kw-760	0.2353	-1.2753	-0.2187	-0.0928
	Kw-1340	-0.5054	2.0599	-1.7354	1.1477
	Kw-1480	0.4346	2.4523	3.7822	--
	Kw	-6.0404	-30.5660	-25.6682	-12.2366
Soil	Ks-760	-1.0229	-4.2936	-1.0953	-0.8308
	Ks-1340	1.3652	5.3538	0.6550	2.0624
	Ks-1480	0.3946	3.5431	2.0015	--
	Ks	-11.3001	-38.9868	-17.1218	-11.3479

Table E.6 **Classification function coefficients obtained for different leek trials from programs runs using 680 nm, 1080 nm and 1520 nm as wavelengths.**

Leek/ weed/soil	Coefficient name	Value of classification function coefficients			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Leek	Kc-680	0.1397	-0.8103	2.7248	1.3765
	Kc-1080	0.3647	0.7419	-0.0068	0.6736
	Kc-1520	-0.3298	1.7768	--	0.1199
	Kc	-8.2518	-42.5021	-20.8371	-33.5397
Weed	Kw-680	0.1095	-0.9788	0.4048	-0.1053
	Kw-1080	-0.0089	-0.2729	0.1294	-0.1899
	Kw-1520	0.2157	2.8624	--	1.2116
	Kw	-5.0971	-30.7389	-4.5681	-12.4294
Soil	Ks-680	0.4651	1.5462	1.5638	0.8119
	Ks-1080	-0.2368	-0.6011	-0.0592	-0.6132
	Ks-1520	0.3931	1.6260	--	1.2312
	Ks	-4.4198	-17.1875	-6.3667	-10.1383

Table E.7 Classification function coefficients for different cabbage varieties having the same weed population obtained from programs runs using 680 nm, 760 nm and 1040 nm as wavelengths.

Cabbage/ weed/soil	Coefficient name	Value of classification function coefficients					
		All weeds classified together			Weed species classification		
		Spring	Autumn	Savoy	Spring	Autumn	Savoy
Cabbage	Kc-680	1.0110	-0.5094	0.8494	4.2774	-4.0651	3.4062
	Kc-760	-1.1817	-1.1061	-1.3581	-5.3751	3.3186	-5.1249
	Kc-1040	2.2375	2.3769	2.6488	10.3334	2.2767	12.5484
	Kc	-26.1717	-28.4467	-33.8490	-118.118	-127.279	-186.297
Weed	Kw-680	0.1016	0.0606	0.1245	--	--	--
	Kw-760	-0.7115	-0.6364	-0.7468	--	--	--
	Kw-1040	1.6176	1.5070	1.6903	--	--	--
	Kw	-16.0039	-15.4272	-16.6480	--	--	--
Soil	Ks-680	2.4217	2.5493	2.1601	6.2864	7.8834	4.1957
	Ks-760	-0.7218	-0.6713	-0.7393	-11.0314	-8.8355	-9.7495
	Ks-1040	0.9691	0.8673	1.0426	12.7117	9.3450	12.1526
	Ks	-17.0657	-17.3476	-16.0425	-53.2723	-47.6132	-48.4159

Table E.8 Classification function coefficients obtained from programs using 680 nm, 1060 nm and 1360 nm for different cabbage varieties and having the same weed population.

Cabbage/ weed/soil	Coefficient name	Value of classification function coefficients					
		All weeds classified together			Weed species classification		
		Spring	Autumn	Savoy	Spring	Autumn	Savoy
Cabbage	Kc-680	1.2004	-0.4472	0.9435	4.9565	-3.4581	2.2663
	Kc-1060	2.5917	1.7568	1.4548	11.2021	6.0789	5.7156
	Kc-1360	-3.2147	-1.3437	-0.9738	-12.1493	-1.2749	1.8265
	Kc	-26.9273	-24.2577	-26.4824	-130.425	-121.324	-168.972
Weed	Kw-680	0.0453	0.0126	0.0176	--	--	--
	Kw-1060	0.4071	0.3896	0.4178	--	--	--
	Kw-1360	0.5292	0.5453	0.5606	--	--	--
	Kw	-13.9261	-13.7274	-14.3941	--	--	--
Soil	Ks-680	2.1092	2.2738	1.7311	3.1923	4.9322	0.9918
	Ks-1060	-2.2798	-2.1804	-1.4963	-9.0029	-7.0437	-2.5305
	Ks-1360	4.0548	3.8410	2.8393	18.0505	13.9732	8.5291
	Ks	-25.3492	-25.4485	-20.2193	-72.1643	-64.2926	-44.2514

Table E.9 **Cabbage coefficient comparison from programs runs grouping the weeds together or by species in various cabbage trials using 680 nm, 760 nm and 1040 nm as wavelengths.**

Cabbage coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Kc-680	All	5.0948	0.3719	1.1947	0.2833	-0.3570	1.0110
	Species	5.8109	0.4543	3.2304	3.3410	12.9127	4.2774
Kc-760	All	2.2099	1.3277	-0.0121	0.0464	-2.2543	-1.1816
	Species	4.1703	1.4200	-3.5357	--	8.6234	-5.3751
Kc-1040	All	-0.3306	-1.4168	1.0026	--	3.8564	2.2374
	Species	4.0706	2.9752	8.6424	8.7192	-7.2116	10.3334
Kc	All	-67.7033	-14.5341	-26.1018	-2.4874	-33.7199	-26.1717
	Species	-221.865	-175.319	-117.455	-153.399	-369.190	-118.118

Table E.10 **Cabbage coefficient comparison from programs runs grouping the weeds together or by species in various cabbage trials using 680 nm, 1060 nm and 1360 nm as wavelengths.**

Cabbage coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Kc-680	All	5.2188	0.6820	1.1599	0.1748	-0.4584	1.2004
	Species	5.0071	0.7497	3.0284	1.2595	12.7295	4.9565
Kc-1060	All	1.9025	2.9887	0.7824	0.0716	10.3753	2.5917
	Species	7.3939	5.1040	5.2136	4.4203	7.1511	11.2021
Kc-1360	All	-0.2500	-3.9936	0.3925	--	-15.4683	-3.2147
	Species	1.2997	-1.6439	-0.5159	10.4128	-12.3244	-12.1494
Kc	All	-64.0383	-51.3986	-25.816	-2.5908	-98.8136	-273
	Species	-212.814	-162.747	-116.161	-191.956	-405.156	-130.425

Table E.11 Soil coefficient comparison from programs runs grouping the weeds together or by species in various cabbage trials using 680 nm, 760 nm and 1040 nm as wavelengths.

Soil coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Ks-680	All	4.1513	0.9731	2.6763	2.2433	1.4496	2.4217
	Species	4.4586	1.0199	4.0593	4.6070	0.4984	6.2864
Ks-760	All	-4.5069	-1.4921	-1.3198	-0.1392	-1.3030	-0.7218
	Species	-11.7084	-2.1698	-11.2557	--	-5.0733	-11.0314
Ks-1040	All	5.0707	1.7239	1.4986	--	1.9663	0.9690
	Species	14.3139	3.5203	13.0971	4.0061	6.3468	12.7117
Ks	All	-30.4168	-9.6590	-18.5721	-8.6285	-14.0849	-17.0657
	Species	-63.383	-20.7703	-46.8152	-47.7588	-24.3776	-53.2732

Table E.12 Soil coefficient comparison from programs runs grouping the weeds together or by species in various cabbage trials using 680 nm, 1060 nm and 1360 nm as wavelengths.

Soil coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Ks-680	All	1.0065	0.6364	1.1472	2.3370	2.8982	2.1092
	Species	1.2315	-0.4857	4.0339	2.8267	0.2353	3.1923
Ks-1060	All	-4.9326	-0.9076	-3.9329	-0.1764	-8.0243	-2.2798
	Species	-3.6794	-1.1012	-9.1601	-1.4712	-4.1397	-9.0029
Ks-1360	All	11.0437	1.2479	9.0727	--	13.3391	4.0548
	Species	12.9228	4.6430	21.0525	13.5335	12.4013	18.0505
Ks	All	-64.0350	-7.4631	-44.0623	-8.3208	-67.5731	-25.3491
	Species	-91.9451	-33.0068	-92.9738	-119.808	-80.1097	-72.1643

Table E.13 Broccoli coefficient comparison from programs runs grouping the weeds together or by species in various broccoli trials using 720 nm, 1060 nm and 1380 nm as wavelengths.

Broccoli coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Kc-720	All	-1.1114	0.0471	0.8426	0.3576	--	0.2343
	Species	-3.5015	0.6725	10.8819	-0.6992	9.9017	0.2099
Kc-1060	All	1.2340	1.4297	1.2447	--	1.9910	1.3851
	Species	8.2695	7.1436	1.9701	3.2651	-2.9865	6.4136
Kc-1380	All	1.7601	-1.9625	-2.5857	-0.2387	-2.3950	-1.9739
	Species	3.5039	1.1884	-12.7209	3.0026	-2.2139	-2.0785
Kc	All	-26.1814	-17.0327	-24.5019	-3.5525	-19.4079	-19.9238
	Species	-169.646	-293.933	-171.790	-67.0526	-110.353	-134.079

Table E.14 Broccoli coefficient comparison from programs runs grouping the weeds together or by species in various broccoli trials using 710 nm, 740 nm and 890 nm as wavelengths.

Broccoli coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Kc-710	All	-0.7633	-0.3668	1.9333	-0.4501	2.9233	--
	Species	-3.1581	-1.0703	6.3422	-2.7858	8.8381	1.4972
Kc-740	All	0.3247	0.3651	-0.7967	1.1324	-3.4409	-0.6642
	Species	-2.0507	4.4531	2.1822	0.8388	-6.2635	-4.3620
Kc-890	All	1.0757	--	--	-0.7992	2.4600	0.8404
	Species	9.4974	3.2460	-0.6173	5.2953	5.6417	9.7518
Kc	All	-27.4272	-9.6073	-16.4045	-5.2539	-24.7309	-6.0277
	Species	-158.015	-298.256	-145.511	-85.0553	-118.446	-149.699

Table E.15 **Soil coefficient comparison from programs runs grouping the weeds together or by species in various broccoli trials using 720 nm, 1060 nm and 1380 nm as wavelengths.**

Soil coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Ks-720	All	-4.2175	0.0095	-0.2998	-0.4520	--	-0.0346
	Species	-6.6514	-0.6348	-8.6806	-2.6227	-5.3141	-1.7819
Ks-1060	All	-0.8594	-0.9484	-0.6804	--	-1.6841	-0.2855
	Species	2.3240	0.2849	-0.1031	-3.1292	-1.4032	-0.3739
Ks-1380	All	14.1165	1.4935	1.4556	0.6129	3.8195	0.5345
	Species	16.9219	4.1861	19.0236	15.4910	20.3749	7.8329
Ks	All	-98.8140	-6.8535	-7.2497	-4.4839	-21.3469	-2.6220
	Species	-138.055	-38.1788	-129.467	-101.203	-145.159	-41.6062

Table E.16 **Soil coefficient comparison from programs runs grouping the weeds together or by species in various broccoli trials using 710 nm, 740 nm and 890 nm as wavelengths.**

Soil Coefficient	Weed class. type	Value of classification function coefficients					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Ks-710	All	0.4677	0.2769	0.5153	0.4938	1.6528	
	Species	3.5713	0.9390	1.5472	3.2405	3.5984	2.0974
Ks-740	All	-2.1970	-0.1161	-0.2201	-1.1307	-2.6035	-0.3452
	Species	-6.5516	-0.9532	-2.9461	-5.0869	-9.2971	-4.1041
Ks-890	All	2.0579	--	--	0.9357	1.9468	0.4018
	Species	6.1255	1.4918	3.3940	5.6557	9.1577	4.6342
Ks	All	-5.5129	-1.6493	-2.1046	-3.5996	-7.5994	-1.7642
	Species	-23.8795	-11.0391	-15.9893	-26.3668	-29.9485	-18.6994

Table E.17 **Leek coefficient comparison from programs runs grouping the weeds together or by species for each leek trial using 760 nm, 1340 nm and 1480 nm as wavelengths.**

Leek coefficient	Weed class. type	Value of classification function coefficients			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Kc-760	All	1.2784	-0.4500	-0.7916	-0.3333
	Species	2.9751	2.7942	-0.6120	-0.0780
Kc-1340	All	-1.8666	2.0850	-1.3469	2.1089
	Species	2.5483	9.6251	6.5817	5.8741
Kc-1480	All	0.1189	1.4646	4.7607	--
	Species	1.0089	-1.3826	4.8569	2.0759
Kc	All	-19.6485	-40.3317	-42.7558	-28.9623
	Species	-197.361	-186.010	-198.418	-137.839

Table E.18 **Leek coefficient comparison from programs runs grouping the weeds together or by species for each leek trial using 680 nm, 1080 nm and 1520 nm as wavelengths.**

Leek coefficient	Weed class. type	Value of classification function coefficients			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Kc-680	All	0.1397	-0.8103	2.7248	1.3765
	Species	0.7204	3.3119	3.4790	3.6335
Kc-1080	All	0.3647	0.7419	-0.0068	0.6736
	Species	7.0281	10.3485	5.9044	1.7767
Kc-1520	All	-0.3298	1.7768	--	0.1199
	Species	-0.01524	-3.4325	1.6557	4.0430
Kc	All	-8.2518	-42.5021	-20.8371	-33.5397
	Species	-241.2448	-201.1827	-209.2818	-155.2946

Table E.19 Soil coefficient comparison from programs runs grouping the weeds together or by species for each leek trial using : 760 nm, 1340 nm and 1480 nm as wavelengths.

Soil coefficient	Weed class. type	Value of classification function coefficients			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Ks-760	All	-1.0229	-4.2936	-1.0953	-0.8308
	Species	-1.6417	-11.2476	-9.3926	-1.8019
Ks-1340	All	1.3652	5.3538	0.6550	2.0624
	Species	4.3752	9.2713	13.0089	4.6318
Ks-1480	All	0.3946	3.5431	2.0015	--
	Species	1.6213	14.8247	4.7683	1.1374
Ks	All	-11.3001	-38.9868	-17.1218	-11.3479
	Species	-46.0701	-101.1996	-109.3019	-32.6118

Table E.20 Soil coefficient comparison from programs runs grouping the weeds together or by species for each leek trial using 680 nm, 1080 nm and 1520 nm as wavelengths.

Soil coefficient	Weed class. type	Value of classification function coefficients			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Ks-680	All	0.4651	1.5462	1.5638	0.8119
	Species	0.3719	5.1120	1.1474	0.5238
Ks-1080	All	-0.2368	-0.6011	-0.0592	-0.6132
	Species	1.1095	11.5215	-0.8881	-1.3027
Ks-1520	All	0.3931	1.6260	--	1.2312
	Species	1.0965	-5.4995	4.4911	4.3705
Ks	All	-4.4198	-17.1875	-6.3667	-10.1383
	Species	-22.1825	-57.8913	-39.3545	-23.8390

Table E.21 Eigenvalues obtained from programs runs using the two wavelengths sets for each cabbage trial.

Wavelength (nm)	Eigen. no.	Eigenvalues					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
680, 1060, 1360	First	10.6425	14.4924	8.8593	1.3365	56.4940	16.4555
	Second	3.1518	0.4509	2.3317	0.0766	0.0154	2.5139
680, 760, 1040	First	7.2370	3.2049	5.6930	1.3237	4.1608	3.9248
	Second	5.6104	0.5474	0.9327	0.0739	0.5292	1.5208

Table E.22 Eigenvalues obtained from programs runs using the two wavelengths sets for each broccoli trial.

Wavelength (nm)	Eigen. no.	Eigenvalues					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
720, 1060, 1380	First	11.7866	4.2041	6.3241	2.1106	9.5455	6.5871
	Second	1.7075	0.2275	0.0924	0.0963	0.3821	0.6314
710, 740, 890	First	3.3028	1.3506	1.5943	3.2287	3.4651	0.6180
	Second	1.3347	0.2640	0.1799	0.7608	1.0217	0.5204

Table E.23 Eigenvalues obtained from programs runs using the two wavelength sets for each leek trial.

Wavelength (nm)	Eigen. no.	Eigenvalue			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
760, 1340, 1480	First	6.0245	7.9162	1.8449	1.9207
	Second	0.1227	0.4229	1.5832	0.8753
680, 1020, 1520	First	1.4921	7.5847	4.2507	4.4740
	Second	0.2422	1.2304	0.2177	1.3875

APPENDIX F

Table F.1 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies under different tolerances for different wavebands.**

Wave-band (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
600-700	100 %	40.91	30	47.33	60	55.45	57.27
	99 %	53.64	39.29	67.33	66.36	72.73	60.91
	95 %	54.55	40.71	69.33	66.36	75.45	63.64
	σ	0.776	2.968	0.991	0.793	0.737	1.769
600-800	100 %	35.45	36.43	40	70	45.45	54.55
	99 %	37.27	42.14	40	70.91	50	55.45
	95 %	37.27	42.86	40	70.91	50.91	55.45
	σ	1.566	0.775	1.071	0.332	0.962	0.996
600-900	100 %	27.27	36.43	40	70	48.18	52.73
	99 %	33.64	43.57	41.33	70.91	60	55.45
	95 %	34.55	43.57	41.33	70.91	60.91	55.45
	σ	2.313	1.031	1.437	0.528	1.399	1.404
600-1000	100 %	27.27	37.14	40.67	70.91	56.36	51.82
	99 %	32.73	44.29	45.33	70.91	60.91	54.55
	95 %	32.73	44.29	46	70.91	60.91	54.55
	σ	2.523	0.974	1.606	0.594	1.582	1.572
600-1100	100 %	27.27	40.71	42	70.91	57.27	50.91
	99 %	30	45	47.33	70.91	60.91	53.64
	95 %	31.82	45	48	70.91	61.82	53.64
	σ	2.609	0.929	1.705	0.642	1.705	1.669
600-1200	100 %	27.27	42.86	44	70.91	57.27	50.91
	99 %	30	45	50	70.91	61.82	53.64
	95 %	31.82	45	50	70.91	62.73	53.64
	σ	2.567	0.838	1.743	0.653	1.748	1.684
600-1300	100 %	27.27	42.86	46.67	70.91	58.18	50
	99 %	30	45.71	52	70.91	62.73	52.73
	95 %	31.82	45.71	52	70.91	62.73	53.64
	σ	2.478	0.779	1.732	0.655	1.747	1.665
600-1400	100 %	27.27	45	48	70.91	59.09	50.91
	99 %	32.73	47.14	52.67	70.91	64.55	53.64
	95 %	32.73	47.14	52.67	70.91	64.55	53.64
	σ	2.294	0.721	1.659	0.639	1.653	1.584
600-1500	100 %	28.18	46.43	46	71.82	59.09	50.91
	99 %	33.64	48.57	52	71.82	64.55	53.64
	95 %	34.55	48.57	52	72.73	64.55	53.64
	σ	2.154	0.706	1.624	0.598	1.583	1.519
600-1600	100 %	30.91	46.43	44.67	71.82	59.09	50.91
	99 %	34.55	48.57	50.67	73.64	64.55	53.64
	95 %	35.45	48.57	50.67	74.55	64.55	53.64
	σ	2.122	0.786	1.639	0.596	1.585	1.501

Table F.2 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies under different tolerances for different wavebands.**

Wave-band (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
600 - 700	100 %	40.91	30	47.33	60	55.45	57.27
	99 %	53.64	39.29	67.33	66.36	72.73	60.91
	95 %	54.55	40.71	69.33	66.36	75.45	63.64
	σ	0.777	2.969	0.991	0.793	0.737	1.769
700 - 800	100 %	35.45	36.43	40	70	45.45	54.55
	99 %	37.27	42.14	40	70.91	50	55.45
	95 %	37.27	42.86	40	70.91	50.91	55.45
	σ	3.134	1.549	2.142	0.664	1.924	1.992
800 -900	100 %	27.27	35	42	70	57.27	50
	99 %	27.27	42.14	48.67	70.91	61.82	53.64
	95 %	27.27	42.86	48.67	70.91	61.82	53.64
	σ	3.833	1.896	2.222	1.004	2.281	2.342
900-1000	100 %	27.27	41.43	46	70	58.18	49.09
	99 %	27.27	45.71	52.67	70.91	62.73	52.73
	95 %	27.27	46.43	52.67	70.91	62.73	52.73
	σ	3.185	0.991	2.136	0.885	2.139	2.126
1000-1100	100 %	27.27	42.86	48.67	70.91	58.18	48.18
	99 %	27.27	46.43	52.67	71.82	62.73	50
	95 %	27.27	47.14	52.67	71.82	64.55	50.91
	σ	3.023	0.936	2.132	0.882	2.203	2.101
1100-1200	100 %	27.27	46.43	51.33	70.91	59.09	49.09
	99 %	30.91	47.86	54.67	71.82	68.18	51.82
	95 %	31.82	47.86	54.67	71.82	68.18	51.82
	σ	2.407	0.696	1.945	0.75	1.972	1.796
1200-1300	100 %	27.27	45	52	70	60	49.09
	99 %	32.73	47.14	56	71.82	70	50.91
	95 %	34.55	47.14	56	71.82	70	51.82
	σ	2.004	0.872	1.688	0.719	1.759	1.615
1300-1400	100 %	36.36	48.57	60	70	75.45	53.64
	99 %	38.18	50	65.33	72.73	88.18	56.36
	95 %	38.18	50	66.67	72.73	88.18	56.36
	σ	1.072	1.355	1.211	0.733	1.039	1.295
1400-1500	100 %	51.82	53.57	38	99.09	56.36	51.82
	99 %	54.55	55	42.67	100	65.45	56.36
	95 %	54.55	55	44	100	65.45	56.36
	σ	1.135	1.472	1.6	0.747	1.078	1.512
1500-1600	100 %	37.27	44.29	41.33	84.55	59.09	54.55
	99 %	43.64	52.14	46	86.36	66.36	58.18
	95 %	45.45	52.14	46.67	86.36	66.36	58.18
	σ	1.877	2.255	1.807	0.895	1.622	1.401

Table D.49 Leek leaf tissue, weed species and soil misclassification for each program run in trial 5 using direct wavelengths.

Crop/Weed/Soil	Misclassified Crop leaf/Weed/Soil in various program runs						
	PROGRAM RUN 1371	**PROGRAM RUN 1373**	**PROGRAM RUN 1377**	**PROGRAM RUN 1374**	**PROGRAM RUN 1376**	**PROGRAM RUN 1375**	**PROGRAM RUN 1378**
LEEK LEAF					*P. periscaria*		
S. vulgaris			*C. bursa-pastoris*		*P. persicaria*	*C. album* *P. aviculare*	
P. aviculare	*C. album*	*C. album*	*C. album*	*C. album*		*C. album*	*C. album* *P. persicaria*
C. album	*L. purpureum*	*L. purpureum* *P. aviculare*	*P. aviculare*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare* *C. bursa-pastoris*	*P. aviculare*
Vol. oilseed rape							*C. bursa-pastoris*
C. arvense		*P. aviculare*	*P. aviculare*	*L. purpureum* *P. aviculare*	*L. purpureum*	*L. purpureum* *P. aviculare*	*L. purpureum* *C. album*
C. bursa-pastoris				*P. aviculare* *C. album*	*P. aviculare* *C. album*	*P. aviculare* *C. albume*	
L. pupureum		*C. album*	*C. album*	*C. album*	*P. aviculare*	*C. album*	*C. album*
P. persicaria				**LEEK LEAF**	*S. vulgaris*	**LEEK LEAF**	**LEEK LEAF** *C. album*
S. media							
E. repens							
SOIL							

Table F.3 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies obtained after calculating the discriminant integration index with different tolerances for different wavebands.**

Wave-band (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
600 - 700	100 %	66.36	50	83.33	99.09	96.36	60
	99 %	91.82	71.43	100	100	100	83.64
	95 %	91.82	71.43	100	100	100	86.36
	σ	0.318	1.359	0.358	0.339	0.343	0.761
600 - 800	100 %	90.91	86.43	90.67	100	93.64	93.64
	99 %	97.27	95	100	100	100	95.45
	95 %	98.18	95	100	100	100	95.45
	σ	0.78	0.435	0.55	0.169	0.543	0.504
600 -900	100 %	84.55	87.86	85.33	100	90.91	92.73
	99 %	97.27	95	100	100	96.36	95.45
	95 %	99.09	95	100	100	96.36	95.45
	σ	1.181	0.501	0.754	0.233	0.79	0.738
600-1000	100 %	86.36	85.71	83.33	100	84.55	92.73
	99 %	96.36	95.71	100	100	93.64	95.45
	95 %	97.27	95.71	100	100	93.64	95.45
	σ	1.289	0.515	0.851	0.285	0.891	0.842
600-1100	100 %	86.36	87.14	82.67	100	84.55	92.73
	99 %	92.73	95.71	98.67	100	93.64	95.45
	95 %	92.73	97.14	98.67	100	93.64	95.45
	σ	1.341	0.519	0.911	0.319	0.958	0.914
600-1200	100 %	86.36	88.57	83.33	100	84.55	91.82
	99 %	92.73	96.43	98.67	100	93.64	95.45
	95 %	92.73	97.86	98.67	100	94.55	96.36
	σ	1.323	0.475	0.939	0.332	0.977	0.929
600-1300	100 %	86.36	89.29	84	100	84.55	91.82
	99 %	91.82	97.86	98.67	100	94.55	96.36
	95 %	93.64	97.86	99.33	100	95.45	96.36
	σ	1.278	0.447	0.934	0.336	0.972	0.921
600-1400	100 %	86.36	93.57	86.67	100	84.55	91.82
	99 %	96.36	100	100	100	97.27	96.36
	95 %	98.18	100	100	100	99.09	96.36
	σ	1.18	0.433	0.887	0.317	0.908	0.871
600-1500	100 %	92.73	100	86	100	86.36	90.91
	99 %	98.18	100	100	100	97.27	96.36
	95 %	98.18	100	100	100	99.09	96.36
	σ	1.093	0.413	0.852	0.284	0.858	0.825
600-1600	100 %	94.55	100	85.33	100	86.36	90.91
	99 %	98.18	100	100	100	97.27	96.36
	95 %	98.18	100	100	100	98.18	96.36
	σ	1.073	0.424	0.855	0.274	0.849	0.814

Table F.4 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies obtained after calculating the discriminant integration index under different tolerances for different wavebands.**

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
600 - 700	100 %	66.36	50	83.33	99.09	96.36	60
	99 %	91.82	71.43	100	100	100	83.64
	95 %	91.82	71.43	100	100	100	86.36
	σ	0.318	1.359	0.358	0.339	0.343	0.761
700 - 800	100 %	90.91	86.43	90.67	100	93.64	93.64
	99 %	97.27	95	100	100	100	95.45
	95 %	98.18	95	100	100	100	95.45
	σ	1.56	0.869	1.101	0.339	1.086	1.009
800 -900	100 %	85.45	84.29	82	98.18	83.64	90
	99 %	90.91	90	91.33	99.09	91.82	93.64
	95 %	91.82	90	92	99.09	92.73	93.64
	σ	2.021	0.887	1.213	0.439	1.296	1.282
900 - 1000	100 %	86.36	86.43	81.33	97.27	84.55	90
	99 %	91.82	92.86	96	100	90.91	94.55
	95 %	91.82	92.86	96	100	90.91	94.55
	σ	1.673	0.769	1.173	0.508	1.202	1.201
1000-1100	100 %	87.27	89.29	80	96.36	83.64	90
	99 %	91.82	95	96	99.09	90.91	93.64
	95 %	91.82	95	97.33	99.09	91.82	93.64
	σ	1.659	0.728	1.185	0.492	1.234	1.238
1100-1200	100 %	85.45	93.57	83.33	98.18	80	89.09
	99 %	91.82	94.29	94	99.09	90.91	93.64
	95 %	92.73	94.29	94	100	90.91	93.64
	σ	1.325	0.579	1.098	0.437	1.091	1.048
1200-1300	100 %	84.55	90.71	82	95.45	79.09	88.18
	99 %	91.82	95	92	99.09	90	92.72
	95 %	93.64	95.71	92.67	99.09	90	92.72
	σ	1.098	0.704	0.929	0.408	0.969	0.933
1300-1400	100 %	91.82	97.14	81.33	94.55	93.64	90
	99 %	97.27	100	100	100	99.09	95.45
	95 %	98.18	100	100	100	99.09	96.36
	σ	0.572	0.813	0.612	0.358	0.521	0.757
1400-1500	100 %	88.18	94.29	82	99.09	87.27	81.82
	99 %	97.27	100	94.67	100	95.45	93.64
	95 %	97.27	100	96	100	96.36	93.64
	σ	0.519	0.666	0.806	0.418	0.534	0.809
1500-1600	100 %	74.55	91.43	81.33	100	84.55	90
	99 %	84.55	95.71	96	100	91.82	96.36
	95 %	85.45	95.71	96	100	91.82	96.36
	σ	0.971	0.976	0.951	0.397	0.791	0.808

Table F.5 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies using different tolerances for different wavebands.

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
600 - 700	100 %	33.33	21.43	41.67	30	67.5	45
	99 %	33.33	29.29	41.67	30	85.83	47.5
	95 %	34.17	30	41.67	30	87.5	47.5
	σ	1.864	4.777	1.355	49.518	0.933	1.355
600 - 800	100 %	34.17	25	40.83	50	38.33	42.5
	99 %	35.83	31.43	55	51	40	50
	95 %	35.83	32.86	55.83	52	41.67	50.83
	σ	0.636	3.18	1.184	2.271	1.198	1.184
600-900	100 %	33.33	25	35.83	50	38.33	39.17
	99 %	33.33	32.86	48.33	52	38.33	47.5
	95 %	33.33	33.57	48.33	52	38.33	47.5
	σ	0.988	4.351	1.73	1.858	1.397	1.73
600-1000	100 %	33.33	26.43	35.83	50	36.67	38.33
	99 %	33.33	34.29	47.5	52	38.33	47.5
	95 %	33.33	37.14	48.33	54	38.33	47.5
	σ	1.155	4.664	1.956	1.704	1.466	1.956
600-1100	100 %	33.33	27.86	35	50	36.67	38.33
	99 %	33.33	37.14	45.83	54	38.33	45.83
	95 %	33.33	37.86	45.83	54	38.33	45.83
	σ	1.245	4.784	2.092	1.666	1.502	2.092
600-1200	100 %	33.33	30	35	50	36.67	38.33
	99 %	33.33	42.86	45.83	54	38.33	45.83
	95 %	33.33	43.57	46.67	56	38.33	46.67
	σ	1.255	4.699	2.148	1.608	1.505	2.148
600-1300	100 %	33.33	30.71	35	50	36.67	38.33
	99 %	33.33	45	46.67	54	38.33	46.67
	95 %	33.33	45.71	47.5	56	38.33	46.67
	σ	1.232	4.538	2.164	1.552	1.481	2.164
600-1400	100 %	33.33	33.57	35	50	36.67	38.33
	99 %	33.33	47.86	47.5	54	38.33	46.67
	95 %	33.33	48.57	48.33	56	38.33	47.5
	σ	1.137	4.231	2.076	1.409	1.43	2.077
600-1500	100 %	33.33	34.29	35	54	36.67	38.33
	99 %	33.33	48.57	48.33	57	38.33	47.5
	95 %	33.33	48.57	48.33	57	38.33	48.33
	σ	1.026	4.016	1.954	1.227	1.465	1.954
600-1600	100 %	33.33	36.43	35	55	36.67	38.33
	99 %	33.33	48.57	48.33	57	38.33	48.33
	95 %	33.33	48.57	48.33	59	38.33	49.17
	σ	0.998	3.91	1.924	1.224	1.459	1.924

Table F.6 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances using different wavebands.

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
600 - 700	100 %	33.33	21.43	41.67	30	67.5	45
	99 %	33.33	29.29	41.67	30	85.33	47.5
	95 %	34.17	30	41.67	30	87.5	47.5
	σ	1.863	4.776	1.355	49.518	0.933	1.355
700 - 800	100 %	34.17	25	40.83	50	38.33	42.5
	99 %	35.83	31.43	55	51	40	50
	95 %	35.83	32.86	55.83	52	41.67	50.83
	σ	1.271	6.36	2.368	4.543	2.397	2.368
800 -900	100 %	33.33	25.71	34.17	50	36.67	38.33
	99 %	33.33	33.57	45	52	38.33	45.83
	95 %	33.33	34.29	45.83	52	38.33	46.67
	σ	1.857	6.753	2.838	2.084	1.888	2.838
900-1000	100 %	33.33	30.71	35	50	35.83	38.33
	99 %	33.33	41.43	45.83	54	37.5	45.83
	95 %	33.33	44.29	46.67	54	37.5	45.83
	σ	1.682	5.626	2.638	1.822	1.713	2.638
1000-1100	100 %	33.33	30.71	35	52	35	36.67
	99 %	33.33	44.29	45.83	57	36.67	42.5
	95 %	33.33	45	46.67	57	36.67	45
	σ	1.625	5.286	2.639	1.718	1.683	2.639
1100-1200	100 %	33.33	43.57	35	52	36.67	38.33
	99 %	33.33	50	47.5	56	38.33	46.67
	95 %	33.33	50	48.33	56	38.33	46.67
	σ	1.322	4.324	2.446	1.472	1.541	2.446
1200-1300	100 %	33.33	47.86	35	52	36.67	36.67
	99 %	33.33	50	47.5	56	38.33	49.17
	95 %	33.33	50	47.5	56	38.33	49.17
	σ	1.147	3.685	2.276	1.327	1.365	2.276
1300-1400	100 %	33.33	51.43	35.83	50	40.83	38.33
	99 %	33.33	56.43	54.17	53	50	60
	95 %	34.17	59.29	54.17	55	50	60.83
	σ	0.891	2.781	1.529	0.942	1.165	1.529
1400-1500	100 %	34.17	50.71	58.33	81	46.67	52.5
	99 %	41.67	53.57	74.17	98	65	66.67
	95 %	42.5	53.57	74.17	99	65.83	66.67
	σ	1.34	3.163	1.093	0.983	1.975	1.093
1500-1600	100 %	34.17	48.57	39.17	64	38.33	41.67
	99 %	37.5	52.86	65.83	78	41.67	60.83
	95 %	37.5	52.86	65.83	80	42.5	62.5
	σ	0.903	3.298	1.687	2.295	1.419	1.687

Table F.7 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index using different wavebands.

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
600-700	100 %	75.83	65	78.33	30	83.33	45
	99 %	95	85.71	95.83	30	100	47.5
	95 %	96.67	88.57	96.67	30	100	48.33
	σ	0.849	2.029	0.57	46.558	0.5	1.165
600-800	100 %	99.17	72.86	70.83	57	98.33	74.17
	99 %	100	80	97.5	80	100	82.5
	95 %	100	80	97.5	83	100	83.33
	σ	0.279	1.627	0.653	1.972	0.723	1.083
600-900	100 %	98.33	75	68.33	61	100	76.67
	99 %	100	81.43	95	88	100	88.33
	95 %	100	82.14	95	88	100	89.17
	σ	0.469	2.223	0.971	1.389	0.872	1.512
600-1000	100 %	98.33	75.71	70	65	98.33	77.5
	99 %	100	82.14	94.17	90	100	88.33
	95 %	100	82.86	95	90	100	89.17
	σ	0.543	2.407	1.104	1.158	0.918	1.719
600-1100	100 %	98.33	77.14	71.67	73	98.33	77.5
	99 %	100	83.57	93.33	90	100	89.17
	95 %	100	84.29	94.17	92	100	89.17
	σ	0.583	2.507	1.188	1.053	0.942	1.8
600-1200	100 %	98.33	78.57	71.67	74	98.33	76.67
	99 %	100	85.71	93.33	92	100	86.67
	95 %	100	87.86	93.33	92	100	89.17
	σ	0.578	2.482	1.216	0.978	0.942	1.869
600-1300	100 %	98.33	80	70.83	78	98.33	76.67
	99 %	100	93.57	92.5	92	100	85.83
	95 %	100	96.43	93.33	92	100	86.67
	σ	0.558	2.394	1.219	0.914	0.925	1.899
600-1400	100 %	98.33	82.86	70	81	98.33	76.67
	99 %	100	100	92.5	92	100	85
	95 %	100	100	93.33	92	100	85
	σ	0.502	2.183	1.159	0.838	0.884	1.839
600-1500	100 %	98.33	84.29	70	76	99.17	75
	99 %	100	100	93.33	98	100	85
	95 %	100	100	94.17	98	100	85
	σ	0.437	2.024	1.083	0.813	0.89	1.739
600-1600	100 %	98.33	87.14	67.5	72	99.17	73.33
	99 %	100	100	94.17	99	100	82.5
	95 %	100	100	94.17	100	100	83.33
	σ	0.408	1.937	1.064	0.856	0.889	1.729

Table F.8 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index using different wavebands.

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
600 - 700	100 %	75.83	65	78.33	30	83.33	45
	99 %	95	85.71	95.83	30	100	47.5
	95 %	96.67	88.57	96.67	30	100	48.33
	σ	0.849	2.029	0.57	46.558	0.5	1.165
700 - 800	100 %	99.17	72.86	70.83	57	98.33	74.17
	99 %	100	80	97.5	80	100	82.5
	95 %	100	80	97.5	83	100	83.33
	σ	0.558	3.254	1.307	3.94	1.446	2.166
800 -900	100 %	98.33	76.43	67.5	81	98.33	81.67
	99 %	99.17	82.14	90.83	91	98.33	87.5
	95 %	99.17	82.14	90.83	91	98.33	88.33
	σ	0.908	3.498	1.628	1.225	1.226	2.394
900 - 1000	100 %	98.33	80	71.67	84	97.5	78.33
	99 %	100	85	90	92	98.33	88.33
	95 %	100	85.71	90.83	92	98.33	89.17
	σ	0.784	3.027	1.512	1.054	1.086	2.346
1000-1100	100 %	98.33	79.29	73.33	87	96.67	80.83
	99 %	100	87.86	90.83	93	98.33	88.33
	95 %	100	88.57	91.67	94	99.17	88.33
	σ	0.76	2.948	1.527	0.959	1.061	2.146
1100-1200	100 %	96.67	86.43	68.33	86	97.5	75
	99 %	98.33	97.14	88.33	94	100	80.83
	95 %	98.33	97.86	88.33	94	100	83.33
	σ	0.604	2.441	1.38	0.802	0.977	2.233
1200-1300	100 %	96.67	88.57	67.5	89	95	71.67
	99 %	98.33	98.57	86.67	95	100	80.83
	95 %	99.17	98.57	86.67	96	100	81.67
	σ	0.534	2.039	1.274	0.732	0.861	2.109
1300-1400	100 %	96.67	90	60.83	91	98.33	66.67
	99 %	96.67	100	94.17	95	100	74.17
	95 %	96.67	100	94.17	95	100	75.83
	σ	0.399	1.265	0.817	0.479	0.683	1.5
1400-1500	100 %	82.5	87.86	80.83	64	75.83	65
	99 %	94.17	97.14	97.5	93	100	70
	95 %	94.17	97.14	98.33	96	100	70
	σ	0.562	1.579	0.596	1.025	1.115	1.062
1500-1600	100 %	95	89.29	63.33	50	80.83	66.67
	99 %	100	97.14	87.5	87	99.17	72.5
	95 %	100	97.14	89.17	90	99.17	73.33
	σ	0.423	1.503	0.945	1.831	0.905	1.685

Table F.9 Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances using different wavebands.

Waveband (nm)	Tolerance and standard deviation	Discriminant accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
600 - 700	100 %	21.43	47.27	27.33	25
	99 %	40.71	62.73	32	25.63
	95 %	50.71	62.73	32	26.25
	σ	12.112	1.014	3.26	3.526
600 - 800	100 %	46.43	38.18	40	25
	99 %	48.57	40	40	26.88
	95 %	48.57	40	40	26.88
	σ	1.309	0.521	0.705	2.625
600 -900	100 %	44.29	37.27	39.33	25
	99 %	48.57	37.27	39.33	26.88
	95 %	48.57	37.27	39.33	26.88
	σ	1.756	0.899	0.834	3.611
600- 1000	100 %	45.71	36.36	38	25
	99 %	48.57	36.36	39.33	26.25
	95 %	48.57	36.36	39.33	26.88
	σ	1.818	1.077	0.928	3.949
600- 1100	100 %	46.43	36.36	37.33	25
	99 %	48.57	36.36	38	25.63
	95 %	48.57	36.36	38	26.25
	σ	1.868	1.193	0.991	4.147
600- 1200	100 %	47.86	36.36	37.33	25
	99 %	48.57	36.36	37.33	25.63
	95 %	48.57	36.36	37.33	25.63
	σ	1.863	1.233	1.027	4.132
600- 1300	100 %	48.57	36.36	36	25
	99 %	48.57	36.36	37.33	25.63
	95 %	48.57	36.36	37.33	25.63
	σ	1.811	1.234	1.049	4.052
600- 1400	100 %	48.57	36.36	36	25
	99 %	49.29	36.36	37.33	25.63
	95 %	49.29	36.36	37.33	25.63
	σ	1.743	1.18	1.054	3.754
600- 1500	100 %	48.57	36.36	36	25
	99 %	50	36.36	37.33	25.63
	95 %	50	36.36	37.33	25.63
	σ	1.649	1.076	1.073	3.51
600 -1600	100 %	49.29	36.36	36	25
	99 %	50	36.36	36.67	25.63
	95 %	50	36.36	36.67	25.63
	σ	1.682	1.074	1.108	3.456

Table F.10 Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances using different wavebands

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
600 - 700	100 %	21.43	47.27	27.33	25
	99 %	40.71	62.73	32	25.63
	95 %	50.71	62.73	32	26.25
	σ	12.112	1.014	3.26	3.526
700 - 800	100 %	46.43	38.18	40	25
	99 %	48.57	40	40	26.88
	95 %	48.57	40	40	26.88
	σ	2.617	1.042	1.41	5.25
800 -900	100 %	40.71	36.36	37.33	25
	99 %	45	36.36	38.67	26.88
	95 %	45	36.36	38.67	26.88
	σ	3.152	1.755	1.245	5.595
900 - 1000	100 %	48.57	36.36	36	25
	99 %	48.57	36.36	37.33	25.63
	95 %	48.57	36.36	37.33	25.63
	σ	2.218	1.636	1.293	4.975
1000 - 1100	100 %	45	36.36	36	25
	99 %	48.57	36.36	36	25
	95 %	48.57	36.36	36	25
	σ	2.283	1.674	1.326	4.948
1100 - 1200	100 %	48.57	36.36	36	25
	99 %	49.29	36.36	36	25
	95 %	50	36.36	36	25.63
	σ	1.954	1.449	1.267	4.104
1200 - 1300	100 %	50	36.36	35.33	25
	99 %	50	36.36	36	25
	95 %	50	36.36	36	25
	σ	1.642	1.276	1.22	3.663
1300 - 1400	100 %	50	36.36	34.67	25
	99 %	50.71	36.36	35.33	25.63
	95 %	50.71	36.36	36	25.63
	σ	1.476	0.904	1.261	2.541
1400 - 1500	100 %	54.29	42.73	34.67	25
	99 %	55.71	49.09	36.67	25
	95 %	56.43	49.09	36.67	25
	σ	1.723	0.793	1.746	2.271
1500 -1600	100 %	52.14	37.27	35.33	25
	99 %	52.86	38.18	36	26.25
	95 %	53.57	39.09	36	26.25
	σ	4.009	1.079	1.576	3.099

Table F.11 **Leek standard deviations and leek/weed/soil discrimination accuracies for differnt tolerances obtained after calculating the discriminant integration index using different wavebands.**

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
600 - 700	100 %	21.43	58.18	41.33	71.88
	99 %	27.14	84.55	99.33	95
	95 %	29.29	84.55	99.33	96.25
	σ	5.938	0.425	1.418	2.023
600 - 800	100 %	92.86	92.73	98.67	92.5
	99 %	97.86	99.09	100	95.63
	95 %	98.57	99.09	100	96.25
	σ	0.538	0.308	0.349	1.294
600 -900	100 %	87.86	92.73	100	91.88
	99 %	96.43	99.09	100	96.25
	95 %	96.43	99.09	100	96.25
	σ	0.749	0.547	0.42	1.821
600- 1000	100 %	91.43	94.55	100	91.88
	99 %	97.86	99.09	100	96.25
	95 %	98.57	99.09	100	96.25
	σ	0.75	0.653	0.482	1.996
600- 1100	100 %	92.86	94.55	100	92.5
	99 %	98.57	99.09	100	96.88
	95 %	99.29	99.09	100	97.5
	σ	0.801	0.725	0.527	2.091
600- 1200	100 %	92.86	95.45	100	92.5
	99 %	99.29	99.09	100	96.25
	95 %	99.29	99.09	100	97.5
	σ	0.839	0.745	0.545	2.077
600- 1300	100 %	95	96.36	100	93.75
	99 %	99.29	99.09	100	97.5
	95 %	99.29	99.09	100	98.13
	σ	0.826	0.745	0.555	2.034
600- 1400	100 %	97.14	96.36	100	94.38
	99 %	100	99.09	100	98.13
	95 %	100	99.09	100	98.13
	σ	0.786	0.703	0.547	1.845
600- 1500	100 %	98.57	96.36	100	94.38
	99 %	100	99.09	100	98.13
	95 %	100	99.09	100	98.13
	σ	0.709	0.634	0.541	1.685
600 -1600	100 %	100	96.36	100	94.38
	99 %	100	99.09	100	97.5
	95 %	100	99.09	100	98.13
	σ	0.659	0.632	0.547	1.652

Table F.12 Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index using different wavebands.

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
600 - 700	100 %	21.43	58.18	41.33	71.88
	99 %	27.14	84.55	99.33	95
	95 %	29.29	84.55	99.33	96.25
	σ	5.938	0.425	1.418	2.023
700 - 800	100 %	92.86	92.73	98.67	92.5
	99 %	97.86	99.09	100	95.63
	95 %	98.58	99.09	100	96.25
	σ	1.077	0.617	0.697	2.589
800 -900	100 %	82.86	92.73	98	88.75
	99 %	94.29	99.09	100	95.63
	95 %	95	99.09	100	96.25
	σ	1.409	1.054	0.657	2.895
900 - 1000	100 %	94.29	93.64	98.67	90.63
	99 %	98.57	99.09	98.67	96.25
	95 %	98.57	99.09	98.67	96.88
	σ	1.044	0.986	0.721	2.539
1000 - 1100	100 %	92.86	96.36	98.67	95.63
	99 %	98.57	100	100	98.13
	95 %	98.57	100	100	98.75
	σ	1.151	1.023	0.766	2.49
1100 - 1200	100 %	94.29	95.45	98.67	94.38
	99 %	100	99.09	100	97.5
	95 %	100	100	100	98.13
	σ	1.139	0.879	0.695	2.097
1200 - 1300	100 %	97.14	92.73	98.67	96.88
	99 %	100	99.09	99.33	99.38
	95 %	100	99.09	99.33	99.38
	σ	0.812	0.784	0.656	1.915
1300 - 1400	100 %	95.71	90.91	98.67	94.38
	99 %	100	99.09	98.67	100
	95 %	100	99.09	98.67	100
	σ	0.692	0.509	0.598	1.033
1400 - 1500	100 %	90.71	84.55	92.67	95.63
	99 %	96.43	97.27	98	98.13
	95 %	97.14	97.27	98	98.13
	σ	0.595	0.374	0.826	0.936
1500 -1600	100 %	86.43	84.56	94.67	90
	99 %	90.71	99.09	99.33	95.63
	95 %	90.71	99.09	99.33	96.25
	σ	1.614	0.654	0.742	1.508

Table F.13 Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances using the selected wavelengths.

Wave-band (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
First	100 %	37.27	39.29	40	70.91	44.55	53.64
wave-	99 %	38.18	42.14	40	70.91	48.18	55.45
band	95 %	40	42.14	40	70.91	49.09	55.45
680-780	σ	2.507	1.237	1.898	0.560	1.598	1.7211
Second	100 %	27.27	42.14	46.67	70.91	58.18	48.18
wave-	99 %	27.27	46.24	52.67	70.91	62.73	50.91
band	95 %	28.18	47.14	52.67	70.91	63.64	51.82
960-1060	σ	2.980	0.99	2.104	0.905	2.15	2.049
Third	100 %	37.27	50	54.67	74.55	79.09	53.64
wave-	99 %	48.18	50	62.67	85.45	88.18	58.18
band	95 %	48.18	50	63	86.36	89.09	58.18
1320-1420	σ	0.809	1.495	1.236	0.761	0.848	1.316

Table F.14 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index in each trial using the selected wavebands.**

Wave-band (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
First	100 %	90.91	87.14	92.67	100	95.45	92.73
wave-	99 %	97.27	95.71	100	100	100	95.45
band	95 %	98.18	95.71	100	100	100	95.45
680-780	σ	1.217	0.75	0.944	0.280	0.874	0.856
Second	100 %	85.45	90	79.33	98.18	83.64	88.18
wave-	99 %	91.82	92.86	96.67	98.18	91.82	94.55
band	95 %	91.82	92.86	96.67	98.18	91.82	94.55
960-1060	σ	1.6	0.814	1.173	0.517	1.207	1.189
Third	100 %	89.09	100	80	100	99.09	88.18
wave-	99 %	100	100	100	100	100	95.45
band	95 %	100	100	100	100	100	95.45
1320-1420	σ	0.393	0.814	0.593	0.361	0.399	0.727

Table F.15 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index with the reference spectrum compensated for the selected wavebands.**

Wave-band (nm)	Toleance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
First	100 %	85.45	82.14	70	98.18	60.91	91.82
wave-	99 %	95.45	86.43	79.33	99.09	70	95.45
band	95 %	95.45	87.14	80	99.09	70	95.45
680-780	σ	1.136	0.677	1.124	0.401	0.953	0.858
Second	100 %	81.82	77.14	75.33	89.09	83.64	85.45
wave-	99 %	87.27	80	86.67	90	91.82	90.91
band	95 %	88.18	80	89.33	90	91.82	90.91
960-1060	σ	1.889	0.989	1.731	0.904	1.497	1.582
Third	100 %	77.27	97.86	70.66	99.09	70.91	85.45
wave-	99 %	90.91	100	78.67	100	87.27	93.64
band	95 %	90.91	100	78.67	100	87.27	93.64
1320-1420	σ	0.413	0.539	0.465	0.205	0.461	0.756

EQUATION SUMMARY

Equation number	Description
Eq. 4	WAV2/WAV1
Eq. 5	WAV3/WAV1
Eq. 6	WAV1/WAV2
Eq. 7	WAV1/WAV3
Eq. 8	(WAV2-WAV1)/(WAV2+WAV1)
Eq. 9	Abs((WAV2-WAV1)/(WAV2+WAV1)
Eq. 10	(WAV3-WAV1)/(WAV3+WAV1)
Eq. 11	Abs((WAV2+WAV1)/(WAV2-WAV1))
Eq. 12	(WAV1-WAV2)/(WAV1+WAV2)
Eq. 13	(WAV1-WAV3)/(WAV1+WAV3)
Eq. 14	Sqrt(((WAV2-WAV1)/(WAV2+WAV1))+1)
Eq. 15	Sqrt(((WAV3-WAV1)/(WAV3+WAV1))+1)
Eq. 16	Sqrt((WAV2-WAV1)**2+(WAV2+WAV1)**2)
Eq. 17	Sqrt((WAV3-WAV1)**2+(WAV3+WAV1)**2)

	WAV1	WAV2	WAV3
CABBAGE	680-780 nm	820-920 nm	980-1080 nm
BROCCOLI	680-780 nm	960-1060 nm	1320-1420 nm
LEEK	680-780 nm	980-1080 nm	1350-1450 nm

Table F.16 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances using waveband ratios for each trial.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.4	100 %	34.55	52.86	78.67	48.18	90.91	38.18
	99 %	36.36	63.57	86.67	65.45	94.55	48.18
	95 %	36.36	65.71	90	65.45	96.36	49.09
	σ	0.038	0.021	0.029	0.029	0.021	0.042
Eq.5	100 %	84.55	73.57	100	86.36	100	83.64
	99 %	97.27	87.86	100	90	100	90
	95 %	99.09	90	100	90	100	90
	σ	0.027	0.034	0.012	0.025	0.012	0.027
Eq.6	100 %	73.64	41.43	29.33	48.18	38.18	79.09
	99 %	90	50	31.33	60.91	39.09	86.36
	95 %	91	52.86	31.33	60.91	39.09	86.36
	σ	0.0184	0.014	0.023	0.019	0.018	0.022
Eq.7	100 %	27.27	21.43	26.67	37.27	36.36	37.27
	99 %	27.27	25	26.67	44.55	36.36	40.91
	95 %	28.18	26.43	26.67	44.55	36.36	42.73
	σ	0.078	0.084	0.043	0.062	0.042	0.067

§ refer to page F-16 for equations

Table F.17 **Broccoli/weed/soil discrimination accuracies for different tolerances in waveband ratios obtained after calculating the discriminant integration index, together with the broccoli standard deviations of the ratios for each trial.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.4	100 %	28.18	29.29	27.33	36.36	36.36	37.27
	99 %	78.18	88.57	38.67	50	50.91	90
	95 %	80.91	88.57	39.33	58.18	51.82	90
	σ	0.625	0.68	0.468	0.628	0.436	0.478
Eq.5	100 %	29.09	36.43	28.67	36.36	36.36	36.36
	99 %	53.64	47.86	51.33	42.73	55.45	48.18
	95 %	63.63	48.57	51.33	42.73	56.36	48.18
	σ	0.198	0.474	0.271	0.725	0.661	0.390
Eq.6	100 %	34.54	25	28.67	36.36	53.64	36.36
	99 %	36.36	29.29	37.33	41.82	84.55	41.82
	95 %	37.27	30	40	41.82	84.55	41.82
	σ	1.405	0.670	1.407	1.705	0.228	1.698
Eq.7	100 %	27.27	21.43	62.67	36.36	49.09	36.36
	99 %	27.27	27.14	72.67	55.45	65.45	63.64
	95 %	33.63	31.43	72.67	56.36	65.45	66.36
	σ	0.370	1.389	0.524	1.301	0.917	1.168

§ refer to page F-16 for equations

Table F.18 **Broccoli/weed/soil discrimination accuracies for different tolerances in waveband ratios obtained after calculating the discriminant integration index with the reference spectra compensated as well as broccoli standard deviations for each trial.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.4	100 %	29.09	21.43	36	36.36	73.64	36.36
	99 %	67.27	25.72	90.67	36.36	94.55	39.09
	95 %	77.27	26.43	92.67	36.36	94.55	39.09
	σ	0.643	0.543	0.455	0.845	0.328	1.124
Eq.5	100 %	27.27	44.29	42.67	39.09	64.55	38.18
	99 %	30	47.86	54	45.45	69.09	40.91
	95 %	32.72	48.57	56	45.45	72.73	41.82
	σ	0.255	0.226	0.196	0.306	0.158	0.518
Eq.6	100 %	28.18	35	26.67	44.55	36.36	38.18
	99 %	34.55	88.57	28.67	90.91	37.27	42.73
	95 %	35.45	90	28.67	95.45	37.27	43.64
	σ	2.162	0.140	5.75	0.274	8.528	1.461
Eq.7	100 %	61.82	72.14	37.33	72.73	45.45	39.09
	99 %	84.55	72.86	59.33	78.18	57.27	75.45
	95 %	87.27	72.86	60.67	81.82	58.18	75.45
	σ	0.396	0.159	0.709	0.237	0.602	0.962

§ refer to page F-16 for equations

Table F.19 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies using different tolerances with multiratio algorithms for each trial.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.8	100 %	34.55	52.86	78.67	48.18	90.91	38.18
	99 %	36.36	63.57	89.33	65.45	94.55	48.18
	95 %	36.36	65.71	90	65.45	96.36	49.09
	σ	0.013	0.008	0.013	0.012	0.010	0.015
Eq.9	100 %	34.55	52.86	78.67	48.18	90.91	38.18
	99 %	36.36	63.57	89.33	65.45	94.55	48.18
	95 %	36.36	65.71	90	65.45	96.36	49.09
	σ	0.013	0.008	0.013	0.012	0.10	0.015
Eq.10	100 %	36.36	28.57	34	45.45	46.36	50.91
	99 %	97.27	88.57	100	90	100	90
	95 %	99.09	90.71	100	90	100	90
	σ	0.021	0.026	0.010	0.019	0.010	0.020
Eq.11	100 %	27.27	43.57	63.33	55.45	86.36	46.36
	99 %	27.27	47.14	83.33	65.45	97.27	48.18
	95 %	27.27	47.14	84	66.36	97.27	48.18
	σ	0.998	0.989	0.973	0.718	0.676	1.132
Eq.12	100 %	36.36	21.43	26.67	36.36	36.36	36.36
	99 %	36.36	63.57	91.33	65.45	96.36	49.09
	95 %	36.36	66.43	92.67	69.09	96.36	50
	σ	0.403	0.823	7.293	1.320	30.168	0.589
Eq.13	100 %	36.36	28.57	34	45.45	46.36	50.91
	99 %	37.27	33.57	34	53.64	46.36	57.27
	95 %	37.27	34.29	34	54.55	46.36	58.18
	σ	0.325	0.5545	0.111	0.393	0.109	0.435

§ refer to page F-16 for equations

Table F.20 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances in multiratio algorithms obtained after calculating the discriminant integration index for each trial.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.8	100 %	28.18	29.29	27.33	36.36	36.36	37.27
	99 %	87.27	88.57	48	66.36	51.82	90
	95 %	88.18	82.29	53.33	68.18	51.82	90
	σ	0.302	0.209	0.2511	0.315	0.1354	0.242
Eq.9	100 %	34.54	25.71	28.67	36.36	42.73	36.36
	99 %	43.64	37.86	41.33	41.82	70	43.64
	95 %	44.54	38.57	42.67	42.73	73.64	44.55
	σ	0.188	0.141	0.159	0.202	0.105	0.205
Eq.10	100 %	29.09	36.43	28.67	36.36	36.36	36.36
	99 %	63.63	48.57	52	44.55	58.18	48.18
	95 %	75.45	48.57	52	45.45	60	49.09
	σ	0.184	0.289	0.160	0.32	0.291	0.242
Eq.11	100 %	93.63	92.14	70	92.73	81.82	95.45
	99 %	98.18	95.71	88.67	100	94.55	95.45
	95 %	99.09	96.43	92	100	96.36	95.45
	σ	0.489	0.478	0.417	0.265	0.424	0.369
Eq.12	100 %	28.18	21.43	30.67	36.36	37.27	36.36
	99 %	39.09	22.14	55.33	40	65.45	36.36
	95 %	39.09	23.57	62.67	41.82	81.82	36.36
	σ	20.61	24.419	20.304	39.577	38.405	33.206
Eq.13	100 %	28.18	22.14	27.33	36.36	37.27	40
	99 %	30	33.57	38	36.36	56.36	41.82
	95 %	30	47.86	38	37.27	56.36	41.82
	σ	13.671	36.93	26.387	26.864	10.245	14.360

§ refer to page F-16 for equations

Table F.21 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances in multiratio algorithms obtained after calculating the discriminant integration index with the reference spectrum compensated for each trial.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.8	100 %	29.09	21.43	36	36.36	73.64	36.36
	99 %	82.73	26.43	92.67	36.36	94.55	40.91
	95 %	82.73	27.14	92.67	36.36	94.55	51.82
	σ	0.367	0.114	0.365	0.194	0.308	0.389
Eq.9	100 %	28.18	21.43	26.67	36.36	36.36	38.18
	99 %	37.27	26.43	32	38.18	40.91	43.64
	95 %	38.18	27.14	34	38.18	41.82	43.64
	σ	0.213	0.112	0.310	0.165	0.297	0.201
Eq.10	100 %	27.27	44.29	40	39.09	61.82	38.18
	99 %	33.64	48.57	55.33	45.45	70.91	47.27
	95 %	34.55	48.57	60	45.45	72.73	50
	σ	0.144	0.91	0.158	0.126	0.133	0.260
Eq.11	100 %	79.09	70.71	40.67	65.45	43.64	91.82
	99 %	81.82	72.14	62.67	70.91	58.18	91.82
	95 %	81.82	72.14	66	71.82	60.91	91.82
	σ	0.939	1.777	2.057	1.035	1.919	0.940
Eq.12	100 %	28.18	22.14	27.33	40.91	37.27	36.36
	99 %	34.55	26.43	30.66	58.18	42.73	36.36
	95 %	35.45	31.43	40	58.18	44.55	37.27
	σ	7.735	21.643	42.205	10.909	12.327	63.99
Eq.13	100 %	28.18	21.43	40	38.18	61.82	37.27
	99 %	63.64	21.43	77.34	38.18	88.18	41.82
	95 %	84.55	21.43	84	39.09	89.09	41.82
	σ	7.116	147.94	7.501	45.097	2.127	33.879

§ refer to page F-16 for equations

Table F.22 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances with complex multiratio algorithms.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.14	100 %	34.55	52.86	78.67	48.18	90.91	38.18
	99 %	36.36	63.57	89.33	65.45	94.55	48.18
	95 %	36.36	65.72	90	65.45	96.36	49.09
	σ	0.006	0.004	0.006	0.005	0.005	0.007
Eq.15	100 %	84.55	73.57	100	86.36	100	83.64
	99 %	97.27	88.57	100	90	100	90
	95 %	99.09	90.71	100	90	100	90
	σ	0.012	0.014	0.006	0.011	0.006	0.011
Eq.16	100 %	30	43.57	40.67	70.91	57.27	51.82
	99 %	34.55	45	45.33	70.91	60.91	53.64
	95 %	34.55	45.71	46	70.91	60.91	53.64
	σ	5.419	1.973	3.893	1.355	3.741	3.623
Eq.17	100 %	45.45	21.43	26.67	36.36	60	58.18
	99 %	45.45	21.43	49.33	36.36	74.55	63.64
	95 %	45.45	21.43	52	36.36	74.55	63.64
	σ	10.154	6.896	8.770	24.495	9.585	12.701

§ refer to page F-16 for equations

Table F.23 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances in complex multiratio algorithms obtained after calculating the discriminant integration index.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.14	100 %	28.18	29.29	27.33	36.36	36.36	37.27
	99 %	88.19	88.57	50.67	67.27	51.82	90
	95 %	88.19	89.29	54.67	68.18	51.82	90
	σ	0.165	0.115	0.143	0.182	0.064	0.175
Eq.15	100 %	29.09	36.43	28.67	36.36	36.36	36.36
	99 %	68.18	48.57	52	45.45	59.09	48.18
	95 %	80	48.57	52	45.45	63.64	51.82
	σ	0.126	0.169	0.088	0.176	0.155	0.142
Eq.16	100 %	94.54	88.57	90.67	100	90	94.55
	99 %	98.18	100	100	100	99.09	95.45
	95 %	98.18	100	100	100	100	96.36
	σ	2.66	1.369	2.004	0.729	2.086	1.907
Eq.17	100 %	41.81	87.14	29.33	36.36	47.27	56.36
	99 %	70.91	90	46.67	36.36	81.82	87.27
	95 %	70.91	90	46.67	36.36	83.64	90.91
	σ	5.27	4.773	2.833	24.616	4.738	10.592

§ refer to page F-16 for equations

Table F.24 **Broccoli standard deviations and broccoli/weed/soil discrimination accuracies for different tolerances in complex multiratio algorithms after calculating the discriminant integration index with the reference spectra compensated.**

Equation §	Tolerance and standard deviation	discrimination accuracies(%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 5	TRIAL 8	TRIAL 10	TRIAL 11
Eq.14	100 %	29.09	21.43	36	36.36	73.64	36.36
	99 %	82.73	26.43	93.33	36.36	94.55	44.55
	95 %	86.36	27.14	94	36.36	94.55	60.91
	σ	0.217	0.050	0.254	0.088	0.230	0.21
Eq.15	100 %	27.27	44.29	42.67	39.09	64.54	38.18
	99 %	33.64	48.57	57.33	45.45	71.82	49.09
	95 %	34.55	48.57	60.67	45.45	72.73	50.91
	σ	0.077	0.044	0.095	0.062	0.080	0.144
Eq.16	100 %	90	80	78.67	90.91	80	90.91
	99 %	96.36	82.14	85.33	97.27	85.46	95.45
	95 %	96.36	82.14	85.33	97.27	85.46	95.45
	σ	2.324	1.296	1.411	0.984	1.351	1.976
Eq.17	100 %	41.82	84.29	29.33	36.36	69.09	56.36
	99 %	60	87.14	45.33	36.36	74.55	81.82
	95 %	63.64	87.14	48	36.36	76.36	87.27
	σ	7.909	4.92	2.578	24.697	3.198	10.74

§ refer to page F-16 for equations

Table F.25 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances for the selected wavebands.

wave-band (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
First	100 %	33.33	22.14	37.5	50	38.33	41.67
wave-	99 %	35.83	30.71	53.33	52	44.17	49.17
band	95 %	35.83	30.71	55	55	44.17	49.17
680-780	σ	1.045	5.386	1.941	3.913	2.155	1.941
Second	100 %	33.33	25.7	34.17	50	35.83	38.33
wave-	99 %	33.33	34.28	45	52	37.50	45
band	95 %	33.33	35	45.83	53	38.33	45
820-920	σ	1.862	6.602	2.806	2.025	1.859	2.806
Third	100 %	33.33	31.43	35	51	35	36.67
wave-	99 %	33.33	44.29	46.67	56	36.67	45
band	95 %	33.33	45.71	46.67	57	36.67	45
980-1080	σ	1.607	5.278	2.626	1.7075	1.671	2.626

Table F.26 **Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index in each trial using the selected wavebands.**

wave-band (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
First	100 %	100	71.43	77.5	50	99.17	71.67
wave-	99 %	100	80.72	100	77	100	78.33
band	95 %	100	82.86	100	83	100	79.17
680-780	σ	0.449	2.678	1.05	3.496	1.277	1.723
Second	100 %	98.33	75.72	68.33	81	97.5	80.83
wave-	99 %	100	82.14	90	89	98.33	87.5
band	95 %	100	82.14	91.67	91	98.33	87.5
820-920	σ	0.889	3.447	1.622	1.162	1.098	2.343
Third	100 %	98.33	80	72.5	86	96.67	80
wave-	99 %	100	88.57	90.83	94	97.5	87.5
band	95 %	100	88.57	91.67	94	98.33	88.33
980-1080	σ	0.753	2.924	1.514	0.968	0.939	2.201

Table F.27 **Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index with the reference spectrum compensated for the selected wavebands.**

wave-band (nm)	Tolerance and standard deviation	Discriminant accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
First	100 %	99.17	72.14	75	50	91.67	73.33
wave-	99 %	100	81.43	90.83	75	98.33	80
band	95 %	100	82.86	91.67	77	99.17	80
680-780	σ	0.514	2.647	0.671	3.345	0.91	1.798
Second	100 %	97.5	71.43	63.33	80	97.5	80.83
wave-	99 %	98.33	78.57	87.5	91	98.33	87.5
band	95 %	98.33	80	88.33	91	98.33	87.5
820-920	σ	1.086	4.755	2.099	1.26	1.095	2.225
Third	100 %	94.17	70	62.5	86	96.67	81.67
wave-	99 %	97.5	72.86	86.67	91	97.5	88.33
band	95 %	97.5	72.86	90.83	91	98.33	90
980-1080	σ	1.348	5.277	2.294	1.278	0.939	1.794

Table F.28 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances using waveband ratios.

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.4	100 %	33.33	39.29	33.33	30	33.33	33.33
	99 %	35	59.29	33.33	30	33.33	33.33
	95 %	36.67	62.14	33.33	30	33.33	33.33
	σ	0.045	0.035	0.0237	0.758	0.055	0.024
Eq.5	100 %	41.67	78.57	40	30	41.67	39.17
	99 %	41.67	86.43	43.33	35	41.67	44.17
	95 %	41.67	86.43	43.33	35	41.67	44.17
	σ	0.037	0.027	0.023	0.655	0.052	0.023
Eq.6	100 %	80	32.86	96.67	45	98.33	95
	99 %	82.50	48.57	99.17	47	100	99.17
	95 %	82.50	50	99.17	54	100	99.17
	σ	0.021	0.019	0.010	0.101	0.024	0.010
Eq.7	100 %	75	29.29	85.83	45	91.67	84.17
	99 %	81.67	31.43	90	45	91.67	87.50
	95 %	83.33	33.57	90	54	91.67	87.50
	σ	0.020	0.020	0.011	0.110	0.027	0.011

§ refer to page F-16 for equations

Table F.29 **Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index using waveband ratios.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.4	100 %	56.67	21.43	40	30	33.33	91.67
	99 %	97.50	80.71	72.5	31	95	93.33
	95 %	97.50	81.43	73.33	33	95	93.33
	σ	0.423	0.413	0.343	0.846	0.455	0.24
Eq.5	100 %	55	34.29	49.17	31	37.5	90
	99 %	97.50	84.29	75.83	58	95	91.67
	95 %	97.50	87.14	75.83	70	95	91.67
	σ	0.364	0.372	0.356	0.586	0.431	0.22
Eq.6	100 %	33.33	22.14	40	30	33.33	33.3
	99 %	33.33	31.43	53.33	34	35	36.67
	95 %	33.33	32.86	53.33	34	35	36.67
	σ	1.074	0.719	0.401	3.155	2.34	1.18
Eq.7	100 %	33.3	21.43	35.83	30	33.33	35
	99 %	33.3	26.43	44.17	30	36.67	38.33
	95 %	33.3	26.43	45.83	31	36.67	38.33
	σ	0.904	1.523	0.904	3.342	2.588	0.86

§ refer to page F-16 for equations

Table F.30 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index with the reference spectrum compensated using waveband ratios

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.4	100 %	33.33	21.43	33.33	30	95	60
	99 %	95	21.43	85.83	53	96.67	90
	95 %	97.5	24.29	87.5	54	96.67	91.67
	σ	0.637	1.468	0.749	0.983	0.334	0.281
Eq.5	100 %	33.33	21.43	33.33	30	49.17	33.33
	99 %	51.67	21.43	80.83	42	95	85
	95 %	64.17	21.43	85	53	95	85
	σ	0.926	2.783	0.885	1.106	0.326	0.404
Eq.6	100 %	33.33	23.57	33.33	30	33.33	33.33
	99 %	34.17	25.72	36.67	34	34.17	36.67
	95 %	34.17	26.43	36.67	35	34.17	37.50
	σ	0.960	1.094	1.88	2.915	5.15	0.927
Eq.7	100 %	33.33	21.43	34.17	30	33.33	35
	99 %	34.17	32.86	34.17	34	37.50	40
	95 %	34.17	32.87	34.17	34	37.50	40
	σ	2.71	1.050	2.033	1.619	1.508	1.227

§ refer to page F-16 for equations

Table F.31 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances using multiratio algorithms.

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.8	100 %	33.33	39.29	33.33	30	33.33	33.33
	99 %	35	59.29	33.33	30	33.33	33.33
	95 %	36.67	62.14	33.33	30	33.33	33.33
	σ	0.015	0.012	0.007	0.098	0.017	0.007
Eq.9	100 %	33.33	39.39	33.33	30	33.33	33.33
	99 %	35	59.29	33.33	30	33.33	33.33
	95 %	36.67	62.14	33.33	30	33.33	33.33
	σ	0.015	0.012	0.007	0.098	0.017	0.007
Eq.10	100 %	41.67	78.57	40	30	41.67	39.17
	99 %	41.67	86.43	43.33	40	41.67	44.17
	95 %	41.67	86.43	43.33	40	41.67	44.17
	σ	0.013	0.011	0.008	0.100	0.018	0.008
Eq.11	100 %	33.33	33.57	33.33	30	33.33	33.33
	99 %	33.33	42.14	35	50	33.33	33.33
	95 %	33.33	42.85	36.67	50	33.33	34.17
	σ	1.463	2.086	1.008	3.871	1.021	1.008
Eq.12	100 %	33.33	21.43	33.33	45	33.33	33.33
	99 %	35.83	60.71	33.33	57	33.33	33.33
	95 %	37.50	65	33.33	59	33.33	33.33
	σ	0.434	0.556	0.178	1.609	40.959	0.178
Eq.13	100 %	75	29.29	85.83	30	91.67	84.17
	99 %	79.17	31.43	90	38	91.67	87.50
	95 %	82.50	31.43	90	44	91.67	87.50
	σ	0.520	2.820	0.240	0.967	0.705	0.240

§ refer to page F-16 for equations

Table F.32 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances using multiratio algorithms obtained after calculating the discriminant integration index.

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.8	100 %	56.67	21.43	40	30	33.33	91.67
	99 %	97.50	81.43	73.33	35	95	93.33
	95 %	97.50	82.14	75	45	95	93.33
	σ	0.237	0.208	0.159	0.299	0.301	0.18
Eq.9	100 %	33.33	22.14	40	30	33.33	33.33
	99 %	68.3	46.43	82.50	36	38.33	90
	95 %	70	47.86	84.17	36	44.17	90.83
	σ	0.140	0.149	0.102	0.199	0.244	0.176
Eq.10	100 %	55	34.29	49.17	31	37.5	90
	99 %	97.5	87.86	75.83	78	95	91.67
	95 %	99.17	90.71	76.67	83	95	91.67
	σ	0.2259	0.248	0.203	0.330	0.302	0.168
Eq.11	100 %	97.5	77.86	71.67	30	96.67	88.33
	99 %	98.33	91.43	92.5	69	99.17	95.83
	95 %	98.33	92.14	93.33	71	99.17	95.83
	σ	0.360	0.879	0.598	3.392	0.489	0.566
Eq.12	100 %	35	21.43	33.33	30	33.33	33.33
	99 %	35	21.43	37.5	40	33.33	33.33
	95 %	35.83	22.14	38.33	40	33.33	33.33
	σ	67.463	143.188	22.239	12.7191	94.19	250
Eq.13	100 %	33.33	21.43	33.33	45	33.33	33.33
	99 %	60	37.14	34.17	90	33.33	33.33
	95 %	97.5	41.43	35	91	33.33	33.33
	σ	26.700	67.972	37.87	18.338	95.71	335

§ refer to page F-16 for equations

Table F.33 **Cabbage standard deviations and cabbage/weed/soil discrimination accuracies using different tolerances in multiratio algorithms after calculating the discriminant integration index with the reference spectrum compensated.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.8	100 %	33.33	21.43	33.33	30	95	60
	99 %	97.50	32.14	91.67	76	97.50	90
	95 %	97.50	40.71	94.17	89	97.50	92.50
	σ	0.3147	0.424	0.389	0.385	0.297	0.195
Eq.9	100 %	33.33	21.43	33.33	30	33.33	33.33
	99 %	36.67	23.57	36.67	36	35	85.83
	95 %	40	23.57	36.67	38	35	87.50
	σ	0.146	0.126	0.157	0.218	0.275	0.170
Eq.10	100 %	33.33	21.43	33.33	30	49.17	33.33
	99 %	71.67	21.43	91.67	60	95	86.67
	95 %	95.84	21.43	91.67	61	95	89.17
	σ	0.446	0.354	0.447	0.437	0.227	0.223
Eq.11	100 %	93.33	70.14	60.83	30	99.17	86.67
	99 %	97.50	72.14	75	74	100	94.17
	95 %	97.50	72.86	75.83	78	100	94.17
	σ	0.491	1.788	0.767	3.287	1.034	0.475
Eq.12	100 %	33.33	28.57	40	30	33.33	33.33
	99 %	34.17	35	42.50	31	33.33	33.33
	95 %	34.17	35	43.33	32	34.17	33.33
	σ	14.913	2.904	2.724	42.175	13.972	70.50
Eq.13	100 %	33.33	22.14	34.17	35	65	84.17
	99 %	80	31.43	50	69	99.17	94.17
	95 %	90.83	75.71	62.50	87	99.17	95
	σ	8.069	25.578	17.397	6.213	2.787	7.031

§ refer to page F-16 for equations

Table F.34 Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances with complex multiratio algorithms.

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviation					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.14	100 %	33.33	39.29	33.33	30	33.33	33.33
	99 %	35	59.29	33.33	30	33.33	33.33
	95 %	36.67	62.14	33.33	30	33.33	33.33
	σ	0.007	0.006	0.003	0.041	0.008	0.003
Eq.15	100 %	41.67	78.57	40	30	41.67	39.17
	99 %	41.67	86.43	43.33	40	41.67	44.17
	95 %	41.67	86.43	43.33	40	41.67	44.17
	σ	0.006	0.006	0.003	0.043	0.008	0.003
Eq.16	100 %	33.33	25	35.83	50	36.67	38.33
	99 %	33.33	32.86	48.33	53	38.33	47.50
	95 %	33.33	33.57	48.33	54	38.33	47.50
	σ	2.77	11.92	4.798	3.904	3.757	4.798
Eq.17	100 %	48.33	21.43	36.67	36	45	65
	99 %	56.67	21.43	90	60	73.33	90
	95 %	58.33	21.43	95	60	75	90
	σ	6.75	8.013	16.164	46.022	16.933	14.612

§ refer to page F-16 for equations

Table F.35 **Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances in complex multiratio algorithms obtained after calculating the discriminant integration index.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.14	100 %	56.67	21.43	40	30	33.33	91.67
	99 %	60	81.43	73.33	34	95	93.33
	95 %	97.50	82.14	75	48	95	93.33
	σ	0.134	1.113	0.821	0.175	0.189	0.116
Eq.15	100 %	55	34.29	49.16	31	37.5	90
	99 %	97.50	87.86	75.83	80	95	91.67
	95 %	99.17	90.71	76.67	91	95	91.67
	σ	1.129	0.152	0.115	0.200	0.192	0.102
Eq.16	100 %	99.17	75.71	70.83	60	100	78.33
	99 %	100	82.14	96.67	87	100	88.33
	95 %	100	82.14	97.5	87	100	88.33
	σ	1.24	5.977	2.69	4.920	2.377	3.93
Eq.17	100 %	48.33	90	33.33	36	33.33	33.33
	99 %	66.67	94.29	33.33	60	43.33	33.33
	95 %	66.67	94.29	33.33	60	46.67	33.33
	σ	7.078	4.342	11.99	44.093	14.90	14.41

§ refer to page F-16 for equations

Table F.36 **Cabbage standard deviations and cabbage/weed/soil discrimination accuracies for different tolerances obtained after calculating the discrimination integrating index with the reference spectrum compensated in complex multiratio algorithms.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations					
		TRIAL 2	TRIAL 3	TRIAL 4	TRIAL 6	TRIAL 7	TRIAL 9
Eq.14	100 %	33.33	21.43	33.33	30	95	60
	99 %	97.50	35	94.17	86	97.50	90
	95 %	97.50	73.57	94.17	91	97.50	92.5
	σ	0.168	0.218	0.221	0.220	0.214	0.116
Eq.15	100 %	33.33	21.43	33.33	30	49.17	33.33
	99 %	94.17	21.43	92.5	60	95	87.50
	95 %	96.67	22.14	94.17	74	95	89.17
	σ	0.261	0.173	0.255	0.236	0.143	0.132
Eq.16	100 %	98.33	72.14	65.83	60	100	78.33
	99 %	100	78.57	89.17	87	100	88.33
	95 %	100	80.71	90	87	100	89.17
	σ	1.379	6.164	2.528	4.591	1.516	3.898
Eq.17	100 %	48.33	94.29	33.33	30	33.3	33.33
	99 %	66.67	97.14	33.33	60	40	33.33
	95 %	66.67	97.14	33.33	60	43.33	33.33
	σ	6.996	4.651	12.477	43.23	16.05	14.565

§ refer to page F-16 for equations

Table F.37 **Leek standard deviations and leek/weed/soil discrimination accuracies using different tolerances for the selected wavebands.**

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
First	**100 %**	41.43	40	39.33	25
waveband	**99 %**	50	40	40	25.63
680-780	**95 %**	50	40	40	26.25
	σ	2.299	0.862	1.59	4.395
Second	**100 %**	47.14	36.36	36	25
waveband	**99 %**	48.57	36.36	36	25
980-1080	**95 %**	48.57	36.36	36	25
	σ	2.222	1.658	1.308	4.907
Third	**100 %**	52.85	47.3	34.67	25
waveband	**99 %**	56.43	47.3	36	25.63
1350-1450	**95 %**	56.43	47.3	36	25.63
	σ	1.411	0.753	1.59	2.327

Table F.38 **Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index using the selected wavebands.**

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
First	**100 %**	91.43	93.64	100	95.63
waveband	**99 %**	95.71	99.09	100	98.75
680-780	**95 %**	96.43	99.09	100	99.38
	σ	1.032	0.4876	0.727	2.098
Second	**100 %**	91.43	96.36	98.67	95.63
waveband	**99 %**	98.57	99.09	100	98.13
980-1080	**95 %**	98.57	100	100	98.13
	σ	1.145	1.012	0.746	2.484
Third	**100 %**	92.85	86.36	94.67	93.13
waveband	**99 %**	97.14	93.64	100	100
1350-1450	**95 %**	97.14	93.64	100	100
	σ	0.528	0.343	0.705	1.119

Table F.39 **Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index with the reference spectra compensated for each trial.**

Waveband (nm)	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
First	**100 %**	77.14	86.36	98	71.86
waveband	**99 %**	86.43	94.55	99.33	86.25
680-780	**95 %**	86.43	94.55	99.33	86.88
	σ	1.783	0.765	0.726	2.213
Second	**100 %**	73.57	96.36	98.67	90
waveband	**99 %**	77.86	100	100	97.5
980-1080	**95 %**	77.86	100	100	97.5
	σ	2.22	1.273	0.726	2.418
Third	**100 %**	57.86	72.73	34.67	88.75
waveband	**99 %**	62.14	82.73	36	94.38
1350-1450	**95 %**	62.14	83.64	36	94.38
	σ	1.412	0.752	1.59	0.743

Table F.40 Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances using waveband ratios.

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.4	100 %	32.14	40.91	36	69.38
	99 %	51.43	46.36	40.67	74.38
	95 %	52.86	46.36	40.67	74.38
	σ	0.0346	0.0347	0.0509	0.0205
Eq.5	100 %	100	88.18	40.67	54.38
	99 %	100	92.73	40.67	73.13
	95 %	100	92.73	40.67	73.13
	σ	0.018	0.0154	0.016	0.0568
Eq.6	100 %	40	83.64	79.33	45
	99 %	56.43	89.09	83.33	48.13
	95 %	57.86	90	84..67	48.75
	σ	0.0224	0.017	0.0258	0.0149
Eq.7	100 %	21.43	36.36	77.33	25
	99 %	21.43	40.91	83.33	30.63
	95 %	21.43	41.82	83.33	33.13
	σ	0.0796	0.041	0.0254	0.1646

§ refer to page F-16 for equations

Table F.41 **Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index using waveband ratios.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.4	100 %	41.43	38.18	26.67	29.38
	99 %	97.86	87.27	93.33	66.88
	95 %	98.57	97.27	93.33	70.63
	σ	0.2387	0.0574	0.4581	0.2422
Eq.5	100 %	51.43	36.36	30	25
	99 %	52.86	37.27	34	25
	95 %	52.86	39.09	35.33	25.63
	σ	0.163	0.333	0.3206	0.4769
Eq.6	100 %	21.43	36.36	28	25.63
	99 %	22.86	36.36	29.33	29.38
	95 %	22.86	36.36	29.33	32.5
	σ	0.651	0.7413	1.1012	0.5729
Eq.7	100 %	40	51.82	33.33	25
	99 %	66.43	90.91	53.33	26.25
	95 %	67.14	91.82	56	27.5
	σ	0.631	0.6747	0.3989	1.6313

§ refer to page F-16 for equations

Table F.42 **Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances obtained after calculating the discriminant integration index with the reference spectrum compensated using waveband ratios.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.4	100 %	26.43	96.36	88	95
	99 %	71.43	100	97.33	98.13
	95 %	71.43	100	98	98.13
	σ	0.364	0.2522	0.2262	0.2524
Eq.5	100 %	21.43	39.09	26.67	43.13
	99 %	21.43	42.73	26.67	91.88
	95 %	21.43	42.73	26.67	93.13
	σ	0.2638	0.106	1.32	0.103
Eq.6	100 %	37.14	36.36	26.67	25
	99 %	45.71	36.36	28	26.25
	95 %	47.14	36.36	28	26.25
	σ	0.3346	4.943	2.454	1.8686
Eq.7	100 %	97.14	89.09	98	26.25
	99 %	100	91.82	99.33	28.13
	95 %	100	91.82	99.33	28.75
	σ	0.1087	0.0902	0.098	0..6162

§ refer to page F-16 for equations

Table F.43 Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances using multiratio algorithms.

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.8	100 %	32.14	40.91	36	69.38
	99 %	51.43	46.36	40.67	74.38
	95 %	54.19	46.36	40.67	74.38
	σ	0.0137	0.0117	0.0176	0.0087
Eq.9	100 %	32.14	40.91	36	69.38
	99 %	51.43	46.36	40.67	74.38
	95 %	54.29	46.36	40.67	74.38
	σ	0.137	0.0117	0.0176	0.0087
Eq.10	100 %	28.57	50	33.33	34.38
	99 %	100	92.73	40.67	73.13
	95 %	100	92.73	40.67	73.13
	σ	0.0165	0.0118	0.01	0.0447
Eq.11	100 %	38.57	36.36	31.33	35.63
	99 %	46.43	36.36	35.33	43.13
	95 %	47.14	36.36	35.33	45
	σ	1.561	1.174	1.351	0.9778
Eq.12	100 %	21.43	36.36	26.67	25
	99 %	52.14	46.36	40.67	74.38
	95 %	57.14	46.36	40.67	74.38
	σ	1.223	0.3808	0.6474	1.446
Eq.13	100 %	28.57	50	33.33	34.38
	99 %	28.57	54.545	90	47.5
	95 %	28.57	55.45	90.67	53.75
	σ	0.1328	0.2075	0.8057	0.7398

§ refer to page F-16 for equations

Table F.44 **Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances obtained in multiratio algorithms after calculating the discriminant integration index for different trials.**

Equation §	Tolerance and standard deviation	Discrimination accuracies and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.8	100 %	41.43	38.18	26.67	29.38
	99 %	98.57	97.27	94	68.75
	95 %	98.57	97.27	94.67	73.13
	σ	0.163	0.2702	0.2647	0.1544
Eq.9	100 %	21.43	36.36	28	25.63
	99 %	23.57	62.73	29.33	34.38
	95 %	24.29	63.64	30.67	36.88
	σ	0.1376	0.1249	0.1889	0.1199
Eq.10	100 %	51.43	36.36	30	25
	99 %	52.86	39.09	36.67	27.5
	95 %	52.86	40.91	38	33.13
	σ	0.1318	0.1962	0.1609	0.305
Eq.11	100 %	75	94.55	92.67	78.75
	99 %	86.43	97.27	94	88.13
	95 %	87.14	97.27	94.67	90
	σ	0.8781	0.4312	0.4024	0.3517
Eq.12	100 %	22.14	36.36	27.33	26.25
	99 %	24.29	36.36	29.33	33.13
	95 %	24.29	36.36	30	35.63
	σ	36.68	11.226	14.3167	66.682
Eq.13	100 %	21.43	36.36	28	25
	99 %	21.43	37.27	34	25
	95 %	21.43	37.27	35.33	25
	σ	98.585	33.457	77.5126	12.938

§ refer to page F-16 for equations

Table F.45 **Leek standard deviations and leek/weed/soil discrimination accuracies using differnt tolerances obtained in multiratio algorithms after calculating the discriminant integration index with the reference spectrum compensated for different trials.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.8	100 %	26.43	94.55	87.73	95
	99 %	72.14	100	98	98.13
	95 %	72.14	100	98	98.13
	σ	0.1568	0.256	0.2283	0.2289
Eq.9	100 %	40.71	36.36	26.67	25
	99 %	68.57	37.27	28	28.75
	95 %	82.86	38.18	28	28.75
	σ	0.1003	0.256	0.2283	0.2269
Eq.10	100 %	21.43	39.09	26.67	26.88
	99 %	21.43	42.73	26.67	92.5
	95 %	21.43	42.73	26.67	93.13
	σ	0.0793	0.0484	0.1144	0.098
Eq.11	100 %	72.86	80.91	84.67	65.63
	99 %	92.86	82.73	86.67	76.25
	95 %	95	83.64	87.33	77.5
	σ	1.925	0.9954	0.814	1.766
Eq.12	100 %	21.43	38.18	27.33	25.63
	99 %	22.86	41.82	33.33	26.88
	95 %	22.86	41.82	34	26.88
	σ	34.785	4.477	6.1681	10.335
Eq.13	100 %	24.29	36.36	34.67	26.88
	99 %	25.71	36.36	36	30.63
	95 %	26.43	36.36	36	31.88
	σ	3.133	148.856	46.197	0.97

§ refer to page F-16 for equations

Table F.46 **Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances using complex multiratio algorithms.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.14	100 %	32.14	40.91	36	69.38
	99 %	51.43	46.36	40.67	74.38
	95 %	55	46.36	40.67	74.38
	σ	0.0065	0.005	0.0081	0.0042
Eq.15	100 %	100	88.18	40.67	54.38
	99 %	100	92.73	40.67	73.13
	95 %	100	92.73	40.67	74.38
	σ	0.0103	0.0067	0.0053	0.026
Eq.16	100 %	47.14	36.36	37.33	25
	99 %	48.57	36.36	37.33	25
	95 %	48.57	36.36	37.33	25.63
	σ	4.211	2.483	2.508	9.278
Eq.17	100 %	21.43	36.36	26.67	25
	99 %	21.43	100	49.33	37.5
	95 %	21.43	100	53.33	37.5
	σ	6.814	8.9914	8.24	21.715

§ refer to page F-16 for equations

Table F.47 **Leek standard deviations and leek/weed/soil discrimination accuracies using different tolerances obtained in complex multiratio algorithms after calculating the discriminant integration index for different trials.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.14	100 %	41.43	38.18	26.67	29.38
	99 %	98.57	97.27	94	68.75
	95 %	98.57	98.18	94.67	74.38
	σ	0.0942	0.1418	0.1516	0.0869
Eq.15	100 %	51.43	36.36	30	25
	99 %	52.86	39.09	36.67	31.88
	95 %	52.86	41.82	41.33	44.38
	σ	0.08	0.1089	0.0835	0.1812
Eq.16	100 %	94.29	96.36	100	94.38
	99 %	97.86	99.09	100	100
	95 %	98.57	99.09	100	100
	σ	1.9096	1.494	1.3217	4.53
Eq.17	100 %	75.71	36.36	32	25
	99 %	78.57	36.36	53.33	31.25
	95 %	78.57	36.36	56	42.5
	σ	6.208	7.3511	7.615	17.7916

§ refer to page F-16 for equations

Table F.48 **Leek standard deviations and leek/weed/soil discrimination accuracies for different tolerances obtained in complex multiratio algorithms after calculating the discriminant integration index with the reference spectrum compensated.**

Equation §	Tolerance and standard deviation	Discrimination accuracies (%) and standard deviations			
		TRIAL 3	TRIAL 4	TRIAL 5	TRIAL 7
Eq.14	100 %	26.43	96.36	88	95
	99 %	72.14	100	98	98.13
	95 %	72.14	100	98	98.13
	σ	0.0785	0.1933	0.1634	0.1526
Eq.15	100 %	21.43	39.09	26.67	43.13
	99 %	21.43	42.73	26.67	93.13
	95 %	21.43	42.73	26.67	93.13
	σ	0.036	0.023	0.0461	0.064
Eq.16	100 %	78.57	93.64	99.33	83.75
	99 %	82.14	99.09	100	94.38
	95 %	82.14	99.09	100	95.63
	σ	3.013	1.6226	1.1535	3.997
Eq.17	100 %	84.29	36.36	26.67	25
	99 %	87.14	36.36	45.33	28.75
	95 %	87.14	36.36	48	33.75
	σ	4.478	8.063	3.211	15.65

§ refer to page F-16 for equations

useful in certain cases for disclosing systematic errors.

3. References

ISO 3534. Statistical vocabulary and symbols*.
ISO 2854. Statistical treatment of data – Problems of estimation and tests of means and variances.

4. Definitions and symbols

The vocabulary and symbols used in this International Standard are in conformity with ISO 3534*.

5. Estimation of the mean

5.1 Case of ungrouped results. After the discarding of any doubtful results, the series comprises n measurements x_i (where $i=1, 2, 3, \ldots, n$), some of which may have the same value.

The mean m of the underlying normal distribution is estimated by the arithmetic mean $\bar{x}$ of the n results:

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n} x_i$$

5.2 Case of results grouped in classes. When the number of results is sufficiently high (above 50 for example), it may be advantageous to group them into classes of the same width. In certain cases, the results may also have been directly obtained grouped into classes.

The frequency of the ith class, i.e. the number of results in class i, is denoted by n_i.

The number of classes being denoted by k, we have:

$$n=\sum_{i=1}^{k} n_i$$

The midpoint of class i is designated by y_i. The mean m is then estimated by the weighted mean of all midpoints of classes:

$$\bar{y}=\frac{1}{n}\sum_{i=1}^{k} n_i y_i$$

6. Confidence interval for the mean

The confidence interval for the population mean is calculated from the estimates of the mean and of the standard deviation.

The alternative method of calculating the confidence interval by use of the range is given in the annex.

6.1 Estimation of the standard deviation from the squares of the deviations from the arithmetic mean

* At present at the stage of draft.

6.1.1 *Case of ungrouped results.* The estimate of the standard deviation σ, calculated from the squares of the deviations from the arithmetic mean, is given by the formula:

$$s=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

where

x_i is the value of the ith measurement ($i=1, 2, 3, \ldots, n$);

n is the total number of measurements;

$\bar{x}$ is the arithmetic mean of the n measurements, calculated as in clause 5.1.

For ease of calculation, the use of the following formula is recommended:

$$s=\sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{n} x_i^2-\frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2\right]}$$

6.1.2 *Case of grouped results.* In the case of grouping by classes, the formula for the estimate of the standard deviation is written:

$$s=\sqrt{\frac{1}{n-1}\sum_{i=1}^{k} n_i (y_i-\bar{y})^2}$$

For ease of calculation, the use of the following formula is recommended:

$$s=\sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{k} n_i y_i^2-\frac{1}{n}\left(\sum_{i=1}^{k} n_i y_i\right)^2\right]}$$

where

y_i is the midpoint of the ith class ($i=1, 2, 3, \ldots, k$);

n is the total number of measurements;

$\bar{y}$ is the weighted mean of all midpoints of classes calculated as in clause 5.2.

6.2 Confidence interval for the mean. For a chosen confidence level (95% or 99%), according to the specific case, a two-sided or a one-sided confidence interval has to be determined.

6.2.1 *Two-sided confidence interval.* The two-sided confidence interval for the population mean is defined by the following double inequality:

(a) at the confidence level 95%:

$$\bar{x}-\frac{t_{0.975}}{\sqrt{n}}s<m<\bar{x}-\frac{t_{0.975}}{\sqrt{n}}s$$

(b) at the confidence level 99%:

$$\bar{x}-\frac{t_{0.995}}{\sqrt{n}}s<m<\bar{x}-\frac{t_{0.995}}{\sqrt{n}}s$$

Table 1

	Confidence level two-sided case		Confidence level one-sided case	
	95%	99%	95%	99%
n	$\frac{t_{0.975}}{\sqrt{n}}$	$\frac{t_{0.995}}{\sqrt{n}}$	$\frac{t_{0.95}}{\sqrt{n}}$	$\frac{t_{0.99}}{\sqrt{n}}$
2	8.985	45.013	4.465	22.501
3	2.484	5.730	1.686	4.021
4	1.591	2.920	1.177	2.270
5	1.242	2.059	0.953	1.676
6	1.049	1.646	0.823	1.374
7	0.925	1.401	0.734	1.188
8	0.836	1.237	0.670	1.060
9	0.769	1.118	0.620	0.966
10	0.715	1.028	0.580	0.892
11	0.672	0.956	0.546	0.833
12	0.635	0.897	0.518	0.785
13	0.604	0.847	0.494	0.744
14	0.577	0.805	0.473	0.708
15	0.554	0.769	0.455	0.678
16	0.533	0.737	0.438	0.651
17	0.514	0.708	0.423	0.627
18	0.497	0.683	0.410	0.605
19	0.482	0.660	0.398	0.586
20	0.468	0.640	0.387	0.568
21	0.455	0.621	0.376	0.552
22	0.443	0.604	0.367	0.537
23	0.432	0.588	0.358	0.523
24	0.422	0.573	0.350	0.510
25	0.413	0.559	0.342	0.498
26	0.404	0.547	0.335	0.487
27	0.396	0.535	0.328	0.477
28	0.388	0.524	0.322	0.467
29	0.380	0.513	0.316	0.458
30	0.373	0.503	0.310	0.449
40	0.320	0.428	0.266	0.384
50	0.284	0.379	0.237	0.340
60	0.258	0.344	0.216	0.309
70	0.238	0.317	0.199	0.285
80	0.223	0.295	0.186	0.265
90	0.209	0.277	0.175	0.250
100	0.198	0.263	0.166	0.236
200	0.139	0.184	0.117	0.166
500	0.088	0.116	0.074	0.104

6.2.2 *One-sided confidence interval.* The one-sided confidence interval for the population mean is defined by one or other of the following inequalities:

(a) at the confidence level 95%:

$$m < \bar{x} - \frac{t_{0.95}}{\sqrt{n}} s$$

or

$$m > \bar{x} - \frac{t_{0.95}}{\sqrt{n}} s$$

(b) at the confidence level 99%:

$$m < \bar{x} - \frac{t_{0.99}}{\sqrt{n}} s$$

or

$$m > \bar{x} - \frac{t_{0.99}}{\sqrt{n}} s$$

with $\bar{x}$, if necessary, replaced by $\bar{\bar{x}}$, in the case of results grouped in classes.

The coefficients $\frac{t_{0.975}}{\sqrt{n}}$, $\frac{t_{0.995}}{\sqrt{n}}$, $\frac{t_{0.95}}{\sqrt{n}}$, $\frac{t_{0.99}}{\sqrt{n}}$ are derived from Student's t distribution and are given in table 1.

When n becomes large, interpolation is easier for t than for $\frac{t}{\sqrt{n}}$. Table 2 gives the corresponding values for t.

Table 2

n	$\frac{120}{n}$	$t_{0.975}$	$t_{0.995}$	$t_{0.95}$	$t_{0.99}$
60	2	2.000	2.660	1.671	2.390
120	1	1.980	2.617	1.658	2.358
—	0	1.960	2.576	1.645	2.326

If $\frac{120}{n}$ is used as argument, linear interpolation for t at any value of $n > 60$ is possible.

7. Presentation of the results

Express the results in the form of the double inequality of 6.2.1 or one of the inequalities of 6.2.2. stating the confidence level (95% or 99%) and giving the number n of results effectively used as well as the number of results discarded as being doubtful and the reasons for discarding.

APPENDIX G

APPENDIX G. REMOTE SENSING MEASUREMENTS AND ANALYSIS

Two experiments for sampling remotely leaves using an optical fibre probe were carried out to study their spectral reflectance and the effect of distance measurements on crop/weed/soil discrimination.

The first remote sensing experiment measured spectral reflectance from a sample located 5 and 10 cm away from a fixed optical fibre probe connected to the MONOLITE Optical Spectrum Analizer. The small section area of the optical fibre probe was unable to capture reflectance irradiated at angles different than 90 degrees. Reduction in *C. album* reflectance resulted from moving the probe away from the sample, Fig. G1, although having the same illumination conditions used with contact measurements.

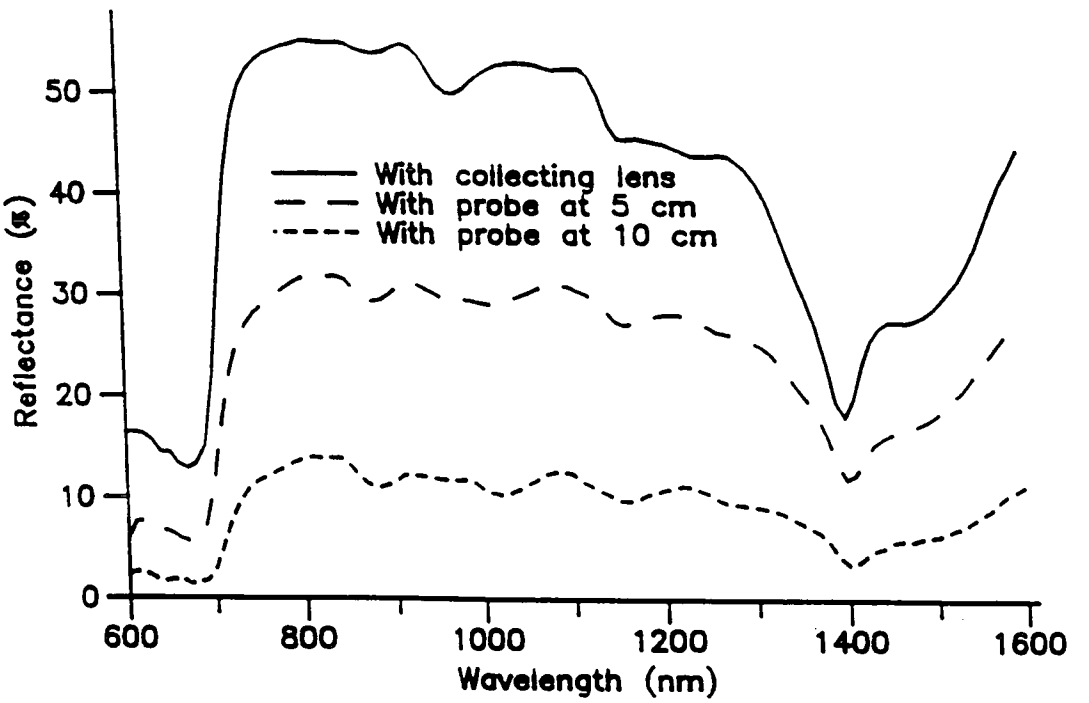


Fig G1 Remote sensing signatures of fathen

Table G1 Number of spectra in each of the Crop/Weed/Soil categories, in the training group and in the trial group used to test discrimination accuracy in the remote sensing measurements.

Crop/weed/soil	Number of spectra		
	Total	**Training group**	**Trial group**
BRO/LEEK	30	21	9
Rumex spp.	10	7	3
S. arvensis	10	7	3
C. album	10	7	3
S. media	10	7	3
S. vulgaris	10	7	3
P. persicaria	10	7	3
Soil	10	7	3
Total	110	77	33

Broccoli, leek and weed species signatures were taken from each distance and analyzed using discriminant analysis. From a total of 110 spectra used in each analysis, 30 were crop spectra, 10 soil spectra and the remaining 70 were weed spectra, Table G1. A total of 77 spectra trained the classifier and 33 spectra formed a trial group to test it.

Discrimination accuracies from broccoli leaves, weed species and soil from remote measurements taken five and ten cm away from the sample are shown in Tables G2 and G3 presenting 100% crop/weed/soil discrimination with three direct wavelengths. The three wavelengths selected using the closest arrangement (5 cm) were 770 nm, 840 nm and 870 nm differing substantially from the wavelengths achieved at a sensing distance of 10 cm (720 nm, 1140 nm and 1500 nm). Program run B5R2 misclassified broccoli with *A. patula*, while program run B5R4, using three wavelengths, misclassified *P. persicaria* with broccoli. Program runs of data sampled 10 cm away had problems misclassifying *P. persicaria* with broccoli. A 78% crop/weed species/soil discrimination accuracy was achieved when sampling at a distance of 10 cm which was higher than the 63% obtained from measurements taken 5 cm away from the sample.

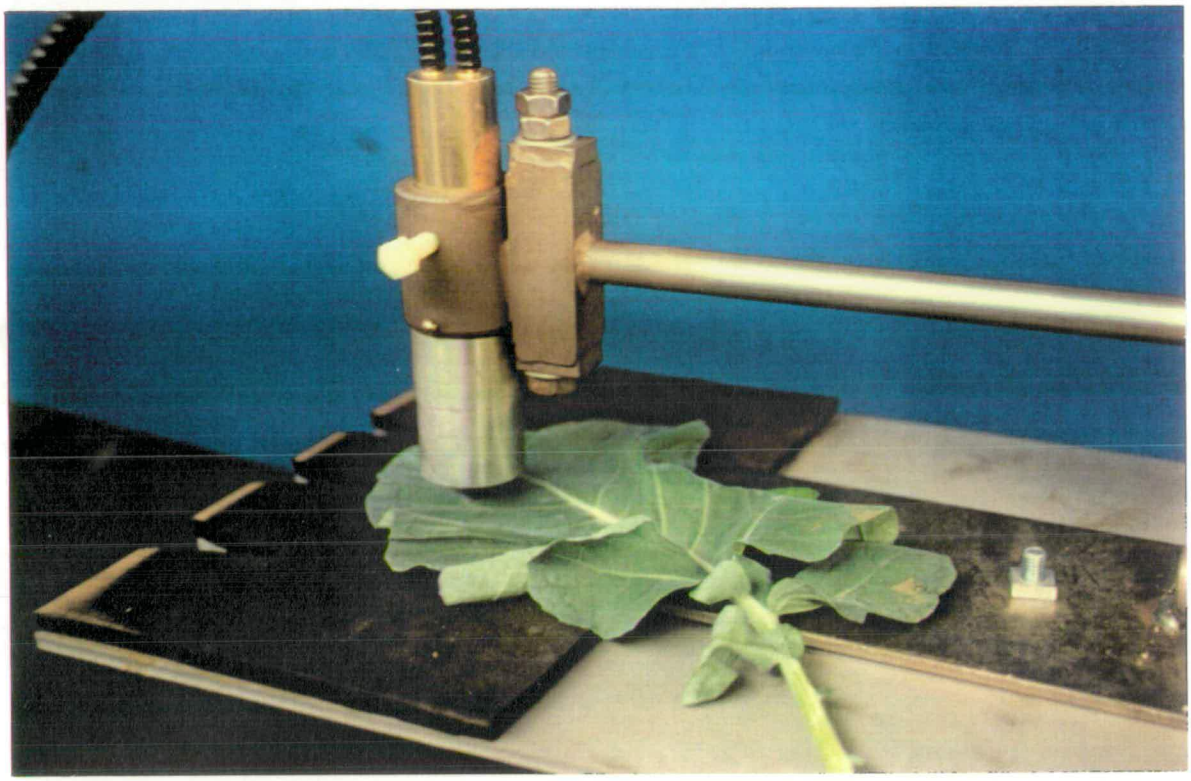
Leek was sensed also with the probe attached five and ten cm away from the sample and the discrimination accuracies are shown in Tables G4 and G5. Crop/weed/soil discrimination accuracies of 100% with three wavelengths were achieved in both cases, having similar wavelengths in the 720-740 nm, 840 nm and 1420-1460 nm wavebands. Program runs L5R5 and L5R7, Table G4, misclassified *S. media* with leek, while program run L1R6 misclassified *P. persicaria* with leek. High discrimination accuracies with two wavelengths were achieved in both remote sensing experiments using wavelengths below 900 nm. Higher crop/weed species/soil discrimination accuracies were achieved with the probe standing ten cm away from the sample.

A condenser lens was introduced between the sample and the optical fibre for collecting maximum radiation and two reflectors illuminated the sample. The condenser lens, having a focal length of 4 cm was adjusted until maximum reflectance was collected. The assembly unit showed in Plate 7, allowed a fine adjustment of the lense towards the sample.

Discriminant analysis was also carried out to study the effect of this technique in crop/weed/soil discrimination using leek, broccoli and the same weed species. A 100% crop/weed/soil discrimination accuracy was achieved in all the program runs with broccoli, Table G6, having similar crop/weed species/soil discrimination accuracies with the results obtained at a distance of 10 cm without lens. Wavelengths selected in program runs BR7 (Table G6) and B1R6 (Table G3) were similar at the 720-740 nm and 1500 nm wavebands. Leek also achieved 100% crop/weed/soil discrimination with three wavelengths in program run LR7, Table G7, but the wavelengths (770 nm, 970 nm and 1050 nm) differed substantially from the ones achieved by the other experiments. Crop/weed species/soil discrimination was higher when the lens was used.

Finally, iterative discriminant analyses were carried out with the best contact and remote sensing wavelengths for each crop. The best average broccoli/weed/soil discrimination accuracy was obtained using either the wavelength set of 740 nm, 1460 nm and 1500 nm or the wavelength set of 770 nm, 840 nm and 870 nm, Table G8. The two wavelength sets obtained from contact measurements performed poorly with remote sensing data.

The best average leek/weed/soil discrimination accuracy was achieved with the wavelength set of 740 nm, 840 nm and 1460 nm, Table G9, and the contact wavelengths performed very well. The effect of adding a lens improved the signature collection, but did not reduce discrimination accuracies.



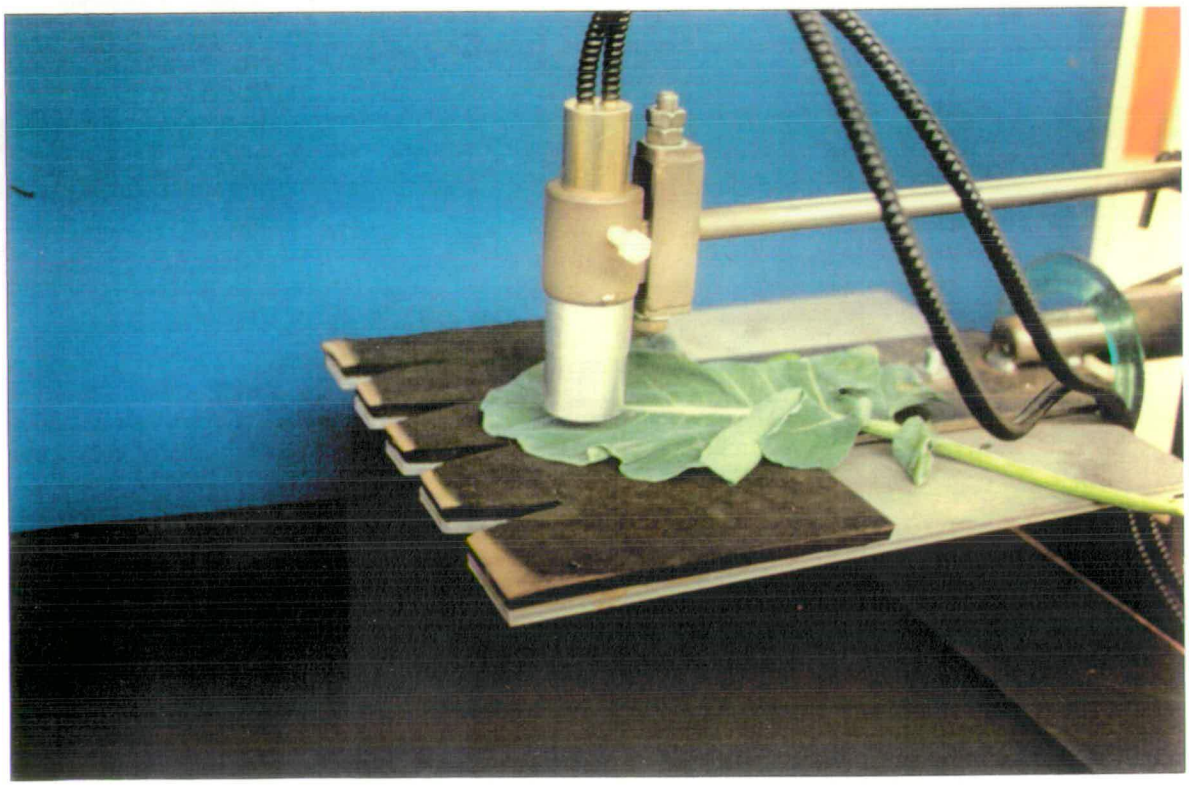


Plate 7. Attachment for condenser lens and optical probe.

Table G2 **Broccoli/weed/soil and broccoli/weed species/soil discrimination accuracies from broccoli, weed and soil sensed five cm away using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		General crop/weed/soil	Specific crop/weed species/soil
B5R2	7	96.96	81.82
B5R3	4	100	72.72
B5R5	3	100	63.63
B5R4	3	93.93	66.66
B5R6	2	84.84	42.41

Program run no.	Selected wavelengths (nm)			
B5R3	720	770	840	870
B5R5	770	840	870	
B5R4	770	840	1240	
B5R6	770	840		

Table G3 **Broccoli/weed/soil and broccoli/weed species/soil discrimination accuracies from broccoli, weed and soil sampled ten cm away using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		General crop/weed/soil	Specific crop/weed species/soil
B1R2	13	100	90.91
B1R3	4	100	96.96
B1R4	4	90.91	69.69
B1R6	3	100	78.78
B1R5	3	90.91	78.78
B1R7	2	87.87	57.57

Program run no.	Selected wavelengths (nm)			
B1R3	680	730	970	1020
B1R4	680	720	1140	1500
B1R6	680	730	970	
B1R5	680	730	1020	
B1R7	680	730		

Table G4 **Leek/weed/soil and leek/weed species/soil discrimination accuracies from leek, weed and soil sampled five cm away using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		General crop/weed/soil	Specific crop/weed species/soil
L5R1	11	100	84.84
L5R3	4	100	78.78
L5R4	4	100	66.66
L5R6	3	100	72.73
L5R5	3	96.96	57.57
L5R7	2	96.96	62.50

Program run no.	Selected wavelengths (nm)			
L5R3	740	840	1380	1460
L5R4	740	840	1030	1100
L5R6	740	840	1460	
L5R5	740	840	1030	
L5R7	740	840		

Table G5 **Leek/weed/soil and leek/weed species/soil discrimination accuracies from leek, weed and soil sampled ten cm away using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		General crop/weed/soil	Specific crop/weed species/soil
L1R2	15	100	87.87
L1R4	4	100	90.91
L1R3	4	100	81.81
L1R10	3	100	60.61
L1R6	3	96.96	84.84
L1R7	2	100	69.69

Program run no.	Selected wavelengths (nm)			
L1R4	680	730	800	1020
L1R3	720	840	1140	1420
L1R10	720	840	1420	
L1R6	680	730	1020	
L1R7	680	730		

Table G6 **Broccoli/weed/soil and broccoli/weed species/soil discrimination accuracies sensed from a distance of three cm with a condenser lens using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		General crop/weed/soil	Specific crop/weed species/soil
BR1	9	100	83.87
BR6	4	100	80.65
BR3	4	100	70.97
BR7	3	100	77.42
BR4	3	100	70.97
BR13	2	100	67.74

Program run no.	Selected wavelengths (nm)			
BR6	740	1400	1460	1500
BR3	720	800	880	1050
BR7	740	1460	1500	
BR4	800	880	1050	
BR13	800	1050		

Table G7 **Leek/weed/soil and leek/weed species/soil discrimination accuracies sensed from a distance of three cm. with a condenser lens using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy (%)	
		General crop/weed/soil	Specific crop/weed species/soil
LR1	9	100	90.32
LR4	4	100	77.42
LR3	4	100	70.96
LR7	3	100	70.96
LR5	3	96.77	70.96
LR13	2	96.77	64.52

Program run no.	Selected wavelengths (nm)			
LR4	800	1240	1380	1440
LR3	720	770	970	1050
LR7	770	970	1050	
LR5	800	1380	1440	
LR13	770	1050		

Table G8 **Remote sensed Crop/Weed/Soil (C/W/S) and Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for broccoli using the best wavelength sets.**

Remote sensing techniques	Discr. type	Discrimination accuracies (%)				
		WAV-1	WAV-2	REM	REM-5	REM-10
With lens 3 cm	C/W/S	77.42	96.77	100	96.77	77.42
	C/Ws/S	48.38	64.52	77.42	64.52	41.16
Without lens 5 cm	C/W/S	87.87	78.78	93.93	100	81.81
	C/Ws/S	57.57	42.42	63.63	63.63	48.48
Without lens 10 cm	C/W/S	75.75	100	96.96	93.93	100
	C/Ws/S	51.51	75.75	69.69	75.75	78.78
Wavelength (nm)		720, 1060,	710, 740, 890	740, 1460,	770, 840, 870	680, 730, 970

Table G9 **Remote sensed Crop/Weed/Soil (C/W/S) and Crop/Weed species/Soil (C/Ws/S) discrimination accuracies for leek using the best wavelength sets.**

Remote sensing techniques	Discr. type	Discrimination accuracies (%)				
		WAV-1	WAV-2	REM	REM-5	REM-10
With lens 3 cm	C/W/S	93.54	90.32	100	93.54	93.54
	C/Ws/S	67.74	67.74	70.96	67.74	64.52
Without lens 5 cm	C/W/S	93.93	90.91	87.87	100	96.96
	C/Ws/S	72.73	69.69	57.57	72.73	66.66
Without lens 10 cm	C/W/S	87.87	93.93	96.96	100	100
	C/Ws/S	69.69	69.69	75.75	74.72	60.61
Wavelength (nm)		760, 1340,	680, 1080, 1520	770, 970, 1050	740, 840, 1460	720, 840, 1420

APPENDIX H

APPENDIX H

MACHINE VISION FOR CROP/WEED DISCRIMINATION

A machine vision system using a Pulnix camera and a Matrox image processing board were used to acquire remote spectral measurements of crop and weed leaves. Plate 8 shows the camera setup together with the illumination system, which included four sixty watt bulbs.

A narrowband filter was inserted between the camera body and the lens to measure different spectral bands using as reference a white acrylic, with a flat spectral response in the 600-1300 nm waveband, Fig H1. The sample was introduced over a black painted wood panel and referred to the acrylic reference to obtain the relative reflectance. A more accurate result can be achieved compensating for the black wood panel spectral response plotted in Fig H1.

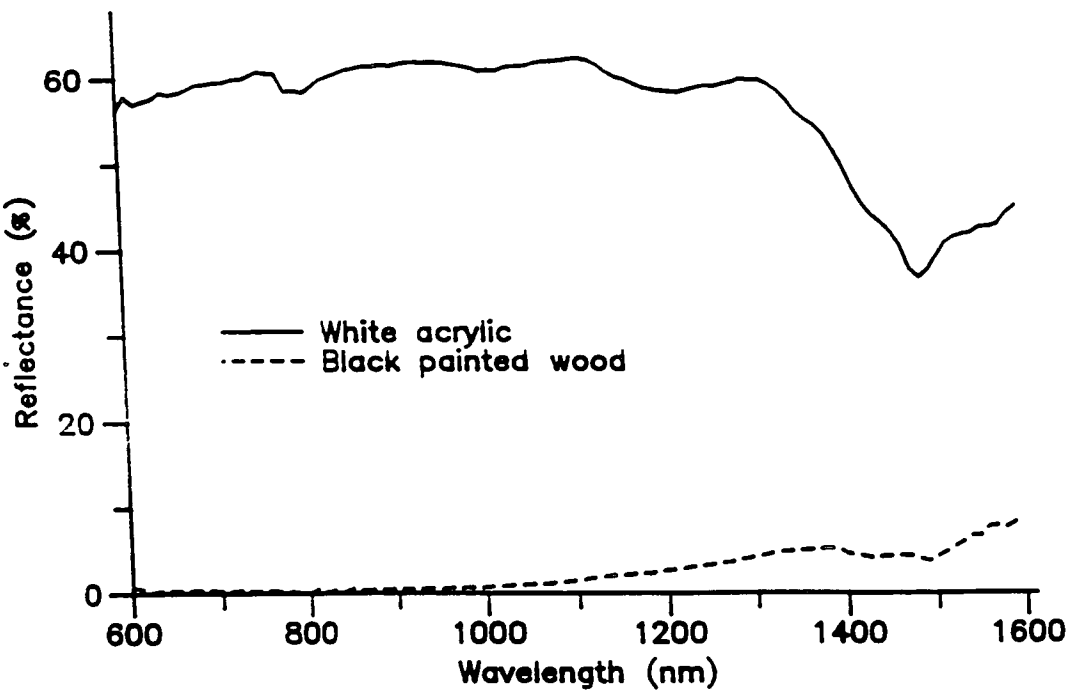


Fig. H1 Reflectance signatures of black painted wood and white acrylic.

Measurements were taken pixelwise from cabbage, broccoli, *A. patula* (common orache) and *S. arvensis* (charlock) and the results stated in Table H1. Three filters were used, 680 nm, 780

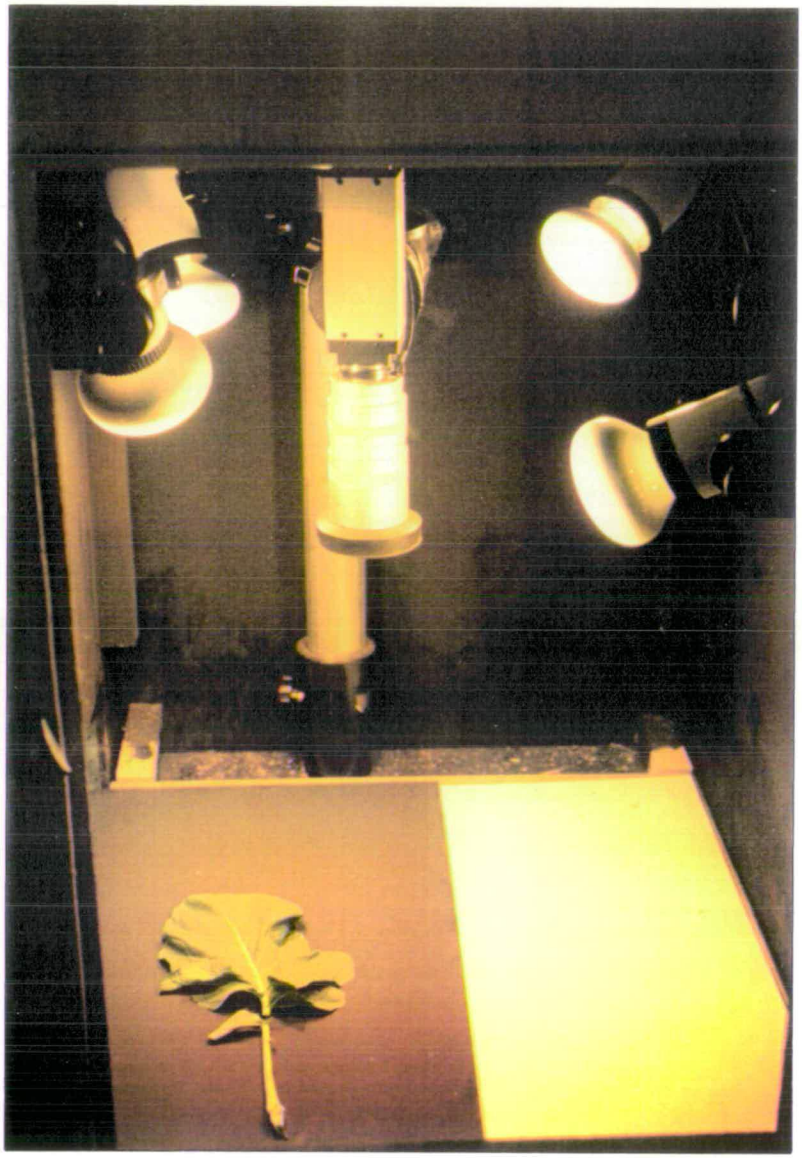


Plate 8. Camera setup.

780 nm and 820 nm, and the white reference measurements indicate similar readouts for both 680 nm and 780 nm. At 820 nm the response of the camera decreases, reducing the accuracy of the measurements.

The Pulnix camera provided 8 binary bits of information, representing a total of 256 cases. Considering a sample measurement with the value of the white reference as a maximum 100% reflectance, the contribution of each case increased the sample reflectance by 0.00724 at 680 nm and 780 nm and 0.0161 at 820 nm. Differences between weed species and crops were negligible at 680 nm, increasing to approximately 6.3% between *A. patula* and cabbage at 780 nm and to 8% between the same plants at 820 nm. The highest reflectance was achieved with *S.arvensis*.

Table H1 Binary measurements of crops and weeds obtained with the camera system.

Crop/ weed	Filter (nm)	Camera binary measurements						
		Black reference	White reference	Leaf measurements				
Broccoli		12	138	22	21	23	28	23
Cabbage	**680**	12	138	29	24	20	31	26
A. patula		12	138	21	16	26	22	28
S. arvensis		12	138	17	22	20	23	20
Broccoli		14	138	104	108	105	104	107
Cabbage	**780**	14	138	99	98	101	97	105
A. patula		14	138	91	86	91	92	88
S. arvensis		14	138	108	110	113	115	110
Broccoli		11	62	48	44	44	52	48
Cabbage	**820**	11	62	47	43	46	54	42
A. patula		11	62	39	39	46	41	40
S. arvensis		11	62	47	43	45	42	45

If good results are expected from a remote sensing system, the illumination system has to be optimized and broadband filters used. The discimination accuracy will depend also in the sensitivity of the CCD array used as was noted in this experiment.

APPENDIX I

SCOTTISH CENTRE OF AGRICULTURAL ENGINEERING

DEPARTMENTAL NOTE 57

April 1993

REFLECTANCE SPECTRA OF BRASSICA CROPS AND SOME WEEDS

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ISSN 0953 413X

ISBN 1 85482 342 6

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SUMMARY

Mature leaves of three brassicas (cauliflower, broccoli and cabbage) grown in fields local to Bush Estate were sampled and spectrophotometric measurements made. Reflectance differences were found in the stalk and other tissue of the leaves. Maturity and senescence also affected visible and near infrared reflectance. Several common weeds, encountered in the field, were also sampled and their spectra obtained. This comparison of the spectral reflectances of various crops and weed leaves has confirmed the feasibility of developing a procedure to discriminate between different plants using specific wavelength data.

CONTENTS

		Page
1.	INTRODUCTION	1
2.	EXPERIMENTAL PROCEDURE	1
3.	RESULTS	2
	3.1 Cabbage leaf spectra	2
	3.2 Broccoli leaf spectra	2
	3.3 Cauliflower leaf spectra	3
	3.4 Weed leaf, oilseed rape and soil spectra	3
4.	DISCUSSION	4
5.	CONCLUSIONS	5
6.	ACKNOWLEDGEMENTS	6
REFERENCES		6

REFLECTANCE SPECTRA OF BRASSICA CROPS AND SOME WEEDS

1. INTRODUCTION

Recent research has suggested that optical reflectance has great potential for detecting disease and defects in fruit and vegetables (Porteous *et al* 1981; Muir *et al*, 1982; Muir *et al*, 1989). Optical reflectance may also be useful for moisture and nutrient measurements for optimum management of crops and for weed and pest control. Spectral studies of vegetation and the interaction of light with plant cells are fundamental to an understanding and the furtherance of this work.

In this present study, optical spectral reflectance for weed/crop identification is taken a stage further than that recently reported by Hahn and Muir (1992). Three brassica crops, cabbage, cauliflower and broccoli, were sown during the spring of 1991 and samples of each were collected from the field during the months of August, September and October, as the plants reached maturity. The samples were taken from different places within the field in order to include typical variability such as soil status, plant nutrition, moisture content, growth stage and attack by pests and diseases.

Spectral reflectance of the brassica crops and main weeds was obtained with a computerised spectrophotometer scanning the range from 500 nm up to 1900 nm with a resolution of 20 nm. Leaf spectra exhibit a steep positive slope known as the *red edge* which occurs at or near 700 nm and represents the transition between low reflectance in the visible region and high reflectance in the NIR region. The slope, RE, can be defined as :

$$RE = (R_{\lambda_1} - R_{\lambda_2}) / 39$$

where R is the percentage reflectance at wavelengths λ_1 = 748 nm and λ_2 = 709 nm. Reflectance reaches its maximum after the red edge and maintains a high value up to 1300 nm. The region from 1500 nm up to 1900 nm includes the water absorption band at 1450 nm which causes leaf reflectance to decay abruptly. The slope of this abrupt change was named the *far edge*, FE. and can be mathematically expressed as :

$$FE = (R_{\lambda_3} - R_{\lambda_4}) / 39$$

where R is the percentage reflectance at wavelengths λ_3 = 1309 nm and λ_4 = 1349 nm. The far and red edge expressions were used to compare the different leaf species and to evaluate the possibility of using these slopes in future algorithms.

2. EXPERIMENTAL PROCEDURE

The dimensions of brassica leaves at maturity are large and it was suspected that there might be different spectral responses from different parts of leaf blade. Spectra taken from the edge or margin of leaves are referred to throughout the report as "margin" spectra. The mid part of the leaves include more pronounced

veins and spectra from this area are identified as "centre" spectra . Spectra taken from the principal vein forming the midrib of the leaf or the stalk attachment at the base of the leaf are identified as "stalk" spectra.

Ten leaves from each of the three brassica crops were collected from the field and analysed in the laboratory spectrophotometer. Samples taken from the upper and lower surfaces of leaves formed five different groups, namely, top margin, top centre, underside margin, underside centre and stalk. Twenty spectra were taken from each position on ten leaves of each crop and averaged.

3. RESULTS

3.1 Cabbage leaf spectra

The average reflectance of cabbage leaf top margin, top centre and stalk are shown in Fig.1. All three spectra show low reflectance in the visible band. Stalk, however, shows higher reflectance at 650 nm, indicating slightly lower chlorophyll content. The maximum reflectance was found at the margin and centre of the leaf, with peak values at 900 nm. Above 750 nm, stalk tissues exhibit much lower reflectance values than either the margin or centre. Large reflectance differences between the leaf tissue and the stem are found from 900 up to 1350 nm and Table 1 gives some typical reflectance values.

Fig. 2 shows the reflectance difference between the top margins and underside margins of cabbage leaves. The chlorophyll content is marginally higher in the top surface, which is directed towards the sun. Maximum differences occur at 520 nm and at 1700 nm. The reflectance difference is generally small.

During the sampling, leaves collected at different stages of growth were characterised by their visible colour. The younger leaves beginning to unfold at the tip of the plant had a fresh light green tone, while the mature leaves were darker. Leaves beginning to senesce presented a contoured red margin and green centre. Spectral comparison between leaves at different stages of growth in the visible and red edge regions are shown in Fig.3. The red senescing leaf exhibits the steepest slope and the highest reflectance, while mature and immature leaf show progressively lower reflectance between 700 and 850 nm. The far edge slope values present in the two different growth stages are similar, while the reflectance is higher in the senescing red leaves.

3.2 Broccoli leaf spectra

Spectra of broccoli leaves were classified in five groups as previously. Spectra are compared in Fig. 4 showing, in the visible region, a generally higher reflectance in the stalk than in the blade. The red edge slope is similar for the leaf centre and the leaf margin, with higher reflectance in the stalk. Leaf margin and centre reflectances are very similar across the spectrum, while stalk exhibits the highest reflectance up to 820 nm and the lowest reflectance thereafter . Table 2 gives some typical reflectance values.

Reflectance differences are to be found between the upper and lower surfaces of the leaves, Fig. 5, with the underside showing generally higher reflectance. Chlorophyll and water content are higher in the top surface of the leaf, as shown by values at 650 nm and 1450 nm. In the red edge and far edge regions, the reflectance differences between the upper and lower surfaces are larger than those between the margin and centre of the upper surface of the leaf.

Broccoli samples were collected randomly from the field so that a variance study might give information about uniformity across the plant population, Fig. 6. The variance of the top margin of the leaf is small

for wavelengths up to 1300 nm. In the case of centre and margin spectra, the variance remains constant up to 1150 nm, but increases in all wavelengths when both sides of the leaf are analysed together. Points of maximum variance occur at the red edge, far edge and at 1850 nm.

3.3 Cauliflower leaf spectra

Cauliflower was treated in the same manner as broccoli and cabbage. At the time of sample collection, the cauliflowers were mature and ready for harvesting and broad colour differences between the leaves existed. Cauliflower leaves have a different texture from the other brassicas, making them more vulnerable to dessication, so it was necessary to transport the leaves quickly to the laboratory, inside plastic bags, in order to avoid water loss.

The average spectra for the upper surface of the leaf, Fig. 7, show high reflectance differences between stalk and other leaf tissues in the visible region. The highest magnitudes are exhibited on the leaf margin over the entire near infrared region. The calculated red edge slope is slightly greater for the leaf margin compared to those for the stalk and leaf centre. The water presence shown at 970 nm, indicates the lowest content in the leaf margin, and highest in the stalk, as might be anticipated. Table 3 shows some typical values of reflectance at some chosen wavelengths.

Reflectance differences between top and underside margins of the leaf, Fig.8, indicates little difference in chlorophyll level. The null reflectance difference might be attributable to the leaf thinness. The largest differences are to be found between the margin and centre of the top surface of the leaf. This is fundamentally different from observations in cabbage and broccoli, where highest differences seen were between top surface and underside of leaves.

The spectral comparison of the senescing yellowish leaf and healthy green leaf, Fig. 9, shows an apparent displacement of the red edge and a lowering of reflectance of the yellow leaf up to 1200 nm. An important characteristic of yellow leaf is the near disappearance of the far edge as a result of high water loss. Longer wavelengths, generally affected by water content, also shows very high values and a shifted curve pattern.

The variance of senescing, top suface, leaf spectra was analysed, Fig. 10, to examine where the samples differed most. In the margin samples it was noted that the reflectance had low variance, from 500 nm up to 1200 nm, but in the longer wavelength region the variance could be greater than 50. The centre of the leaf showed different behaviour, having a higher variance in the region up to 1300 nm while decreasing in the longer wavelengths. Variance of the whole top leaf, excluding the stalk, is highest in the far edge and at wavelengths greater than 1150 nm although there is a reduction in all cases at 1450 nm.

3.4 Weed leaf, oilseed rape leaf and soil spectra

The fields near Bush Estate which had not been sprayed with herbicide presented a large number and variety of weeds. After a simple evaluation, the five dominant weeds were selected and their spectra studied. The weeds were:

Redshank	(polygonum persicaria)
Chickweed	(stellaria media)
Mayweed	(matricaria inodora)
Grass	(poa annua)

The competition from the re-emergence of the previous years' crop of oilseed rape was especially interesting as oilseed rape is a member of the brassica family.

Leaf dimensions of these weeds are relatively small and it was thought unnecessary to carry out spectral measurements on different sections. Twenty measurements were obtained from each side of each weed leaf and oilseed rape leaf were made and some of the principal wavelengths are stated in Table 4 for comparative purposes. Redshank leaves had to be collected and sampled quickly, due to their delicacy. In order to avoid water loss, complete plants with all their roots were transported inside plastic bags. As the average redshank leaves were 5 cm long and 1.5 cm wide, several leaves were required for each measurement in order to cover the sampling port in the spectrophotometer. A characteristic of chickweed is that it has a large number of small leaves, the biggest being 7 mm long and 5 mm wide. Again, a quantity of leaves was required to fill the sampling port and a black background was inserted behind the leaves to avoid spurious reflections. Oilseed rape leaves were large, although thinner than cabbage and broccoli and only one leaf was required for each sample. Mayweed has leaves in the form of needles and many were required to cover the sample port in the spectrophotometer. Grass was collected and cut into pieces before performing reflectance measurements.

Spectra of each weed and of oilseed rape were averaged and Figs 11 and 12 show a comparison of the top leaf reflectances for each species. High reflectance differences were found between redshank and both chickweed and oilseed rape at wavelengths above 700 nm. Oilseed rape and chickweed have similar reflectances at short wavelengths and differ only above 1500 nm. The water content, observed at 1450 nm is slightly lower in redshank than in chickweed and oilseed rape. Maximum differences for mayweed occur in the ranges 800 to 1200 nm. and 1600 to 1800 nm. A slightly lower water content than mayweed and chickweed was apparent for the grass sample.

It is essential for remote sensing purposes to be able to distinguish vegetation from background soil. Soil spectra were analysed after drying, otherwise near zero reflectance values were obtained. Fig. 13 shows a comparison of chickweed, broccoli and soil. Soil and vegetation spectra are completely different, the soil having a generally low reflectance across the waveband and only at 600-700 mm is it slightly higher.

Fig. 14 indicates the variance found for each of the weeds including grasses. Chickweed shows the lowest variance but these results have to be compared with the variance found for the crop plants, Figs 6 and 10, which presented much higher values. Fig. 15 shows where the highest variances occur but this has again to be taken in comparison with the much higher variance in crop plants, Figs 6 and 10.

4. DISCUSSION

The high values of variance in nearly all brassica spectra indicate the presence of leaves at different stages of growth, possibly with different nutrient levels, different states of health and water content.

This study permitted familiarisation with the spectral interpretation of leaves, the following points being of main importance.

a. The chlorophyll content, directly related to the spectral reflectance at 650 nm, tends to be slightly higher in the top surface of the leaf as this side is directed towards the sun. The reflectance at this wavelength is affected by leaf senescence.

b. The water content of the leaf can be measured at two wavelengths, 970 nm and 1450 nm. All the brassicas showed troughs in both these absorption bands. Most weeds, however, did not have pronounced water absorption bands at 970 nm. Measurements on brassicas and leafy weeds indicate a generally higher water content in the top surface of leaves, possibly related to the process of evapotranspiration.

c. As the red edge is characteristic of all leaves, it varies little with the leaf measurement location but changes with the growth stage of the leaf. Senescing yellow leaves presented an apparent red edge displacement in comparison with healthy ones. In addition, brassica leaves presented red edge displacements between stalk and blade tissues.

d. The peak reflectance in the wavelengths up to 1300 nm in all brassicas and weeds is always higher than the peak reflectance in the longer wavelengths. Comparisons between all the leaves are shown in Tables 1 to 4.

e. The absorption band at 1450 nm indicates water presence, but its magnitude in many samples was effectively zero and its use for moisture measurement might be problematic in turgid samples. In order to overcome this problem in brassicas, the water absorption band at 970 nm or some function of it might be used, but the investigation of moisture measurement was not a primary part of this study.

f. Soil and leaf spectra presented different patterns and magnitudes across the spectral band. Without making an optimum and intensive study, the ratio between 820 nm and 650 nm discriminated soil from all the leaves studied.

Spectral differences in the top margin of the three brassica crops, Fig. 16, show that cabbage leaves present the lowest reflectance near 1200 nm and at wavelengths above 1500 nm. Cauliflower leaves showed the lowest water content of the three crops. Cauliflower leaves showed susceptibility to dessication and had to be handled with care to avoid water loss during sampling. When comparing the appearance of brassica leaves, it was noted that cabbage was the thickest, followed by broccoli and then cauliflower. Cabbage leaves could be left in the laboratory for up to three days without showing marked differences in their spectra.

The spectral differences in the top surface between the margin and centre of each of the crop leaves, Fig. 17, are highest for cauliflower across the waveband, but the differences found between top and underside of the leaves were minimum for this crop, Fig. 18. The spectral differences in cabbage and broccoli between the top and underside margin of the leaves are also shown.

5. CONCLUSIONS

The differences between the spectral reflectances for cabbage stalk and other parts of cabbage leaf are substantial. There is little difference between the spectra for the leaf margin and leaf centre; this is also true for broccoli. Differences between the spectra for the upper and lower leaf surfaces of cabbage occur at 550 nm and 1600 nm. For broccoli, differences between the spectra occur at 550 nm, 700 nm and in the band 1350 to 1800 nm.

There are substantial differences between cauliflower stalk, leaf margin and leaf centre spectra, whereas there is less difference between the spectra for the upper and lower leaf surfaces.

There is little difference between the spectral reflectances for chickweed and oilseed rape, except in the band 1600 to 1800 nm. The redshank spectra, however, is substantially different. Mayweed and grass spectra are slightly different from each other and are both different from chickweed.

This comparison of the specral reflectances of various crop and weed leaves has confirmed the feasibility of developing a procedure to discriminate between different plants using specific wavelength data.

6. ACKNOWLEDGEMENTS

This work was funded by The Scottish Office Agriculture and Food Department. F. Hahn is a research student funded by the Mexican Government and we wish to acknowledge their support.

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Table 1 **Typical average reflectance values taken from different sections of cabbage leaves.**

Leaf section	Wavelength, nm				
	650	**820**	**1100**	**1200**	**1700**
Top margin	1.26	67.40	69.14	45.63	5.38
Underside margin	6.71	65.38	67.40	47.30	13.39
Top centre	1.76	67.10	65.90	36.80	1.81
Underside centre	6.50	64.80	64.50	41.10	8.90
Stalk	14.1	68.80	47.00	12.10	1.10

Table 2 **Typical average reflectance values taken from different sections of broccoli leaves.**

Leaf section	Wavelength, nm				
	650	**820**	**1100**	**1200**	**1700**
Top margin	0.00	67.30	71.10	54.95	16.29
Underside margin	3.14	66.18	70.30	57.25	21.90
Top centre	0.63	67.30	71.24	52.80	12.80
Underside centre	3.33	65.67	70.36	53.76	18.02
Stalk	11.81	70.25	53.73	23.20	2.11

Table 3 Typical average reflectance values taken from different sections of cauliflower leaves.

Leaf section	Wavelength, nm				
	650	820	1100	1200	1700
Top margin	0.08	64.86	70.57	59.50	22.70
Underside margin	2.88	64.09	70.38	58.87	24.60
Top centre	3.37	63.04	63.67	43.46	8.28
Underside centre	6.16	65.20	67.52	48.30	13.50
Stalk	35.12	71.75	53.30	24.90	2.66

Table 4 Typical weed and oilseed rape reflectances from both leaf surfaces.

Leaf shank	Wavelength, nm				
	650	820	1100	1200	1700
Redshank top	0.20	63.20	69.55	62.01	32.02
Redshank underside	5.00	64.20	69.75	62.13	34.80
Chickweed top	0.03	47.50	41.33	36.55	17.80
Chickweed underside	0.58	43.05	36.27	31.90	15.40
Oilseed top	0.02	45.82	38.22	31.75	9.43
Oilseed underside	2.76	45.05	38.43	33.56	15.65
Mayweed	0.02	34.75	35.75	31.09	13.55
Grass	0.10	37.11	30.45	29.58	18.48

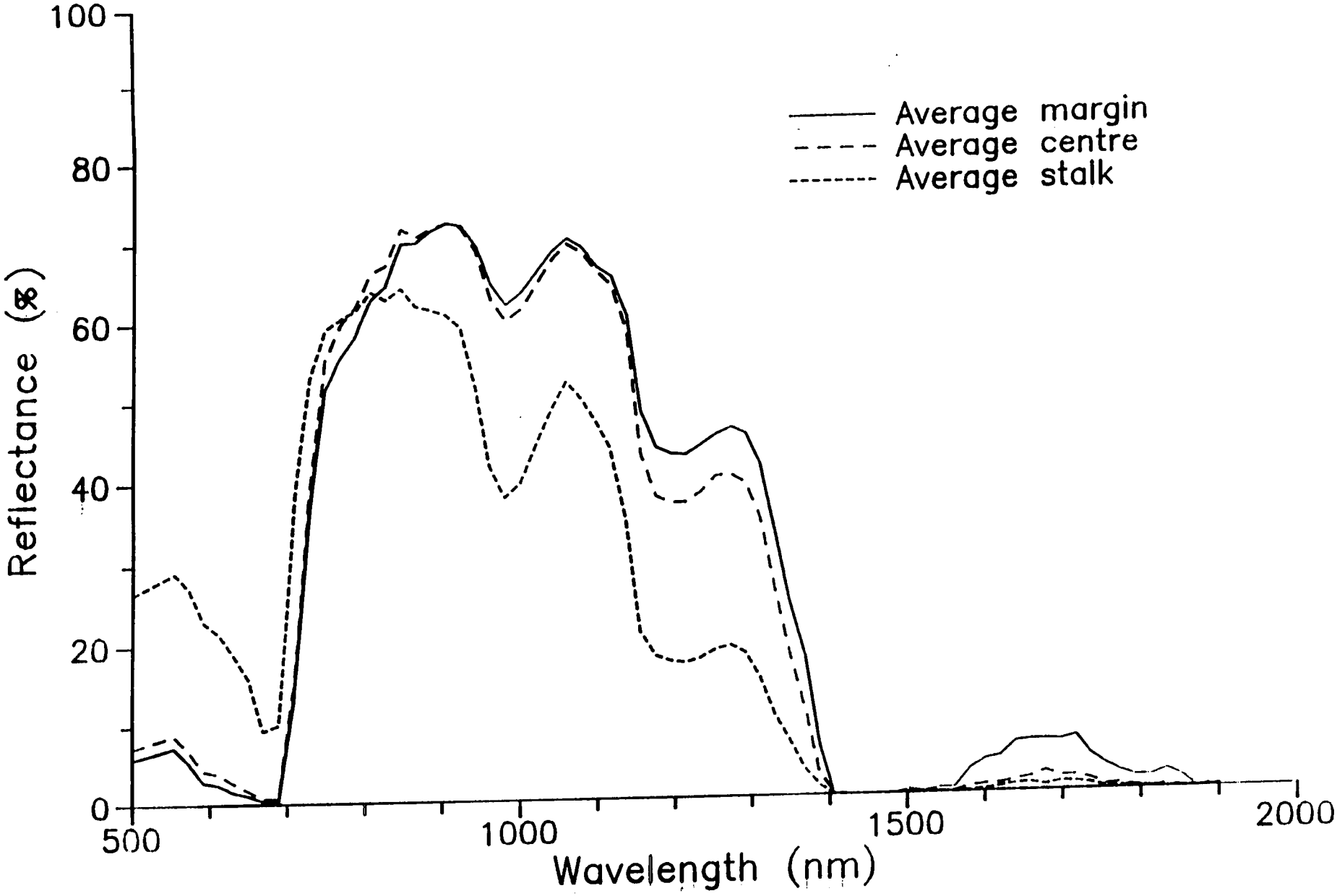

Fig. 1 Typical average reflectance spectra for the upper surfaces of cabbage leaves.

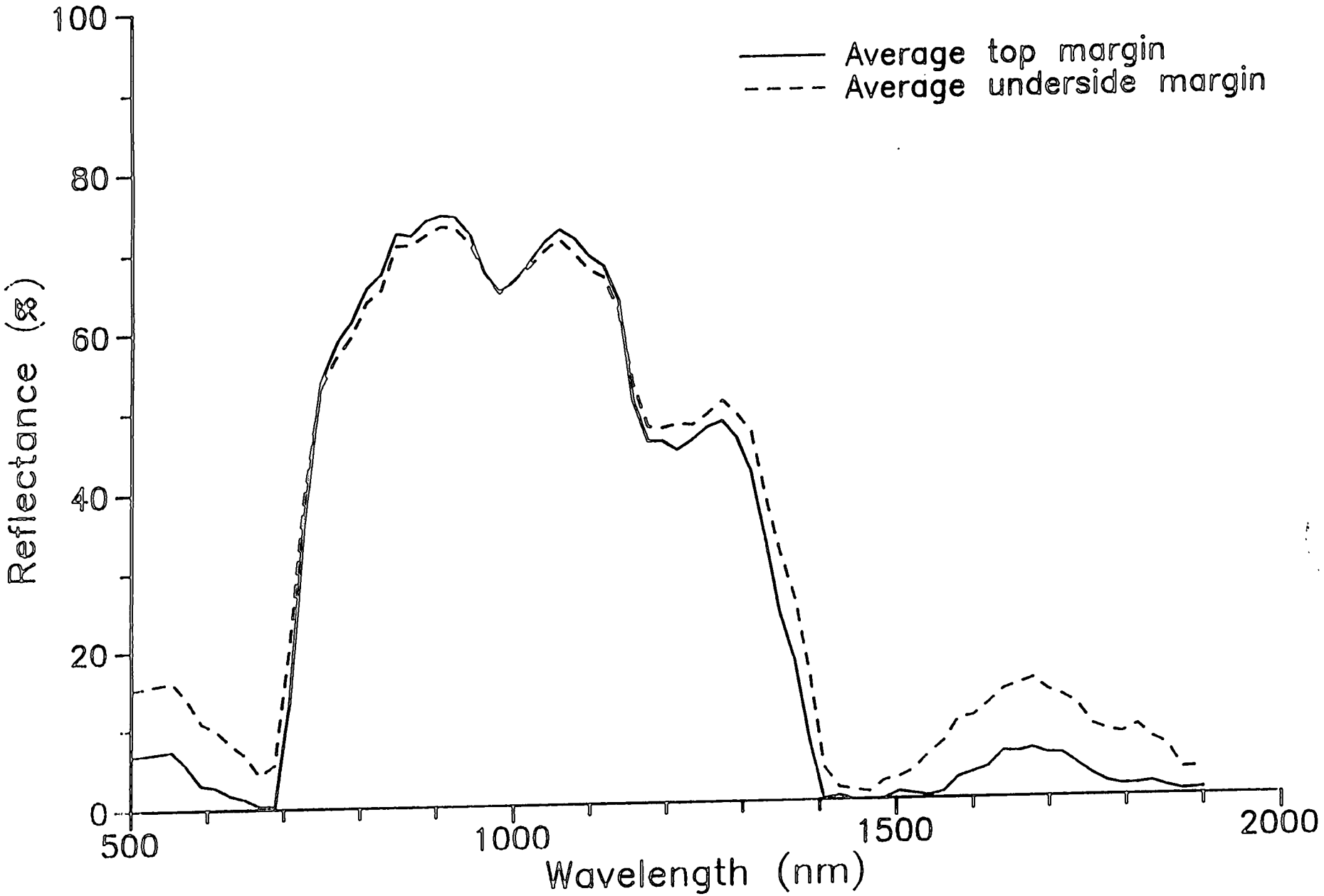

Fig. 2 Typical reflectance spectra for the upper and lower surface margins of cabbage leaves.

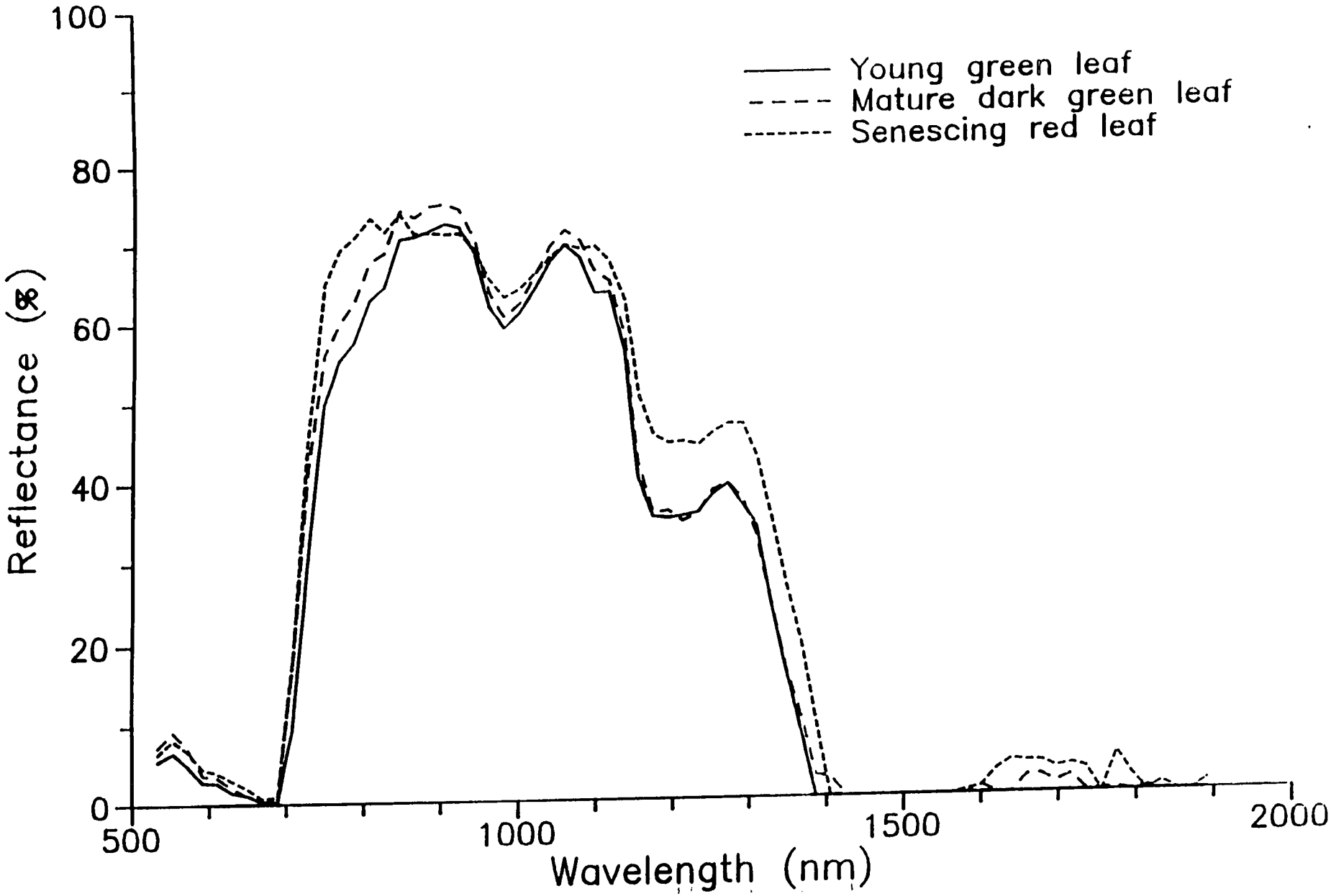

Fig. 3 Comparisons of spectra for cabbage leaves at different stages of growth.

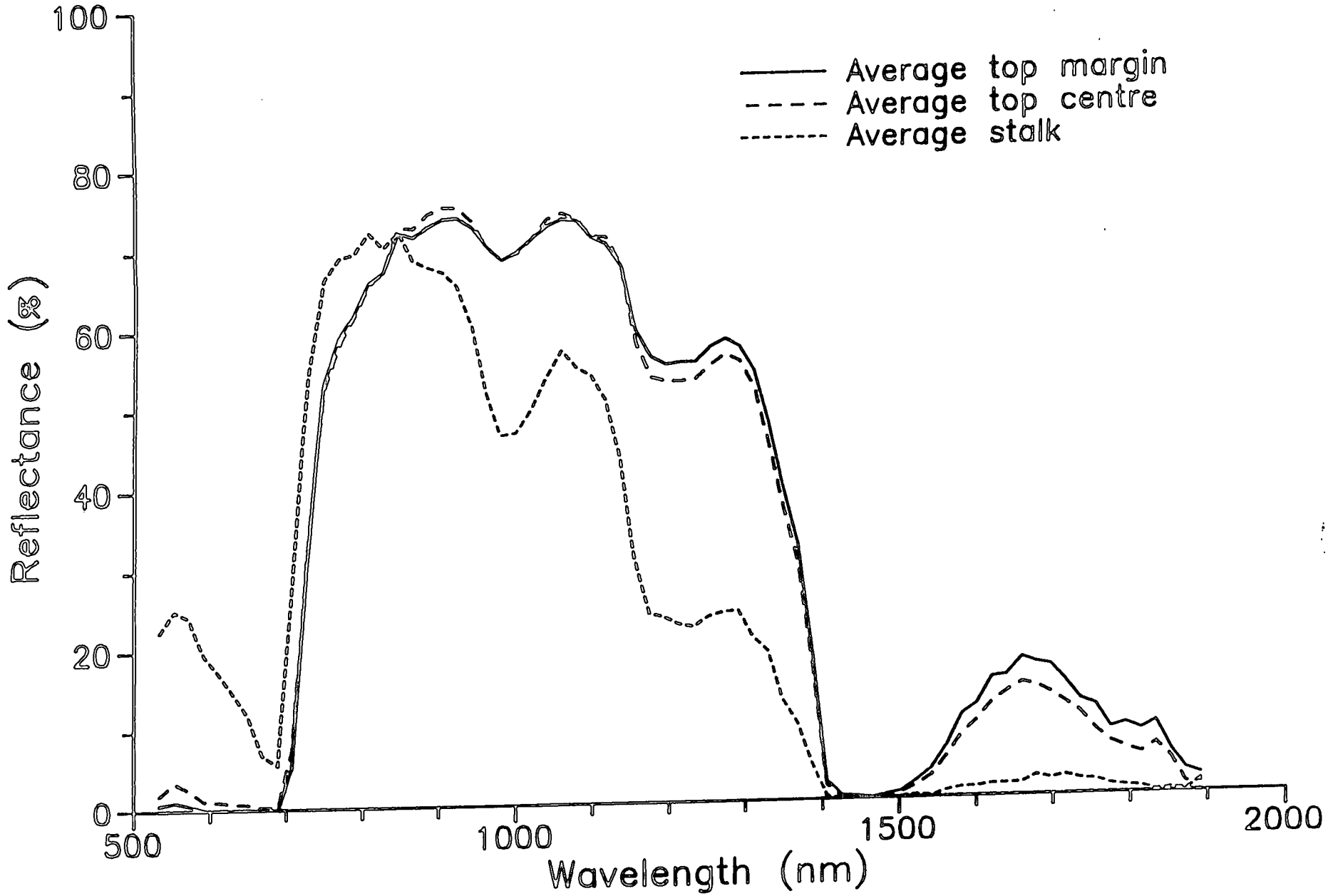

Fig. 4 Typical reflectance spectra for the upper surfaces of broccoli leaves.

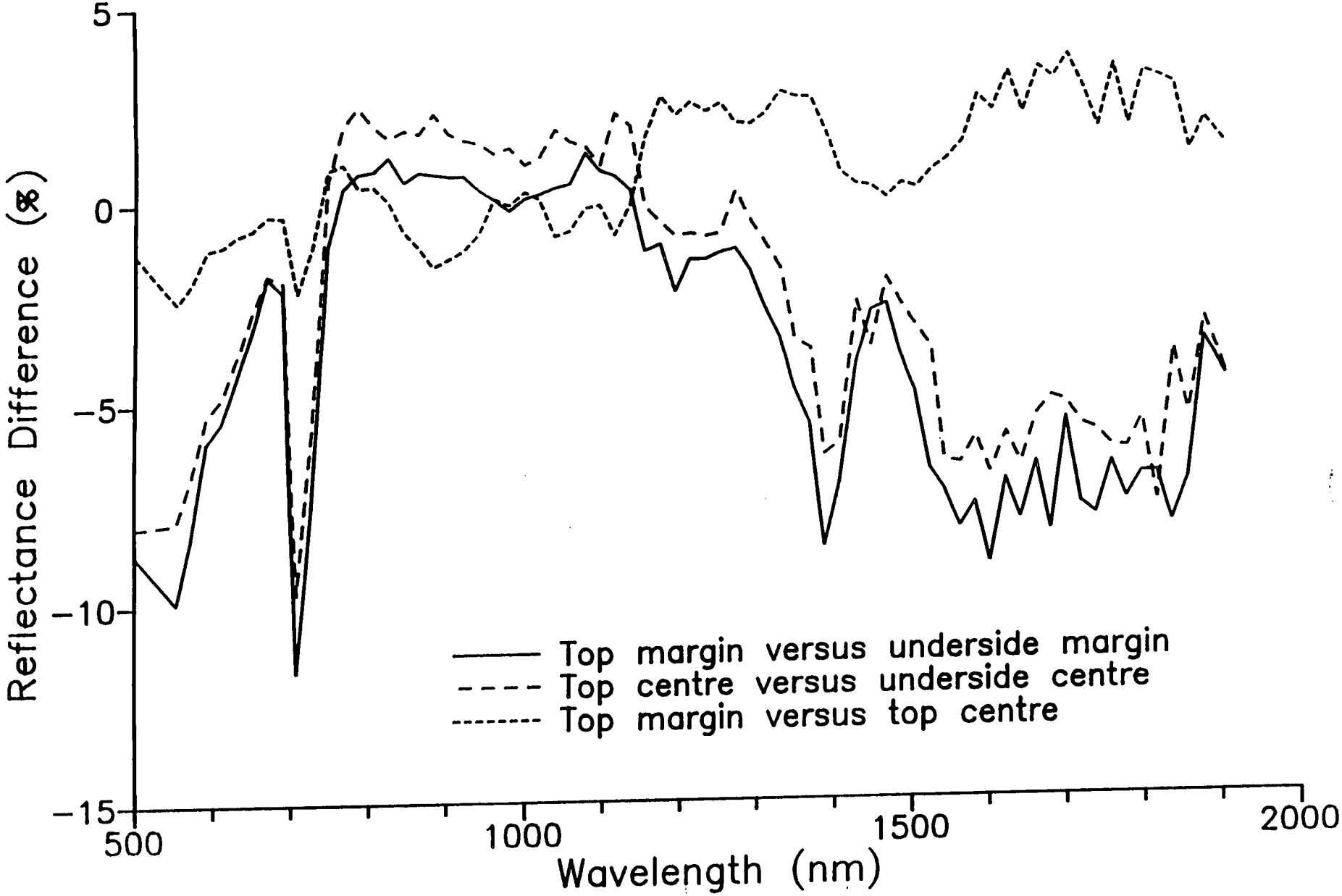

Fig. 5 Difference in spectral reflectances between the upper and lower surfaces of broccoli leaves.

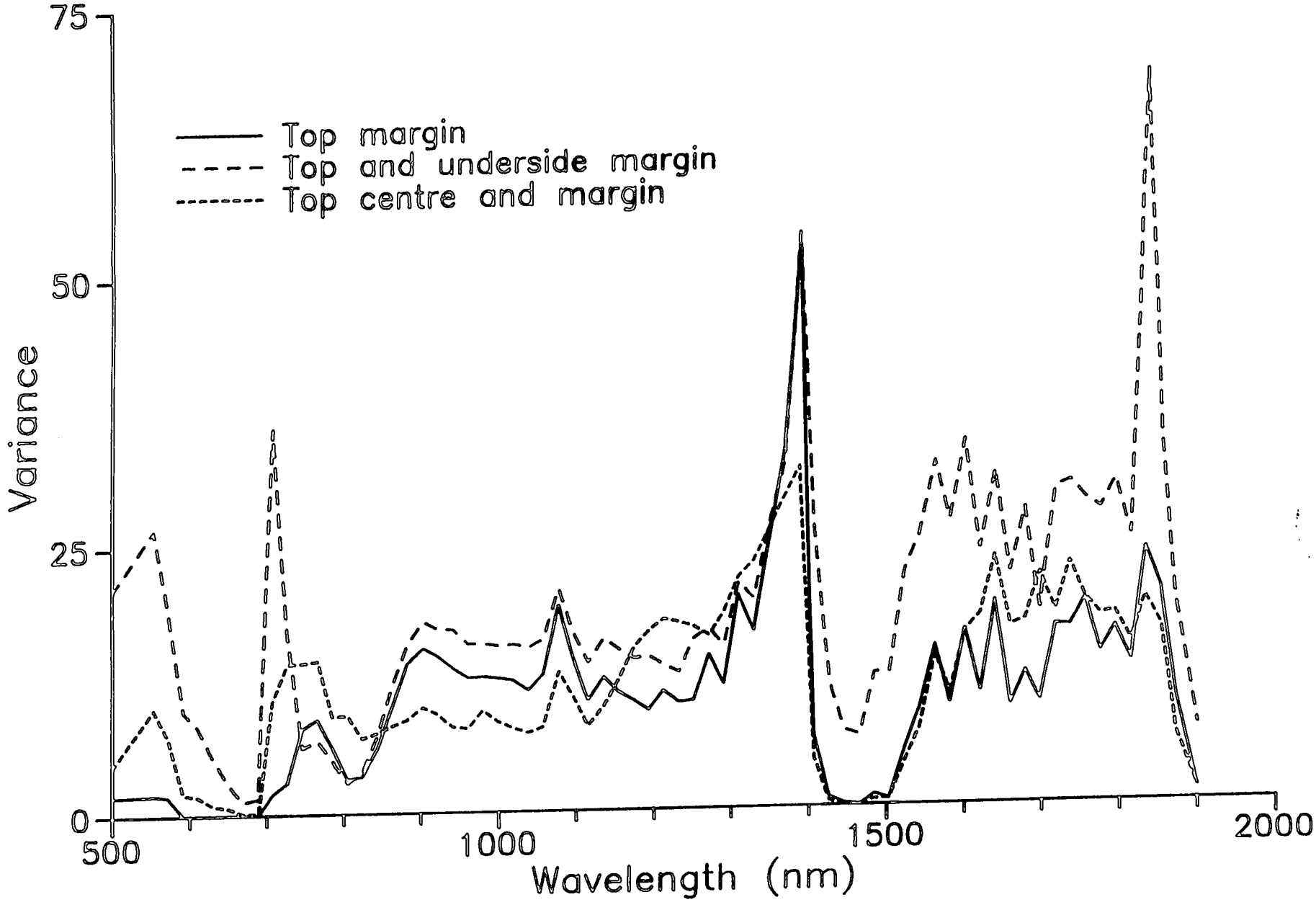

Fig. 6 Variance of measurements on broccoli.

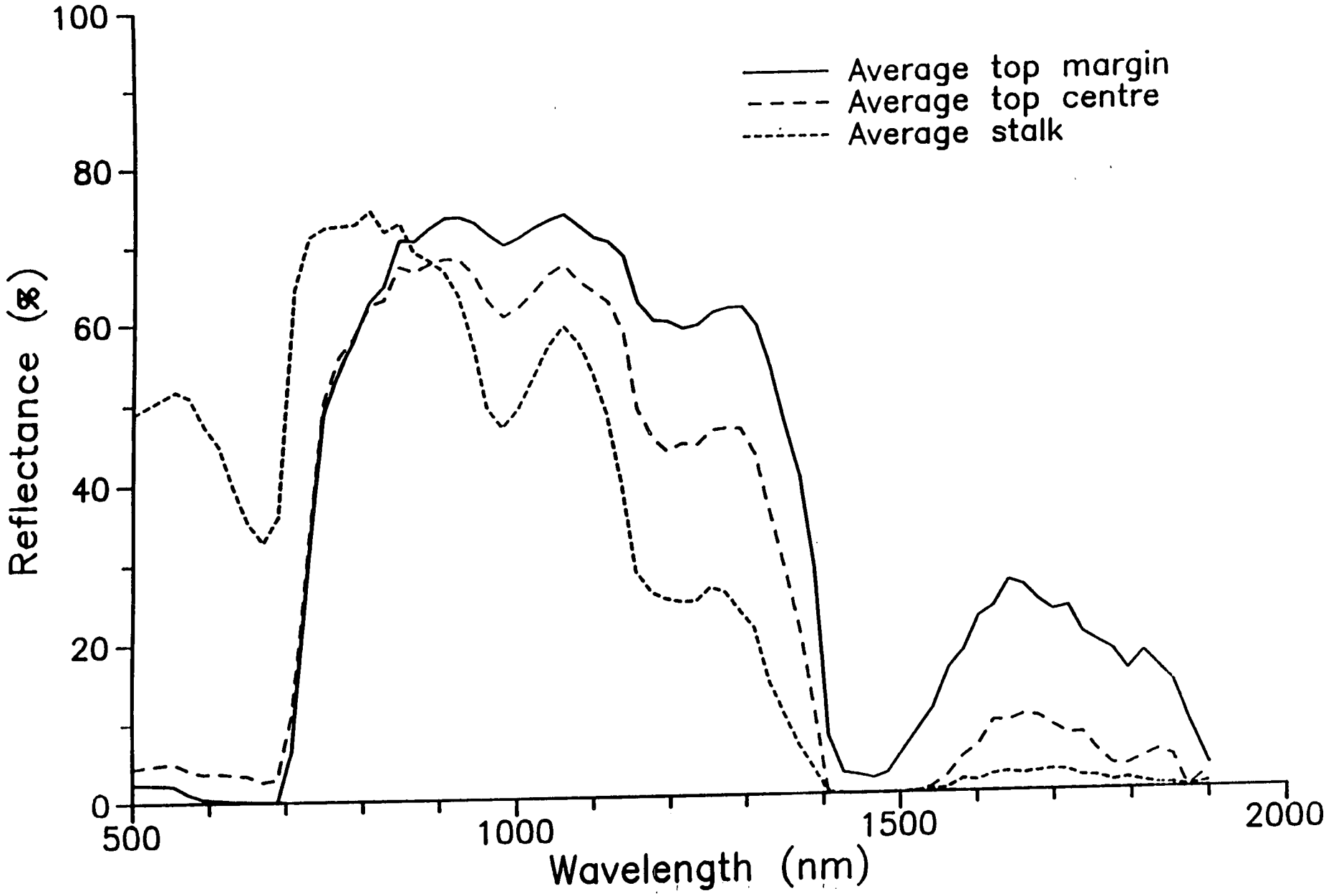

Fig. 7 Average reflectance spectra for the upper surfaces of cauliflower leaves.

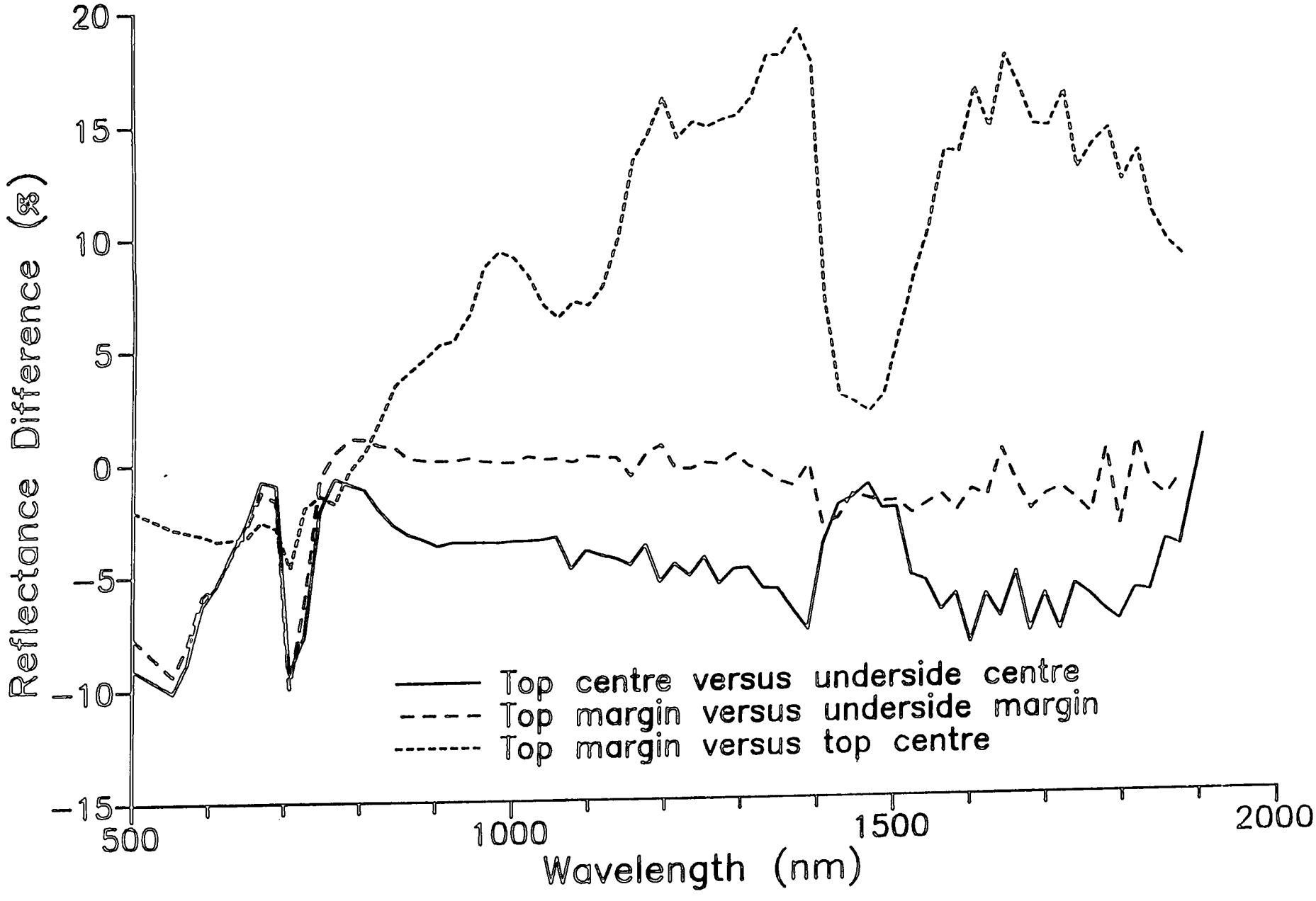

Fig. 8 Differences in spectral reflectances between various areas of cauliflower leaves.

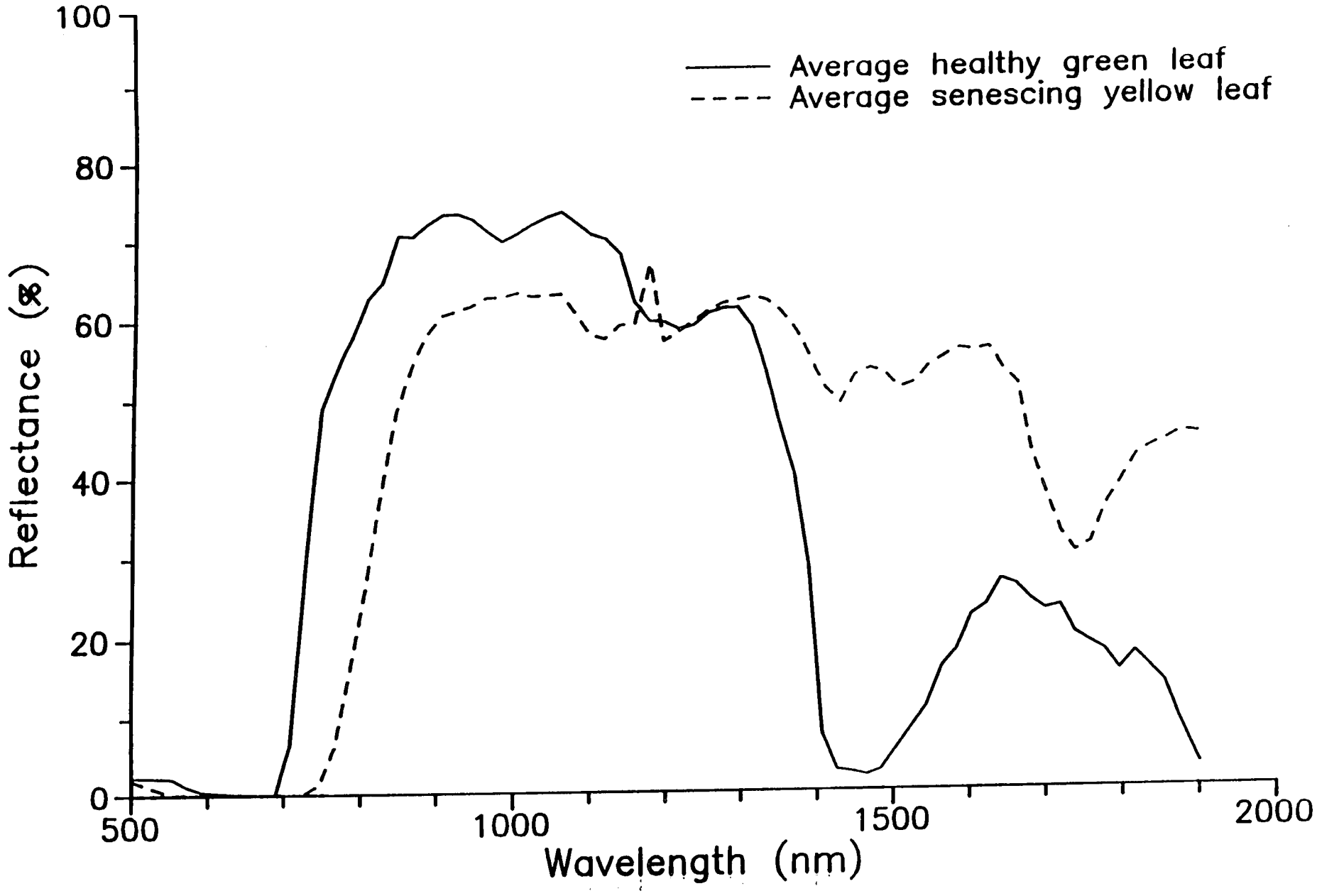

Fig. 9 Spectra for mature and senescing cauliflower leaves.

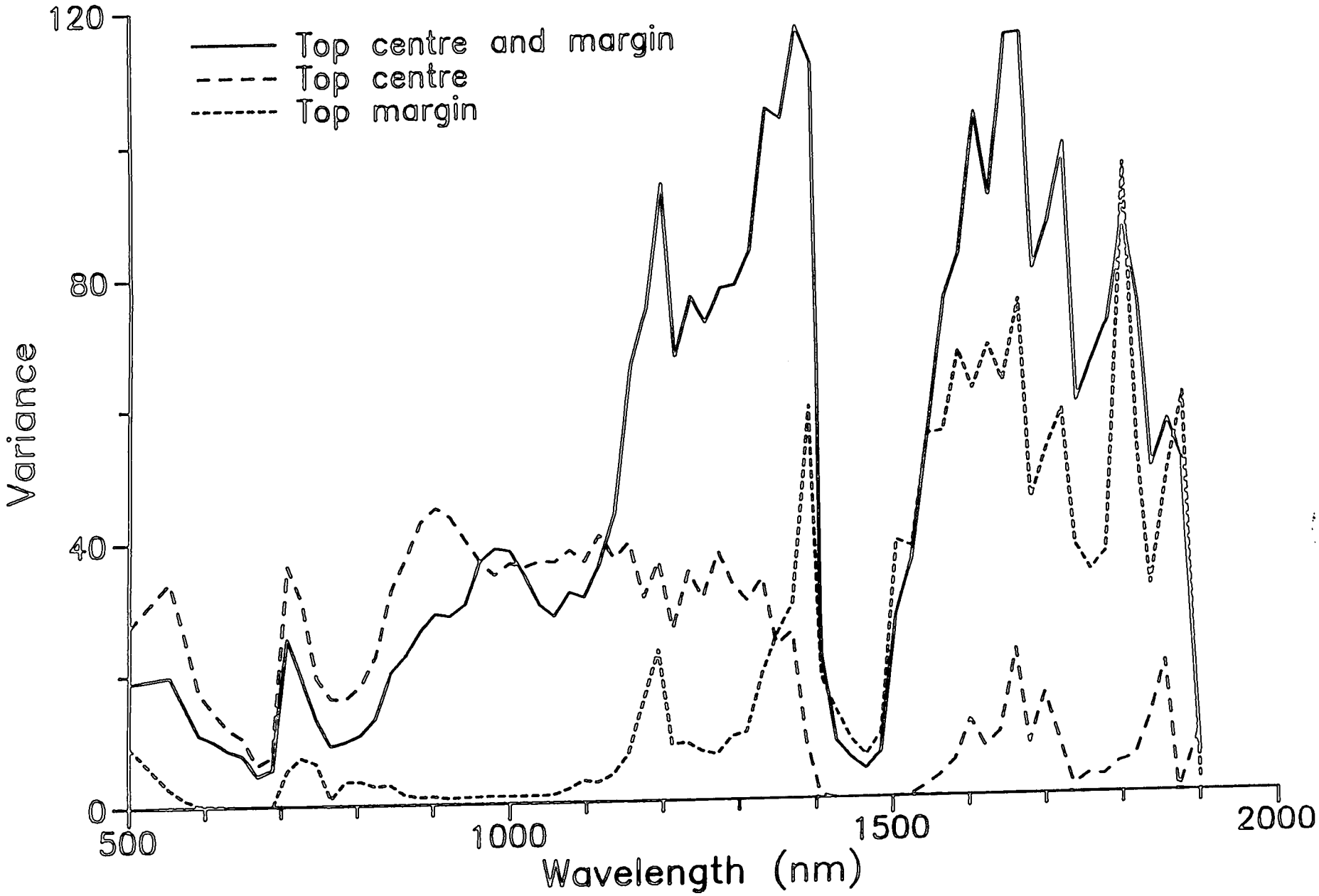

Fig. 10 Variance of measurements on cauliflower.

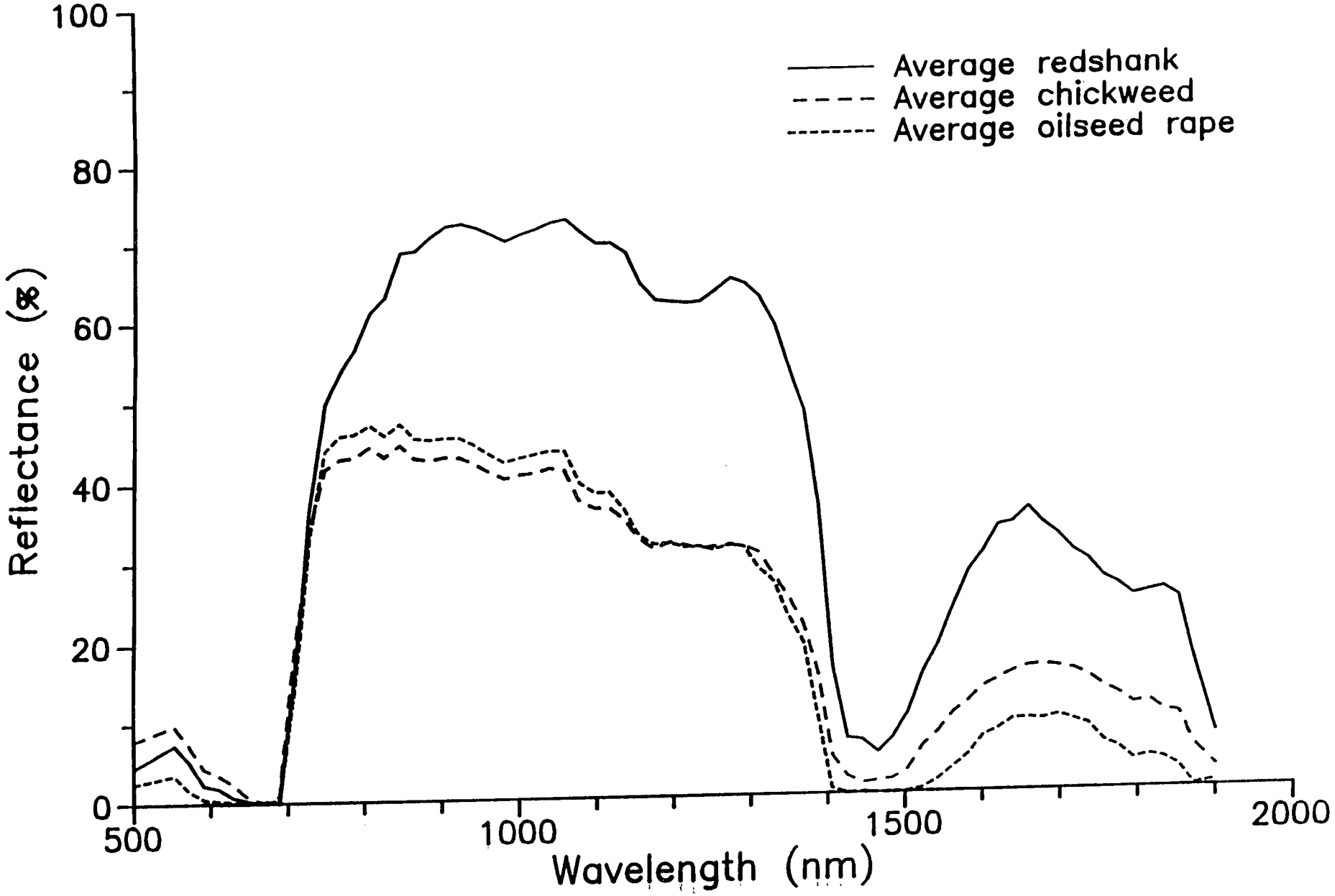

Fig. 11 Average spectra for redshank, chickweed and oilseed rape.

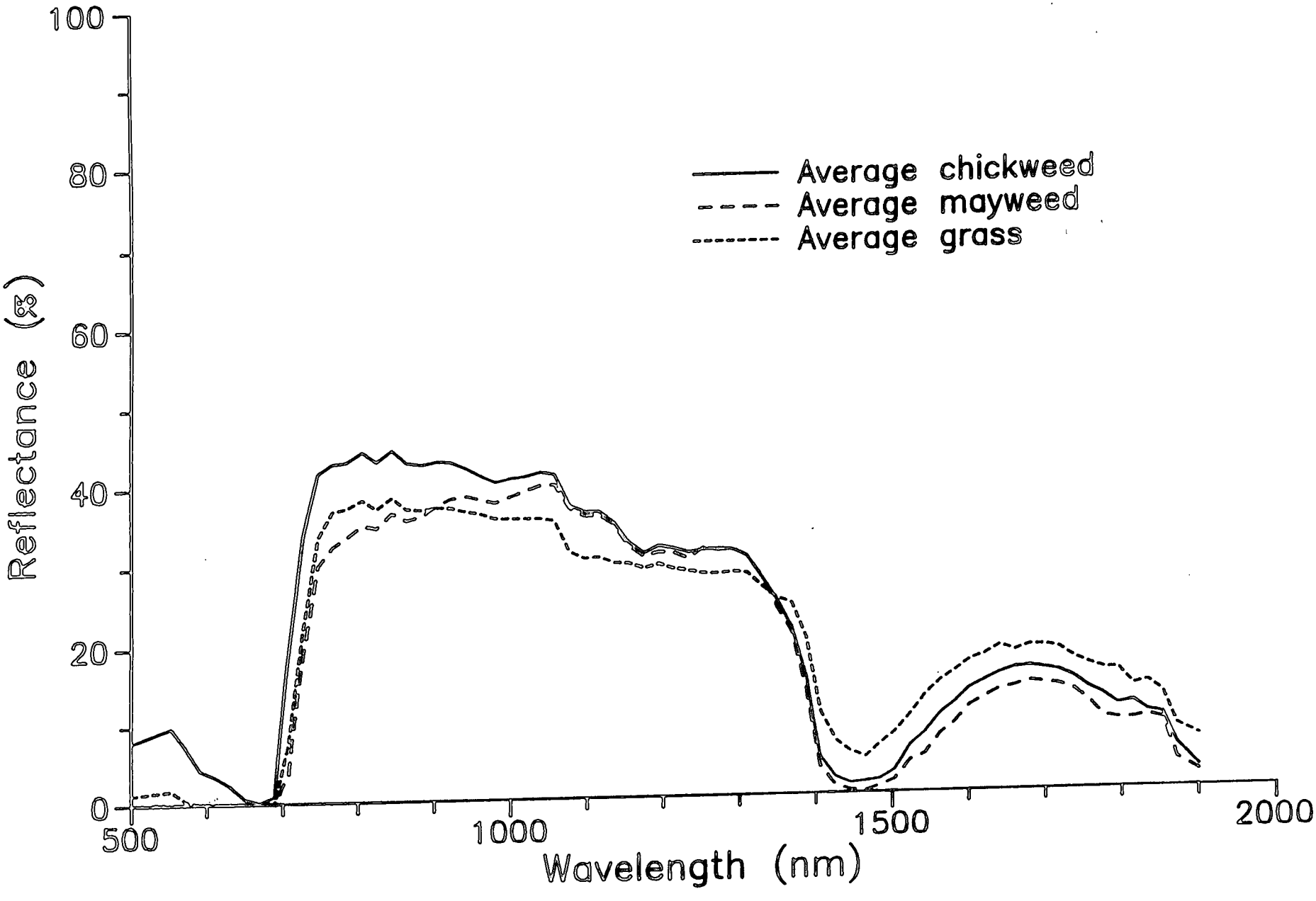

Fig 12 Average spectra of chickweed, mayweed and grass.

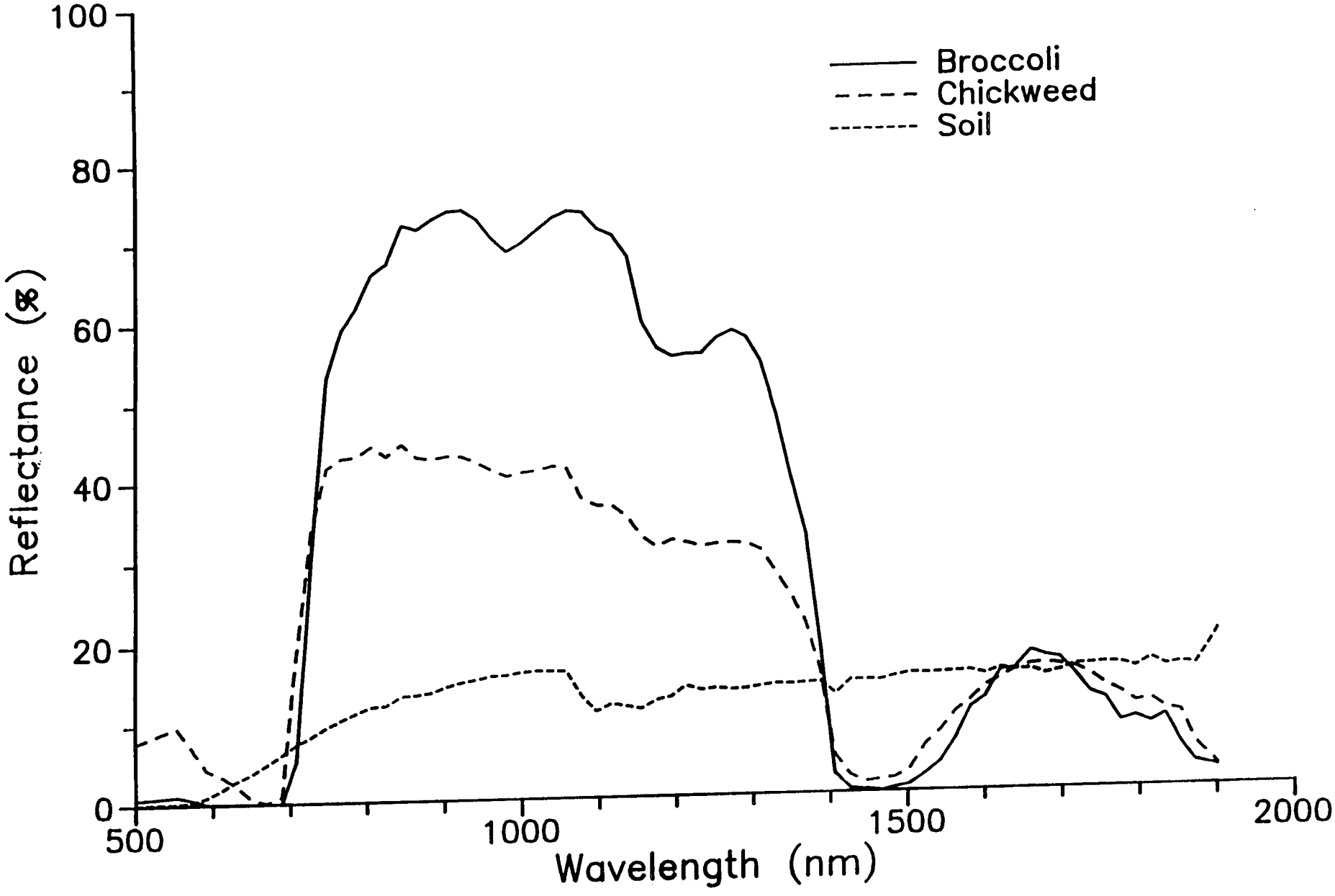

Fig. 13 Spectral comparison with soil.

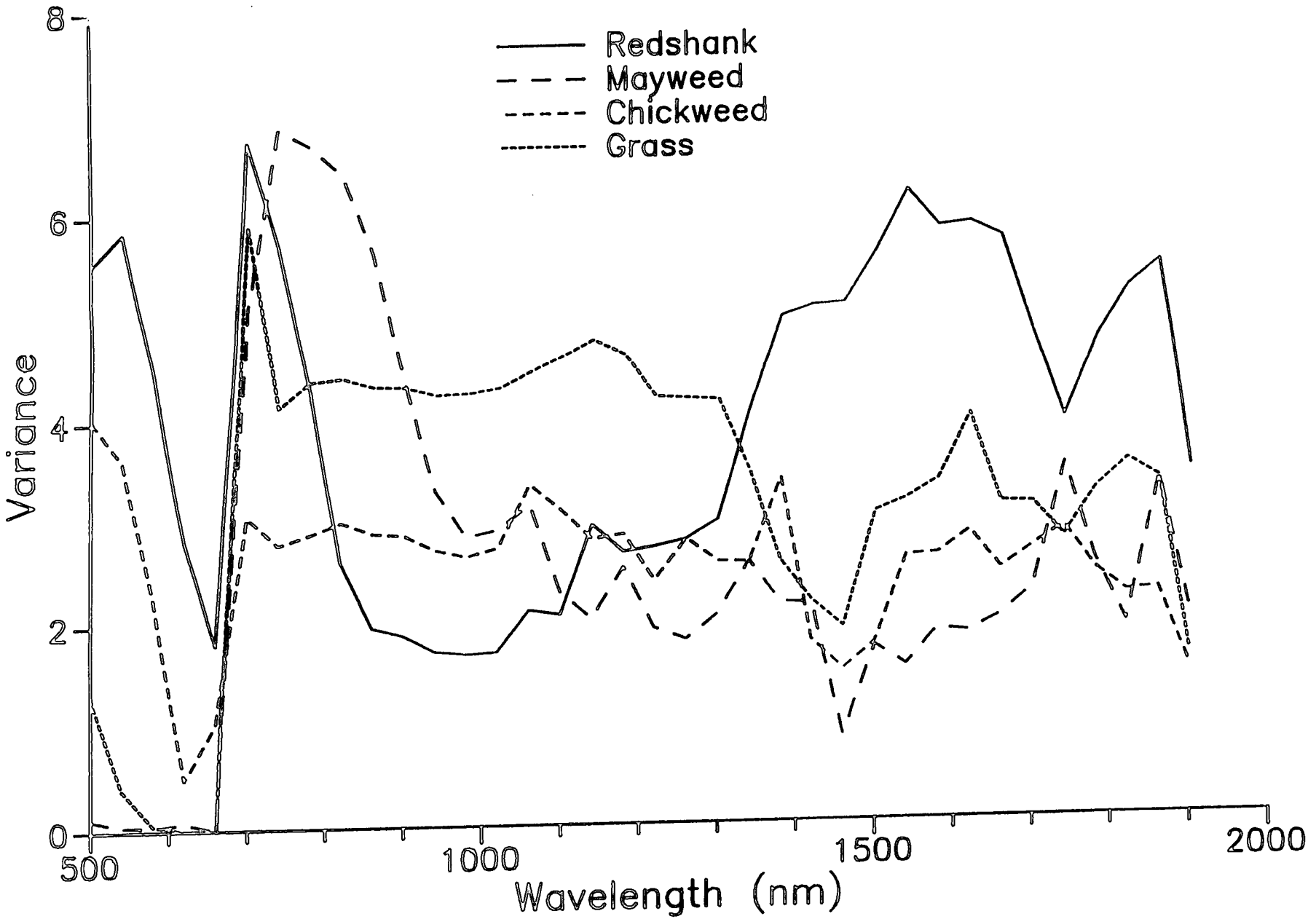

Fig. 14 Variance of weeds.

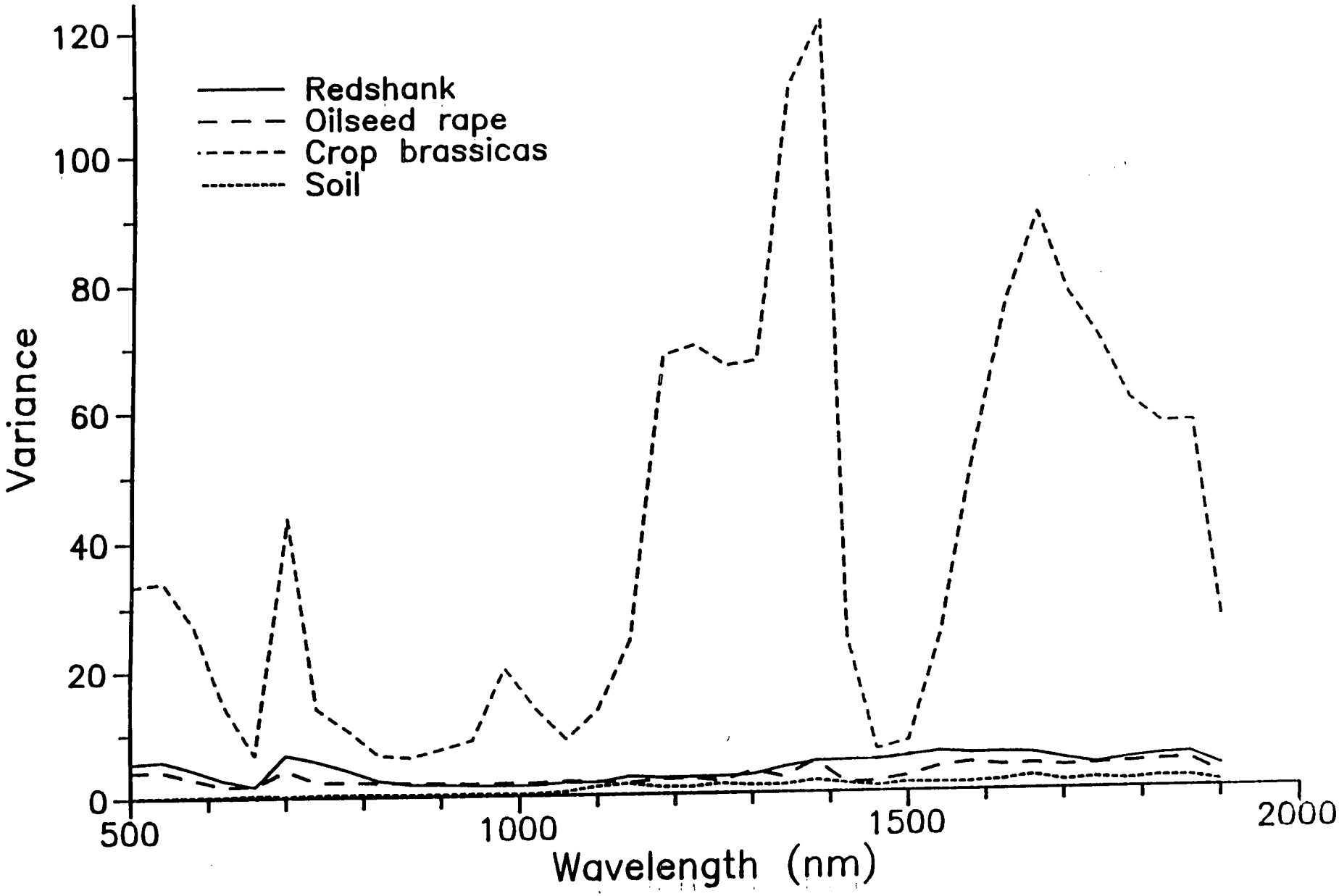

Fig. 15 Typical variance of spectra for crop brassicas, oilseed rape, redshank and soil.

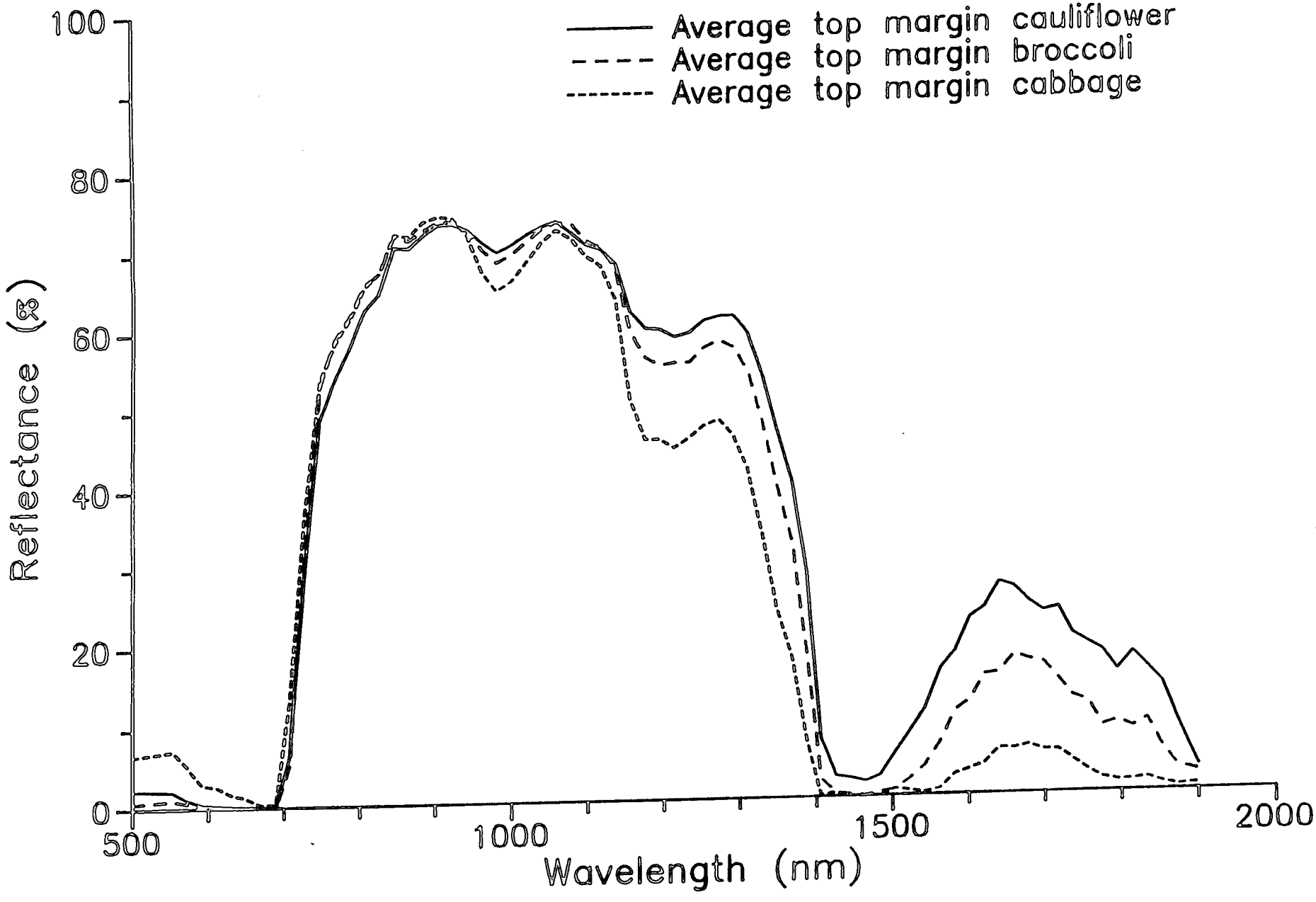

Fig. 16 **Comparison of spectra for brassicas.**

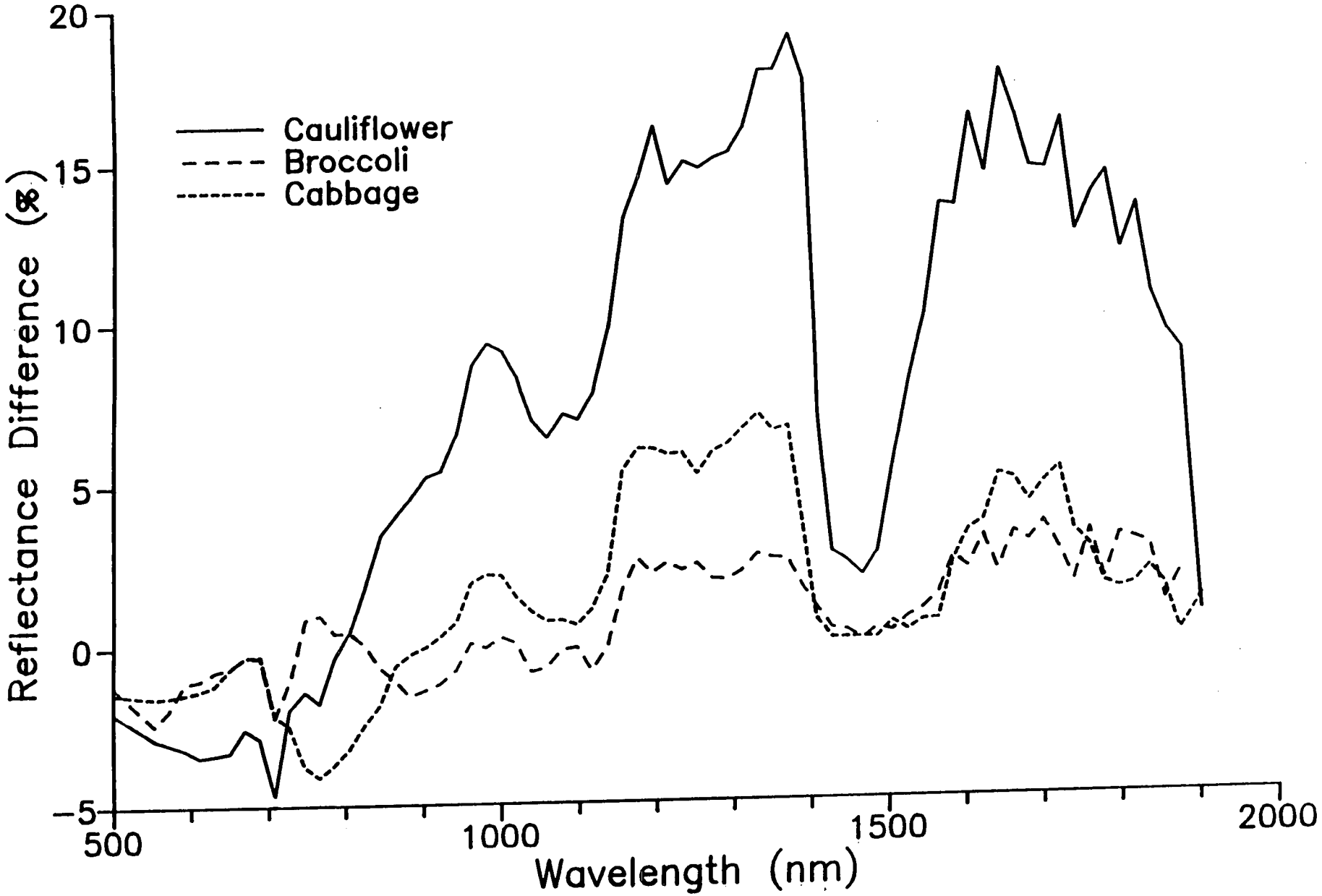

Fig. 17 Differences in spectral reflectances between the margin and centre of the upper surface of the leaves for three brassicas.

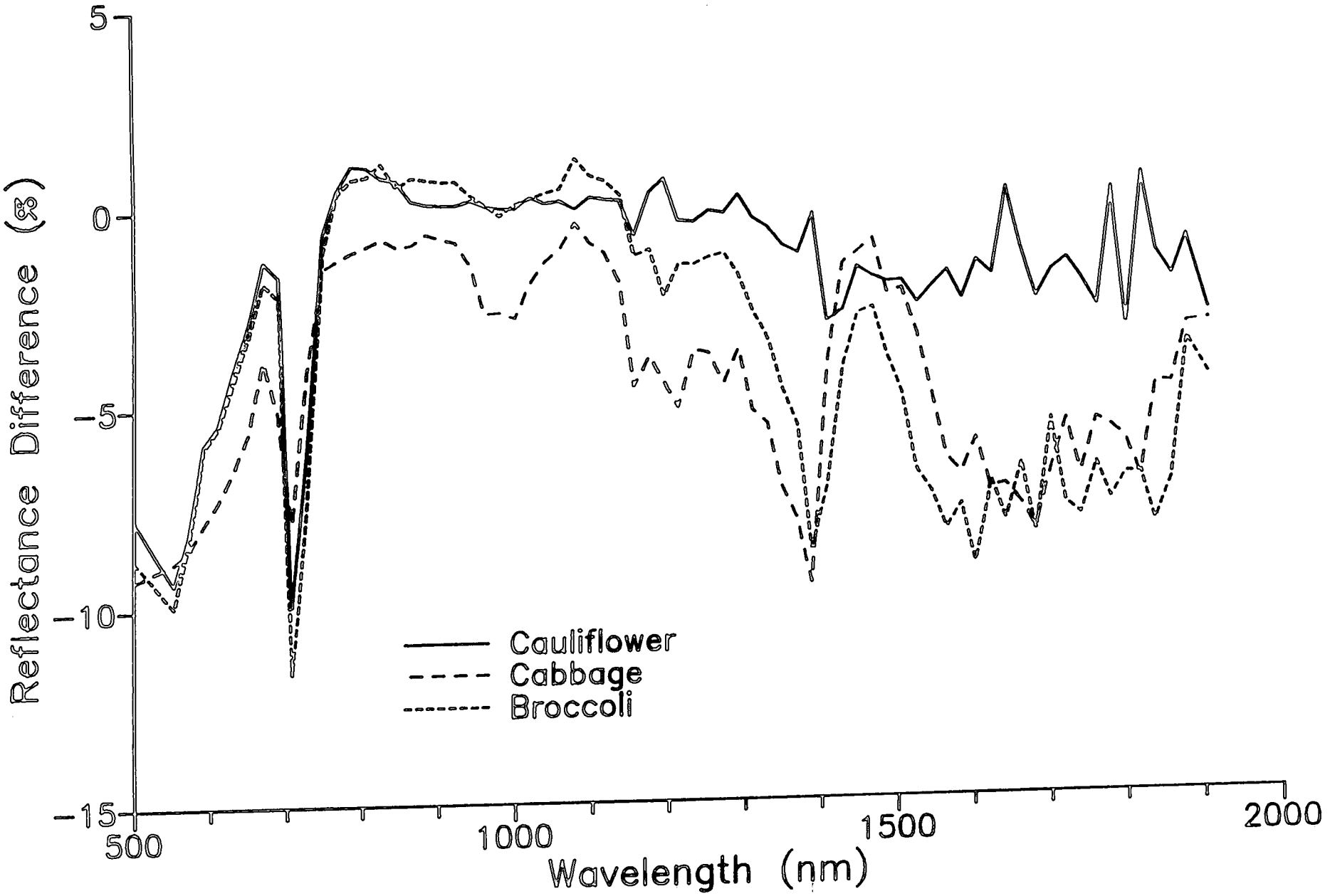

Fig. 18 Differences in spectral reflectances between the upper and lower surface margins for three brassicas.

SCOTTISH CENTRE OF AGRICULTURAL ENGINEERING

DEPARTMENTAL NOTE 59

June 1993

DISCRIMINANT ANALYSIS OF BRASSICAS AND WEEDS

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ISSN 0953 413X

ISBN 1 85482 372 8

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SUMMARY

Spectral data was collected from cauliflower, broccoli, cabbage and weeds. The spectra were analysed using the BMDP discriminant analysis technique to determine the discrimination for crop and weeds. Success in recognising individual weed groups was also tested. The data were analysed using direct reflectances, derivative algorithms and reflectance ratios. High success rates were encountered for the three brassicas using as few as two wavelengths.

CONTENTS

		Page
1.	INTRODUCTION	1
2.	EXPERIMENTAL METHOD	1
3.	DISCRIMINANT ANALYSIS	2
	3.1 Discriminant analysis using direct data manipulation	2
	3.2 Discriminant analysis using first derivative algorithm	3
	3.3 Discriminant analysis using ratios	4
4.	CONCLUSIONS	5
5.	ACKNOWLEDGEMENTS	5
	REFERENCES	5

two groups may be considered by putting all the brassicas in one group and all the weeds in another, or it can be arranged so that each weed and crop plant type is a group on its own. This latter approach might be more useful in order to identify those weeds which are difficult to discriminate from crops.

A statistical analysis program of the BMDP suite of software was used to analyse the data.

3. DISCRIMINANT ANALYSIS

In discriminant analysis, the cases (spectra) are divided into groups (i.e. crop, weed) and the analysis is used to find classification functions that seek to maximize differences between the groups. These classification functions are linear combinations of the variables. In this case the variables are wavelengths or functions of wavelengths. At each step the F statistic is computed for each variable to determine which should be added to the function. At each step after a variable is entered, the classification functions are then recomputed, being repeated until group separation stops improving.

Table 1 shows the number of spectra in each of the crop/crop stalk/weed/soil categories. The trial group is a sub group of these spectral cases on which the derived classification functions can be tested. There were 72 cases in this group whereas there were 171 cases in the analysis from which the classification functions were derived. It is worth noting that the brassica spectra consisted of cases of top and underside leaf spectra in equal numbers. This was the same for weeds.

All groups were presented individually within the discriminant program. The individual groups could then be regrouped according to the philosophy of either a simple 2 group system or several group systems.

Data was grouped using one crop in four general categories, i.e. crop, crop stalk, weeds and soil. Another more detailed analysis classified into specific categories weeds by species, in addition to the crop, crop stalk and soil. Crop stalk was designated an individual category being spectrally very different from crop leaf tissue.A total of 8 specific categories were formed and a trial group consisting of 30% of the spectra used to validate the analysis.

The success of a particular program run defining wavelengths was determined in two ways:

(i) success in classifying a case from the trial group into its correct *general category* of crop/crop stalk/weed/soil. i.e. redshank in weed and soil in soil.

(ii) success in classifying a case from the trial group into its correct *specific category* defined by crop tissue, crop stalk, weed species, and soil.

Two hundred analyses were carried out to evaluate the success in recognizing brassicas from weeds and soil.

3.1 Discriminant analysis with data manipulation

Each crop was analysed individually to study its performance.

The analysis of broccoli, Table 2, indicated that the highest success rates for total and individual classification were obtained in program run 11 using 18 wavelengths. As this large number of wavelengths would never be used in an instrument for crop/weed detection, they are not stated in the tables. By using these 18 wavelengths, redshank and grass could be easily discriminated. Chickweed, however was more problematic and was mistaken for mayweed and oilseed rape, and in its own group was misclassified as oilseed rape. As the number of wavelengths was reduced 100% success rates were still obtained, especially when all the weeds were grouped together. Reducing the number of wavelengths to five gave a success rate of 95.23%. Further reduction in discrimination resulted when wavelengths of less than 1100 nm were used. The effect of 1640 nm is demonstrated by the high success rates in program runs 154, 164 and 165 using 4, 3 and 2 wavelengths, respectively. It is worth mentioning that 100% discrimination was obtained with only two wavelengths, but individual weed

DISCRIMINANT ANALYSIS OF BRASSICAS AND WEEDS

1. INTRODUCTION

Previous reports presented the case for the use of optical spectral reflectance for crop/weed discrimination (Hahn and Muir, 1992; Hahn and Muir, 1993). From that work, a more rigourous scrutiny of the data presented was suggested. This paper presents the results of statistical discriminant analysis on the spectral data gathered on cabbage, cauliflower and broccoli.

Brassica crops were selected, (Hahn and Muir, 1993) and measurements made in the months of August and September. The crops were in a mature state with weed patches between the crop rows. Four dominant weeds were identified for the study and oil seed rape included as it appeared as volunteer plants from the previous crop :

redshank (polygonum persicaria)
chickweed (stellaria media)
mayweed (matricaria inodora)
grass (poa annua)
oilseed rape

Samples were taken from different parts of the field and in different states of maturity, creating the worst possible case of discrimination that might be encountered in real conditions.

2. EXPERIMENTAL METHOD

The samples were analysed using a computer controlled spectrophotometer. This instrument incorporates an integrating sphere to measure diffuse reflectance and can be programmed to scan wavelengths from 500 up to 2000 nm with a resolution of 5nm. For these experiments, measurements were made from 500 to 1900 nm, with a resolution of 20 nm.

Fifty leaves of each of the three brassica crops were sampled. As the leaves in their mature condition may present different spectral characteristics from different sections, measurements were made in the margins, in the centre and in the stalk. The margin of the leaf was composed exclusively of leaf blade, while the centre portion samples consisted of vein and leaf blade. Leaves with colours ranging from green to red and yellow, and affected by different pests and diseases were also sampled.

There were 243 spectra in all, each spectrum consisting of 71 data points. These data were stored in four spreadsheet files.

By grouping all the weeds and brassicas individually, it was possible to form different grouping strategies. The brassicas were also classified into subgroups based on the part of the leaf and on the side of the leaf from which the spectra were derived.

The data presented to the software package had to be processed in order to present the information in the proper format. In order to code spectra, several programmes in 'C' were developed.

For the discriminant analysis of the spectral groups, the following data presentations were employed:

- direct data manipulation.
- first derivative algorithm applied to direct data.
- diverse ratios from direct wavelengths.

Data can be manipulated to form different group sets, giving a different result for each analysis, so it is important to define the desired objective of the work before creating the groups. For example, only

classification decreased from 85.71% to 76.19%. Redshank was the only weed to be fully classified in its own group. Mayweed was not identified at all and was mistaken for chickweed and grass. Oilseed rape was taken as chickweed in half the cases.

The best discrimination for cabbage, Table 3, was obtained using 14 wavelengths. All the weeds were successfully classified in their individual groups with these wavelengths, except for oilseed rape where grass was misclassified. Wavelength reduction decreased interweed discrimination. The best discrimination between cabbage, cabbage stalk, weeds, and soil was achieved with five wavelengths under 1500 nm, although better individual weed classification was obtained using a higher wavelength at 1620 nm.

Program runs 156 and 159 have identical success rates of 100% and 73.81% (individual weeds) using 3 and 2 wavelengths, respectively, the important ones being 880 and 960 nm. Redshank proved to be no problem, but mayweed was not recognised at all. Oilseed rape was mistaken for chickweed, and vice versa.

Of the three crops, cauliflower presented the lowest discrimination, Table 4. The highest success rate (92.85%) for the four general categories was obtained with wavelengths under 1100 nm Cauliflower was misclassified as redshank and mayweed. However, individual weeds such as grass, mayweed and redshank were classified successfully, while oilseed rape and chickweed were mistaken for each other.

Discriminant analysis with 3 wavelengths had a 90.48% success rate with the weeds grouped together. Misclassification occurred between cauliflower and redshank. Reduction in interweed classification was noted and none of the groups was fully classified. The addition of a fourth wavelength, 940 nm, correctly classified redshank and mayweed. Oilseed rape and chickweed were again mistaken for each other; meanwhile, mayweed was identified as grass.

3.2 Discriminant analysis with first derivative algorithm

The use of derivatives of spectra is commonplace in NIR analysis for quantifying the presence of chemicals and proteins. Fig. 1, shows the average and derivative spectra for the top margin of cabbage.

$$\text{TOTAL REF}(\lambda) = \text{REF}(\lambda) + k * d(\text{REF}(\lambda))/dt$$

The algorithm introduced for taking advantage of the first derivative multiplied the first derivative magnitude by a constant and then added its value to the original reflectance spectra. The effects of the first derivative algorithm on the top margin of cabbage leaf is shown in Fig. 2, displacing the spectra to the right for negative gains and to the left for positive gains.

Fig. 3 presents the first derivatives superimposed on the initial spectra for top redshank and top margin cabbage spectra with a derivative constant of -2, showing peaks at 1150 and 1450 nm. Negative gains increased reflectance differences visibly at the *red edge*, while positive values only shifted the spectra.

First derivatives were presented as variables with different gains. An initial discriminant analysis used different derivative constants (-0.5,-1, -2, 0.5, 1, 2, 3), and all the brassicas grouped together obtained an overall better performance with negative gains.

Subsequent analyses were made with derivative constants of -1 and +0.5 for each individual crop. Success rates of 100% were obtained for broccoli with a gain of +0.5 and 13 wavelengths, Table 5. A success rate of 92.82% was found with interweed discrimination. Chickweed and grass were well classified within their groups, but chickweed was difficult to discriminate from oilseed rape. Discrimination within the four general categories was reduced to 90.47% with two wavelengths and the success rate in individual weeds from 90.48% to 71.42%. Broccoli and redshank had classification difficulties and none of the individual weeds were successfully grouped.

The use of the negative derivative constant provided the highest discrimination (92.86%) between weed species using seven wavelengths, although one redshank spectra was considered as broccoli. Redshank, chickweed and grass were fully recognized. Results with only two wavelengths (1040 and 1200 nm)

indicate a 100% identification between broccoli, its stalk, soil and the entire weed population. Nevertheless, using individual weeds reduced the overall discrimination to 76.19% and only redshank was fully recognized. A third wavelength at 880 nm increased discrimination to 80.95%.

A maximum success rate of 100% was encountered using cabbage and the other three general categories with a gain of +0.5 and 10 wavelengths below 1100 nm, Table 6. The corresponding success rate considering all the weed species was 80.95%. Redshank and mayweed were fully recognized and each of the other weed species presented high percentages of recognition. The use of only two wavelengths (860 and 960 nm) still showed a 100% success rate with the integrated weed group and 78.57% with individual weed classifications. Redshank was the only weed to be fully identified. Wavelengths over 1100 nm should be used to increase interweed identification.

The use of a derivative constant of -1 also showed a success rate of 100% with two wavelengths (900 and 980 nm), although the rate of success with individual weeds was reduced to 73.80%, with redshank being the only well distinguished weed and mayweed being totally misclassifed. The addition of a third wavelength at 1480 nm served to classify mayweed.

Analysis of cauliflower using derivative algorithms obtained highest success rates with a derivative constant of +0.5, Table 7. A success rate of 100% for the general categories was achieved with 5 wavelengths, and 83.33% for the individual weed groups. Redshank and grass were fully identified. By using 2 wavelengths (700 and 1040 nm), the rate of success was reduced to 95.24%, causing redshank to be casually mistaken for cauliflower. A 71.43% success rate with individual weeds only, recognized redshank completely.

The derivative algorithm with a gain constant of -1 obtained a maximum success rate of 92.86% with all the weeds grouped together; redshank and mayweed were misclassified as cauliflower. An 80.95% success rate was encountered with individual weeds - redshank, grass and mayweed were fully recognized. Oilseed rape and chickweed were not readily differentiated.

Reducing the number of wavelengths to two (720 and 1040 nm) did not decrease the rate of success with respect to all the weed groups, but the individual weed classification was hardly affected and redshank was the only weed to be fully recognized.

It is worth noting that all the program runs listed in Tables 5, 6 and 7 correctly classified soil and crop stalk.

3.3 Discriminant analysis using ratios

Ratios are frequently used in spectrophotometry equipment to suppress instrument noise.

A maximum success rate of 100% for broccoli with all the weeds grouped together was obtained using 6 wavelengths, Table 8. The number of wavelengths in the ratios was then reduced to 3 (880, 1040 and 1440 nm), decreasing the rate of success to 90.48%. Broccoli stalk was not well identified and oilseed rape was misclassified as such. The success rate for individual weeds decreased to 71.43% and only grass was fully identified. The best compromise was obtained using four wavelengths in program run 194 which achieved 97.62% and 92.85% success rates for weeds classified together and individually, respectively. One of the soil spectra was mistaken for grass, but oilseed rape, chickweed and mayweed were completely recognized. The wavelengths used were 520, 1040 and 1720 nm and all of them were divided by 700 nm.

Reflectance ratios applied to cabbage yielded a maximum 100% discrimination using 6 wavelengths, Table 9. A success rate of 88.09% for interweed discrimination was achieved, mayweed being correctly identified. The use of only two ratios and only three wavelengths reduced discrimination between the four general categories to 95.24%. One of the cabbage spectra was mistaken for redshank and the redshank for soil. None of the weed groups was completely identified, causing the success rate to fall to 76.19%.

The maximum rate of success for cauliflower using reflectance ratios and 6 wavelengths below 1100 nm was 95.24%, Table 10. Cauliflower stalk was mistaken for cauliflower tissue spectra. The success rate for individual weeds was 88.09%, with full discriminations of grass, redshank and mayweed. Chickweed and oilseed rape were not easily differentiated. Three wavelengths were chosen for two ratios and the success rate was reduced to 88.09%, the main cause being the difficulty in discriminating mayweed from cauliflower. The rate of success with individual groups of weeds was further reduced to 61.90% as none of the groups could be identified.

4. CONCLUSIONS

Discriminant analyses provided high success rates for brassica/weed discrimination.

Of the three crops used, cauliflower presented greater problems of discrimination. Cauliflower texture is very similar to those encountered for weeds. When compared with broccoli and cabbage, cauliflower tends to wilt quicker.

A success rate of 100% in discriminating cabbage and broccoli from the other three general categories with only two wavelengths was achieved using direct reflectances and derivative algorithms. The use of the latter helped to increase interweed discrimination. Both gains considered in the algorithms worked well and similar interweed discrimination was obtained.

Wavelength ratios with a denominator of 700 nm were successful in discriminating the four general categories and high wavelengths achieve good interweed discrimination.

5. ACKNOWLEDGEMENTS

This work was funded by The Scottish Office Agriculture and Fisheries Department. F. Hahn acknowledges the support from the Mexican Government represented by CONACYT and by the Tecnologico Regional de la Laguna.

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Table 1 **Number of spectra in each of the crop/weed/soil categories, in the training group used to derive classification functions, and in the trial group used for testing discrimination accuracy.**

Crop/weed/soil	Number of spectra		
	Total	Training group	Trial group
Broccoli leaf	40	28	12
stalk	10	7	3
Cauliflower leaf	41	29	12
stalk	10	7	3
Cabbage leaf	40	28	12
stalk	10	7	3
Redshank	22	16	6
Chickweed	20	14	6
Mayweed	10	7	3
Grass	10	7	3
Oil seed rape	20	14	6
Soil	10	7	3
Total	243	171	72

Table 2 **Discrimination accuracy for broccoli using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/weed species/soil
11	18	100	85.71
8	7	92.85	73.81
13	5	95.23	85.71
12	5	92.23	71.43
14	5	90.48	66.66
154	4	95.23	78.57
164	3	97.62	76.19
155	3	88.09	69.05
160	2	100	76.19

Program run no.	Selected wavelengths, nm				
R13	800	1000	1040	1440	1640
R12	500	860	900	980	1020
R14	800	860	1000	1020	1040
R154	800	1000	1040	1640	
R164	1000	1040	1640		
R155	800	1000	1040		
R165	1040	1640			

Table 3 **Discrimination accuracy for cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/weed species/soil
19	14	100	97.62
20	5	100	78.57
18	5	97.61	85.71
17	5	97.61	76.19
156	4	100	73.81
158	3	100	78.57
21	3	95.23	73.81
159	2	100	73.81

Program run no.	Selected wavelengths, nm				
R20	640	880	960	1040	1480
R18	620	860	980	1020	1620
R17	560	640	880	980	1040
R156	880	960	1040	1480	
R158	880	960	1040		
R21	880	980	1040		
R159	880	960			

Table 4 **Discrimination accuracy for cauliflower using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/weed species/soil
22	10	92.85	80.95
28	5	90.48	71.43
27	5	85.71	66.66
24	5	83.33	64.28
160	4	90.48	71.43
161	3	90.48	66.66
162	3	85.71	61.9

Program run no.	Selected wavelengths, nm				
R28	560	700	820	1040	1440
R27	520	560	720	1040	1440
R24	580	820	860	940	1040
R160	580	700	940	1020	
R161	580	700	1020		
R162	560	1040	1440		

Table 5 Discrimination accuracy for broccoli using first derivative algorithm.

Program Run	Derivative constant	Number of wavelengths	Discrimination accuracy, %	
			General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/ weed species/soil
41	-1	7	97.62	92.86
40	-1	5	100	90.48
37	-1	5	95.24	88.09
168	-1	3	100	80.95
169	-1	2	100	76.19
44	0.5	13	100	90.48
47	0.5	5	100	90.48
46	0.5	5	97.62	83.33
171	0.5	3	88.09	66.66
172	0.5	2	90.47	71.42

Program run no.	Selected wavelengths, nm				
R40	880	1040	1200	1480	1640
R37	820	980	1060	1460	1580
R168	880	1040	1200		
R169	1040	1200			
R47	800	1040	1180	1360	1500
R46	660	780	1020	1180	1500
R171	800	1040	1500		
R172	1040	1500			

Table 6 Discrimination accuracy for cabbage using first derivative algorithm.

Program Run	Derivative constant	Number of wavelengths	Discrimination accuracy, %	
			General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/ weed species/ soil
48	0.5	10	100	85.71
51	0.5	5	100	80.95
52	0.5	5	97.62	88.09
175	0.5	3	100	78.57
177	0.5	2	100	78.57
54	-1	9	97.62	80.95
57	-1	5	100	88.09
58	-1	5	100	80.95
179	-1	3	100	80.93
180	-1	2	100	73.80

Program run no.	Selected wavelengths, nm				
R51	640	860	920	960	1040
R52	880	960	1040	1440	1640
R175	640	860	980		
R177	860	960			
R57	900	980	1060	1500	1820
R58	580	900	980	1060	1480
R179	900	980	1480		
R180	900	980			

Table 7 **Discrimination accuracy for cauliflower using first derivative algorithm.**

Program Run	Derivative constant	Number of wavelengths	Discrimination accuracy, %	
			General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/ weed species/soil
60	-1	10	92.86	80.95
63	-1	5	88.09	80.95
62	-1	5	83.33	64.28
183	-1	3	90.47	66.66
185	-1	2	92.86	69.05
65	0.5	10	97.62	78.57
67	0.5	5	100	83.33
69	0.5	5	90.45	73.81
187	0.5	3	97.62	71.42
189	0.5	2	95.24	71.43

Program run no.	Selected wavelengths, nm				
R63	600	720	1040	1480	1760
R62	600	840	880	960	1060
R183	600	720	1040		
R185	720	1040			
R67	560	700	720	820	1040
R69	560	700	820	1040	1440
R187	700	720	1040		
R189	700	1040			

Table 8 **Discrimination accuracy for broccoli using wavelength ratios.**

Program Run	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/weed species/soil
84	6	100	88.09
130	6	97.62	80.95
131	5	90.48	69.05
86	5	85.71	66.66
194	4	97.62	92.85
199	3	90.48	71.43

Program Run No.	Selected wavelength ratios				
R84	520/700	1040/700	1240/700	1440/700	1720/700
R130	1120/720	1200/880	1440/1040		
R131	1200/720	1120/720	1440/560		
R86	520/700	1040/700	1240/700	1440/700	
R194	520/700	1040/700	1720/700		
R199	1040/880	1440/880			

Table 9 **Discrimination accuracy for cabbage using wavelength ratios.**

Program Run	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/weed species/soil
100	6	100	88.09
135	5	100	80.95
95	5	95.24	76.19
142	4	95.24	71.43
141	4	92.86	78.57
102	4	90.48	76.19
143	3	95.24	76.19

Program Run No.	Selected wavelength ratios				
R100	520/700	640/700	1080/700	1440/700	1760/700
R135	840/760	1240/920	1480/840		
R95	640/980	760/980	1040/980	1440/980	
R142	940/860	1420/110			
R141	120/720	1200/720	1440/720		
R102	520/700	1080/700	1440/700		
R143	940/780	940/860			

Table 10 **Discrimination accuracy for cauliflower using wavelength ratios.**

Program Run	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/crop stalk/weed/soil	Specific category of crop/crop stalk/weed species/soil
105	6	95.24	88.09
107	5	85.71	66.66
150	5	85.71	61.90
152	5	83.33	66.66
201	4	90.48	66.66
203	3	88.09	61.90
205	3	83.33	61.90

Program Run No.	Selected wavelength ratios				
R105	640/700	720/700	860/700	940/700	1060/700
R107	560/700	640/700	1060/700	1440/700	
R150	1040/800	1280/720	1440/800	1440/1040	
R152	940/780	940/860	1420/1100		
R201	640/700	940/700	1060/700		
R203	640/700	1060/700			
R205	1040/800	1440/800	1440//1040		

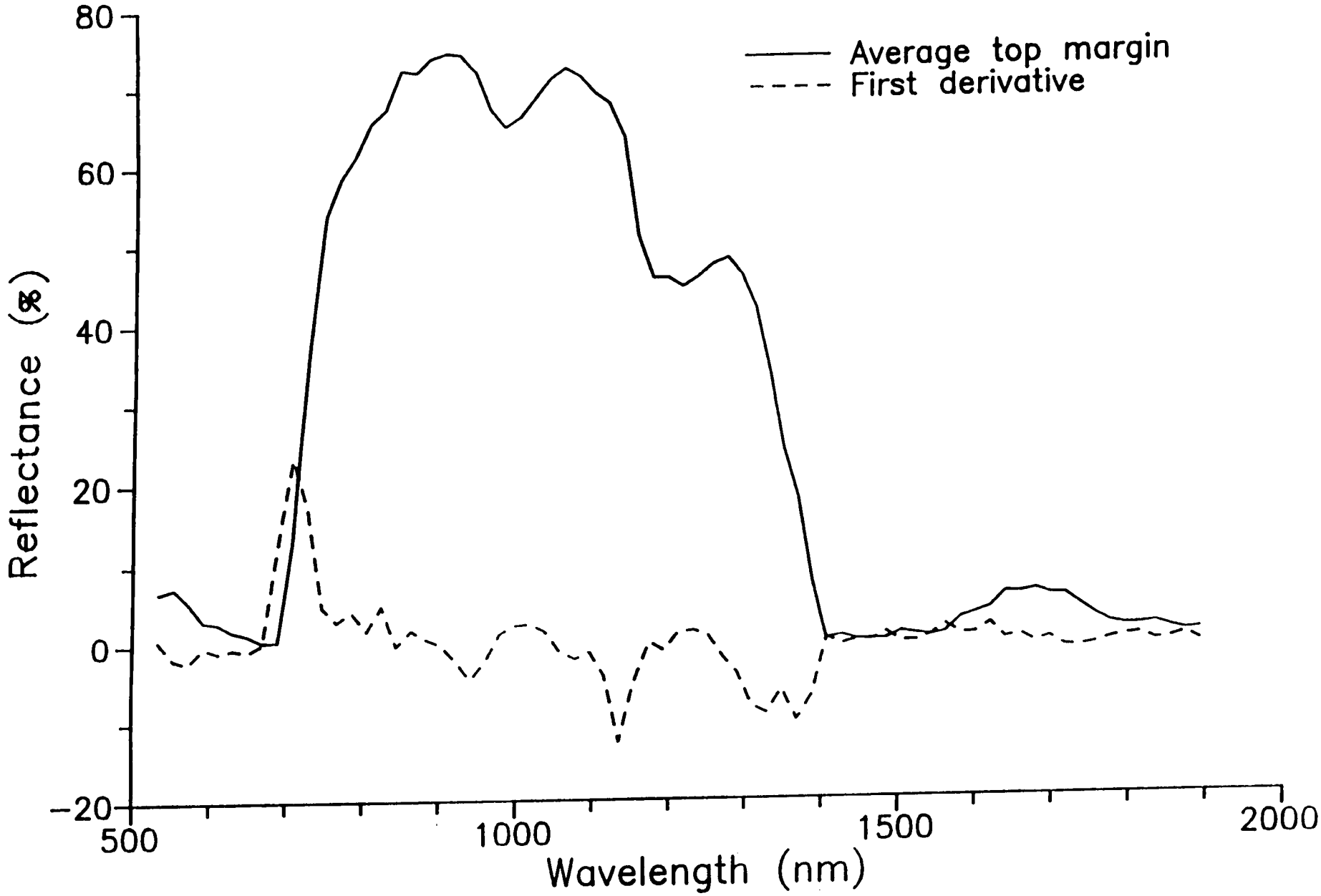

Fig. 1 Average and first derivative spectra of top margin cabbage leaf.

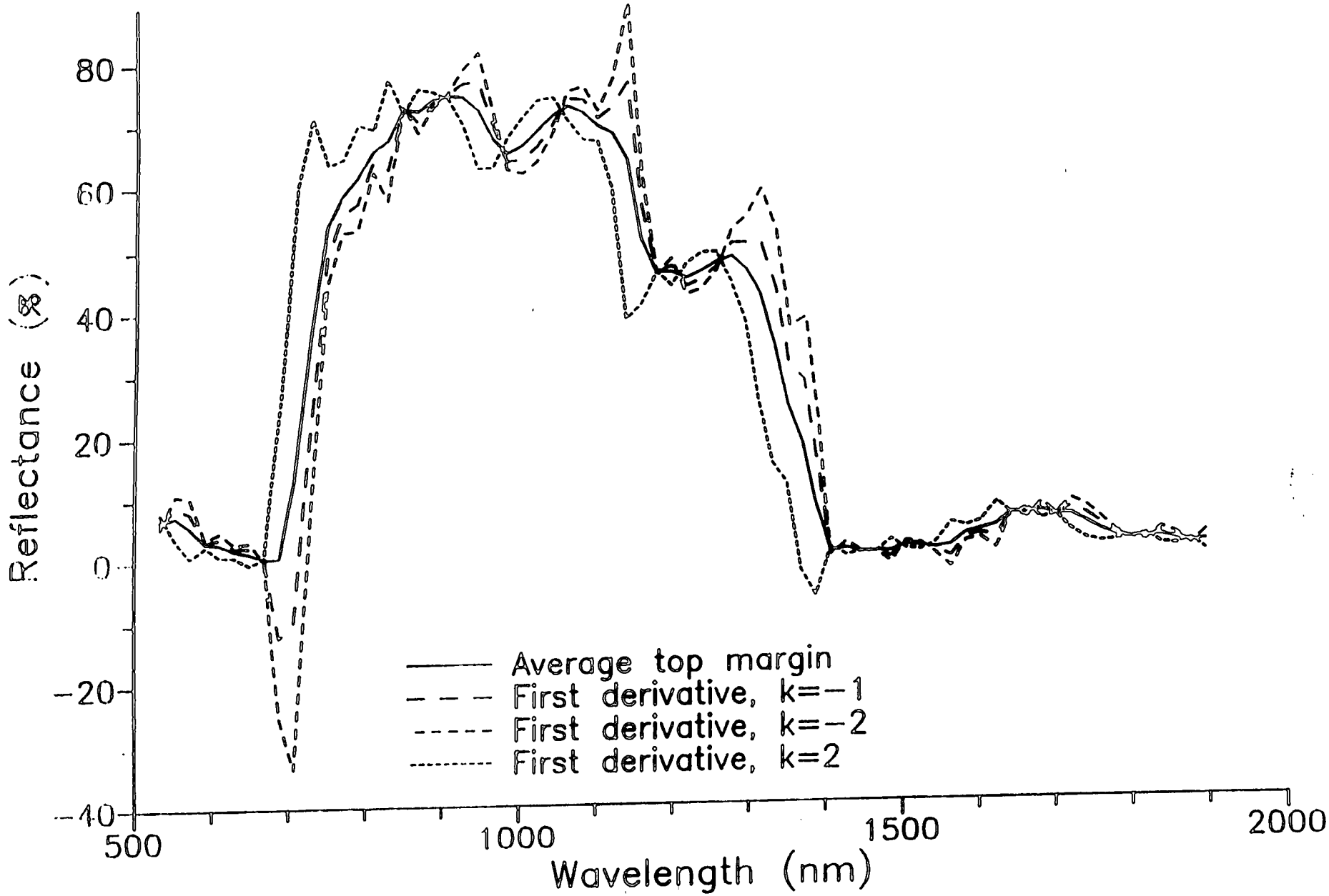

Fig. 2 The addition of spectrum and first derivative multiplied by different constants for top margin cabbage leaf.

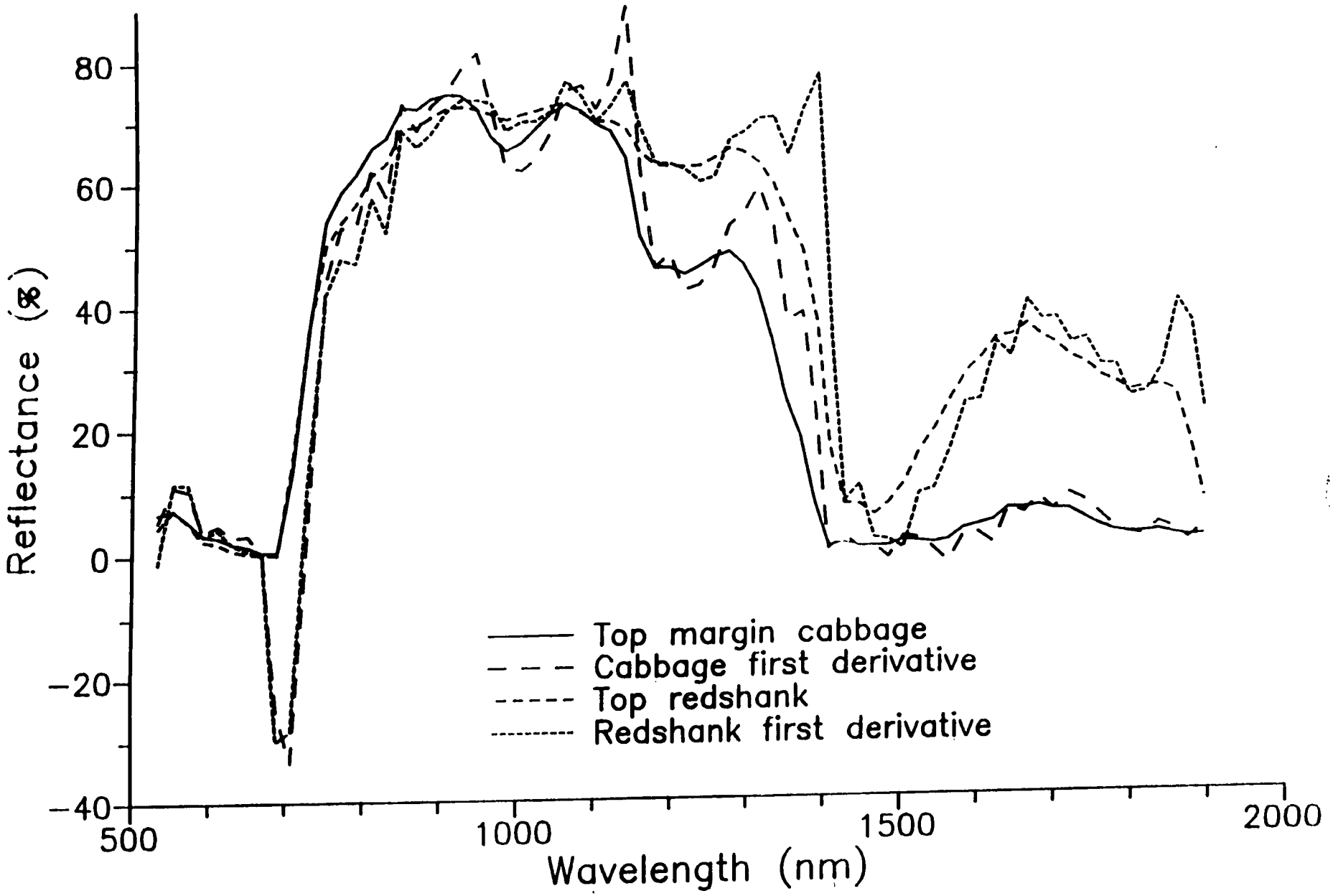

Fig. 3 First derivative superimposed on spectra of cabbage and redshank using a derivative constant of -2.

SCOTTISH CENTRE OF AGRICULTURAL ENGINEERING

DEPARTMENTAL NOTE 61

August 1993

CABBAGE AND BROCCOLI GROWTH STAGES AND THEIR EFFECT ON CROP WEED DISCRIMINATION

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ISSN 0953 - 413X

ISBN 1 85482 374 4

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SUMMARY

Cabbage and broccoli were grown in a greenhouse to study their growth development. Cabbage spectra were taken five times during the first month after crop emergence from three different leaves in each plant. Broccoli spectra were obtained when plants achieved seven, eight and nine true leaves. Reflectance differences between leaves and during different growth stages were found.

Discriminant analyses for cabbage growth stage/weed/soil, cabbage leaf/weed/soil and broccoli growth stage/weed/soil were carried out to determine the wavebands and wavelengths useful for crop/weed recognition.

A discrimination accuracy of 100% for crop/weeds/soil was achieved by using broad spectral bands. Different cabbage and broccoli growth stages were distinguished successfully from weeds and soil using only two wavelengths. Identification of weed species was improved by narrow spectral bands which were different for each experiment.

CONTENTS

		Page
1.	INTRODUCTION	1
2.	EXPERIMENTAL PROCEDURE	3
3.	RESULTS	3
	3.1 Discrimination between different leaves of the cabbage plant	7
	3.2 Discrimination between growth stages of broccoli	8
	3.3 Discrimination between growth stages of cabbage	9
4.	CONCLUSIONS	11
5.	ACKNOWLEDGEMENTS	11
	REFERENCES	11

CABBAGE AND BROCCOLI GROWTH-STAGES AND THEIR EFFECT ON CROP WEED DISCRIMINATION

1. INTRODUCTION

Remote sensing techniques using optical reflectance have been used to monitor vegetative growth of different crop covers. LANDSAT data has been used by many researchers to supervise crop growth analysis. Kanemasu (1974) used a portable spectrophotometer to monitor wheat, sorghum and soybean plots during the growing season. He indicated that wavebands at 545 and 655 nm provided useful information on growth behaviour for the three crops. Tucker (1979) used red and near infrared (NIR) wavelengths in a hand-held radiometer to monitor corn and soybean development and defined five distinct and spectrally measurable stages :

(a) emergence up to 20-30% vegetative cover;
(b) rapid foliar growth and development;
(c) full vegetative cover;
(d) onset of senescence, crop maturity and dry-down;
(e) crop maturity, ready for harvest.

Remote sensing techniques for crop weed recognition require to monitor crops during early growing stages. Bond (1991) and Courtney (1991) studied the optimum weeding time to produce higher crop yields. Roberts (1976) studied weed competition in drilled summer cabbage and concluded that if weeds were erradicated in the first three weeks after 50% crop emergence marketable yield was not affected. A similar study was carried out by Hewson et al.(1973) with broad beans and reported no yield loss if weeds remained up to three and a half weeks after 50% crop emergence. Roberts et al. (1977) reported no yield loss in drilled summer lettuce if weeds were removed three weeks after 50% crop emergence.

Brassica crops grown in rows are generally weeded before foliage covers the soil. Young crops which over-winter in the field are easily overgrown by weeds. Hoeing is commonly used to remove weeds during early crop growth stages and is generally omitted to avoid root damage once the canopy has developed.

Hahn and Muir (1993) showed that weed crop discrimination by optical reflectance was feasible using cabbage, cauliflower and broccoli leaves in their mature stage. A specific spectral study was necessary to examine how growth stage affected crop weed discrimination.

Broccoli and cabbage were grown in a greenhouse and five common weeds were chosen for study. Weeds had growing difficulties in the greenhouse due to existent mild conditions, so weeds were collected from cabbage fields some months later.

Brassica and weed spectra were obtained using a computerised spectrophotometer scanning from 600 to 1600 nm. The heart of this spectrophotomoter is a scanning monochromator and a fibre bundle collects the sample radiation.

Average cabbage spectra during the growing and harvesting season were compared, Fig.1, and substantially higher reflectance was noted in the older plant. However, the spectral form was not affected by plant growth stage.

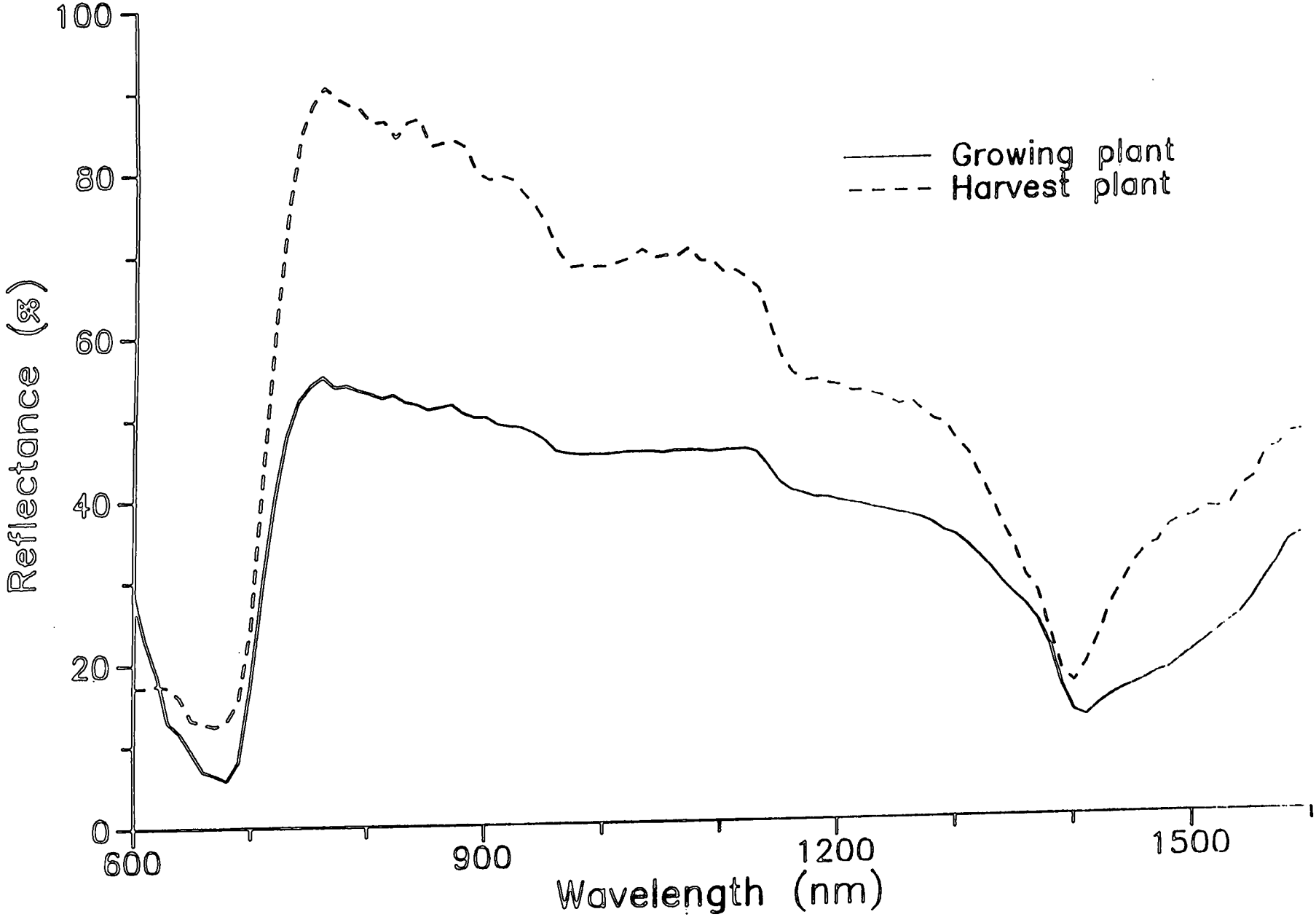

Fig. 1 Cabbage reflectance during growth and at harvest time.

2. EXPERIMENTAL PROCEDURE

Cabbage and broccoli were grown in a greenhouse during the months of March and April of 1992. Twenty cabbage plants and twenty broccoli plants were sown individually in pots and their spectra studied during different growth stages. Brassica growth is calculated from the sowing date and from the number of true leaves in the plant. The number of true leaves takes account of measurable leaves and not newly unfurled leaves.

Discriminant analysis determined the success of various wavelengths in distinguishing broccoli or cabbage from soil and five common weeds encountered in brassica fields:

redshank (polygonum persicaria)
chickweed (stellaria media)
charlock (sinapsis arvensis)
poppy (papaver rhoeas)
nettle (urtica urens)

Broccoli plants with an average seedling emergence time of 9 days were first sampled 29 days after sowing. By then, the plants had seven true leaves. Further samples were taken twice, with 10 day intervals until the plants had nine true leaves. Reflectance increased with plant growth, Fig. 2 and water loss from leaves was noted. Measurements were always taken from the same leaf defined during the first sampling date as the second of the seven true leaves from top to bottom. Five spectra on the top margin of each leaf and three on the top centre of each leaf were taken.

The BMDP statistic software was used to study broccoli/weed/soil discrimination during the sampled broccoli growth stage.

The average seedling emergence for cabbage was 10 days after sowing in the greenhouse. Considering the weeding time suggested by other researchers, spectra were taken during the month following crop emergence. Spectra were obtained for the first time 17 days after the sowing date when the plants had three true leaves. Leaf width, leaf length and ten spectra on the top margin of each of the existing leaves were obtained. At intervals of 5 days, four subsequent measurements were taken from the same three leaves. Cabbage reflectance increased during the first three spectral measurements until five true leaves were present (25 days after sowing). Leaves grew in size but reflectance from data acquired 30 and 35 days after the sowing date decreased, Fig. 3. During the last sampling, cabbages had seven true leaves and the three leaves measured represented 60% of the total foliage. Reflectance of the oldest leaves was higher than reflectance in the younger leaves, Fig. 4.

Two different analyses to discriminate cabbage/weeds/soil were carried out. Cabbage classification was different for each analysis. The first one used three cabbage groups or categories, one for each plant leaf. The spectra analysed were taken 35 days after the cabbage sowing date. The second analysis was composed of five cabbage categories, one for each growth stage.

3. RESULTS

Discriminant analysis was used to determine crop/weed/soil recognition efficiency within given spectral bands. The spectral bands that are not growth stage or plant leaf dependent are fundamental for weed/crop discrimination signature analysis. Two broad band widths of 500 nm (600-1100 nm and 1100-1600 nm) were used and compared with five narrow spectral band widths of 200 nm to get a better understanding of weed species discrimination. The five narrow bands that covered the entire 600-1600 nm waveband were 600-800 nm, 800-1000 nm, 1000-1200 nm, 1200-1400 nm and 1400-1600 nm. Spectral data were grouped by the crop (broccoli or cabbage), soil and five different weed species.

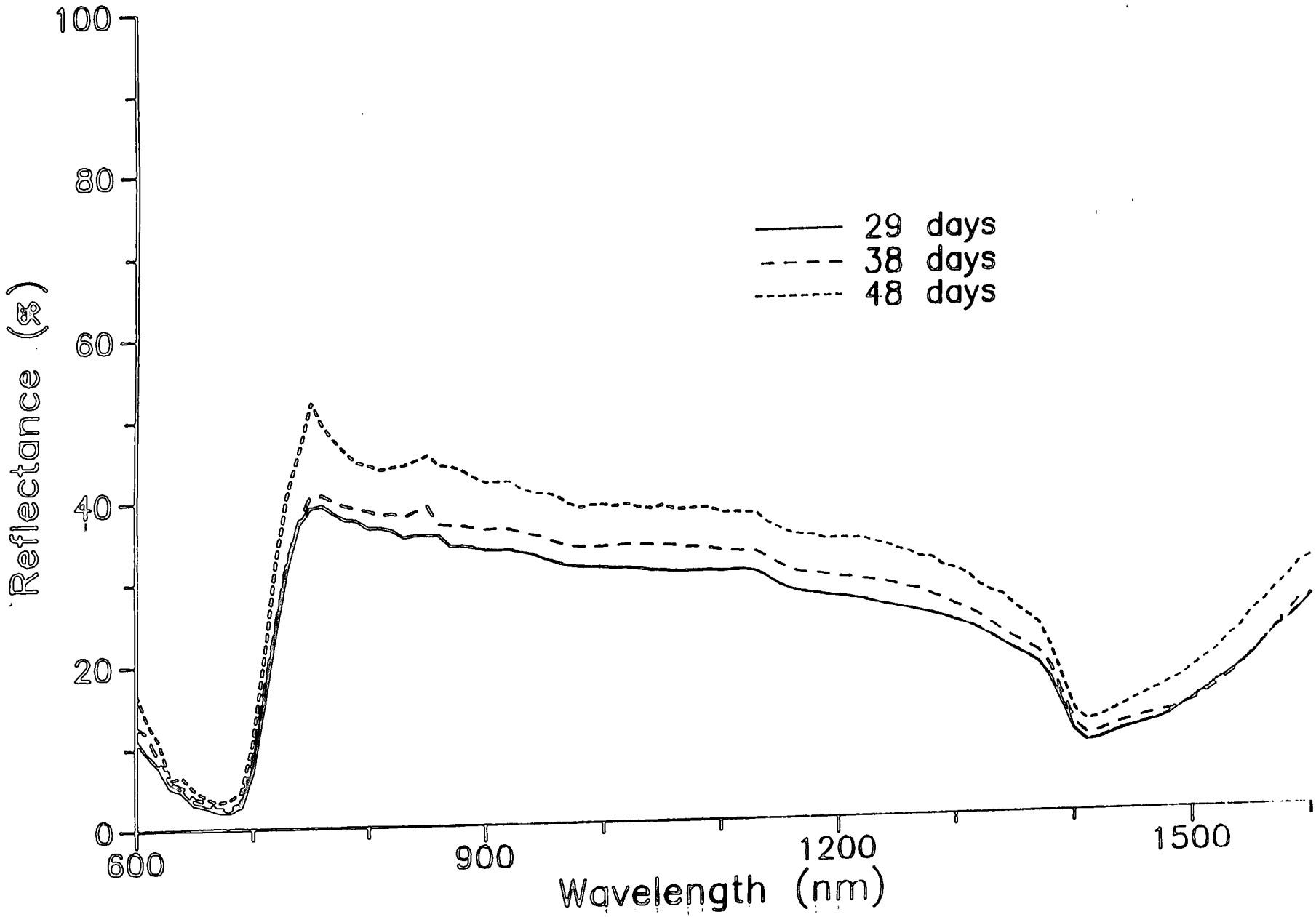

Fig. 2 Broccoli reflectance during different growth stage

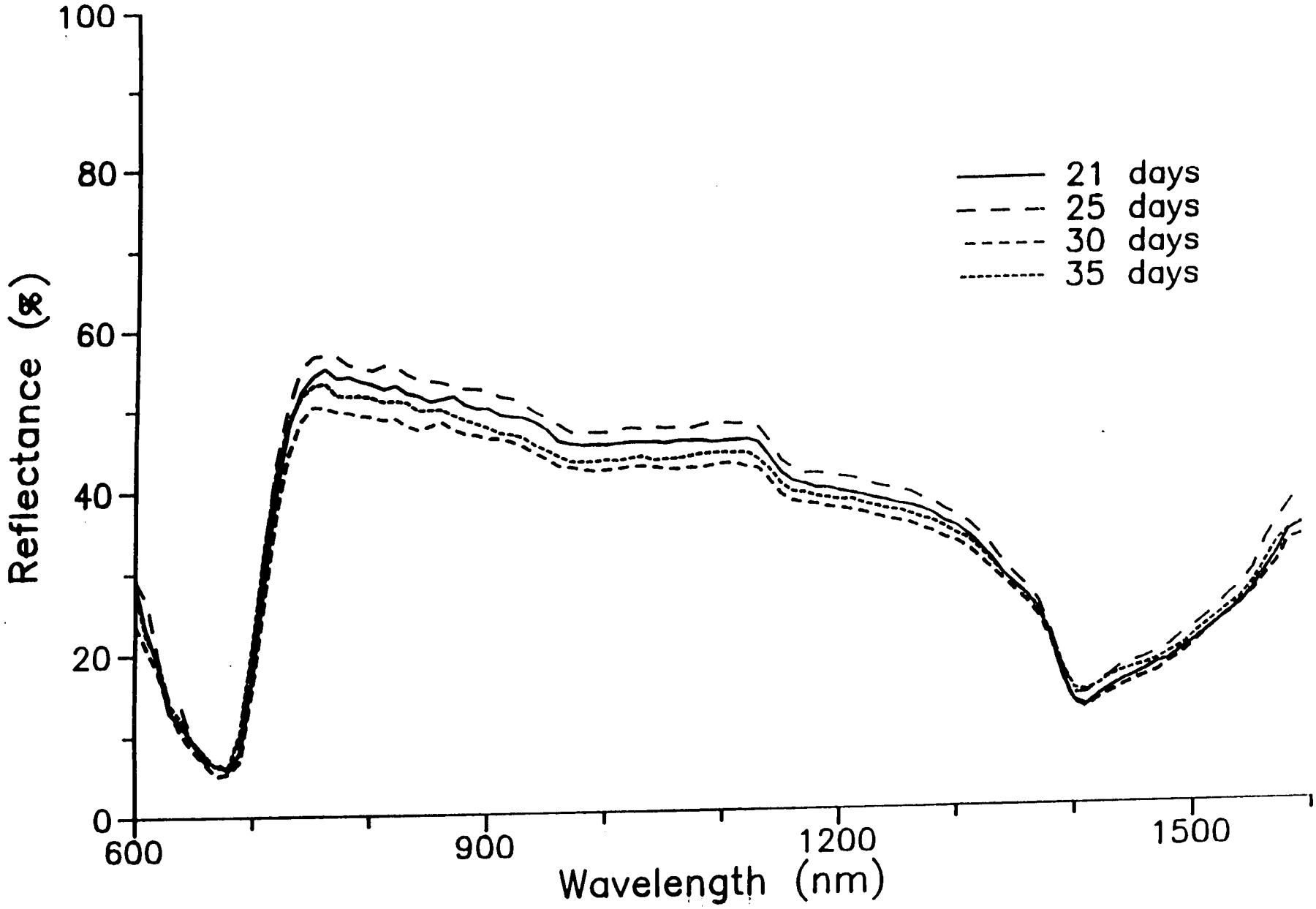

Fig. 3 Cabbage reflectance during different growth stages.

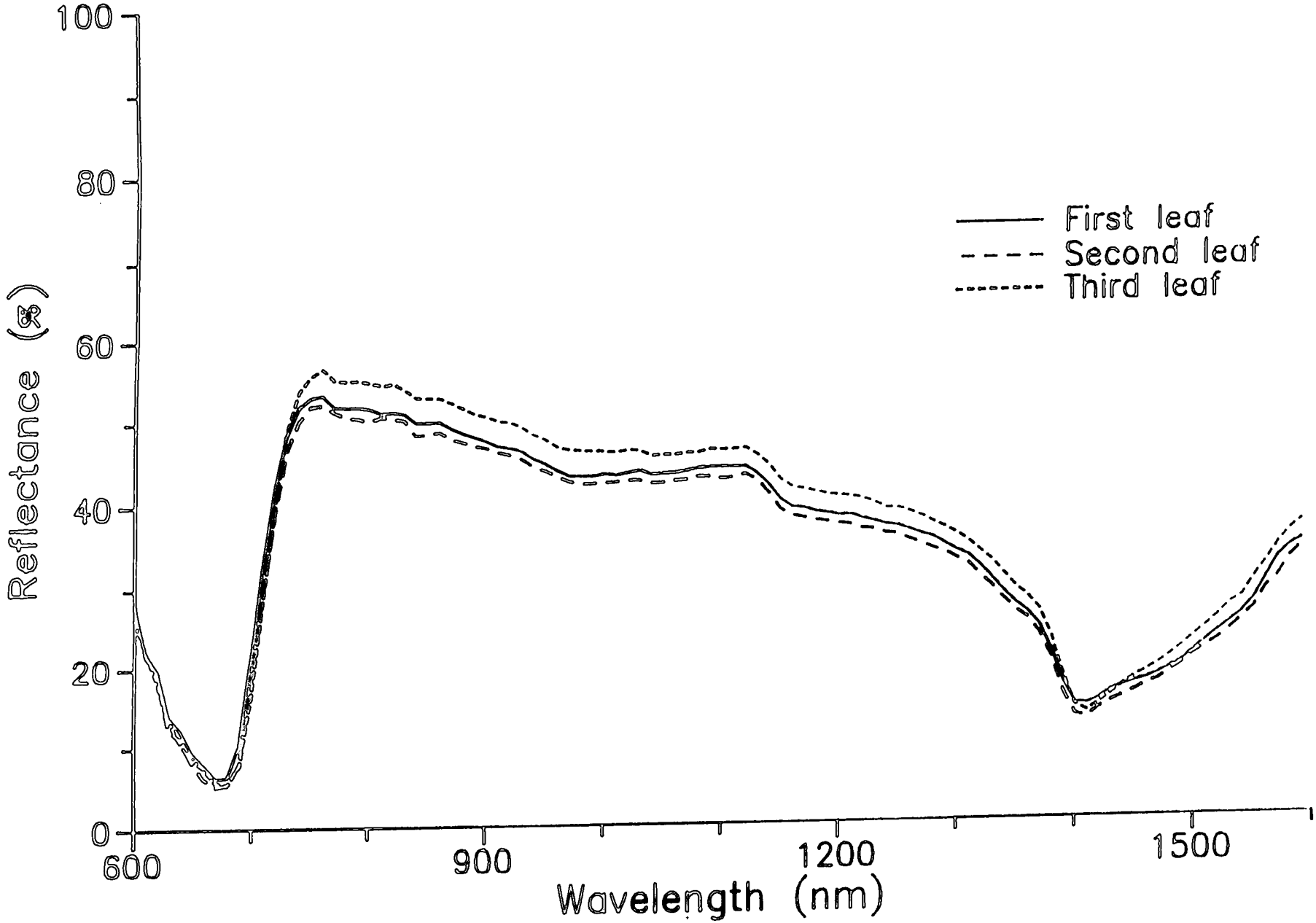

Fig. 4 Cabbage reflectance of three different leaves from the same plant 35 days after sowing.

The success of a program run for a particular *spectral-band* was determined in three ways:

(i) success in classifying a case from the trial group into its general category of crop/weed/soil;
(ii) success in classifying a case from the trial group into its correct specific category defined by crop/weed species/soil;
(iii) success in classifying a case from the trial group into its correct specific category defined by crop growth stage/weed species/soil.

Seventy analyses were carried out on both crops.

3.1 Discrimination between different leaves of the cabbage plant

Cabbage spectra taken from three different leaves of the covering foliage were used to determine cabbage/weed/soil discrimination accuracy-high success rates indicating spectral similarities on the top margin of the covering leaves, as well as spectral differences with weed and soil spectra. Of a total of 90 spectra used for the analysis, 63 were used to train the classifier and the other 27 spectra formed the trial group, Table 1. The cabbage groups had ten spectra each and were named leaf1, leaf2 and leaf 3 after the corresponding leaf sampled.

Table 1 **Number of spectra in each of the crop/weed/soil categories, in the training group used to derive classification functions, and in the trial group used for testing discrimination accuracy with cabbage leaves.**

	Number of spectra		
Crop/weed/soil	Total	Training group	Trial group
Cab Leaf 1	10	7	3
Cab Leaf 2	10	7	3
Cab Leaf 3	10	7	3
Redshank	10	7	3
Chickweed	10	7	3
Charlock	10	7	3
Poppy	10	7	3
Nettle	10	7	3
Soil	10	7	3
Total	90	63	27

Several analyses are summarised in Table 2. Cabbage/weed/soil and weed species discrimination achieved 100% success rates in the 600-1100 nm waveband. This analysis only misclassified one cabbage leaf spectrum in their respective growth stage categories. The 1100-1600 nm waveband reduced its weed species discrimination to 96.29% as chickweed was not classified properly. The higher discrimination accuracies were found in the 1000-1200 nm band and only redshank was misclassified. The lowest success rates in general and the poorest weed species discrimination were found in the 800-1000 nm spectral band.

Table 2 **Discrimination accuracy for three cabbage leaves of the same plant from weeds and soil, using different spectral bands.**

Program run no.	Wavelength range, nm	Discrimination accuracy, %		
		General category of crop/weed/soil	Specific category of crop/weed species/soil	Specific category of crop growth stage/ weed species/soil
43	600 to 800	96.29	85.19	74.07
44	800 to 1000	88.88	77.78	70.37
45	1000 to 1200	100	96.29	74.07
46	1200 to 1400	100	92.59	85.19
47	1400 to 1600	100	88.88	77.78
48	600 to 1100	100	100	96.29
49	1100 to 1600	100	96.29	85.19

Only two wavelengths (740 and 1060 nm) were necessary to achieve a 100% cabbage/weed/soil or general category discrimination. Nettle was not classified correctly reducing weed species discrimination to 96.29%. Identical general and specific category discrimination were obtained with another pair of wavelengths (740 and 1440 nm), although a decrease in individual cabbage leaf recognition was noted.

3.2 Discrimination between growth stages of broccoli

Table 3 shows the number of spectra used for broccoli/weed/soil discrimination. A total of 120 spectra were introduced to the program, using 84 spectra for training the classifier and 36 spectra as the trial group. The latter constituted 30% of the total spectra. The three broccoli groups had twenty spectra each and were named bro-29, bro-38 and bro-48 based on the number of days after sowing. The first group, bro-29 was sampled when the plant had seven true leaves. Nine days later, the eighth true leaf appeared and broccoli leaves were sampled. The final measurements were taken when the ninth true leaf appeared, 48 days after planting.

Table 3 **Number of spectra in each of the crop/weed/soil categories, in the training group used to derive classification functions, and in the trial group used for testing discrimination accuracy with broccoli leaves.**

Crop/weed/soil	Number of spectra		
	Total	Training group	Trial group
Bro-29	20	14	6
Bro-38	20	14	6
Bro-48	20	14	6
Redshank	10	7	3
Chickweed	10	7	3
Charlock	10	7	3
Poppy	10	7	3
Nettle	10	7	3
Soil	10	7	3
Total	120	84	36

Spectral ranges of 600-1100 nm and 1100-1600 nm proved to be 100% succesful in discriminating the three general categories, Table 4. The shorter waveband had a better weed species discrimination (94.44%) and nettle was the only weed misclassified. The higher wavelength range classified nettle correctly but failed with chickweed and redshank, reducing weed species discrimination to 91.66%.

Wavelengths within the 1000-1200 nm waveband presented the highest success rate (91.66%) for broccoli growth stage/weed species/soil discrimination and a 91.66% weed species discrimination. Chickweed was mistaken for broccoli and charlock for redshank. The 1400-1600 nm band classified correctly the three general categories but weed species discrimination was reduced to 88.88%. General recognition of broccoli/weeds/soil was particularly difficult using wavelengths between 800 and 1000 nm.

Table 4 **Discrimination accuracy for three broccoli growth stages from weeds and soil, using different spectral bands.**

Program run no.	Wavelength range, nm	Discrimination accuracy, %		
		General category of crop/weed/soil	Specific category of crop/weed species/soil	Specific category of crop growth stage/ weed species/soil
60	600 to 800	97.22	86.11	80.55
61	800 to 1000	91.66	80.55	77.77
62	1000 to 1200	94.44	91.66	91.66
63	1200 to 1400	94.44	88.88	86.11
64	1400 to 1600	100	88.88	83.33
65	600 to 1100	100	94.44	86.11
66	1100 to 1600	100	91.66	86.11

Broccoli/weed/soil general categories were correctly classified using two wavelengths, 760 and 1480 nm. A 94.44% weed species discrimination was obtained due to identification problems with chickweed and redshank.

3.3 Discrimination between growth stages of cabbage

Cabbage spectra were grouped in five different growth stage categories to study cabbage/weed/soil discrimination. The number of days after the sowing date determined the different cabbage group names: cab-17, cab-21, cab-25, cab-30 and cab-35. The number of true leaves for each sampling date were 3,4,5,6 and 7, respectively. The discriminant analysis used 110 spectra, 77 to obtain the classification function and 33 to form the trial group, Table 5.

Table 5 **Number of spectra in each of the crop/weed/soil categories, in the training group used to derive classification functions, and in the trial group used for testing discrimination accuracy with cabbage leaf growth.**

Crop/weed/soil	Number of spectra		
	Total	Training group	Trial group
Cab-17	10	7	3
Cab-21	10	7	3
Cab-25	10	7	3
Cab-30	10	7	3
Cab-35	10	7	3
Redshank	10	7	3
Chickweed	10	7	3
Charlock	10	7	3
Poppy	10	7	3
Nettle	10	7	3
Soil	10	7	3
Total	110	77	33

The 600-1000 and 1100-1600 spectral ranges discriminated the three general categories with a 100% accuracy, Table 6. Weed species discrimination was greater in the former (96.97%) and all the weeds except nettle were correctly classified. With the 1100-1600 nm spectral band, chickweed and redshank were not identified properly reducing weed species discrimination to 93.94%. The 1400-1600 nm band was the most successful in classifying each specific category (84.85%) and only chickweed was misclassified.

Table 6 **Discrimination accuracy for five cabbage growth stages from weeds and soil, using different spectral bands.**

Program run no.	Wavelength range, nm	Discrimination accuracy, %		
		General category of crop/weed/soil	Specific category of crop/weed species/soil	Specific category of crop growth stage/ weed species/soil
38	600 to 800	96.97	90.91	72.73
39	800 to 1000	96.97	96.97	78.78
40	1000 to 1200	96.97	90.91	75.76
41	1200 to 1400	100	96.97	78.78
42	1400 to 1600	100	96.97	84.85
27	600 to 1000	100	96.97	81.88
28	800 to 1300	100	96.97	78.78
34	1100 to 1600	100	93.94	75.76

A 100% cabbage/weed/soil discrimination in the three general categories was achieved with two wavelengths, 740 nm and 1480 nm. All the weeds were correctly classified except chickweed giving a 96.97% cabbage/weed species/soil discrimination. Adding a third wavelength at 1360 nm, classified each weed species in its respective category. Reduction in number of wavelengths did not decrease drastically specific category classification.

Width and length measurements during the different cabbage growth stages are stated in Table 7. Significant differences were noted in both measurements and could be used in a machine vision system to monitor cabbage growth.

Table 7 **Cabbage leaf length and width for each growth stage.**

Time after sowing, day	Leaf length, min			Leaf width, min		
	Min	Max	Ave	Min	Max	Ave
17	3	4	3.3	2.2	2.8	2.5
21	4	5.5	4.6	3.2	4.2	3.7
25	4.9	6.7	5.5	3.8	5.2	4.4
30	6	8.5	7.5	5.3	6.8	6
35	7.3	11	9.2	6.8	8.8	7.6

4. CONCLUSIONS

Three important conclusions for remote sensing utilisation in crop/weed discrimination emerge from these analyses:

1. the feasibility of crop/weed discrimination at different growth stages;
2. the feasibility of sampling the entire top foliage;
3. spectral band identification for crop/weed discrimination using signature analysis.

Broccoli and cabbage crop/weed/soil discrimination was feasible using crop spectra obtained during different growth stages. Succesful discrimination was also noted when spectra of different leaves from cabbage plants were used.

Different success classifications were used to study the discrimination process in restricted wavebands. In the three analyses carried out, broad spectral bands achieved 100% discrimination in three general categories, crop, weeds and soil.

Weed species discrimination was waveband dependent, although some weeds such as charlock and poppy were classified correctly on most occasions. Chickweed recognition was dependent on lower wavelengths and nettle on higher wavelengths. Broadband classification of weeds by species in the three experiments was higher than narrowband classification, particularly in the 600-1100 range. The 1000-1200 narrow band presented high weed species discrimination in the three experiments. Identification of each specific category was improved by using narrow spectral bands which were different for each experiment.

Broccoli and cabbage at different growth stages were discriminated from weeds and soil with 100% success using only two wavelengths. A common wavelength was located at 1480 nm and the other was located in the red edge, having a particular value in each crop. A 100% weed species discrimination could be obtained by adding a third wavelength.

Discriminant analysis was not successful for cabbage growth stage identification, even using broad spectral bands. The use of reflectance for growth monitoring should be studied more intensively and groups should be more carefully selected.

5. ACKNOWLEDGEMENTS

We wish to thank the Scottish Office Agriculture and Fisheries Department for funding this work. F. Hahn acknowledges the support provided by the Mexican Government represented by the Tecnologico Regional de la Laguna and by CONACYT.

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SCOTTISH CENTRE OF AGRICULTURAL ENGINEERING

DEPARTMENTAL NOTE 62

August 1993

DISCRIMINATION OF WEEDS IN CABBAGE, LEEK, POTATO AND TURNIP CROPS

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ISSN 0953 413X

ISBN 1 85482 375 2

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SUMMARY

Cabbage, turnip, potato and leek were grown in the field and their spectra obtained with a scanning spectrophotometer. Ten different weed species were also collected and their spectra taken.

Crop/weed/soil and crop/weed species/soil discriminations were studied for each crop using direct wavelengths and wavelength ratios.

Leek and cabbage achieved a 100% crop/weeds/soil discrimination with one wavelength ratio and one of the main wavelengths was 990 nm for both crops.

Maximum 100% and 97.62% potato/weeds/soil discrimination success rates for direct wavelengths and wavelength ratios were obtained with four wavelengths.

Turnip was the crop with greatest identification problems using direct wavelengths. A 100% and 95.23% turnip/weeds/soil discrimination was found for direct wavelengths and wavelength ratios using three wavelengths.

Weeds species discrimination was reduced for all the crops when only two wavelengths were used. Each crop had particular identification problems with specific weeds.

CONTENTS

		Page
1.	INTRODUCTION	1
2.	EXPERIMENTAL PROCEDURE	1
3.	RESULTS	2
	3.1 Discriminant analysis with cabbage	2
	3.2 Discriminant analysis with potato plants	3
	3.3 Discriminant analysis with leeks	3
	3.4 Discriminant analysis with turnips	3
4.	CONCLUSIONS	4
5.	ACKNOWLEDGEMENTS	4
	REFERENCES	4

DISCRIMINATION OF WEEDS IN CABBAGE, LEEK, POTATO AND TURNIP CROPS.

1. INTRODUCTION

Hahn and Muir(1993) showed that discriminant analysis was a useful technique for crop/weed discrimination in cabbage, cauliflower and broccoli. Effective discrimination between these crops, weeds and soil were achieved with three or four wavelengths. Weed species discrimination was not as successful and chickweed and oilseed rape generally were misclassified.

Potato, leek, turnip and cabbage were sown in the spring of 1992 and harvested in the months of September and October. During harvest time the main weeds collected from the fields were :

redshank (polygonum persicaria)
chickweed (stellaria media)
charlock (sinapsis arvensis)
nettle (urtica urens)
poppy (papaver rhoeas)
mallow (malva sylvestris)
dandelion (taraxacum officinale)
couchgrass (elymus repens)
timothy (phleum pratense)
willowherb (epilobium sp)

Discriminant analyses between each crop, soil and weeds were carried out using direct wavelengths and wavelength ratios.

2. EXPERIMENTAL PROCEDURE

A different computerised spectrophotometer was used in this application than in previous experiments. Its operating mode is based on a scanning monochromator and the object (leaf) reflectance sampled with a bifurcated fibre bundle. Light is applied on one arm of the bundle and the measured reflectance is available in the other. The radiation obtained is then introduced to the scanning monochromator. A spectral comparison of redshank and chickweed using both type of spectrophotometers is shown in Fig 1. Redshank measured with the integrated sphere spectrophotometer presented a higher reflectance than with the MONOLITE scanning monochromator system. Signature differences are apparent and can be justified by the effect of area and the fact that an integrating sphere was used in the former spectrophotometer.

Crop and weed leaves collected from the field were sampled with the MONOLITE computerised spectrophotometer to produce fine spectral signatures of small leaf tissue areas.

Precautions were taken to prevent water loss from leaves by using plastic bags. Forty spectra of each crop and weed species were taken from the top margin of twenty different leaves. The average and variance spectrum of each crop and weed species were obtained.

The spectral data obtained as ascii files from the spectrophotometer computer were processed by programs written in "C" language and introduced to the BMDP statistic software for analysis.

3. RESULTS

Average spectra of potato and two grasses are shown in Fig 2, and potato reflectance is half couchgrass and timothy reflectance. Leek, mallow, nettle and dandelion average spectra are shown in Fig 3. Dandelion reflectance is very low and presents a flat signature above a wavelength of 800 nm. The leek signature has a higher reflectance than nettle and a lower reflectance than mallow. The average spectra for willowherb and charlock are very similar, Fig 4. Cabbage and willowherb could present recognition problems at wavelengths between 700 and 900 nm. Soil presents a very different signature pattern from vegetation, Fig 5. The average spectra for turnip, chickweed and poppy present marked reflectance differences. The lowest reflectance was found in poppy being similar in its signature to nettle.

Spectral data introduced to the discriminant analysis program was arranged in 12 different groups, Table 1. Of the 140 spectra used, 98 were used for training the classifier and 42 as a trial group. The crop group was formed by 30 spectra from the crop used in the particular analysis.

Three general categories, i.e. crop, weeds and soil were considered in the discrimination study. A more specific classification was adopted to evaluate discrimination accuracy for weed species.

The success of a particular program defining wavelengths was determined in two ways:

(i) success in classifying a case from the trial group into its correct *general category* of crop/weed/soil;

(ii) success in classifying a case from the trial group into its correct *specific category* defined by crop/weed species/soil.

A total of 150 analyses were carried out using direct wavelengths and wavelength ratios. Programs written in "C" language were used to generate the ratios. Three different approaches were taken to create the ratios, i.e. direct wavelengths, peak normalization and minimum variance normalization. The first one used the four most important wavelengths to produce six different ratios. Peak normalization ratios were the result of dividing each individual wavelength against the peak value of the average crop reflectance signature. Finally, the minimum variance normalization, the variance from the entire weed population and different crops was evaluated. The wavelength with lowest variance were 710 and 990 nm. Ratios were obtained by dividing the reflectance from each individual wavelength against the reflectance at 710 or 990 nm.

3.1 Discriminant analysis with cabbage

Cabbage was first analysed using direct wavelengths, Table 2. A discrimination of 100% between general categories was achieved using all the wavelengths. Dandelion and chickweed were not correctly classified and weed species discrimination was reduced to 95.23%. These weeds were fully recognized with four wavelengths (program run 43) and identical results obtained but discrimination difficulties were found with mallow and redshank. After reducing the number of wavelengths to two, the classification into general categories was still 100% accurate, although weed species discrimination was seriously impaired. The only recognisable weeds were charlock, poppy and both grasses (timothy and couchgrass).

Cabbage/weed/soil discrimination with wavelength ratios was 100% accurate using a wide range of wavelengths, Table 3. Weed species discrimination was reduced with the number of wavelengths. Poppy, chickweed, timothy and nettle were not classified properly using three wavelengths in program run 137, achieving a weed species discrimination of 88.09%.

3.2 Discriminant analysis with potato plants

General and specific discriminations of 100% and 97.62% were obtained with potato plants using all the wavelengths, Table 4. Redshank was the only weed to be misclassified. Two different sets of four wavelengths achieved 100% general and weed species discrimination. Both program runs had common wavelengths at 720, 920 and 1380 nm. Willowherb was not classified correctly when only three wavelengths were used (program run 101) reducing weed species discrimination to 97.62%. A 97.62% potato/weed/soil discrimination was achieved with wavelengths (720 and 990 nm). A reduction in the weed species discrimination to 80.95% was caused by charlock and redshank misclassification. An increase in weed species discrimination to 85.71% could be achieved with higher infrared wavelengths (920 and 1380 nm) at the expense of decreasing general discrimination (95.23%).

Wavelength ratios showed a decrease in success rates, Table 5. With all the wavelengths divided by 990 nm, 95.23% general and weed species discrimination were found. Redshank was taken as potato and vice-versa. With three ratios (four wavelengths) against 990 nm, weed species discrimination decreased to 90.48%, while general discrimination increased to 97.62%. Chickweed was taken as potato; and other weeds with discrimination problems were nettle and timothy.

3.3 Discriminant analysis with leeks

Leek plants were analysed using all the wavelengths directly and 100% general discrimination obtained, Table 6. A 95.23% weed species discrimination was the effect of dandelion misclassification. The use of four wavelengths, i.e. 720, 1080, 1380 and 1500 nm increased weed species discrimination to 100%. Further analyses reduced the number of wavelengths to three and two, without affecting the 100% leek/weed/soil discrimination. Weed species discriminations of 97.62% and 88.09% were obtained with three and two wavelengths, respectively. Chickweed was misclassified in the former; and willowherb, mallow and chickweed in the latter.

Leek/weed/soil discrimination was analyzed using wavelength ratios, Table 7. A 100% success rate was obtained using three wavelengths or two ratios against 990 nm (program run 113). Weed species discrimination was reduced to 85.71% with chickweed, nettle, redshank and timothy misclassified. With four wavelengths, weed species discrimination increased to 97.62% (program run 110) where only timothy was not recognised properly.

3.4 Discriminant analysis with turnips

Turnip presented more discrimination difficulties than the other three crops. A 97.62% general discrimination using the entire spectral range, Table 8, was achieved with turnips being taken as chickweed. All the weeds were classified properly and a 97.62% specific discrimination obtained. Program run 27 used three wavelengths, i.e. 730, 1000 and 1360 nm to increase the general discrimination to 100%. A high 95.23% weed species discrimination was obtained, with nettle and willowherb misclassified. Turnip/weed/soil discrimination decreased to 95.23% using two wavelengths and weed species discrimination was affected more drastically.

Wavelength ratios with up to four wavelengths were studied and Table 9 displays the better results. Program run 114 used 28 wavelengths divided by 990 nm to obtain 100% turnip/weed/soil discrimination. Charlock was taken as turnip and a 97.62% discrimination was obtained using four wavelengths and six ratios. A reduction in weed species discrimination to 85.71% took place when poppy was not recognised. The use of only three wavelengths and two ratios decreased the general and specific discrimination to 95.23% and 66.66%, respectively.

4. CONCLUSIONS

A spectrophotometer different from that used in previous experiments and a bifurcated fibre bundle allowed smaller sampling areas and permitted better access to the leaf tissue.

Cabbage, leek, potato and turnip could be identified from soil and ten different weed species with high success rates using direct wavelengths and wavelength ratios.

Cabbage was easy to distinguish from weeds and soil using direct wavelengths and wavelength ratios. A 100% cabbage/weed/soil discrimination was achieved with a single ratio (1360/990). Weed species discrimination was only 45.23%.

Leek was also easily distinguished from weeds and soil. A discrimination accuracy of 100% was obtained for leek/weed/soil with the 1380/990 ratio. Weed species discrimination of 50% was achieved with this ratio, charlock recognition being the most difficult.

Potato identification among weeds using direct wavelengths was not difficult and could be achieved with only two wavelengths. Wavelength ratios presented identification problems caused mainly by mallow and redshank.

Turnip identification problems occurred with chickweed, using direct wavelengths. Charlock and mallow were also difficult to discriminate from turnip with the use of wavelength ratios.

Both crop/weed/soil and crop/weed species/soil discrimination were more successful for cabbage, leeks, and turnips using wavelengths over 1100 nm, whereas lower wavelengths were preferred for potatoes. Higher success rates were achieved with direct wavelengths. The common wavelength used to create ratios that best suited all the crops was 990 nm. High success rates with only three discriminant wavelengths were achieved for the four crops. Leeks, potatoes, and cabbage had in common a good discriminant wavelength at 720 nm in the *red edge*, while a wavelength of 730 nm was best for turnips. The other wavelengths were located near 1360, 1500 and 990 nm for the four crops. Without the wavelength at 1500 nm, weed species discrimination was reduced and could be omitted if only general classification was desired.

5. ACKNOWLEDGEMENTS

This work was funded by The Scottish Office Agriculture and Fisheries Department. F. Hahn acknowledges the support from the Mexican Government represented by the Tecnologico Regional de la Laguna and by CONACYT.

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Table 2 **Discrimination accuracy for cabbage using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/weed/soil	Specific category of crop/weed species/soil
35	35	100	95.23
43	4	100	95.23
46	4	100	92.85
44	3	100	92.85
82	2	100	78.57
84	2	100	76.91

Program run no.	Selected wavelengths, nm			
43	720	990	1170	1360
46	720	1070	1170	1360
44	720	1170	1360	
82	1170	1360		
84	870	990		

Table 3 **Discrimination accuracy for cabbage using wavelength ratios**

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/weed/soil	Specific category of crop/weed species/soil
61	35	100	97.62
62	5	100	92.85
126	4	100	92.85
63	4	100	80.95
137	3	100	88.09
138	3	100	66.66

Program run no.	Selected wavelengths, nm			
62	720/760	1260/760	1380/760	1500/760
126	900/710	1400/710	1480/710	
63	720/760	1260/760	1380/760	
137	1360/990	1500/990		
138	750/990	1360/990		

Table 1 Number of spectra in each of the crop/weed/soil categories, in the training group and in the trial group used to test discrimination accuracy.

	Number of spectra		
Crop/weed/soil	Total	Training group	Trial group
Cab/tur/leek or potato	30	21	9
Charlock	10	7	3
Poppy	10	7	3
Chickweed	10	7	3
Nettle	10	7	3
Redshank	10	7	3
Mallow	10	7	3
Timothy	10	7	3
Dandelion	10	7	3
Couchgrass	10	7	3
Willowherb	10	7	3
Soil	10	7	3
Total	140	98	42

Table 4 Discrimination accuracy for potato using direct wavelengths.

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/weed/soil	Specific category of crop/weed species/soil
13	25	100	97.62
16	4	100	100
22	4	100	100
18	4	100	97.62
101	3	100	97.62
17	3	100	88.09
99	2	97.61	80.95
100	2	95.23	85.71

Program run no.	Selected wavelengths, nm			
17	720	920	1380	1500
22	720	920	1120	1380
18	720	920	1100	1380
101	720	1120	1380	
17	720	920	1380	
99	720	990		
100	920	1380		

Table 5 Discrimination accuracy for potato using wavelength ratios.

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/weed/soil	Specific category of crop/weed species/soil
92	32	95.23	92.86
95	4	97.62	90.47
89	4	95.23	71.42
97	4	92.86	83.33
57	4	90.47	88.09

Program run no.	Selected wavelengths, nm					
95	750/990	1380/990	1500/990			
89	920/710	1120/710	1380/710			
97	690/990	1380/990	1500/990			
57	720/920	720/1380	720/1500	920/1380	920/1500	1380/1500

Table 6 **Discrimination accuracy for leek using direct wavelengths.**

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/weed/soil	Specific category of crop/weed species/soil
1	28	100	95.23
5	4	100	100
9	4	100	95.23
6	3	100	97.62
106	3	100	97.62
7	2	100	88.09
104	2	100	88.09

Program run no.	Selected wavelengths, nm			
5	720	1080	1380	1500
9	720	990	1220	1380
6	1080	1380	1500	
106	720	1080	1380	
7	1080	1380		
104	990	1380		

Table 7 **Discrimination accuracy for leeks using wavelength ratios.**

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/weed/soil	Specific category of crop/weed species/soil
68	24	100	97.62
110	4	100	97.62
55	4	100	90.47
145	4	97.61	90.47
113	3	100	85.71
112	3	97.62	78.57

Program run no.	Selected wavelengths, nm					
110	720/990	1380/990	1500/990			
55	720/1080	720/1380	720/1500	1080/1380	1080/1500	1380/1500
145	1020/710	1400/710	1480/710			
113	1380/990	1500/990				
112	720/990	1380/990				

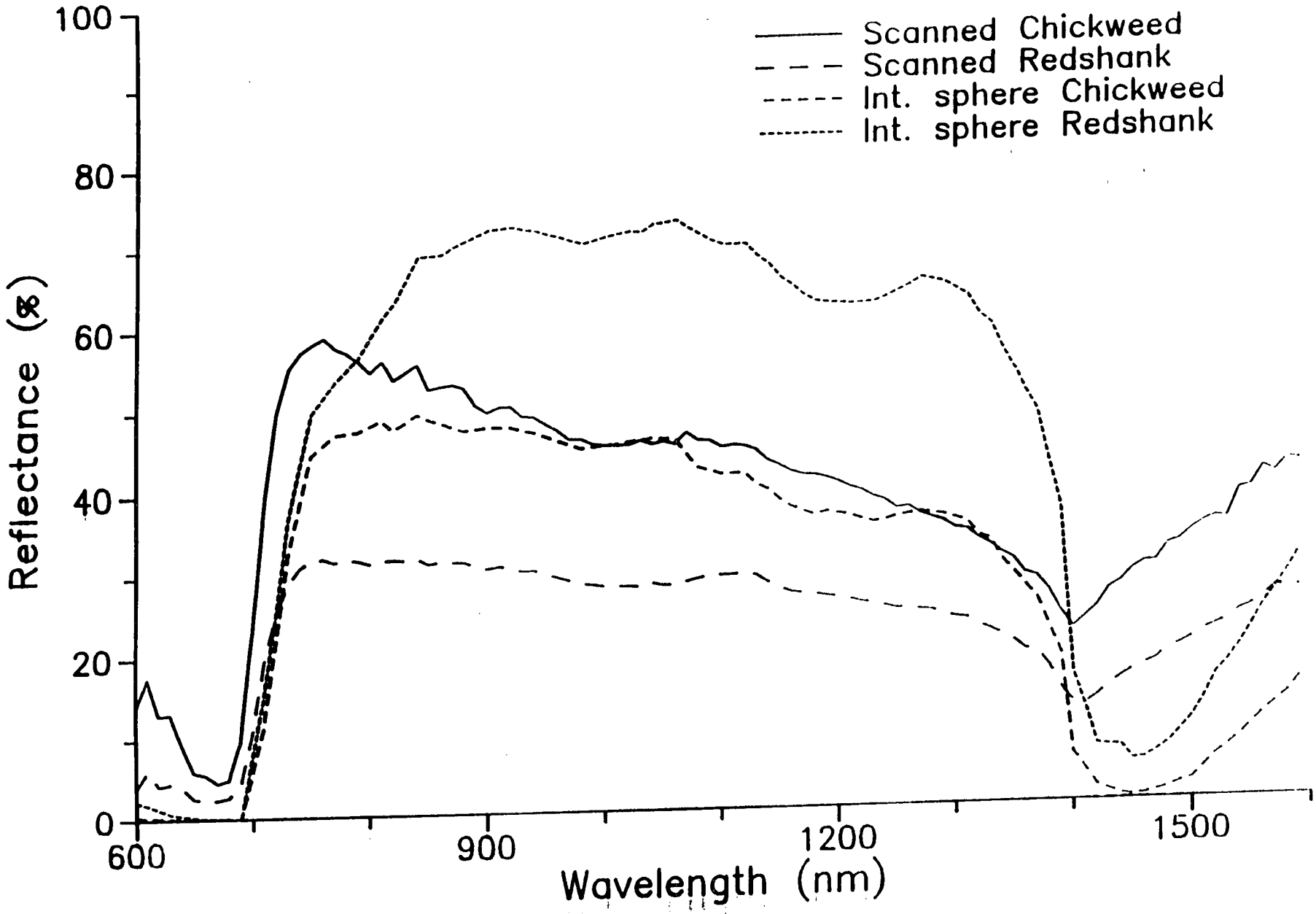

Fig. 1 Spectral differences in redshank and chickweed due to the spectrophotometer used.

Table 8 Discrimination accuracy for turnip using direct wavelengths.

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/weed/soil	Specific category of crop/weed species/soil
23	34	97.62	97.62
28	4	97.62	97.62
32	4	97.62	97.62
27	3	100	95.23
30	3	97.62	95.23
33	3	97.62	92.86
75	2	95.23	76.19
72	2	95.23	73.81

Program run no.	Selected wavelengths, nm			
28	730	100	1360	1480
32	730	990	1360	1480
27	730	1000	1360	
30	1000	1360	1480	
33	990	1360	1480	
75	730	1000		
72	1000	1360		

Table 9 Discrimination accuracy for turnip using wavelength ratios.

Program run no.	Number of wavelengths	Discrimination accuracy, %	
		General category of crop/weed/soil	Specific category of crop/weed species/soil
114	28	100	95.23
52	4	97.62	85.71
116	4	95.23	83.33
133	4	95.23	73.81
120	3	95.23	66 66

Program run no.	Selected wavelengths, nm				
52	730/1000	730/1360	730/1480	100/1480	1380/1480
116	720/990	1340/990	1480/990		
133	740/710	1140/710	1480/710		
120	1340/990	1480/990			

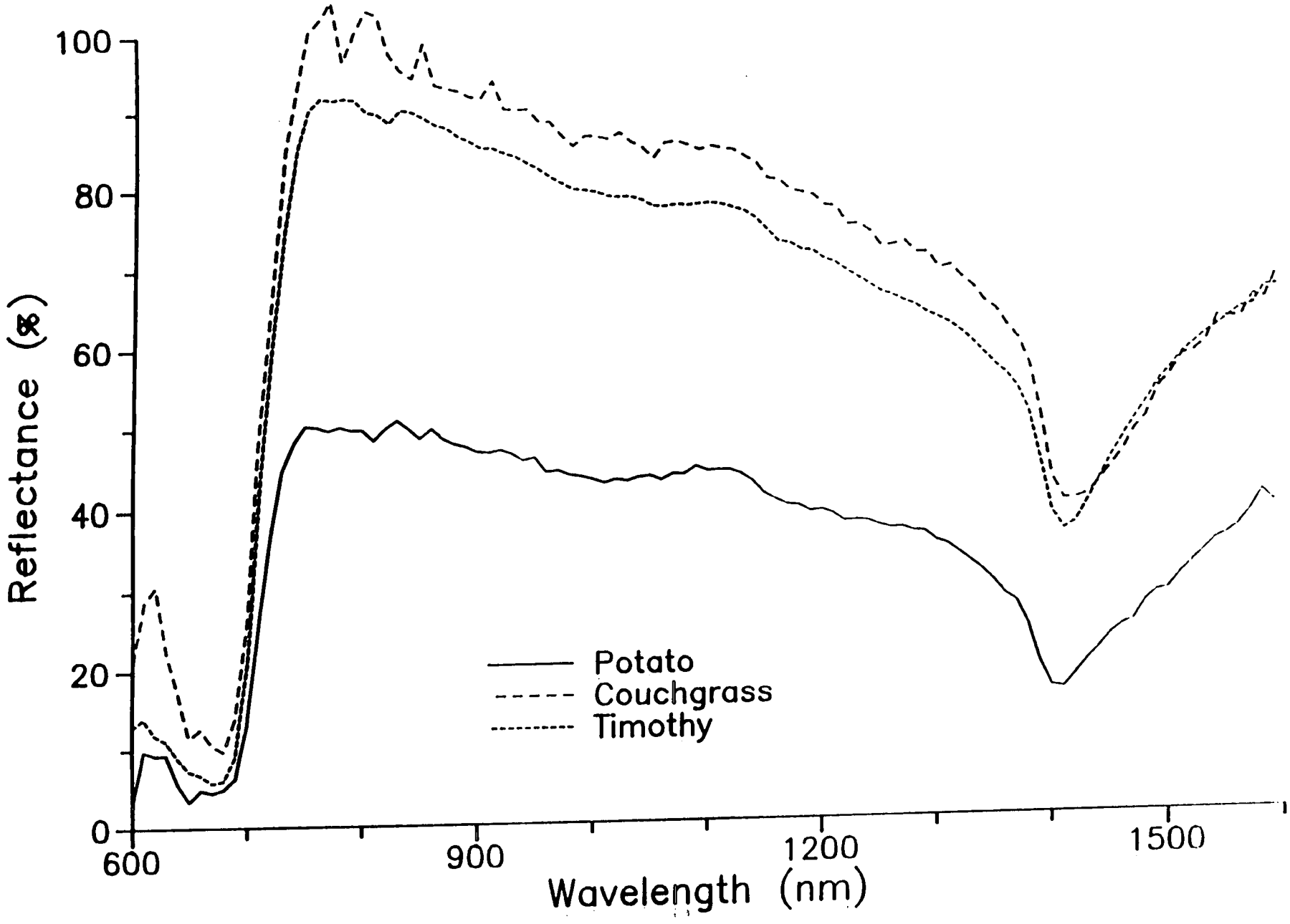

Fig. 2 Potato and grass reflectance

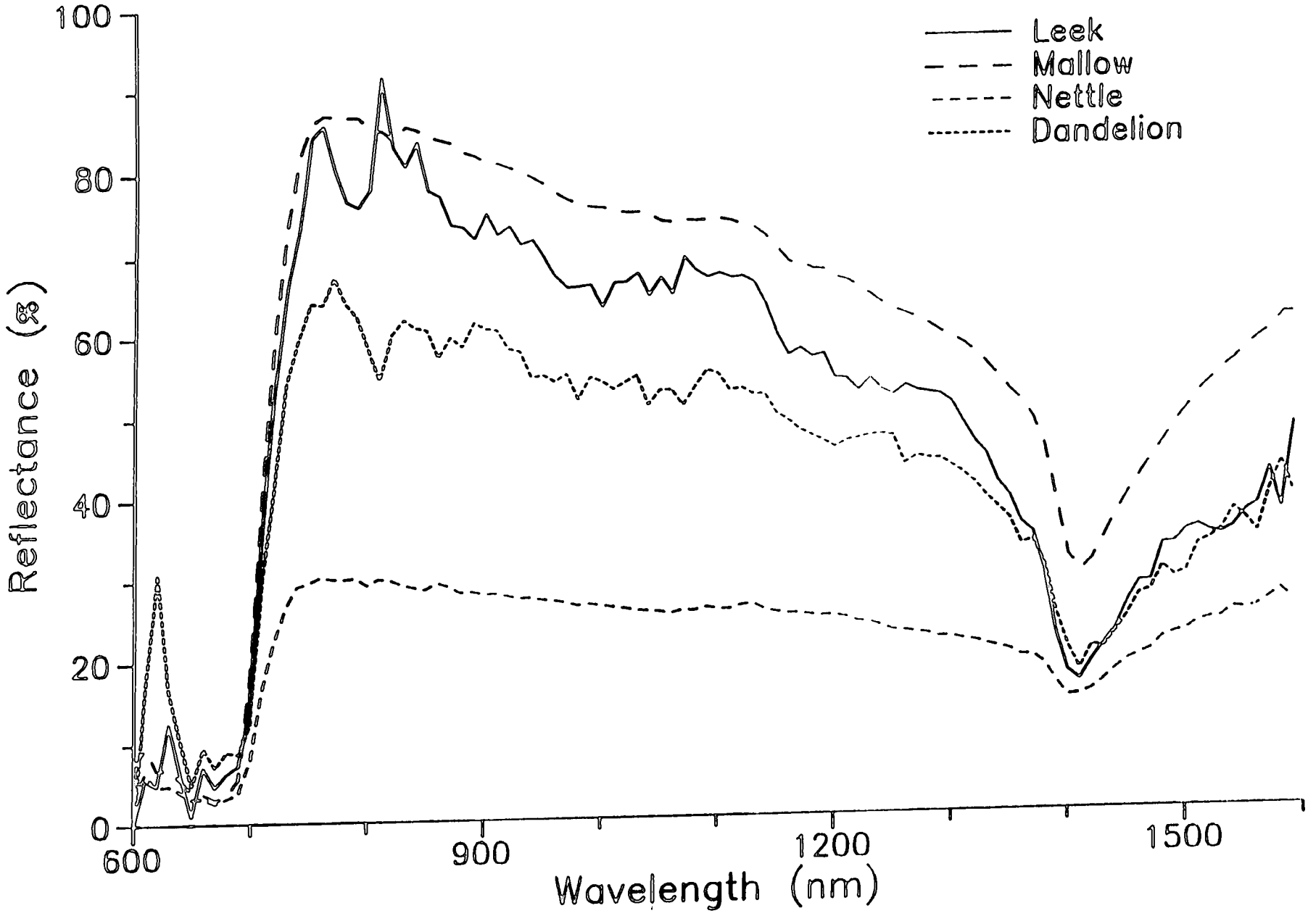

Fig. 3 Leek and weed reflectance

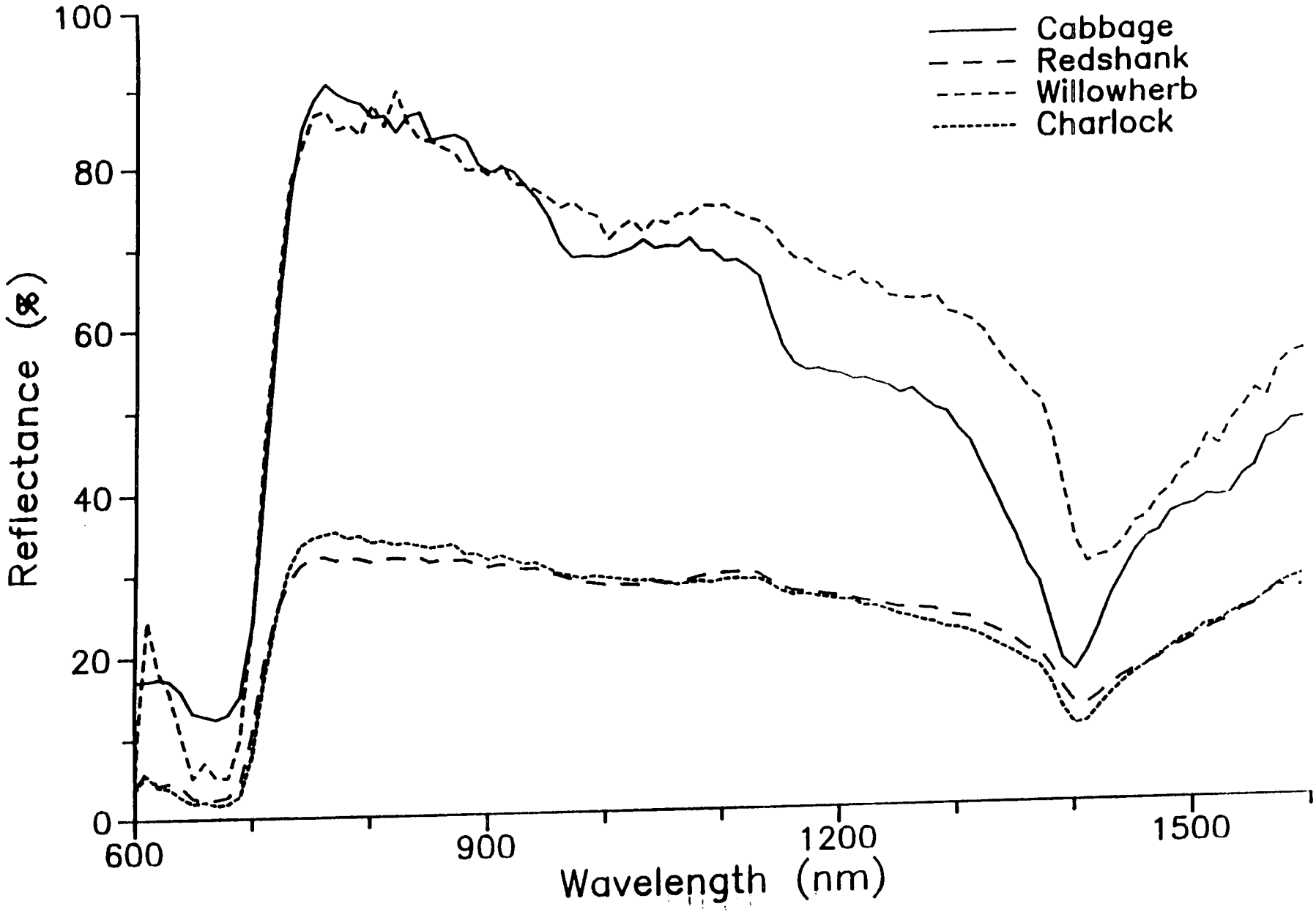

Fig. 4 Cabbage and weed reflectance

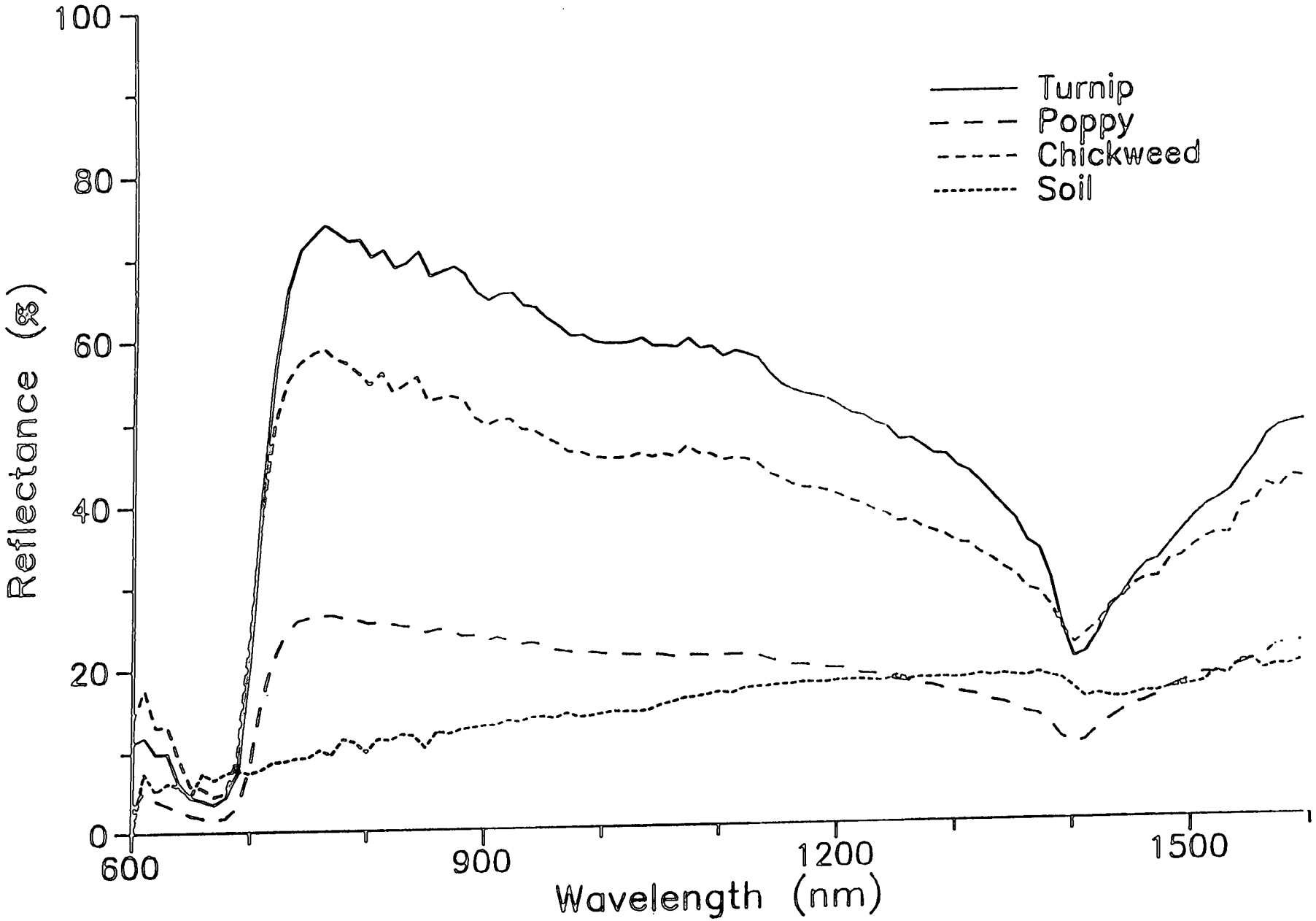

Fig. 5 Turnip, soil and weed reflectance.

SCOTTISH CENTRE OF AGRICULTURAL ENGINEERING

DEPARTMENTAL NOTE 64

November 1993

EFFECT OF BROCCOLI LEAF NITROGEN CONCENTRATION ON CROP/ WEED/ SOIL DISCRIMINATION

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ISSN 0953 413X
ISBN 1 85482 377 9

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SUMMARY

Two experiments were carried out in a greenhouse with broccoli plants grown with different nitrogen concentrations.

Broccoli leaf spectra ranging between 600 and 1600 nm under variable nitrogen concentrations were analysed and the success on crop/weed/soil discrimination obtained.

The second experiment was used to try to correlate different plant nitrogen concentration with optical transmittance in the 400-2500 nm waveband.

It was concluded that nitrogen concentration in broccoli leaves did not affect crop/weed/soil discrimination in the waveband between 600 and 1600 nm.

Regression analysis was carried out on the transmittance data and a good linear fit between optical density and fresh nitrogen was obtained.

CONTENTS

	Page
1. INTRODUCTION	1
2. EXPERIMENTAL PROCEDURE	2
3. RESULTS	2
3.1. Broccoli/weeds/soil discriminant analysis	3
3.2. Discriminant analysis in broccoli with different nitrogen contents	3
4. CONCLUSIONS	4
5. ACKNOWLEDGEMENTS	5
REFERENCES	5

EFFECT OF BROCCOLI LEAF NITROGEN CONCENTRATION ON CROP/ WEED/ SOIL DISCRIMINATION.

1. INTRODUCTION

Nitrogen is required by plants in greater amounts than other soil-derived nutrients as nitrate tends to leach easily. Nitrogen deficiencies limit crop growth and yield. Chemical analyses of foliage are performed by commercial laboratories to monitor nitrogen status, but costs and time for analysis limit their use by farmers.

Analytical studies in different laboratories and agricultural experimental stations have used different spectrophotometers to measure optical transmittance and reflectance in order to obtain a positive correlation with leaf nitrogen concentration. Erez and Weinbaum (1985) correlated transmittance and leaf nitrogen in walnut leaves. Walnut samples were taken from fully expanded leaves in mid-summer, when periods of minimal change in leaf nitrogen concentration were present. Leaf nitrogen may be estimated by light transmittance more accurately in deciduous tree fruit species than in herbaceous annuals, as leaf nitrogen levels change more slowly.

Thomas and Oerther (1972) measured diffuse reflectance from sweet pepper leaves in the 500-2500 nm wavelength interval. Reflectance measurements were taken after 10 weeks of growth. The increased reflectance between 700 and 1300 nm with severe nitrogen deficiency suggested an increase in the intercellular air spaces. The decrease in reflectance of the severely nitrogen-deficient leaves in the 1300 to 2500 nm wavelength interval was associated with their higher water content. Plants were not visibly wilted and reflectance variations in this waveband were small.

Thomas and Gausman (1976) showed that leaf reflectance was a good estimator of nitrogen content in eight different crops including corn. Reflectance on low-nitrogen concentration of maize leaves increased in the visible region and decreased in the NIR range. Al-Abbas et al (1974) noted that all nutrient-deficient plants contained less chlorophyll than the control plants. Higher near infrared reflectance was noted with increasing vegetative cover due to increased light scattering and reflectance by multiple layers. Leaf chronological age did not influence the spectra (750 to 2600 nm) of leaves having the same nutrient treatment. Meyer et al (1992), studying optical reflectance on poinsettia leaves with different nitrogen concentrations, found increments of visible reflectance but virtually no reflectance differences in the NIR range in nitrogen deficient plants. Walburg et al (1982) concluded that agronomic changes such as reduced leaf area, plant height, biomass, chlorophyll content and soil cover caused by nitrogen treatments resulted in detectable reflectance variations.

Nilsson and Linner (1987) reported remote sensing results of wheat and barley field plots affected by nitrogen fertilization and irrigation using a portable radiometer. Four spectral bands of at least 100 nm bandwidth were used. Greatest differences were encountered using the wavelength ratios (800-1100) nm (600-700) nm and (700-800) nm (600-700) nm. The near infrared/red reflectance ratio has been shown to be strongly related to variations in leaf area index of vegetative canopies, while being relatively insensitive to variations in soil background reflectance.

Recent studies have been made to identify crops from weeds using optical reflectance. High success rates in discrimination have been found using six different crops (i.e. potato, leek, turnip, cabbage, cauliflower and broccoli) and a great variety of weeds. Hahn and Muir (1993) studied broccoli/weed/soil discrimination during different broccoli growth stages and concluded that it was not

growth stage dependant. A study, however, was required to determine whether wavebands selected were sensitive to nitrogen status and this paper presents the results.

2. EXPERIMENTAL PROCEDURE

Broccoli plants were sown in the greenhouse in different pots with different nitrogen concentrations. Normal recommendation of nitrogen application for broccoli sown in fields is 250 kg/ha (Anon,1991). Compost was prepared for each pot using peat for root support and different quantities of nitrogen fertiliser were added to each pot in order to produce the 0, 25, 50, 75, 100, 125, 150, 175, 200 and 225 kg/ha application effect. Phosphate and potassium were also added to the compost using the recommended portions of 150 kg/ha. Each seedling was transplanted in its respective pot fifteen days after sowing date.

A MONOLITE scanning spectrophotometer was used to measure leaf spectral reflectance from 600 to 1600 nm in 10 nm increments. Reflectance was measured on the third leaf from top to bottom of each plant 20 days after transplanting. Eight measurements were taken from the top side of each leaf, five of them in the margin and three in the centre of the leaf. The removed leaves were then taken to the SAC laboratory for chemical analysis by the Kjeldahl method.

Five weeds commonly encountered in broccoli fields were sampled for the study:

redshank *(polygonum persicaria)*
chickweed (*stellaria media*)
nettle (*urtica urens*)
poppy *(papaver rhoeas)*
charlock *(sinapsis arvensis)*

Broccoli, weeds and soil spectra were analyzed using the BMDP statistic software.

Another set of broccoli plants were sown in the greenhouse with identical fertilisation applications. Optical transmittance in the 400-2500 nm range with increments of 2 nm was measured with an analytical spectrophotometer. The third leaf from top to bottom was removed and samples mounted in cuvette holders.

3. RESULTS

Discriminant analysis was used to study the effect of broccoli leaf nitrogen concentration on broccoli/weed/soil discrimination. The study was done with spectral data grouped into three general categories, i.e. broccoli, weeds and soil. Two kinds of wavebands were considered for the analyses: broadband and narrowband. The former consisted of sets of 50 or more wavelengths. The broad bands considered were 600-1600 nm, 600-1100 nm and 1100-1600 nm. Narrowbands had a maximum spectral range of 200 nm or 20 wavelengths. Five narrowbands were considered in the study covering all of the 600-1600 nm spectral band: 600-800 nm, 800-1000 nm, 1000-1200 nm, 1200-1400 nm and 1400-1600 nm.

The success of a program run for a particular spectral band or wavelength was determined in three ways:

(i) success in classifying a case from the trial group into its general category of crop/weed/soil;

(ii) success in classifying a case from the trial group into its correct category of crop/weed species/soil;

(iii) success in classifying a case from the trial group into its correct category of crop nitrogen concentration/weed species/soil.

Fifty analyses were carried out studying different spectral bands and wavelength sets.

3.1 Broccoli/weeds/soil discriminant analysis

Broccoli leaf spectra from four different leaves were averaged and plotted, Fig 1. Leaf spectral differences for 0.506%, 1.069% and 1.26% fresh nitrogen concentrations were found to be very small as was the water content.

A total of 90 spectra were used to study broccoli/weeds/soil discrimination. Thirty broccoli spectra were grouped into six different nitrogen concentration categories named NIT1, NIT2,...,NIT6. Each of the five weed species had ten spectra and were categorised separately, Table 1. The program used 60 spectra to obtain the classification function and 30 spectra formed a trial group.

A 100% broccoli/weed/soil and broccoli/weed-species/soil discrimination was obtained with the entire spectral band (600-1600 nm), Table 2. Eleven of the twelve broccoli spectra were well classified into their respective nitrogen categories.

Two broad spectral bands (600-1100 and 1100-1600) were studied and weed species and broccoli nitrogen categories were found to be best classified using the lower waveband. From the five narrowbands the 800-1000 nm and 1000-1200 nm bands could not classify broccoli, weed and soil. The best narrow band was found between 1200 and 1400 nm having 100% and 96.6% success rates in broccoli/weeds/soil and broccoli/weed species/soil discrimination. Chickweed was the only weed misclassified.

A 100% broccoli/weed/soil discrimination was achieved using only two wavelengths, 720 and 1000 nm. The use of only two wavelengths reduced broccoli nitrogen concentration/weed species/soil and broccoli/weed species/soil classification to 70% and 83.3% respectively.

3.2 Discriminant analysis in broccoli with different nitrogen contents.

Leaf transmittance for different nitrogen concentrations was studied using a broader spectral band (400-2500 nm). Some instruments use optical density defined as $\log_{10}$ (T) in order to obtain magnitudes ranging between 0 and 2. Fig. 2 plots optical density spectra from three leaves with different fresh nitrogen concentrations. From ten different plants, five were selected to relate reflectance to leaf nitrogen concentration. For each sample the fresh nitrogen was obtained by multiplying the crude protein by the dry matter and dividing the result by 625, Table 4. An increase in transmittance with nitrogen concentration was noted from 500 to 600 nm and from 2000 to 2500 nm. Discrimination between leaves with different nitrogen concentrations was not easily noted in the other wavelengths of the spectra. Fig. 3 plots the optical density spectra of the top and the underside tissues

of the blade, presenting a higher optical density on the top side. Optical density differences on the top side for different nitrogen concentrations are found in the water and chlorophyll absorption bands. Optical density differences between both sides of the leaf with 0.729% fresh nitrogen are noted between 1500 and 1800 nm.

The success of a program run for a particular set of wavelengths that best discriminates reflectance on leaves for different nitrogen concentrations without the use of trial groups was determined by:

(i) success in the classification matrix, where the number of spectra properly classified into each group and the percent of correct classifications are shown;

(ii) success in the jackknifed classification matrix, where each spectra is classified into a nitrogen concentration group according to the classification functions computed from all the data except the case being classified.

A 100% success rate on nitrogen concentration discrimination was provided by the classification matrix using two wavelengths, although only 70% by jackknife classification was achieved, Table 5. The use of four wavelengths gave the highest discrimination efficiency in the jackknife classification. These wavelengths were considered as variables and linear regression algorithms were evaluated. The use of three wavelengths, 790 nm, 1150 nm and 1230 nm provided the most accurate algorithm for fresh nitrogen, Table 6. The equation defining fresh nitrogen is:

$$\text{FRESH NIT}(\%) = 1.546 + 28.1 * \text{OD}(1150) - 17.87 * \text{OD}(790) - 21.74 * \text{OD}(1230)$$

where OD(790), OD(1150) and OD(1230) represent the optical density at 790,1150 and 1230 nm.

4. CONCLUSIONS

Optical reflectance and transmittance measurements were taken from broccoli leaves with different nitrogen concentrations. Transmittance measurements were expressed as optical density. Optical density throughout the spectra showed differences on the top side of the blade for varying nitrogen concentration. The main differences were noted in the water and chlorophyll absorption bands. The highest optical density difference between both sides of the leaf was encountered on the 1500-1800 nm range.

Broadband and narrowband analyses were carried out to determine the bands having better success rates on crop/weed/soil discrimination for crop samples with different nitrogen concentration. Better crop/weed/soil discrimination was found in the 600-1100 nm broadband than in the 1100-1600 nm broadband.

Broccoli/weed/soil, broccoli/weed species/soil and broccoli nitrogen concentration/weed species/soil achieved discrimination of 100%, 96.6% and 90% with only three wavelengths, 720, 1000 and 1410 nm. The only weed misclassified was redshank. Broccoli/weed/soil discrimination achieved a 100% success rate with only two wavelengths, 720 and 1000 nm. However, broccoli/weed species/soil discrimination was reduced to 83.3% due to charlock and redshank classification problems. Although several N_2 concentrations were used, the discrimination success rates of crop/weed/soil and crop/weed species/soil (Table 2) were found to be very high-apart from results from the narrow band analysis 800-1000 mm. This indicates that the N_2 concentration level did not have a deleterious effect on the reliability of discrimination.

Regression analysis was carried out to correlate fresh nitrogen and optical transmittance expressed as optical density. An accurate correlation was found using three wavelengths. 720 nm, 1150 nm and 1230 nm.

Further analyses with different crops should be carried out to determine possible bands with practical application in the field of fertiliser management.

5. ACKNOWLEDGEMENTS

We wish to thank Dr Ian Murray, at SAC Aberdeen for his assistance and for access to the analytical spectrophotometer. A Y Muir wishes to thank the Scottish Office Agriculture and Fisheries Department for funding this work. F. Hahn acknowledges the support provided by the Mexican Government represented by the Tecnologico Regional de la Laguna and by CONACYT.

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Table 1 **Number of spectra in each of the crop/weed/soil categories, in the training group used to derive classification functions, and in the trial group used for testing discrimination accuracy with broccoli leaves.**

Crop/weed/soil	Number of spectra		
	Total	Training group	Trialing group
NIT1	5	3	2
NIT2	5	3	2
NIT3	5	3	2
NIT4	5	3	2
NIT5	5	3	2
NIT6	5	3	2
Redshank	10	7	3
Chickweed	10	7	3
Charlock	10	7	3
Poppy	10	7	3
Nettle	10	7	3
Soil	10	7	3
Total	90	60	30

Table 2 **Discrimination accuracy for six different broccoli nitrogen concentrations from weeds and soils, using different spectral bands.**

Program run no.	Wavelength range (nm)	Discrimination accuracy (%)		
		Gen. cat. crop/weed/soil	Spec. cat. crop/weed species/soil	Spec. cat. crop nitrogen/ weed species/soil
1	600 to 800	100	93.3	73.3
2	800 to 100	93.3	80.0	53.3
3	1000 to 1200	90.0	90.0	73.3
4	1200 to 1400	100	96.6	76.6
5	1400 to 1600	100	90.0	73.3
18	600 to 1100	100	96.6	80.0
19	1100 to 1600	100	93.3	76.6
20	600 to 1600	100	100	96.6

Table 3 **Discrimination accuracy for six different broccoli nitrogen concentrations from weeds and soil, using direct wavelengths.**

Program run no.	Number of wavelength	Discrimination accuracy (%)		
		Gen. cat. crop/weed/soil	Spec. cat. crop/weed species/soil	Spec. cat. crop nitrogen/ weed species/soil
8	13	100	100	96.6
10	4	100	96.6	90.0
12	3	100	96.6	90.0
11	3	100	83.3	70.0
13	2	100	83.3	70.0
15	2	100	83.3	66.6

Program run no.	Selected wavelengths (nm)
R10	720, 1000, 1250, 1410
R12	720, 1000, 1410
R11	720, 840, 1060
R13	720, 1000
R15	840, 1060

Table 4 **Different nitrogen concentration found in five different broccoli plants using the Kjeldahl method.**

Plant no.	Dry matter (g/kg)	Crude protein (g/kg)	Fresh nitrogen (%)
Plant 1	112	220	0.394
Plant 2	107	326	0.558
Plant 3	107	426	0.729
Plant 4	151	335	0.809
Plant 5	116	498	0.924

Table 5 **Percentage of well classified transmittance spectra within their respective group using the classification function and jackknifed classification criteria.**

Program run no.	Classification function (%)	Jackknife class. (%)	Wavelengths selected (nm)
36	100	80	790, 1150, 1230, 1750
38	100	70	900, 1220
39	100	70	890, 1280
40	90	70	740, 880
33	100	40	740, 900, 1220
31	90	50	1680, 2230

Table 6 **Regression R-squared values for different nitrogen concentrations given a set of wavelengths as variables.**

Regression no.	R squared	Wavelength variables (nm)
9	0.9954	790, 1150, 1230
4	0.9913	1680, 1860, 2230
5	0.977	880, 920, 1280
8	0.8738	790, 1150
6	0.81	890, 1280

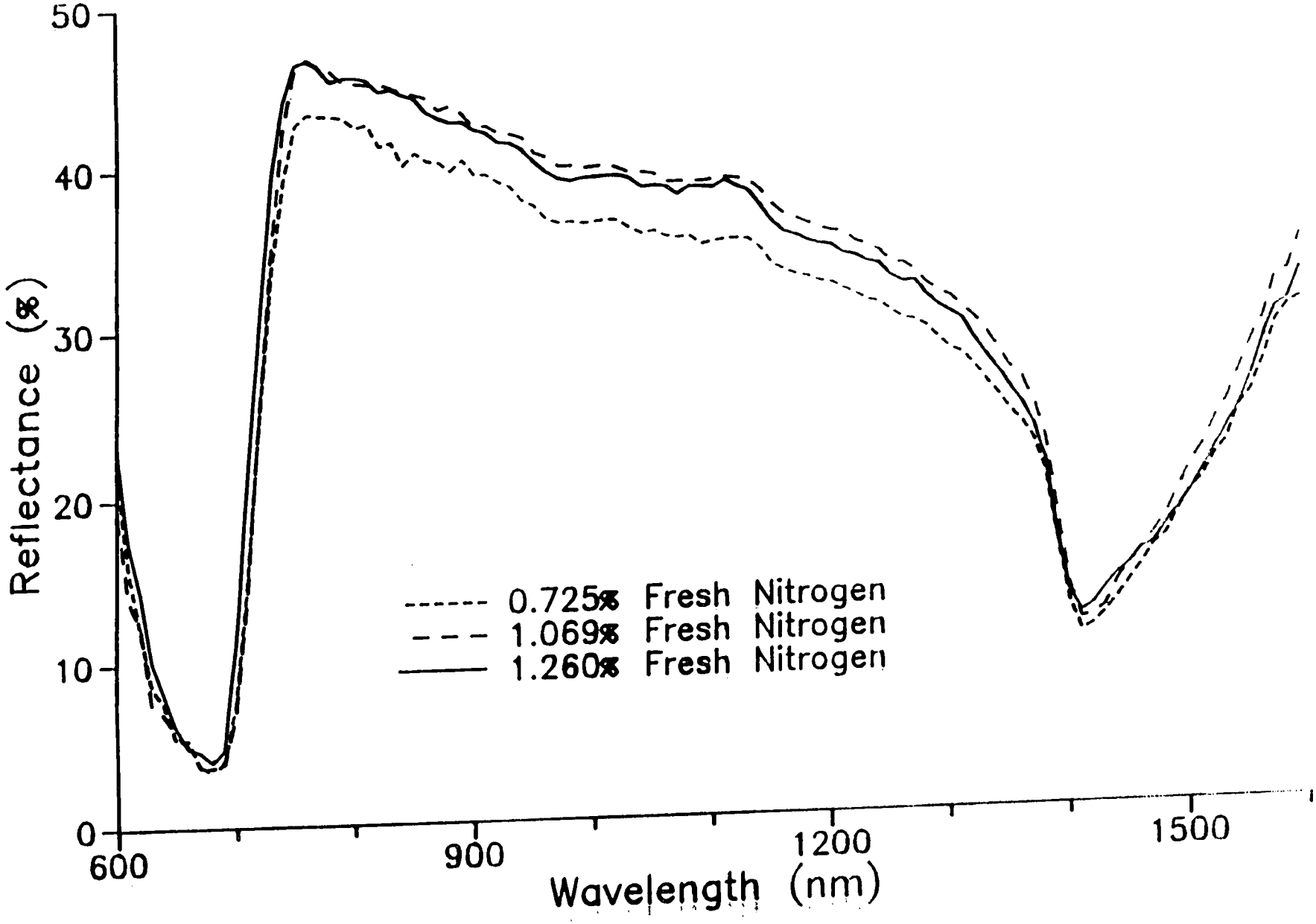

Fig. 1 **Broccoli spectral reflectance for different nitrogen concentrations during experiment 1.**

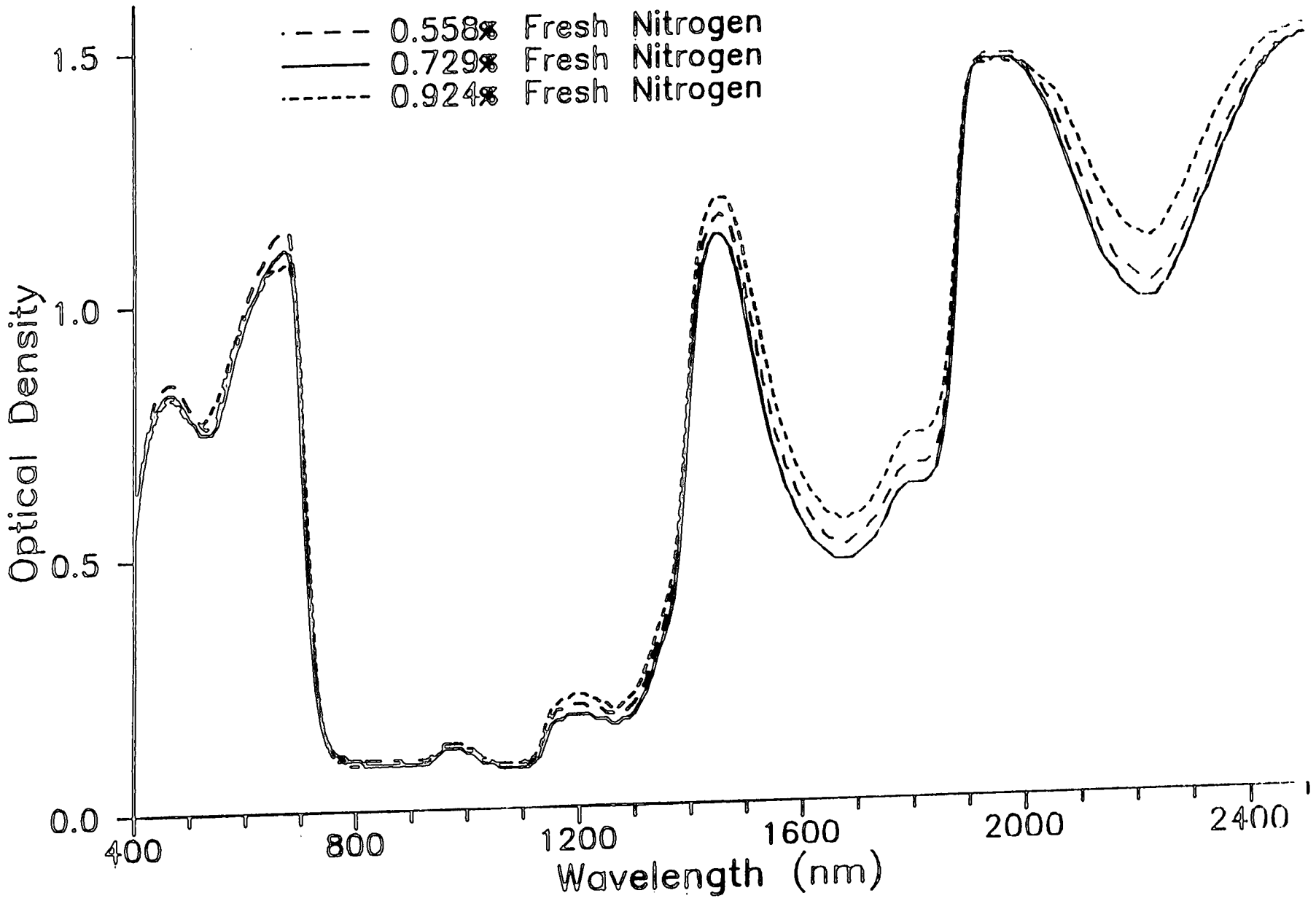

Fig. 2 **Broccoli transmittance expressed in optical density for different nitrogen concentrations during experiment 2.**

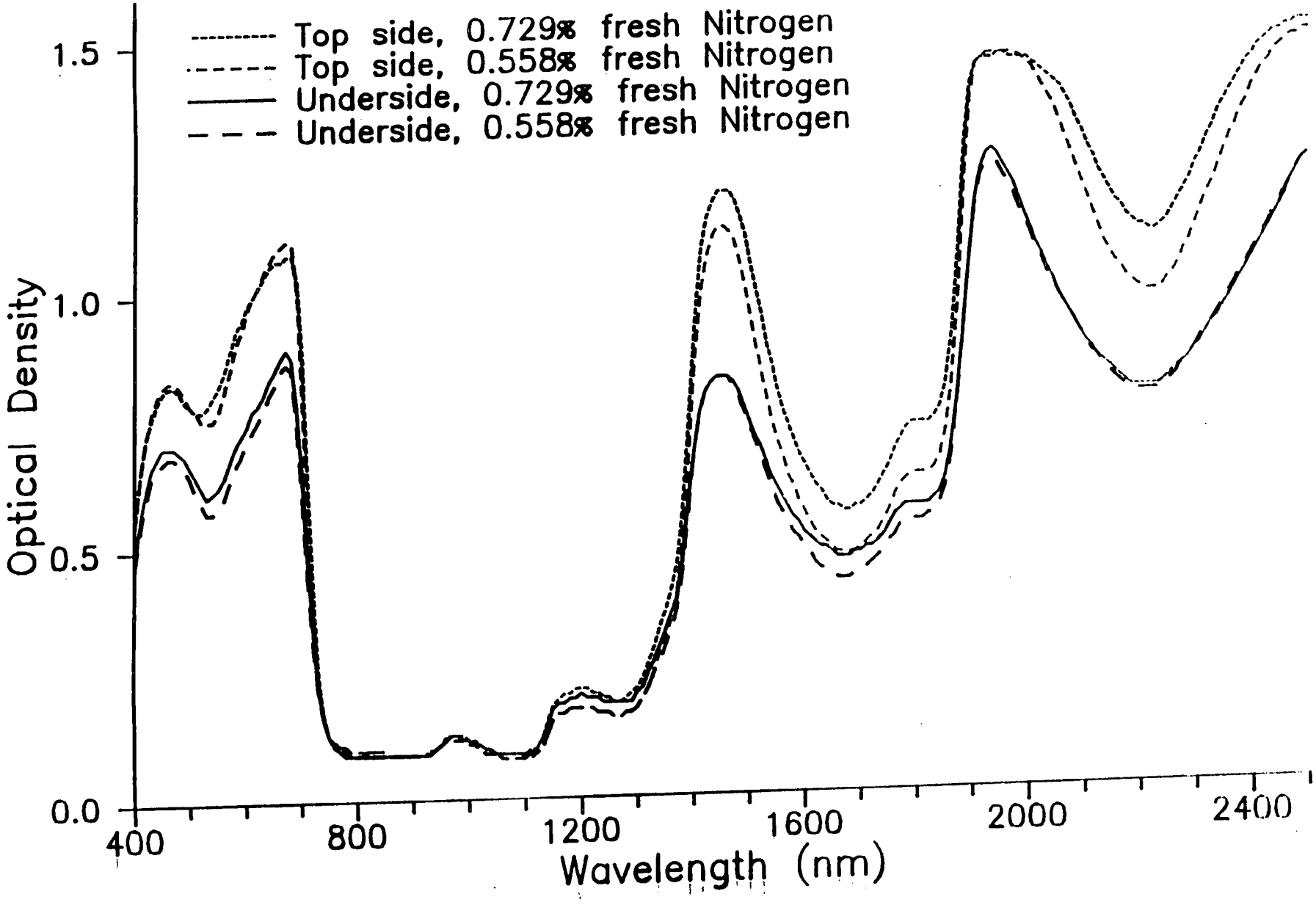

Fig. 3 **Broccoli top and underside spectra for two different concentrations in experiment 2.**