THE INVESTIGATION OF VEGETATION CHANGE USING REMOTE SENSING TO DETECT AND MONITOR MIGRATION OF LANDFILL GAS

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SUMMARY

Decomposition of domestic wastes in an anaerobic environment results in the production of landfill gas. Public concern about landfill disposal and particularly the production of landfill gas has been heightened over the past decade. This has been due in large to the increased quantities of gas being generated as a result of modern disposal techniques, and also to their increasing effect on modern urban developments.

In order to avert disasters, effective means of preventing gas migration are required. This, in turn requires accurate detection and monitoring of gas in the subsurface. Point sampling techniques have many drawbacks, and accurate measurement of gas is difficult. Some of the disadvantages of these techniques could be overcome by assessing the impact of gas on biological systems.

This research explores the effects of landfill gas on plants, and hence on the spectral response of vegetation canopies. Examination of the landfill gas / vegetation relationship is covered, both by review of the literature and statistical analysis of field data. The work showed that, although vegetation health was related to landfill gas, it was not possible to define a simple correlation. In the landfill environment, contribution from other variables, such as soil characteristics, frequently confused the relationship.

Two sites are investigated in detail, the sites contrasting in terms of the data available, site conditions, and the degree of damage to vegetation. Gas migration at the Panshanger site was dominantly upwards, affecting crops being grown on the landfill cap. The injury was expressed as an overall decline in plant health. Discriminant analysis was used to account for the variations in plant health, and hence the differences in spectral response of the crop canopy, using a combination of soil and gas variables.

Damage to both woodland and crops at the Ware site was severe, and could be easily related to the presence of gas. Air photographs, aerial video, and airborne thematic mapper data were used to identify damage to vegetation, and relate this to soil type.

The utility of different sensors for this type of application is assessed, and possible improvements that could lead to more widespread use are identified.

The situations in which remote sensing data could be combined with ground survey are identified. In addition, a possible methodology for integrating the two approaches is suggested.

Key words: landfill gas, vegetation injury, remote sensing, airborne thematic mapper, video remote sensing.

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1. INTRODUCTION

Ground based monitoring for landfill gas is fraught with difficulties, partly due to the lack of spatial and temporal perspective, and also to the transient nature of gas in the subsurface. Remote sensing is suggested to be able to add valuable spatial and temporal information to ground based approaches to monitoring. Consequently, this research was carried out in order to assess the application of remote sensing techniques to detect and / or monitor the migration of landfill gas.

1.1 Landfill Sites

Over 200 million tonnes of solid waste are produced each year in Great Britain (Anon, 1989), approximately 90% being disposed to landfill. Of this, approximately 22 million tonnes are household and commercial refuse, the remainder being mine, quarry, and other industrial wastes. If properly executed, landfilling is an environmentally safe, publicly acceptable means of restoring spoiled or poor quality land to productive use.

However, a complex microbiological system usually develops within the site. As defined by Bogner (1986) a landfill is:

> "an in-ground anaerobic digester consisting of a solid framework of buried refuse, and dependent on natural convection and diffusion processes for liquid and gas transfer in and out of the system."

In recent years, the problems associated with landfills have been exacerbated due to increased quantities of wastes being deposited, combined with rising pressure to develop on and around completed sites. These factors have evolved in combination with a heightened public awareness of environmental issues, both in general terms, and specifically with respect to the impact of landfill gas and leachate.

As defined by McCarthy (1972), an impact can be considered as:

> "a disruption, a change from the norm, or an action preventing normal functioning."

Landfill sites can cause environmental impact in a number of ways. For example, heavy metals from the waste may be taken up by vegetation, damaging the plants, and becoming incorporated within the food chain. However, it is the potential impact of leachate and landfill gas that are generally of more concern.

Leachate is a highly toxic liquid produced within the refuse mass. Its exact composition depends on the the composition of the solid waste, the age of the landfill, the rate of percolation of liquid through the waste mass, and the length of time the percolate is in contact with the waste (Hoeks, 1976). The leachate may enter the local hydrologic system with consequent pollution of groundwater supplies. In order to limit the amount of water infiltrating into the waste, and hence the production of leachate, many sites are completed with an impermeable clay cap. Whilst this may reduce many of the problems with leachate, it creates new ones with respect to the migration of landfill gas.

Although often used synonymously with methane, the term 'landfill gas' actually refers to the combination of gases, predominantly methane and carbon dioxide, that are generated within the landfill. The gas is generated within a complex and dynamic ecosystem, and the total quantities and relative proportions of gases generated, vary as the microbiology of the site develops (Figure 1.1).

Figure 1.1 Temporal changes in gas production in a landfill site (from Cairney, 1987)

Reclamation and redevelopment of the sites and their surroundings is hindered by the ability of the gas to migrate from its point of production and into the surrounding area. This can create a number of problems, including:

(i) the risk of explosion if methane accumulates in concentrations of between 5 and 15%,
(ii) the risk of fire due to the flammability of methane in concentrations of up to 15%,

(iii) injury to vegetation,
(iv) odour and toxicity of trace components of the gas,
(v) risk of asphyxiation if work is carried out in confined spaces where gas has accumulated.

1.2 History of Landfill Gas Problems

Concern about the disposal of waste to landfill, and especially about the production of landfill gas, have become more apparent over the past decade (Clay & Norman, 1989; Heasman, 1989a). An initial assessment carried out in 1987 suggested that approximately 1,400 sites had the potential to produce significant quantities of gas, over half of these being within 250 m of housing or industrial developments (Bottomley, 1989).

The heightened public awareness of landfill gas has been largely due to the encroachment of urban development, to the extent that housing is now in close vicinity to what were previously remote sites (Tankard, 1987; Clay & Norman, 1989; Institute Wastes Management, 1989). This has had disastrous consequences in some situations, the most publicised being the explosion and destruction of a bungalow at Loscoe in 1986.

In addition, modern landfilling techniques have resulted in conditions more conducive to the production of gas. That is:

(i) Modern wastes have a higher proportion of biodegradeable materials than those produced previously (Figure 1.2) and therefore have a greater potential to produce landfill gas (Clay & Norman, 1989; Heasman, 1989; HMIP, 1989).

(ii) The traditional practice of open tipping often resulted in fires on site, litter problems, and infestation with vermin. The sites were usually small, and anaerobic conditions often did not develop. In order to control these problems, numerous measures were introduced, including daily compacting and covering of the refuse, and finishing the site with an impermeable cap to minimise infiltration. In addition, sites became larger and deeper, and the development of anaerobic conditions became commonplace.

These factors have combined to result in increased gas production and migration from sites. As a result, the processes of landfill gas generation and migration can no longer be considered to be of minor interest. They are real and very complex issues, about which there is limited understanding.

Figure 1.2 Changes in composition of domestic waste (from Clay & Norman, 1989)

1.3 Landfill Gas Legislation

One of the major problems concerning the waste management and disposal industry at present is the lack of a clearly defined regulatory structure. Legislation directly relevant to landfill gas, does not exist, legislative control of waste disposal being effected through the issue of a licence to the site operator (Small, 1989). Licensing aims to "ensure that the activities of a waste disposal facility do not cause pollution to water, or danger to public health, or become seriously detrimental to the amenities of the locality affected by the activity" (Rae, 1989). Prior to granting a licence allowing the disposal of waste, The Control of Pollution Act (1974) requires the submission of a working plan, with specific reference to conditions for the monitoring of gas.

To provide a guideline for the monitoring of sites, Waste Management Paper No. 27 was produced in 1989 (HMIP, 1989). This paper proposed that, for all sites, whether active, closed, or planned, the potential for the evolution of landfill gas, and for that gas to migrate from the site, must be assessed (Rae, 1989). This would involve both desk and field studies, the initial desk survey aiming to identify the pertinent features of the site and its surroundings, that might allow the migration of gas from the site. The information would be supplemented, and confirmed, by field studies, such work also determining targets (either developments or flora) at risk.

It is now usual practice to include provision for restoration and monitoring of sites at the initial planning stage (Town and Country Planning Act , 1974). Whilst such an agreement is legally binding if included at the planning stage, there is no legal procedure at present to ensure the restoration and monitoring of existing sites.

1.4 Monitoring Techniques

For the above requirements to be fulfilled, an adequate means of monitoring is required. One of the major disadvantages of traditional monitoring techniques, is that they tend to be laborious and time consuming, and the results only give a direct measure of landfill gas concentration at a specific location and time. The readings are then very difficult to extrapolate, either in space or time.

In order to overcome some of these obstacles, the possibility of using biological approaches to monitor landfill sites has been investigated (McCarthy, 1982; Roberts, 1985). The principle of these techniques has been based on the premise that it is more relevant to measure the effect on the environment, than the cause of that effect. Examples of such biological techniques include the measurement of soil microbial populations (see Section 2.4.1), or assessment of plant health.

If injury to the vegetation caused by landfill gas could be identified as causing a change in the spectral response of the vegetation, then the possibility would exist to combine biological monitoring and remote sensing to assess landfill gas migration. The unique attribute of remote sensing techniques, when compared to other sources of information, is the ability to collect spatially comprehensive data about terrestrial ecosystems on a regular, repetitive basis. However, remote sensing systems cannot record actual concentrations of landfill gas, and the presence of gas in the near surface must be inferred from its impact on vegetation. In addition, the problem solving capability of remote sensing relies on the spectral separability of the classes of interest; that is, the sensor must be able to record a difference between the spectral response of healthy plants, and those damaged by landfill gas.

1.5 Aim and Objectives

The main question to be answered was "how can remote sensing be used to assess vegetation damage caused by the migration of landfill gas?" Within this broad outline, more specific questions could be identified:

1. Effects of Landfill Gas on Vegetation

In order to assess the potential use of remote sensing to detect and monitor landfill gas migration, the confirmation of a relationship between the presence of gas, and the effect on plant growth would be required. The initial investigation of the effects of landfill gas on vegetation health was based on review of the literature, and discussion with landfill workers. In addition, fieldwork was carried out at the Panshanger site to determine whether a relationship existed at this location.

2. Remote Sensing to Detect Vegetation Damage

If a relation between landfill gas and vegetation damage could be identified, the next stage of the research would be to assess if changes in the spectral response of vegetation could be identified, and associated with the presence of landfill gas. The confirmation of such a relationship would establish the use of remote sensing to monitor or detect changes in vegetation health as a result of landfill gas.

The data was also used where possible to detect changes in vegetation health as the growing season progressed. Although this was complicated by different sensors being used, it was hoped to draw conclusions about the changing effects of gas with progressing plant phenology.

3. Potential of Remote Sensing

Having established a relation between landfill gas and the spectral response of vegetation, the next step would be to indicate situations where remote sensing could provide a practical source of data to be used in landfill operations, site development, or site monitoring. In addition, the ideal conditions for the successful use of remote sensing techniques could be specified.

4. Cost and Benefits

The analysis of costs and benefits of remote sensing surveys could be divided into two main issues:

(i) Could a monetary value be put to the remote sensing survey, in terms of a reduction in fieldwork? This would involve the assessment of the accuracy and reliability of the remote sensing results, the costs of acquiring the results, and the expected reduction in fieldwork that could be expected by combining this type of survey with more traditional methods.

(ii) To what degree was the more expensive multispectral scanner able to provide superior information compared to the video system? To be of practical interest, a remote sensing survey would have to be cost-effective. Although producing data of superior radiometric and geometric quality, use of airborne multispectral scanner data would normally raise the cost of a remote sensing survey to a level where it would not be practical to implement. For this reason, the potential for video remote sensing to provide timely and low cost information was investigated in some length.

1.6 Outline of Thesis

Previous research covering numerous aspects of landfill gas and remote sensing are discussed in the following two chapters. The second of these initially introduces remote sensing in general, and proceeds to investigate the remote sensing of vegetation damage in more depth. The chapter concludes with a review of recent work involving the remote sensing of landfill sites. Chapter 4 then highlights some of the features of the remote sensing systems used in the research, and the ways in which these could be expected to affect their practical application in such surveys.

Chapters 5 and 6 cover the use of field data and remotely sensed imagery at two restored domestic landfills, both with records of vegetation damage attributed to landfill gas. At the Panshanger site, poor crop growth, chlorosis, and dieback of vegetation had been observed on the landfill cap; this was attributed to the upward migration of gas through the cap, via land drains and natural pathways within the soil. However, the variability of soil characteristics at this site was anticipated to confuse the relationship between landfill gas and vegetation health.

The situation at the Ware Quarry site was somewhat different, with substantial quantities of gas migrating laterally and affecting local woodland and agricultural areas. In this case, the relation between landfill gas and vegetation damage was more straightforward, firstly due to the high gas concentrations, and secondly as a result of the gas migrating laterally and affecting vegetation on adjacent undisturbed land.

The knowledge gained from these studies was used as the basis for a methodology for the integration of remote sensing and ground-based surveys (Chapter 7). Finally, possible improvements in the sensors and techniques that could affect their future utility, are described.

1.7 Summary

There is a need for a method of gaining geographical information about landfill gas migration due to the problems of ground-based landfill gas monitoring. Although not being able to provide a perfect solution, remote sensing was envisioned to be able to contribute unique information to gas monitoring surveys, and enhance understanding of gas migration at sites. Such information could aid in site investigations and day to day running of sites in certain circumstances.

2 LANDFILL SITES

2.1 Introduction

This chapter reviews some of the work that has been carried out to investigate the problems of landfill gas, specifically concerning the production, migration, and monitoring of gas, and its effect on soils and vegetation. From this understanding, it is possible to comprehend the different ways, in which, landfill gas may affect vegetation, and thus assess the possibilities of using vegetation as an indicator of the presence of gas.

A complex ecology exists within the landfill, and in adjacent soils, with many of the interrelations still not being fully understood. After an initial aerobic stage of waste decomposition, anaerobic conditions develop and landfill gas and leachate are produced in substantial quantities. Whilst leachate poses a very real threat to groundwater and, at times, surface water, the application of remote sensing to leachate - related problems is very restricted (Section 3.4).

Landfill gas may migrate away from the site and into local soils, its movement being controlled by a number of factors. In the adjacent soils, a second series of microbiological reactions effect changes in the gas composition, simultaneously modifying many of the soil characteristics. The presence of gas, and corresponding alteration in soil properties, in turn affects the health of plants growing on these soils. In reality, the situation is extremely complex, and this chapter aims to briefly describe the individual variables and their interrelations.

2.2 Generation of Landfill Gas

The establishment of a balanced anaerobic microbial population in an aqueous landfill environment results in the eventual production of landfill gas and leachate. As described in Section 2.2.2, many factors may influence development of the microbial population, and hence the production of landfill gas in landfill sites (Farquhar & Rovers, 1973; Rees, 1980; McBean & Farquhar, 1980; Barry, 1986; Pacey & DeGier, 1986). The inherent variability of these parameters mean that there is still limited understanding of the factors involved, and accurate prediction of landfill gas production is difficult (Pacey & DeGier, 1986). Often the rates of production of gas are insufficient for its economic collection and utilisation but are rapid enough to cause environmental and safety problems (Rees, 1980). Thus much of the recent work has been directed towards understanding the processes involved in gas generation so that production rates can be maximised with the possibility of economic recovery (Rees & Grainger, 1982; Senior *et al* , 1983b; Lawson, 1988).

2.2.1 Stages in Landfill Gas Production

Carbon dioxide and methane are the major end products of a complex series of biological and biochemical reactions in the refuse mass, as shown in Figure 2.1 (Senior *et al* , 1983a; Senior *et al* , 1983b; Lawson, 1988; Clay & Norman, 1989; Sleat *et al* , 1989). The sequence can be subdivided into four phases, controlled by the evolving microbiological ecosystem within the wastes (see Figure 1.1) (Farquhar & Rovers, 1973; Dessanti & Peter, 1984; Barry, 1986):

Phase I — Organic matter is decomposed aerobically in the presence of water and oxygen. The length of the phase may vary according to the availability of oxygen but is often quite short, typically being several days to weeks. Since the methane-producing bacteria are strict anaerobes, establishment of a methanogenic bacterial population is prevented.

Phase II — This stage commences with the depletion of the oxygen content in the waste and may last several months. Anaerobic 'acid-forming' (acetogenic) bacteria break down cellulose, fats, proteins, and carbohydrates to organic acids as well as carbon dioxide and hydrogen. Simultaneously the methanogenic bacterial population starts to become established. The stage may last several months depending on conditions within the site.

Phase III — Methanogenic bacteria, principally *Methanobacterium sp*., become more important resulting in increased proportions of methane and decreased proportions of carbon dioxide and hydrogen. During this phase the methane concentration increases to a relatively constant value.

Phase IV — The relative proportions and volumes of gases are more stable. The absolute production rate and composition of the gas varies according to external factors (atmospheric pressure, temperature, etc.) as well as conditions internal to the site (moisture status, availability of nutrients, build up of toxins, etc.). This stage usually lasts 10 to 20 years; however in the absence of fully anaerobic conditions it may be prolonged for up to 100 years (Rees, 1980).

Figure 2.1 Production of landfill gas (from Senior *et al* , 1983 a & b; Sleat *et al* , 1989; Lawson, 1988).

These are not distinct phases, rather the different stages merge into each other as each group of bacteria become prominent. In addition, different phases may exist at various locations within the same site.

The presence of components such as plastics, textiles and solvents in the waste often results in the appearance of trace gases such as halocarbons and alcohols (Young & Parker, 1983; Parsons & Smith, 1986; Clay & Norman, 1989). These components may be odorous and give rise to complaint, although their effects on health have not been extensively evaluated.

2.2.2 Factors Affecting Gas Production

Landfill gas is produced by the microbial degradation of organic matter, and any conditions that affect microbial activity will influence the rate of production and/or composition of the gas generated (Dessanti & Peter, 1984). Potentially relevant factors include moisture status, oxygen status, pH, temperature and the availability of nutrients and/or toxins. These are in turn affected by a number of waste characteristics, management, physical and climatic factors (Figure 2.2).

Anaerobic digestion occurs in an aqueous environment that contains the bacteria and their nutrients; the same environment also receiving the by-products of the processes. Previous work has shown that the bacteria which produce methane perform better as the moisture content increases, maximum gas production occurring at 40 to 45 % moisture content by volume (Rees, 1980; Barry, 1986; Pacey & DeGier, 1986). In a landfill, the aqueous environment is initially provided by the moisture content of the wastes. This may then be influenced by surface water infiltration, groundwater ingress, settlement of refuse, and water released during decomposition (Pacey & DeGier, 1986). In addition, reactivation of sites may occur if the local groundwater regime changes and water ingresses into the site (Crowhurst, 1987; Institute Wastes Management, 1989).

Production of landfill gas requires an oxygen-free environment and strongly reducing conditions (Rees, 1980; Pacey & DeGier, 1986). If the conditions have a tendency to be aerobic (for example if the site is shallow), the methanogenic bacterial population cannot

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Figure 2.2 Factors affecting Gas Generation (from Cairney, 1987)

become established and balanced fermentation does not occur. In such situations, the waste may undergo aerobic degradation to carbon dioxide and water (Heasman, 1989a).

Although methane fermentation will proceed in the range 6.5 to 8.0, the optimum pH is around neutral. Most landfills have an initially low pH, but over the first year or two this increases towards neutrality, promoting more favourable conditions. The presence of leachate and its components may have an important effect on pH due to its buffering effect (Rees, 1980; Pacey & DeGier, 1986).

Generally, increases in temperature lead to increased methane production, optimal temperatures being between 29 and 57^{0}C (Pacey & DeGier, 1986); however fluctuating temperatures create unfavourable conditions for gas generation as the microbiological community cannot become stable. Such fluctuations in temperature may be expected in the top layer of the landfill, reflecting the influence of ambient air temperature (Rees, 1980; Pacey & DeGier, 1986). In the case of shallow landfills, the whole waste mass may be affected.

Nutrient availability is not normally a factor restricting bacterial growth in the landfill environment, the usual limiting nutrients, such as nitrogen and phosphorus, being present in excess (Rees, 1980). Other elements such as carbon, hydrogen, sodium, potassium, magnesium, calcium, and sulphur, that are also required for bacterial growth, are again generally present in large quantities. Elements such as calcium or magnesium, may actually be toxic or inhibitory if they are present in high concentrations (Halvadakis *et al*, 1983; Pacey & DeGier, 1986; Grainger, 1987). The interaction of various nutrients is a complex subject and is dealt with in greater detail by Pacey & DeGier (1986) and EMCON Assoc (1980).

In addition to these factors, both gas production rates and the total gas produced are influenced by waste characteristics, specifically waste composition and density (Halvadakis *et al*, 1983; Pacey & DeGier, 1986; Archer *et al*, 1989). The majority of methane in modern landfills is derived from the degradation of paper components due to the high proportion of these components in the waste (Halvadakis *et al*, 1983; Campbell, 1985; Pacey & DeGier, 1986; Archer *et al*, 1989).

An increase in waste density may enhance methane production due to the increase in saturation and decrease in void space, effectively excluding air and shortening the aerobic phase (Halvadakis *et al*, 1983; Pacey & DeGier, 1986). An increase in gas production rates could also be expected with decreasing particle size due to the increase in surface area : volume ratio. However, total methane production may be reduced due to the fact that polymer hydrolysis and fermentation to fatty acids is so rapid that the growth of methanogenic bacteria is inhibited (DeWalle & Chian, 1979; Rees, 1980).

All these variables interact to some degree to produce an environment conducive, or inhibitory, to the production of landfill gas.

2.3 Migration of Landfill Gas

Unlike solid contaminants which generally remain at fixed locations, landfill gas can travel considerable distances, its movement being controlled by the local geology and hydrogeology. The presence of landfill gas has been recorded at distances of up to 200m from the edge of sites (Flower, 1976; Leone *et al*, 1977a; Leone *et al*, 1977b; Carpenter, 1986; Jones, 1990; Jones *et al*, 1990).

Due to the increased awareness of the hazards caused by landfill gas, modern landfill design includes a provision for the monitoring and control of landfill gas; however, older restored sites present much more of a problem (Campbell, 1989a). The hazard of landfill gas migration has been brought into focus in recent years due to numerous incidents, ranging from reports of odours, vegetation damage and dieback, to explosions resulting in damage to properties and injury to residents (County Surveyors Soc., 1982; Zimmerman *et al*, 1982; Barry, 1986; Tankard, 1986; Reeds, 1987; Tankard, 1987; Institute Wastes Management, 1989; Williams & Aitkenhead, 1989). To parties interested in developing land adjacent to completed landfills, the issue of gas migration may be critical (Campbell, 1987; Vosper, 1989; HMIP, 1989).

2.3.1 Causes of Migration

Landfill gas may migrate away from a site due to diffusion, or as a result of the existence of a pressure gradient, the type of movement depending on the conditions internal and external to the site. It is the generation of gas within the site that creates the initial pressure difference causing the gas to migrate; however the rate and extent of migration is strongly influenced by a number of other factors.

In general, during dry weather fractures and other migration pathways are open, pressure gradients are correspondingly lower, and the main mechanism for gas migration is diffusion (Bogner *et al*, 1986; Barry, 1986). However, in most situations a number of variables external to the waste mass combine to create a pressure gradient. Such factors include the obstruction of migration pathways, usually due to sealing of fractures and micropores in the soil with increased soil moisture, a drop in barometric pressure, or changes in the water table creating a 'pumping' effect (Barry, 1986; Bogner *et al*, 1986; Campbell, 1987; DoE, 1988).

The potential of atmospheric pressure changes to affect gas migration was highlighted by an incident in 1986, when a bungalow in Loscoe was destroyed by the explosion of landfill gas. Here a drop of 29 mbars (atmospheric pressure) in 7 hours created a large pressure difference between the landfill and the surroundings. The pressure difference in turn caused gas to migrate from the landfill and accumulate underneath nearby housing where it subsequently exploded (Tankard, 1987; Williams & Aitkenhead, 1989).

2.3.2 Migration Pathways

Landfill gas may migrate upwards through the cap or laterally away from the site, the direction of movement depending on the path of least resistance and the existence of pressure differences. Various factors related to site management can be expected to influence the accumulation of gas within the site, and its release at specific points (Campbell, 1989a).

Within the site, the actual design of the landfill strongly influences lateral migration, the heterogeneous nature of most landfills ensuring that a wide range of permeabilities exist (Campbell, 1989a). Lateral migration predominates over vertical movement for a number of reasons; firstly, waste is commonly emplaced in a layered formation, tending to produce horizontal zones within the site with higher compaction, and hence lower permeability. In addition, modern landfill practice involves the daily covering of waste with inert material, and the completion of sites with a relatively impermeable capping layer to reduce rainwater infiltration. Both these processes create horizontal layers of lower permeability. As a result of the above, localised perched water tables may develop, further reducing vertical gas migration.

All these factors combine to promote the lateral migration of gas towards the site boundaries, and out of the site. Gas migration beyond the site boundaries is controlled by the nature of the strata beneath and adjacent to the landfill. In new landfills, the interface between the waste and the site boundary generally incorporates some sort of barrier or venting system. However, many completed sites have no migration prevention systems and the interface may not significantly impede the movement of gas (Campbell, 1989a). Once beyond the site boundaries, the gas moves through micropores and macropores (fractures) in unconsolidated deposits, or via mechanical discontinuities such as fractures, joints, bedding, and fault planes in more consolidated rocks (Bogner, 1986; Carpenter, 1986; Williams & Aitkenhead, 1989). The boundary itself, may provide a rapid migration route for gases.

There are numerous variables affecting the movement of gas, both spatially and temporally, through the strata external to the site. Within each geological formation there may be a wide range of permeabilities; sands and gravels are rarely homogeneous in nature, and clay deposits may contain discrete layers and lenses of more permeable sand (Flower *et al*, 1981). In addition, fractures and fissures within bedrock tend to be very variable, both in size and extent (Williams & Aitkenhead, 1989). An example of the influence of local geology on gas migration was given by Carpenter (1986), who described gas migrating on two separate levels at a site in Kent. Movement occurred firstly at 3 to 4m depth through permeable gravel strata, and also at 10 to 15m depth through fissures in the underlying Chalk.

A further complication may be added if the dip of the beds is not horizontal, resulting in permeable beds intersecting the land surface at some distance from the site boundary (Figure 2.3) (Campbell, 1989a; Jones, 1990; Jones *et al*, 1990). Such a situation was encountered at the Ware Quarry site, and is discussed in further detail in Chapter 6.

Other factors that influence gas migration pathways include localised perched water tables or groundwater tables that may vary with time, and changes in land use, for example, changing agricultural use, redevelopment for building, completion and restoration of sites.

Artificial migration pathways such as land drains (Spreull & Cullum, 1987) and relicts of mining activities e.g. Chalk/flint workings, mine conduits (Carpenter, 1986) may also provide passageways for gas migration. Carpenter (1986) cited one example where the passage of gas was greatly assisted by the presence of access holes and underground passages in the area, the gas travelling approximately 100m underneath a wood and causing substantial and persistent crop failure.

Attempts have been made to assess or predict the likely extent of gas migration within the strata adjacent to landfill sites (Campbell, 1989a; Metcalfe & Farquhar, 1987; HMIP, 1989). Due to the complexity of gas migration, and the detailed data that would be required to calibrate the models (Campbell, 1989a), it would appear unlikely that the use of such predictive models could become widely accepted.

The above discussion highlights some of the problems involved when considering a scheme to monitor for landfill gas. Due to the many variables controlling the spatial and temporal extent of migration, it cannot be assumed that all potential pathways can be identified. The problems are further exacerbated by practical problems such as lack of access, poorly defined geology, and the absence of detailed site records.

Figure 2.3 Migration of gas through permeable strata (from Campbell, 1989a)

2.3.3 Leachate Migration

It should be noted that some leachates contain a high proportion of carboxylic acids (the intermediate products of anaerobic fermentation) which may then undergo methanogenesis beyond the site boundary (Campbell, 1989a; Williams & Aitkenhead, 1989). Thus migration of leachate may contribute to the presence of landfill gas in the soils of adjacent land.

2.3.4 Prevention of Migration

Landfill gas moves along the pathway of least resistance, and so the aims of any preventative techniques should be either to offer an alternative 'easier' route than the one along which the gas is presently migrating, or to prevent lateral migration by use of an impermeable barrier. Carpenter (1986) and workers at Bush Farm (DoE, 1988) both reported success with venting methods such as vertical venting and flaring boreholes, and gravel filled trenches. Spreull & Cullum (1987) considered vertical venting pipes to be impractical in agricultural situations, and instead made an assessment of the effectiveness of a horizontal perforated pipe system, overlain by a clay cap. Their results (both in terms of direct gas measurements, and crop damage) with this system indicated that very little gas was migrating upwards but appeared to be efficiently dispersed through the pipe system.

Although the prevention of gas migration is a very important issue, it is beyond the range of the project. For further information, the reader is directed to Palmer (1985), Carpenter (1986), Campbell (1989a), and Spreull & Cullum (1987).

2.4 Impact of Landfill Gas

This project is based on the premise that landfill gas has an adverse effect on vegetative health, and that this response can be measured as a difference relative to healthy vegetation. Although it is widely accepted that landfill gas causes a decline in plant health, previous research has not been able to identify an unambiguous relationship, largely due to the complexity of the soil - plant - landfill gas association.

2.4.1 Soils

The study of the relationship between soils and landfill gas on completed sites, is complicated by the inherent variability of the restored soil. The complexity of the situation is outlined in the following section by considering the factors responsible for the production and migration of landfill gas in combination with soil parameters.

2.4.1.1 Soils and Site Restoration

Many of the problems associated with vegetation growth on restored landfill, can be related to restoration practices, as well as, or instead of, landfill gas. Therefore, before examining the effects of landfill gas on soil properties, it is worth briefly covering some of the aspects of restoration.

There are several reasons for requiring quality restoration of completed sites, one of the most important being maintenance of the integrity of the clay cap and preventing soil erosion, by establishment of a healthy vegetative cover (Wilson, 1990). In addition, legislation, specifically the Town and Country Planning (Minerals) Act (1981) places emphasis on the necessity of high quality restoration and aftercare. It should also be noted that quality restoration has far reaching implications in terms of public relations, the finished state having a strong influence on the public's impression of overall site management.

The most critical step in the restoration of completed sites is the replacement of the three layers of overlying materials that were removed prior to mineral extraction i.e. the topsoil, subsoil and overburden. It is considered essential that these are returned to the restored land in the correct sequence, and in quantities that result in a complete profile across the site (McRae, 1980).

The major difficulty to be overcome or rectified in respread soils is the destruction of soil structure (McRae, 1983). Structure can be thought of as being the network of pores of various sizes which conduct air and water, and strongly influences soil fertility. A soil lacking structure may have reduced water retaining or drainage capacity (McRae, 1983; Wilson, 1990). With careful soil replacement, cropping, and aftercare, soil structure can be developed and the land returned to productive use.

Work by Wigfull & Birch (1987) indicated that the disturbance of soils associated with the reclamation of landfill sites altered their chemical and microbial profile, as well as their structure. The work showed a gradual decrease of nutrients with depth (up to 30 cm) for undisturbed soils, whereas disturbed soils showed no such gradient, even after four years. This may have implications for plant growth on such soils, as the high levels of nutrients required for plant growth usually available in the top 15 cm of the soil profile, are not present.

A further problem associated with the restoration of domestic landfills is the settlement of the refuse mass as the waste undergoes decomposition. With older sites, this frequently resulted in ponding on the surface of the site, although the problem is largely avoided now by 'doming' the final profile to allow for settlement.

It is important to appreciate the above points, as a poorly restored or managed site will have inherent difficulties in supporting plant growth, in addition to any caused by landfill gas.

2.4.1.2 Soils and Landfill Gas

The 'normal' problems of restoration are complicated by a number of factors on completed landfills. The presence of landfill gas may upset the physical, chemical and microbiological balance of the soil atmosphere, with resultant morphological and physiological changes to any vegetation growing on the soils (see Section 3.4).

The typically elevated concentrations of methane, carbon dioxide and other trace gases, and low concentrations of oxygen in gas affected soils often results in an anaerobic soil atmosphere (DoE, 1988; McRae and Hewitt, 1986). The lack of oxygen is thought to be due either to the physical displacement of soil gases by the migrating landfill gas, or to oxidation of methane to carbon dioxide with consequent depletion of oxygen.

Research on soil affected by natural gas leaks in the 1970's (Pankhurst, 1973; Hoeks, 1972) initially identified some of the complex microbiological, chemical and physical changes occurring in the soil due to the lack of oxygen or presence of other gases in the soil atmosphere. On a restored landfill, the problems of anaerobic conditions are often exacerbated by the poor structure, high clay content and compaction of the soil, which restricts the free movement of soil gases.

Most soils contain some bacteria capable of oxidising methane to carbon dioxide, and, in the presence of methane and oxygen and suitable conditions, these bacteria oxidise methane to carbon dioxide with by-products of water and energy (Pankhurst, 1973; Hoeks, 1972; Mancinelli *et al*, 1981; Dalton & Leak, 1985; Hill, 1985; Bogner *et al*, 1986; DoE, 1988; Williams & Aitkenhead, 1989; Williams & Hitchman, 1989).

The reaction is complex, involving the oxidation of methane to methanol, formaldehyde, formate and, finally, carbon dioxide (Dalton & Leak, 1985). It may be summarised as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{energy} \qquad \text{Equation 2.1}$$

Under suitable conditions i.e. sufficient nutrients, optimal temperatures, and abundant methane, almost all the oxygen may be used; similarly when there is sufficient oxygen most of the methane is oxidised, the remainder being used as a carbon source for the bacteria (Hoeks, 1972). It has been suggested that up to 10% of the methane produced in the site may be consumed by methanotrophic bacteria in near surface aerobic zones (Mancinelli & McKay, 1985), resulting in very high oxygen consumption in these soils (Hoeks, 1972).

The reaction rate is strongly affected by temperature (Figure 2.4), maximum oxidation rates occurring in the summer months and slowing down during the winter (Hoeks, 1972). Work at Bush Farm (DoE, 1988) confirmed that, while in winter the methane : carbon dioxide ratio tended to be constant down the soil profile, in summer the ratio decreased with depth. The study therefore concluded that the additional oxygen available near the soil surface was being used only for oxidation of methane in the warmer summer months.

Gas affected soils would also be expected to exhibit increased soil moisture and temperature when compared with unaffected soils (Hewitt and McRae, 1985; Hill, 1985; Tankard, 1987; DoE, 1988; Williams & Aitkenhead, 1989). Hill (1985) recorded soil temperatures of up to $50^{0}C$, which he associated with the oxidation reaction. More moderate increases of between 1 and 3^{0}C in soil temperature were recorded by Hewitt & McRae (1985) in conjunction with high levels of gas. Williams & Aitkenhead (1989) reported a gradual decrease in soil temperature from 20.7^{0}C between 0 and 50 cm depth, to 18^{0}C at 2.27m below ground level, the decrease in temperature being accompanied by a relative increase in concentration of methane.

Figure 2.4 Effect of temperature and average oxygen content of soil air on the consumption of oxygen in a gas affected soil (from Hoeks, 1972).

Providing structure and nutrient status of soils are adequate, temperature is frequently the dominating environmental factor controlling germination and growth of plants (Payne & Gregory, 1988). Plants start to grow once a base (minimum) temperature is reached, growth rate then increasing up to the optimum temperature. Thereafter, rate of growth decreases until it ceases at the maximum temperature. Base, optimum, and maximum temperatures differ between crop species, but are usually in the ranges 0 - 5^{0}C, 20 - 25^{0}C, and 35 - 40^{0}C respectively (Gregory, 1988). Thus, temperatures of 50^{0}C in association with the oxidation of methane to carbon dioxide (Hill, 1985), would be expected to have a severely detrimental affect on plant health. Conversely, more moderate increases in temperature (Hewitt & McRae, 1985; Williams & Aitkenhead, 1989) would be more likely to have a beneficial effect on plant growth.

From equation 2.1, a significant increase in soil moisture would be expected in gas affected soils. Conversely, work carried out by Williams & Aitkenhead (1989) indicated that, although water is produced as a by-product of the reaction, soil moisture may actually decrease. Their work suggested that the heat produced by the reaction causes the water to evaporate, with a net loss of moisture from the soil. On occasion, the rapid release of water vapour has been observed after drilling monitoring holes (Williams, Pers. Comm.). As a result of the moisture loss, desiccation cracks develop, the gas then moving preferentially through the cracks and by-passing the methane oxidising zone.

The oxidation reaction has the additional effect of increasing the soil microbial population. Brisbane & Ladd (1965) and Davis (1967) originally described the potential use of such increases in hydrocarbon prospecting. Later work (Mancinelli *et al*, 1981) investigated the feasibility of using numbers of methanol-oxidising bacteria (methylotrophs), as an index of the methane content of the soil. They concluded that changes in the numbers of methylotrophs did not vary to the same extent as actual methane concentrations, and that the bacteria could be used to assay methane concentration in the soil.

The reducing conditions that result from microbial activity and physical displacement of oxygen in gas affected soils, may lead to further microbiological imbalances, often resulting in chemical and physical changes in soil condition. Many of the restoration problems associated with landfill sites e.g. poor vegetation establishment, vegetation death, and low nutrient status (Flower *et al*, 1978; Gilman *et al*, 1985; McRae, 1983) may be a consequence of changes in the nature and activity of microbial communities in disturbed soils (Wigfull & Birch, 1987).

The presence of landfill gas appears to have little effect on the major soil nutrients, although changes in concentrations and oxidation states of trace elements have been noted (Hoeks, 1972; Pankhurst, 1973; Flower *et al*, 1977; Leone *et al*, 1977a; Flower *et al*, 1981; Roberts, 1985; DoE, 1988; Wong, 1988). Similar changes in soil chemistry have also been recorded simply due to reducing conditions in the soil (Payne & Gregory, 1988), introducing doubt as to whether it is the presence of gas or simply reducing conditions, that are significant.

Gas affected soils may exhibit increased levels of reduced manganese and iron (Mn^{2+} and Fe^{2+}), nitrogen-containing compounds, and other trace elements such as phosphorus, Na, Cu and B (DoE, 1988; Hewitt & McRae, 1985). The reduced forms of manganese and iron are more soluble and therefore more mobile than the oxidised forms; this is thought to explain their relative abundance in gas affected soils (Gilman *et al* , 1982b; Roberts, 1985). In some cases such elevated concentrations have been used as an indication of the presence of landfill gas (Gregson, 1990), although such techniques should be used with caution due to similar changes occurring in anaerobic soils. The increased availability to vegetation of the elements in their reduced forms, may have an adverse effect on plant health (Gilman *et al* , 1982b; Senior, 1984; Roberts, 1985; Payne & Gregory, 1988).

Changes in soil colour are briefly described by Wong (1988) and Leone *et al* (1977) who mentioned dark grey 'reduced' regions of gas affected soil, similar in appearance to waterlogged soils. Workers at Bush Farm (DoE,1988) and Hewitt & McRae (1985) also described colour changes in some detail; in gas affected soils they observed dominantly green/bluish grey colours with bright orange-brown streaks in the subsoil, and red-brown streaks between structural units in the topsoil. The dark colours originate through the presence of reduced iron, and could be expected to occur in any anaerobic situation, with the orange colouration developing in aerobic zones within the soil profile (FitzPatrick, 1980).

Little work has been carried out on the effects of landfill gas on soil pH; initial work by Wong (1988) suggested that pH is lower in these soils. He recorded 'normal' soil pH of around 6 to 7, acidity increasing in affected soils down to a pH of 4. Possible reasons for the decrease in pH were not suggested; however it is likely to be a result of the increase in carbon dioxide associated with elevated concentrations of methane, the carbon dioxide dissolving in the soil pore water and reducing the pH.

It has been suggested that root growth and function may be directly affected at pH 5 and below, the actual value depending on species (Rowell, 1988). It can therefore be appreciated that low values of pH that may develop as a result of the solution of carbon dioxide in pore water, can directly limit plant growth.

This section has described some of the variables within the soil environment that may be affected by the presence of landfill gas, and hence influence vegetation health. All these variables interact within the soil microbiological environment, to produce a dynamic system of physical and chemical soil conditions (Figure 2.5). The way in which these factors interact with landfill gas to provoke changes in vegetation health are described in the following section.

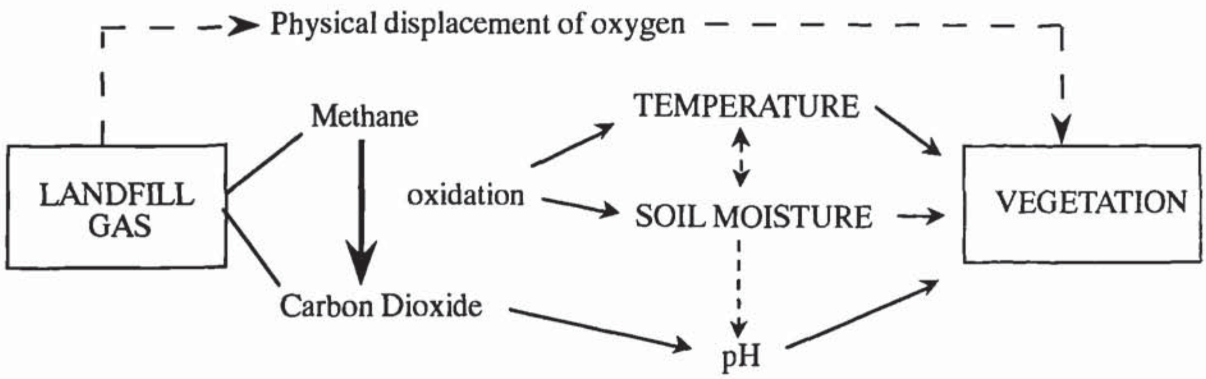


Figure 2.5 Interrelation of Gas and Soil Characteristics

2.4.2. Vegetation and Landfill Gas

As observed by Grable (1966):

> "Few areas of scientific investigation are as unintelligible as the relationships between soil properties, aeration and plant growth".

The problems inherent within the normal study of the soil / plant relationship are further complicated in the landfill situation due to the presence of landfill gas, poor soil quality (lack of structure, high soil compaction, lack of nutrients, low pH), lack of sufficient soil cover, drought conditions, waterlogged conditions, high soil temperatures, and presence of toxic elements (DoE,1988; Arthur *et al* , 1981; Wong, 1988). A simplified outline of the processes occurring in the soil is shown in Figure 2.6. The infinite number of combinations of soil, plant and gas parameters implicit in the investigations mean that attempts to quantitatively relate plant behaviour to a specific factor (such as landfill gas), are unlikely to succeed in any but extreme cases. This is illustrated by the two sites studied in this project (Chapters 5 and 6).

Figure 2.6 Influences on Plant Growth (from Cairney, 1987)

Although it is widely accepted that the presence of landfill gas in the root zone of vegetation has an adverse effect on the health and growth of vegetation (Gilman *et al* , 1985; Leone *et al* , 1977; Arthur *et al* , 1981; Flower *et al* , 1981; Hewitt & McRae, 1985; Hill, 1985; Roberts, 1985; Stonell, 1985; Carpenter, 1986; Parsons & Smith, 1986; Spreull & Cullum, 1987; Tankard, 1987; DoE, 1988), precise effects, reasons for the effects, and the concentrations and combinations of gases which influence plant growth, are complex and poorly understood. This section collates previous research, in order to gain an understanding of the situation.

2.4.2.1 Reasons for Adverse Effects

Although methane is often used synonymously with landfill gas, and may be the major component of it, it is generally assumed that it has no direct effect on plant growth. Therefore, it would be reasonable to assume that vegetation injury associated with the presence of landfill gas must be either a consequence of indirect effects, or due to one or more of the secondary constituents of the gas.

(i) Indirect Effects

The most frequently cited explanation to account for injury to vegetation in association with landfill gas, is the exclusion of oxygen from the root zone. This could be either as a result of gas being emitted from the landfill site at such a rate that it physically replaces the normal soil gases, or due to the oxidation of methane to carbon dioxide (DoE,1988; Hoeks, 1972; Pankhurst, 1973; Flower *et al*, 1981; Spreull & Cullum, 1987; Heasman, 1989a).

Oxygen controls respiration in the roots of plants; if it is not available in sufficient quantities electron transfer and respiration may be limited, and fermentation (anaerobic respiration) occurs. Although many plants can survive these conditions, growth can be detrimentally affected due to the inefficiency of anaerobic respiration, and the production of toxic compounds in the root tissues (Flower *et al*, 1981; Payne & Gregory, 1988). In addition, some plants may lose the ability to uptake certain nutrients when there is insufficient oxygen in the root zone.

Other indirect effects of landfill gas on vegetation include changes in soil physical and chemical conditions. The ways in which these may affect plant growth have been discussed in Section 2.4.1.2.

(ii) Direct Effects

In addition, vegetation damage may be associated with the presence of the ancillary components of landfill gas, particularly carbon dioxide. The concentration at which carbon dioxide inhibits plants growth, varies depending on the plant species and other environmental conditions, a generally accepted figure being approximately 5 to 10% by volume (DoE, 1988; Pankhurst, 1973; Leone *et al*, 1977; Arthur *et al*, 1981; Flower *et al*, 1981; Wong, 1988).

Additional components of landfill gas may include phytotoxic trace gases such as hydrogen sulphide and ethylene (Leone *et al*, 1977a; Flower *et al*, 1981; Hewitt & McRae, 1985; McRae & Hewitt, 1986; Spreull & Cullum, 1987; DoE, 1988; Wong, 1988). For example, Spreull & Cullum (1987) recorded ethylene concentrations up to 104 ppm. As ethylene concentrations of as little as 10 ppm are known to inhibit plant growth (Smith & Russell, 1969), the levels recorded would be sufficient to severely affect plant growth.

The symptoms observed in plants grown on landfill bear some similarity to those seen in plants on waterlogged soil (Arthur *et al*, 1981; Gilman *et al*, 1982; Barry, 1986; Spreull & Cullum, 1987; Wong, 1988). Spreull & Cullum (1987) explained the similarity by the fact that the roots in both cases suffer from a lack of oxygen; this disrupts many of the plant's physiological processes including the uptake of nutrients. This implies that flood-tolerant species may also be useful for revegetating landfills.

As with any biological system, all these variables may interact to a greater or lesser degree, and a great deal of caution should be exercised when attempting to attribute vegetation damage to a single cause.

2.4.2.2 Effects of Landfill Gas on Plant Growth

The adverse effect of landfill gas on plant health is well accepted, the gas affecting plants at much lower concentrations than would normally be associated with explosive hazards (Roberts, 1985). The possibilities of using vegetation injury as an indication of landfill gas has been indicated by some authors (Flower, 1976; DoE,1988; Roberts, 1985). However attempts to draw any conclusions from previous work are hindered by different experimental conditions, types of vegetation, species, etc. (Table 2.1).

(i) Modifications to Root Systems

If the root system of a plant is damaged, all or part of the aerial parts will die (Hocks, 1972; Pankhurst, 1973). Numerous compensatory modifications to the root system

Author	Vegetation	Gas Characteristics	Symptoms	Experimental Conditions
Leone *et al* 1977a	Corn, rye, sweet potato	50% CO_2 12% CO_2 6% O_2	Chlorosis and stunting	Crops adjacent to landfill
Leone *et al* 1977b	Red pine	0% CH_4 6.5% CO_2 19.5% O_2	Leaf tip chlorosis	On landfill cap
		50% CH_4 21% CO_2 12% O_2	Death	On landfill cap
	Peach	High concentrations of anaerobic gases	Death	Trees planted adjacent to domestic site
	Eucalyptus	0% CH_4 0% CO_2 20% O_2	Healthy	Trees planted on landfill
		>50% CH_4 5% CO_2 9.5% O_2	Poor	
Arthur *et al* 1981	Red & sugar maple	50% CH_4 40% CO_2 3% O_2	Chlorosis and abscission lower leaves	Seedlings grown in sterilised soil, fumigated with simulated LFG mix
Gilman *et al* 1982a	Green ash Hybrid poplar	3% CH_4 8% CO_2 17% O_2	Adventitious & stunted roots	High and low gas areas on landfill
		0% CH_4 1.2% CO_2 19.5% O_2	Normal root growth	
Arthur *et al* 1985	Tomato	29% CO_2 6 - 17% O_2	Adventitious roots, chlorosis, wilting	Seedlings grown in 4 litre glass culture vessels, gas mixtures circulated through root zone
		0.3% CO_2 6% O_2	More gradual decline	
DoE, 1988	Wheat	> 10% CH_4	Reduction in biomass, height and fertile ears	Crop grown on restored landfill
Wong 1988	Various types	0 - 3% CH_4	Well vegetated areas	On restored landfill
		6 - 8% CH_4	Bare ground	

Table 2.1 Summary of previous research on landfill gas and vegetation condition

have been observed, including growth of root systems close to the soil surface, either by production of roots from the root collar (adventitious roots); or redirection of roots from deeper soil layers to the surface (Gilman *et al*, 1982a; Arthur *et al*, 1981). Other modifications may be initiated, including a decrease in total root length and reduction in depth of maximum root penetration, or production of a dense mat of short roots at shallow depth (Gilman *et al* , 1982a).

The ability of the particular plant to modify its root systems will determine its probability of surviving It has been noted that small specimens are more capable of adapting to landfill conditions than are larger (i.e. older) ones of the same species (Gilman *et al* , 1982a; Gilman *et al* , 1982b), probably due to the much shallower root systems of the smaller plants. In addition, the mechanisms by which plants modify their root systems and adapt to the anaerobic conditions, vary for different species (Gilman *et al* , 1982a; Gilman *et al* , 1982b). All the modifications involve either redirecting roots towards the surface, or growing additional roots near the surface, such that more of the root area is in an aerobic environment.

(ii) Damage to Foliage

As it is the aerial components of vegetation that are most easily observed, the majority of work has been carried out to study the changes in foliage of affected vegetation (Flower et al , 1977; Leone *et al* , 1977a; Leone *et al* , 1977b; Arthur *et al* , 1981; Hewitt & McRae, 1985; Carpenter, 1986; Spreull & Cullum, 1987; Tankard, 1987).

A wide range of symptoms have been recorded; most of these can be as a result of many stresses, and cannot be considered to be confirmation of the presence of gas:

(a) Chlorosis is often the first symptom of landfill gas-induced stress (Leone *et al* , 1977a; Arthur *et al* , 1981; McRae & Hewitt, 1986; DoE,1988; Wong, 1988). This symptom is almost invariably recorded in cases of landfill gas - induced injury, implying that, if the plant suffers any injury due to landfill gas, the symptoms will include chlorosis. However, it may also indicate the sampling procedure used, or the fact that other signs of damage may not be as readily apparent to the untrained observer. For example, if the sampling procedure is to take several point measurements at random locations across the site, human nature is such that the survey would be biased towards areas of chlorosis, and an anomalously high correlation between gas and vegetation damage would be expected.

(b) Reduction in plant height (Leone *et al*, 1977a; Hewitt & McRae, 1985; McRae & Hewitt, 1986; DoE,1988; Wong, 1988). Leone *et al* (1977a) reported a relation between methane at 30 cm depth and height of corn, with a correlation coefficient of -0.9712. The correlation between plant height and carbon dioxide concentrations was -0.9274. Overall, the healthiest corn was observed where methane and carbon dioxide were low and oxygen concentrations approached normal. Although apparently indicating an almost perfect correlation between landfill gas and corn height, due to the small sample sizes and the lack of a temporal aspect, these relationships cannot be considered to be statistically significant.

(c) Reduction of all components of yield in crops (McRae & Hewitt, 1986; DoE,1988), including reduction in number of grains per ear, number of tillers, number of fertile tillers (ears), individual grain weights and numbers, and overall yield. Work at Bush Farm (DoE, 1988) also noted that fertility appeared to be affected by the presence of landfill gas, with the numbers of infertile plants being significantly higher in unaffected areas. However, the plants in these areas tended to be relatively healthy compared with plants growing in gassed areas.

(d) Early maturation, typified in crop plants by early ripening, and in other vegetation by early senescence (Pankhurst, 1973; McRae & Hewitt, 1986; DoE, 1988). Work at Bush Farm (DoE, 1988) located anaerobic areas of soil, due to the corn in these areas maturing earlier than the rest of the crop.

(e) Defoliation, expressed in crops as abscission of lower leaves, and in trees by loss of foliage from the crown or lower branches (Arthur *et al* , 1981; Flower *et al* , 1981).

(f) In extreme cases, complete dieback of areas of crop (Flower *et al* , 1977; DoE, 1988; Stonell, 1985; McRae & Hewitt, 1986) or death of individual trees (Hoeks, 1972; Arthur *et al* , 1981; Tankard, 1987; Jones, 1990) has been observed.

(g) Other symptoms such as sparse growth (DoE, 1988), late leaf flush (Pankhurst, 1973), wilting, shriveling and necrosis. McRae & Hewitt (1986) also noted that areas of dieback may be surrounded by 'haloes' of luxurious growth. This could be attributed to the low concentrations of carbon dioxide and slightly enhanced soil temperatures that may be associated with low levels of landfill gas, these fractional changes actually being beneficial to plant growth.

It is important to have an understanding of the effects of landfill gas on the foliage of vegetation, as it is the resultant changes that will be recorded by remote sensing surveys. The most frequently reported symptoms i.e. chlorosis and height reduction, would be expected to affect the spectral response of vegetation.

2.4.2.3 Effects of Landfill Gas at Different Stages of Phenology

It has been observed that the susceptibility of plants to landfill gas differs according to the stage of phenology of the plant (DoE,1988; Gilman *et al* , 1982a; Rys & Johns, 1986).

There appears to be little effect on the germination of crops (DoE,1988; Rys & Johns, 1986); however, workers at Bush Farm (DoE,1988) observed a decrease in plant height early in the growing season, followed by a reduction in cover, and in extreme cases, death. Surviving plants exhibited differences in plant height, fresh weight and leaf area, the contrast between affected and unaffected plots increasing with time. As the plants approached maturity, normal competition between plants in the unaffected areas resulted in differences in cover becoming less apparent. However, the differences in plant height, fresh weight and leaf area continued to increase. Overall, it appeared that many plants died at the seedling stage; those that survived developing compensating mechanisms which allowed survival, although with reduced growth and health.

Limited research of the affects of landfill gas on different ages of trees, indicated that young individuals were more able to adapt to landfill conditions than older specimens. Comparisons of shoot growth between trees planted on landfill and controls for small trees (30 to 60 cm) and large trees (3 to 4 m) were carried out by Gilman *et al* (1982b). Results indicated little difference in shoot growth for the small individuals, whilst shoot growth on the large specimens was significantly lower. Gilman *et al* (1982b) reported that young trees (1 year) planted on completed landfills had less difficulty adapting to the conditions due to their shallow root system; older trees (6 years) often died due to their inability to produce a shallow root system quickly enough to survive.

2.4.2.4 Effects of Landfill Gas on Different Species

Little work has been carried out to compare the effects of gas on different crop species at a sinhle site. However, work carried out on trees grown on restored sites has suggested that species with a shallow root system are significantly more adaptable to the landfill environment than those requiring a deeper root system (Leone *et al* , 1977b; Arthur *et al* , 1981; Gilman *et al* , 1982a). This would be due to the fact that deeper roots are subjected to higher concentrations of methane and carbon dioxide, and lower concentrations of oxygen. It has also been shown that slow growing species are more adapted to growing on landfill sites than rapid growers (Gilman *et al* , 1982b). Apparently those species with the ability to grow quickly cannot maintain the rapid growth rate in the landfill environment.

Since anaerobic conditions exist both in flooded soils and in landfill soils, it might be expected that species known to be tolerant to flooding might also be more able to cope with the anaerobic conditions typical of landfill sites. Work by Arthur *et al* (1981) supported this theory; after research with Red Maple (flood tolerant) and Sugar Maple (intolerant) they concluded that flood tolerant species may have some potential to be planted on landfills. The more tolerant species were able to undergo anaerobic respiration, develop secondary and adventitious roots, and withstand elevated levels of carbon dioxide in the soil.

The differing effects of landfill gas according to species would be expected to restrict the extension of a single remote sensing survey from one area to another. If the gas migration was extending over more than one field, or affecting an area of mixed woodland, the differing spectral response of species and effects of gas on these species, could account for more variation than the changes due to the effects of landfill gas.

2.4.2.5 Gas Concentrations and Combinations

Due to the variability of the factors involved, most researchers are reluctant to state a minimum concentration at which plants may start to suffer due to the presence of landfill gas, although most workers indicate that concentrations are much lower than would constitute an explosive risk (Roberts, 1985; Tingley, 1989).

Several authors have observed that a combination of high carbon dioxide with low oxygen concentrations is particularly damaging to vegetation (Grable, 1966; Pankhurst, 1973; Arthur *et al*, 1985; Wong, 1988; DoE,1988). Grable (1966) observed that excess carbon dioxide and deficient oxygen in the root atmosphere suppressed the growth of most plants and the associated soil microorganisms; however, he also stated that oxygen diffusion to the root zone would only be a limiting growth factor under the most extreme conditions.

Laboratory based work on tomato plants by Flower *et al* (1981) and Arthur *et al* (1985) implied that injury due to carbon dioxide toxicity may be brought about by a different mechanism to that causing injury as a result of oxygen deficiency. Arthur *et al* (1985) used various combinations of gases and concluded that:

(i) Even with high levels of oxygen, carbon dioxide still had a detrimental effect on vegetation. This indicates a direct toxic effect on the part of carbon dioxide.
(ii) High methane concentrations took longer to cause damage to vegetation; this injury was attributed to the lack of oxygen.

In addition, the different combinations of gases resulted in different symptoms. Plants subjected to high carbon dioxide, with or without high concentrations of oxygen, had decreased dry weight and stem growth, adventitious root development, and foliar chlorosis. Those subjected to high levels of methane showed decreased stem growth and no loss in dry weight. They later developed adventitious roots, swollen stems, chlorosis of lower leaves, and epinasty (downward curving) of lower leaves.

2.5 Landfill Gas Monitoring

Monitoring of landfills is carried out in order to ensure protection of property, and maintenance of environmental quality (Rae, 1985; Roberts, 1985). Traditionally, monitoring programmes have relied purely on physical and chemical techniques. However, such procedures have several drawbacks, and recent studies have investigated the use of biological monitoring techniques (Roberts, 1985). Some of the limitations of both physical and biological techniques are outlined, although exact procedures for carrying out monitoring surveys are not given here. Further details on monitoring for landfill gas can be found in a number of publications (Palmer, 1985; Rae, 1985; Young, 1986; Crowhurst, 1987; Inst. Wastes Management, 1989; Heasman, 1989b).

Landfills vary both in their ability to produce landfill gas, and for the gas generated to become an environmental hazard. Thus the monitoring scheme should be aimed towards identifying the presence of gas and establishing whether it is present in quantities likely to pose an unacceptable risk.

The major drawback of physical measurement of landfill gas is due to the ephemeral character of landfill gas in the subsurface. Within soils, the gas concentration varies erratically with time, influenced by gas production rates within the landfill, climatic parameters, and soil conditions (Mancinelli *et al*, 1981). To overcome these drawbacks, frequent and widely spaced monitoring is required, such procedures being laborious, time-consuming, and frequently expensive.

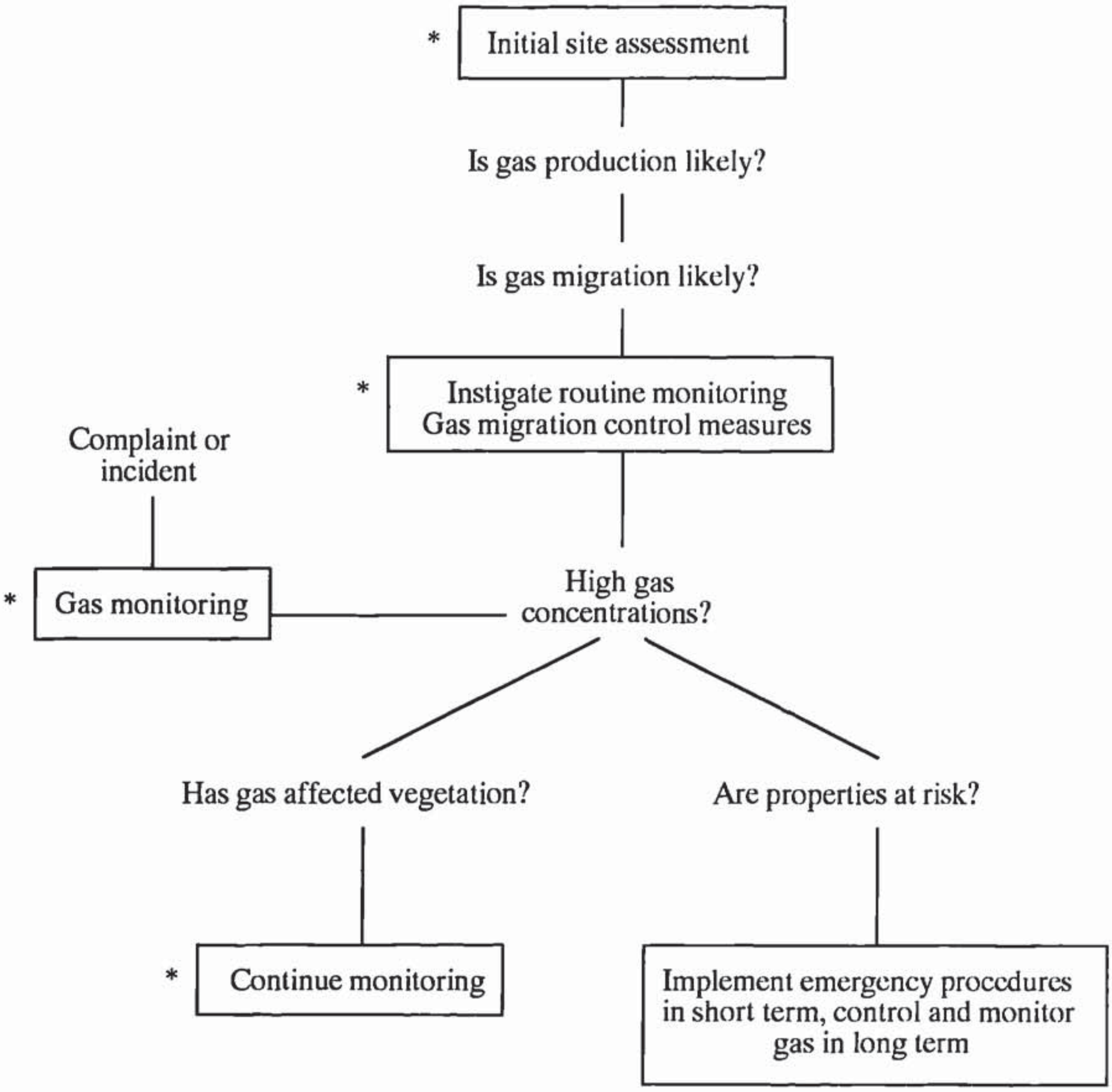
In order to overcome these problems, biological monitoring techniques have been put foreward as alternative, or supplementary, methods of monitoring for gas. Two hypothesised techniques have been suggested:

(i) the monitoring of vegetation stress caused by landfill gas in the root zone of plants,

(ii) assay of the methane-oxidising bacteria in the soil.

2.5.1 Physical Monitoring Techniques

The accepted approach to landfill gas monitoring is the physical determination of gas concentrations, usually methane, carbon dioxide , and oxygen being measured at depth, or on the ground surface (Hill, 1985; Palmer, 1985; Rae, 1985; Crowhurst, 1987; Heasman, 1989b). Prior to commissioning a monitoring survey, waste, geological, and hydrogeological characteristics need to be assessed, such that an appropriate scheme can be designed (Campbell, 1987; Crowhurst, 1987; Heasman, 1989b). Each monitoring scheme is site specific, and requires an assessment of the site characteristics and areas potentially at risk from gas migration. Figure 2.7 illustrates a simplified decision



(* indicates possible remote sensing input)

Figure 2.7 Gas monitoring problems - Decision flowchart (adapted from Campbell, 1987).

flowchart, and considers some of the initial aspects of undertaking monitoring procedures.

Apparent short term variations in gas concentrations may be caused by measurement techniques, temperature, and moisture conditions (Crutcher *et al* , 1982; Young, 1986; Crowhurst, 1987), and such readings should be interpreted with care. Due to the many variables influencing gas production and migration, the absence of gas on a single monitoring survey cannot be taken as proof that a gas problem does not exist (Institute Wastes Management, 1989).

Whilst such an approach provides direct measurement of the gases present, the results are highly specific in terms of the parameters measured, the exact location of each sample, and the point in time when the gases were measured (Roberts, 1985). In order to gain any real understanding of the on-going processes, comprehensive surveys would be required, involving the frequent measurement of several parameters at a number of locations. Even with detailed surveys, it would be impossible to extrapolate between sample points.

2.5.2 Biological Monitoring Techniques

Some of the problems with physical measurement of gas parameters may be overcome using biological monitoring, that is, assessing the impact of landfill gas, as opposed to recording gas concentrations. However, as described in Section 2.4, the extrapolation of physical measurements to organisms can be fraught with difficulties. This approach to monitoring is most likely to be successful if a number of pre-requisites are fulfilled:

(i) the plant variable being monitored has a known sensitivity to landfill gas, and can be easily identified / measured,

(ii) control samples are available,

(iii) extraneous variables are controlled i.e. the same crop type, and similar soil type and condition exists across the area of interest.

Complications may arise due to the ability of some plants to develop tolerance to landfill gas, and the effects of other environmental variables on plant growth (see also Section 3.3.3).

Despite the complicating factors, this approach has many advantages over direct physical measurement of gas; it does not rely on the measurement of a specific parameter at a precise point in time, and may yield a great deal of information regarding the spatial distribution of gas.

2.6 Summary

All sites containing biodegradable waste have the potential to produce landfill gas. Once generated, the gas tends to migrate, both within and away from the site, as a result of the development of pressure gradients. The migration of gas poses a threat to the developments and flora in the vicinity of the site; potentially sensitive target areas frequently requiring extensive monitoring. However, the location and extent of migration pathways can be very difficult, or impossible, to predict; when considered in combination with the variability in production and migration rates, the difficulties in obtaining accurate point measurements of gas concentration are overwhelming.

Landfill gas in the soil environment undergoes oxidation. This in turn affects the microbiology of the soil, and subsequently physical and chemical conditions. The extent to which the changes in conditions are due to the oxidation reaction, as opposed simply to anaerobic conditions, is not clear, however the result tends to be an adverse effect on the health of vegetation growing on affected soils. The degree to which the plants are affected depends on a number of parameters, including the species and type of vegetation, stage of phenology, and the composition and concentration of the gases involved.

It has been suggested that the difficulties involved in point sampling for landfill gas may be partly overcome by assessing the effects of the gas on soils or vegetation (Flower *et al* , 1977; DoE,1988, Roberts, 1985). Using this approach, it may be possible to gain a spatial and temporal perspective of the migration pattern. However, specific and quantified estimates of the relationship between landfill gas and injury to vegetation are not possible for a number of reasons:

(i) the inherent response of individual plants within a single species, and the response of different species, is highly variable,

(ii) there is limited information available concerning the reaction of plants to landfill gas, and much of this information concerns experiments where plants have been exposed to very high concentrations of gas,

(iii) a large part of the work has been carried out on small specimens under controlled and artificial conditions. In reality, plant response in the field would be expected to be affected by a number of interrelated factors. In the disturbed soil environment typical of a completed landfill, there were likely to be difficulties in attributing differences in plant condition to any single parameter.

In spite of the drawbacks outlined above, the potential for biological monitoring techniques to be used as an indication of landfill gas migration exists, and the possibility of using remote sensing to detect the response of plants to landfill gas was considered to be feasible.

3 FUNDAMENTALS OF REMOTE SENSING

The aim of the project were to use remote sensing to detect or monitor landfill gas - related vegetation injury; this chapter introduces the subject of remote sensing in general, and explores the literature covering the discipline. The remote sensing of vegetation, and the application of remote sensing techniques to landfill sites, are covered in greater depth.

Sections 3.1 and 3.2 are intended to provide an introduction to remote sensing, as it is relevant to the project. The reader unfamiliar with the subjects discussed may wish to follow up some of the techniques and concepts covered, and is directed to any of the widely available introductory texts (Swain & Davis, 1978; Lillesand & Kiefer, 1979; Barrett & Curtis, 1982; Jensen, 1986; Thomas *et al* , 1987a).

Remote sensing may be defined as:

> "the science and art of obtaining information about an object, area , or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation" (Lillesand & Kiefer, 1979).

Using various sensors, data is collected remotely and analysed to obtain information about the features being investigated. Remote sensing instruments record, in selected bands of wavelengths (wavebands), variations in the amount of energy being reflected or emitted by objects on the earth's surface.

As electromagnetic radiation strikes a surface, three basic physical processes may take place:

(i) part of the incoming radiation is reflected back into the space containing the source (reflection),
(ii) part of the energy is absorbed by the material and is lost to the system (absorption),
(iii) a third part is passed through the material and transmitted beyond it (transmittance).

The basic interrelations between incident radiation and reflectance, absorption, and transmittance are linked by the following equation (Swain & Davis, 1978):

$$I = R + A + T \qquad \text{Equation 3.1}$$

where I is the incident energy, R is energy reflected, A is energy absorbed and T is energy transmitted. This can be rearranged such that the other variables are a function of reflectance:

$$R = I - (A + T) \qquad \text{Equation 3.2}$$

i.e. the energy reflected is equal to the incident energy reduced by an amount equal to the amount being absorbed or transmitted.

Sensors capable of recording electromagnetic energy include the photographic camera, video camera, multispectral scanner, and a number of other imaging and non-imaging devices. The data is later analysed to provide information about the features under investigation. Although, in principle, remote sensing systems could measure energy emanating from the earth's surface in any range of wavelengths, technical limitations of the sensors, effects of the earth's atmosphere, and scattering from atmospheric particulates exclude certain wavelengths.

If the spectral reflectance characteristics of different surface features are examined (Figure 3.1), it can be seen that they are spectrally separable, the degree of separation being a function of the wavelengths being examined. For example, although water and vegetation have similar reflectance values in the visible wavelengths, they are easily distinguished in the infrared. Although this implies that each surface type has a unique 'spectral signature', in reality such a well defined relation does not exist (Colwell, 1983). Instead it should be considered that for a particular point in time, at a specific geographical location, there may be measurable spectral response patterns from various cover types. When considered together, these may be distinctive enough to allow the discrimination of the cover types. For this reason, the term 'spectral response pattern' is used to indicate a quantitative but relative set of measurements which correspond to a specific cover type on a particular set of multispectral scanner data (Swain & Davis, 1978).

Figure 3.1 Spectral response of surface features (from Colwell, 1983)

The analysis of multispectral images usually involves coregistering several spectral bands into one composite image, the bands being chosen to yield maximum information with the minimum amount of redundant information. A general rule is that the closer the bands in the spectrum, the higher the degree of redundancy, the further apart, the greater degree of independence.

3.1 Remote Sensing Systems

Various sensors are available for use in airborne remote sensing surveys. In this section, the sensors used in the project are briefly outlined. Further details, where relevant, are given in Chapter 4.

3.1.1 Aerial Photography

The photographic camera is one of the oldest and most widely applied sensors, recording information in the visible and near infrared wavelengths onto photographic film. The framing camera (as used in this project) provides a square 23 x 23 cm image, either as a diapositive or as a negative photograph. Surveys are carried out so that a sequence of photos with 60% overlap along the flight line are obtained, the overlap being essential for stereoscopic viewing (Vass & van Genderen, 1978; Barrett & Curtis, 1982). Analysis of the photographs for most purposes utilises a stereoscope, such that the three-dimensional nature of the images can be exploited.

The scale of photography is dependent on the focal length of the camera, and the altitude of the sensor platform. Resolving power is usually defined in terms of the minimum resolvable object size, and is measured by imaging a standard target pattern and determining the spatial frequency in lines/mm, at which the image is no longer distinguishable (Slater, 1980; Barrett & Curtis, 1982; King, 1988).

Although not directly amenable to digital image processing techniques, air photos can be scanned or video digitised to produce digital images, these images then being subjected to computer enhancement or classification (Hills, 1986). However, there is doubt that such techniques can replace visual interpretation techniques, particularly for large area studies (Smith, 1988; Groves, 1989).

3.1.2 Airborne Video

In recent years, while confidence in the concept of remote sensing has grown, the costs and delays involved in the collection and processing of data has proved a barrier to its widespread use. Thus there has developed a pressing need for remote sensing systems that provide information more quickly and less expensively than traditional methods, and one in which the user has greater control over the collection of data..

Simultaneously, there has been an increase in available video technology and quality, and decrease in cost of the equipment, such that the use of video systems in remote sensing applications has become now viable. At present, video remote sensing (videography) cannot replace more traditional techniques due to problems with radiometric, spectral, and spatial resolution (see below), however it can provide a low cost alternative to these methods.

The data is recorded on video tape, and qualitative analysis may proceed by visual examination of this imagery. Quantitative analysis involves the digitisation of the recorded imagery, and the availability of an image processing system (Section 4.2).

Video remote sensing systems enjoy several advantages compared to conventional systems, including:

(i) Real time collection of imagery, thus reducing the possibility of collecting poor quality images, and allowing minor adjustments, such as exposure settings or zoom settings, to be made (Vlcek, 1983; Meisner, 1985; Nixon *et al*, 1985; Richardson *et al*, 1985; King *et al*, 1986). This factor also assists in the navigation of the plane such that the correct area is imaged.

(ii) Low cost - both the initial outlay for equipment, and the materials used (King et al, 1986; Hame & Rantasuo, 1988).

(iii) Flexibility and low cost of collecting the data. The flexibility of the system can be important both in terms of the ability to rapidly set up the system when required, and in terms of the ability to select those wavelengths required for a particular project by using specific narrow band filters (Vlcek, 1983; King *et al*, 1986).

(iv) High light sensitivity, coupled with a wide spectral response. This allows for the collection of imagery under conditions of low illumination, and for the use of narrow wavebands (Vlcek, 1983; King *et al*, 1986).

(v) The high rate of image production (every 1/60th second) means that features can be viewed at various angles along the direction of flight. It also enables the possibility of stereoscopic viewing and the production of 3D terrain models (Vlcek, 1988).

(vi) The electronic recording format allows for immediate playback, either for visual interpretation or for digital analysis (Vlcek, 1983; Meisner, 1985; King *et al*, 1986).

(vii) Due to the consistent radiometric characteristics of video tapes, the problems associated with variations in film emulsion which are experienced with colour infrared films can be avoided. However, in the author's experience, this is offset by problems with maintaining consistent gain settings between successive frames (see Section 4.2.3).

From the above list, it would appear that the advantages of video remote sensing are overwhelming. However, the technique also has its drawbacks, one of the most important and obvious being the poor resolution of the imagery, resolution being defined in terms of the minimum resolvable object size (resolving power) (King *et al* , 1986; King, 1988). The resolving power of the video system is affected by the camera, lens, tape format, recorder, and monitor, and can be expected to be approximately one third of that of aerial photography (King, 1988). The poor resolution could be partially offset by use of long focal length lenses or low flight heights (Hame & Rantasuo, 1988); however, the problems of geometrically registering such images would simultaneously increase. One possible new approach that may improve the horizontal resolution of imagery is the use of super VHS tapes.

Other disadvantages include:

(i) Image motion - in the time required to generate a video field (1/50th second for tube cameras), the plane may have moved sufficiently to create a problem with image motion.

(ii) Video systems suffer from several sources of optical and electronic noise, which may effectively reduce the contrast between objects (King, 1988; Ammon *et al* , 1987).

(iii) There are severe difficulties in co-registering images from multiple cameras.

(iv) Radiometric variation between successive frames due to auto-gain settings on the camera (Wiegand *et al* , 1988).

The features of video remote sensing that were relevant to this research are discussed in further detail in Chapter 4.

3.1.3 Airborne Multispectral Scanner Imaging

The traditional role of the airborne multispectral scanner was a means of testing the design specifications of scanners to be used in satellites. However, they rapidly developed a role in their own right, providing far superior spatial and spectral resolution, and the flexibility of being able to acquire user-specified data.

The images are recorded as 11 bands of 8 bit data on computer compatible tape (CCT). Each image is 750 pixels in width, the length varying according to the flight specifications. Analysis of the imagery requires considerable computer back up, including a tape reader and image processing system.

3.2 Data Processing

Section 3.2 refers to the preprocessing and automatic classification of digital images, specifically with consideration of the requirements of this project.

A digital image is a discrete record of a scene, the information being recorded as a discrete number of spatial elements (pixels) and brightness (intensity) values. Data that has not been recorded in digital form initially can be converted into discrete data by use of digitising equipment. The spatial resolution is controlled by the pixel size, the pixel being the smallest picture element. The relative brightness of the ground area covered by each pixel is assigned a brightness value between 0 and 256, corresponding to a particular grey level.

3.2.1 Preprocessing

The term 'preprocessing' includes a wide range of techniques which may be applied to the raw digital data in order that the image may be restored to an accurate representation of the original scene.

3.2.1.1 Geometric Correction

When using aircraft as a sensor platform, problems of geometric distortion can be expected, with variations in platform altitude, attitude and velocity occurring. The deviations will vary according to local flying conditions, and can be expected to be especially severe for low altitude flights.

Random errors, caused by movements of the airborne platform, are corrected by establishing the relation between the addresses of pixels in the image and the corresponding coordinates on the ground via a geometrically correct map. This requires the selection of well defined control point pairs. The relationship between the image and map ground control points (GCPs) is then calculated, and each image pixel resampled at a new location determined by the model. This can be achieved either by choosing the nearest neighbour, or by interpolating between adjoining pixels (Figure 3.2).

Figure 3.2 Nearest neighbour and linear interpolation resampling to geometrically correct remotely sensed data (from Thomas et al , 1987a)

The underlying assumption of the method is that the relationship between corresponding image and map space GCP's is representative of the distortion within the image i.e. the image can be considered to be a 2-dimensional plane, with distortions being averaged into one global parameter set. This assumption is valid for data such as video images and aerial photography. However, line scanners (such as the Daedalus 1268) record sequential lines of data, and may be subject to high frequency distortion, in which the polynomial equation cannot adequately model the localised distortions (Devereux *et al* , 1990). The geometric problems specific to the Daedalus scanner are explored further in Section 4.3.3.1.

The problems of geometric distortion are especially significant when considering spatial registration of multitemporal imagery, registration of images to a map base, or when requiring spatial quantities to be extracted from the imagery.

3.2.1.2. Radiometric Correction

Radiometric errors are errors in the measured brightness of pixels and may be caused by sensor attributes or environmental effects. Two broad types of distortion can be described, both of which may be as a result of sensor or environmental effects:

(i) those in which the relative distribution of brightness over the image in a given band is different to that on the ground,

(ii) those in which the relative brightness of a single pixel from band to band is distorted compared to the reflectance characteristics of the same area on the ground.

In the absence of an atmosphere the signal measured by a sensor would be the function of the level of solar energy incident on a pixel and the reflectance properties of the pixel itself. Environmental distortions are created by the interaction of reflected radiation with the atmosphere which selectively absorbs and scatters radiation in particular wavelengths; the shorter wavelengths being more affected than longer ones. Because of this, the short wavelengths are often 'noisy', and of limited use in analysis.

Random errors within one band and between bands can also be caused by the design characteristics and operation of the sensor system. In the case of the ATM, the gain on each waveband can be set to one of five settings; this ensures that maximum sensitivity in each waveband is achieved under the conditions at the time of flight. The imagery can then be corrected using calibration data so that pixel values can be related to scene radiance (Wilson, 1986). The imagery used in this project was not corrected for radiometric errors, as the emphasis was on variation in spectral response over an area, rather than absolute radiance values.

3.2.2 Image Enhancement

The objective of image enhancement is the production of a more useful image from the original, the enhanced image then being visually interpreted by an analyst to obtain the desired information (Hoffer & Swain, 1980). Use of appropriate techniques means that features of interest are enhanced thereby making interpretation faster, more accurate and more reliable.

Two very useful spectral enhancement techniques are considered, the first being contrast stretching. Within each waveband the pixel brightness values frequently only take up a small proportion of the available 256 levels. Contrast stretching effectively expands these values to make use of the full 256 grey levels. Various stretches are available e.g. manual piecewise, autolinear, autogaussian and autoequalise (Colwell, 1983; Curran, 1985).

The second enhancement technique is band arithmetic, and includes addition, subtraction, multiplication and division of pixel brightness values from two or more bands of image data. Two frequently used techniques are: (i) band subtraction to detect change between multitemporal images, and (ii) band ratioing to reduce the effects of variable illumination.

Image enhancement may also involve spatial operations, such as the use of filters to either smooth the image (low pass filtering), or increase variation within the image (high pass filters). Low pass filters are frequently used to reduce high frequency variability ('noise') in an image i.e.unwanted variations in the signal. The noise may be a result of natural variation within the target (scene noise), or system noise caused by the sensor (Slater, 1980).

It has been observed that as spatial resolution increases, scene noise also increases, 'scene noise' referring to the variability within a given class which tends to reduce classification accuracy (Markham & Townshend, 1981; Townshend *et al* , 1988). For example, small gaps and shadow within the tree crown which may be assigned to component cover types rather then to the overall category to which they belong.

Such scene noise can be reduced by smoothing the data with a low pass filter which replaces the central pixel with the mean, median, or mode of the pixels in the window. The benefit derived from such filtering depends on a number of factors. Firstly, the effect of low pass filtering is the reduction of the probability density function for a given class, and thus the reduction of overlap with other classes Therefore the greatest improvements in classification accuracy will be achieved for heterogeneous classes with large variance (Markham & Townshend, 1981; Atkinson *et al* , 1985; Townshend *et al* , 1988).

In addition, boundary pixels may contain a mixed response from two or more contributory classes, the proportion of the true class decreasing with decreasing resolution, as the pixel's signature migrates away from that class and towards another. Classes with larger variance can be expected to absorb more of the mixed pixels.

The effects of filtering can therefore be expected to be a balance between the advantages of reducing class variance, and the drawbacks of smoothing training area boundaries. Maximum benefit will be achieved for heterogeneous classes with large training areas, least for small, homogeneous classes.

3.2.3 Image Classification

Having carried out enhancement, the image may then be qualitatively interpreted by an analyst; however, it is more usual to proceed to computer classification, the end product being a thematic map showing particular features of interest. Classification proceeds through a number of steps including definition of training areas, extraction of class statistics, classification of the imagery, and testing of the results.

3.2.3.1 Ground Information Sampling

> "Seldom, if ever, does a remote sensing device measure what we really want to know. Thus, what we want to know must, in some way, be correlated with what can be measured" (Olson, 1984).

It can be seen that one of the advantages of remote sensing is the acquisition of large quantities of data in a short time, from a synoptic viewpoint. However, the sensor does not measure the ground variables directly; rather, it records the intensity of energy in a specific wavelength region, this record is affected by any factor that affects the flow of energy from target to sensor (Colwell, 1983).

Ground reference data provides information for training the classifier (training data), and verification of classification results (test data) (Hoffer, 1978; Townshend, 1981; Colwell, 1983). The type of data collected, and the timing of acquisition, varies according to the survey objectives, budgetary, time, and scale constraints, and the accessibility of the area being surveyed. However, it must be closely related to the objectives of the project (Hoffer, 1978; Justice & Townshend, 1981). The success of calibrating any remote sensing data, and hence the ultimate success of the project, is dependent on the correct selection of variables to be recorded on the ground, and their accurate measurement.

Ground observations can be subject to many errors, including instrumental errors, operator errors, ground location errors, lack of temporal synchronisation with aerial data, and inadequate sampling design (Justice & Townshend, 1981). The minimisation of such errors is important in the practical application of remote sensing techniques, since the reliability of the ground data will strongly affect the extrapolation of classes to areas not visited.

The timing of ground data collection depends on the stability of ground conditions. If surface conditions are dynamic, such as crop state, it is preferable to obtain near-synchronous ground data, a maximum lapse of two weeks being suggested by Hardy (1980). However, for more stable systems the most common form of verification of data interpretation is the field checking of results (Colwell, 1983).

3.2.3.2 Unsupervised Classification

Unsupervised classification techniques are used when the land cover types to be specified as information classes are not generally known *a priori* due to a lack of ground truth or lack of definition between surface features within the scene (Swain & Davis, 1978; Lillesand & Kiefer, 1979; Barrett & Curtis, 1982; Jensen, 1986; Thomas *et al*, 1987a). The image properties themselves are used to define classes by using the computer to cluster the pixel data into spectral classes using statistical techniques. These spectral classes are then interpreted by relating the classes to ground locations with known properties. Unsupervised classification, by definition, will only define those classes which are spectrally distinct and thus ground data collection requirements are reduced.

This approach may reveal discriminable classes unknown from ground based work (Townshend & Justice, 1980), and has been reported to be superior in its ability to classify areas of complex terrain (Hoffer & Staff, 1975; Fleming *et al* , 1975).

3.2.3.3 Supervised Classification

In supervised classification of remote sensing data, the identity and location of some of the ground cover types are known *a priori* through fieldwork, aerial photography, maps, and the experience of the analyst. The analyst then attempts to locate sites within the image which represent homogeneous examples of these land cover types, the sites being referred to as training areas. The objective of developing training statistics is to produce estimates of the statistical character of each cover type of interest; therefore the training areas for each class need to be of sufficient size for derivation of the relevant statistical information. They should also be relatively homogeneous, and spectrally separable. The success of image classification is very much reliant on the selection of suitable training areas; this section of the classification procedure frequently accounting for a large proportion of the time spent in image classification. The statistics derived from the training areas are eventually used to 'train' the classification algorithms, and subsequently classify the entire image (Colwell, 1983; Curran, 1985).

When processing the data it is necessary to establish which spectral bands contain the best information to separate the classes of interest to the user, redundant information frequently existing in correlated bands. In this way, unnecessary bands can be eliminated from the analysis.

Appropriate bands are selected by compiling the statistical profiles of each training class for each waveband (Teillet *et al*, 1981). If the spectral classes are considered to be represented by probability distributions, class separability in each waveband is indicated by the degree of overlap (see Figure 3.3). By statistical examination of the training class data, the decision can be made as to which bands to use in the classification., the classification procedure being restricted to those bands that are most effective in separating the classes of interest (Thomas *et al* , 1987b).

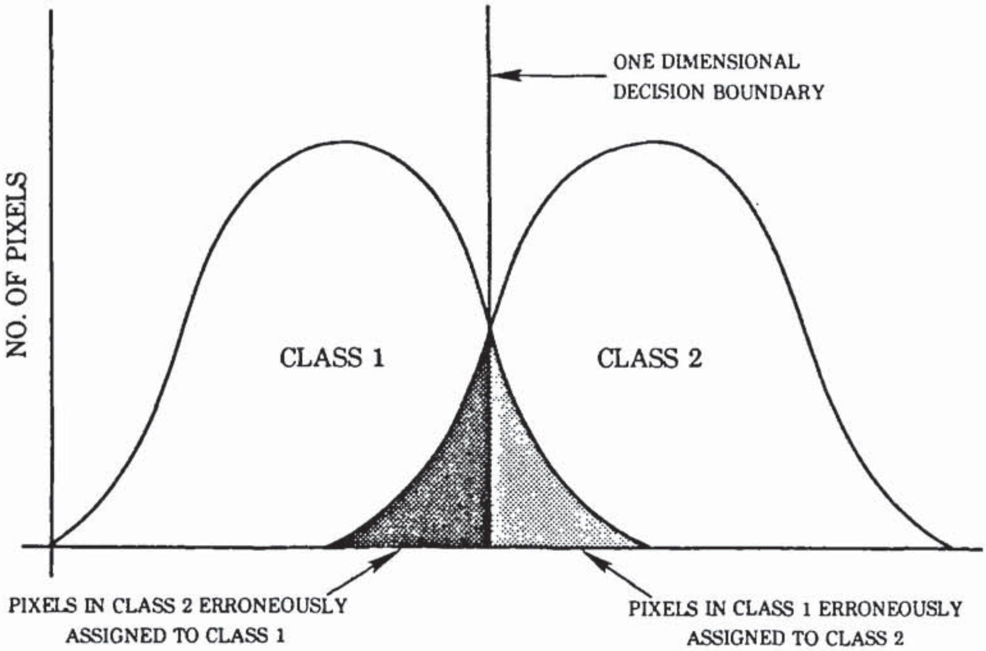


Figure 3.3 Hypothetical distributions of two classes in one-dimensional feature space

Two classification algorithms were used; these were the minimum distance and maximum likelihood classifiers. The simpler 'minimum distance to means' classifier operates on the rule that, for inclusion in a class, the distance (in pixel brightness) from each pixel to the means of each class in each band must be a minimum. The analyst is required to specify a threshold value, such that for inclusion in a class, the distance of the pixel to the nearest class mean must be less than the specified threshold.

The maximum likelihood classifier is more complex, and may usually be expected to yield the best results. However, the increase in accuracy is offset by the increase in computation time. The method involves computing the probability density function for each class in each band, pixels being placed in the class to which they have the greatest probability of belonging. The user is required to enter a threshold, specified in terms of a percentage probability, such that the probability of a pixel being assigned to a class must be greater than the threshold i.e. if a threshold of 90% is chosen, for a pixel to be assigned to a class, it must have a 90% or greater probability of belonging to that class.

3.2.3.4 Accuracy Assessment

The widespread acceptance of remote sensing as a data source will inevitably rest on the accuracy of the classification result. This in turn requires the specification of the expected level of accuracy of the final product (van Genderen & Lock, 1976). Usually, accuracy assessment involves the comparison of two maps - one based on the analysis of the remote sensing data (the map to be tested), and the other based on a different source of information (considered to be the standard for comparison) (Campbell, 1983).

For supervised classification, it has been suggested that the simplest strategy would be to compare the classified data with the training data used to actually generate the classification (Campbell, 1983), the theory being that if the training samples have been positioned at random throughout the mapped area, they can be considered to be a representative sample of the scene as a whole. However, such accuracy testing is simply an indication of the statistical separability of the training data (Jensen, 1986).

The usual technique is accuracy evaluation based on areas of known identity that have not been used to train the classifier (test data). Although producing a much more useful result, the procedure also requires extra input of time and resources to collect the data. Serious disagreement between the classification result and the test areas indicates that either the training data, or the test set (or both) were not adequately representative of the overall data set.

The accuracy assessment results are usually presented in the form of a "confusion matrix", also known as an error matrix or contingency table (for example, see Table 6.5). The confusion matrix identifies the overall classification accuracy, classification accuracy for each individual class, and also mis-classifications due to confusion between classes (known as errors of commission and errors of omission). It is an (n x n) array with 'n' being equal to the number of classes. The upper row of the table is labelled with the reference ('correct') classes; the left hand column is labelled with the same classes, this time referring to the map (classified) classes.

Thus, the diagonal from top left to bottom right gives the number of, or percentage of, correctly classified pixels for each class. The percentage of correctly classified pixels is calculated by dividing the number of correctly classified pixels by the total number of reference pixels in the column (van Genderen & Lock, 1976; Campbell, 1983; Story & Congalton, 1986). Any entries in the matrix other than the diagonal represent misclassified pixels. Misclassification can take one of two forms; either pixels are wrongly assigned to a class (commission error), or they may not be assigned to the class to which they belong (omission error). Commission errors are those given in the bottom left part of the table, omission errors are shown in the top right section.

Although confusion matrices provide an indication of the accuracy of classification, they do not indicate the degree of confidence that can be placed in the results. A measure of the reliability of the results can be attained by calculating confidence intervals for each class. Jensen (1986) put forward an equation to assess classification accuracy at the 95% confidence level:

$$p = p\sim \pm [\ 1.96\sqrt{(p\sim)(q\sim)/n}\ +\ 50/n] \qquad \text{Equation 3.3}$$

where:
p = actual class accuracy expressed as a percent,
p~ = percent of class calculated as being accurately classified (the number of pixels correctly identified divided by the total number of pixels in the class),
q~ = 100 - p~,
n = number of pixels in the class.

For example, if 90% of the pixels had been correctly identified, and there was a total of 200 in the class, the bracketed section of equation 3.3 would sum to 4.4. That is, the analyst could be 95% confident that the true map accuracy was between 85.6% and 94.4%. By estimating the confidence intervals for each result, the analyst can assess the range of values, within which, the true map accuracy lies.

3.3 Remote Sensing of Vegetation

Any study involving the interactions of plants and soils is complex because of the inherent characteristics of the objects of study. The remote sensing of such systems must allow for this complexity, and requires an understanding firstly of the reactions within the system, and secondly of the interactions with the electromagnetic spectrum. The interactions of vegetation, soil, and landfill gas have been introduced in Chapter 2. The subsequent interactions with the electromagnetic spectrum are discussed here.

3.3.1. Spectral Reflectance of Vegetation

Green vegetation has a distinctive spectral response which shows marked variation with wavelength (Figure 3.4). Incident radiation is reflected, transmitted, and absorbed by plant leaves in a manner that is 'uniquely characteristic of pigmented cells containing water solutions' (Gates, 1970), the response from individual leaves often being referred to as 'leaf hemispherical reflectance' (Curran, 1982).

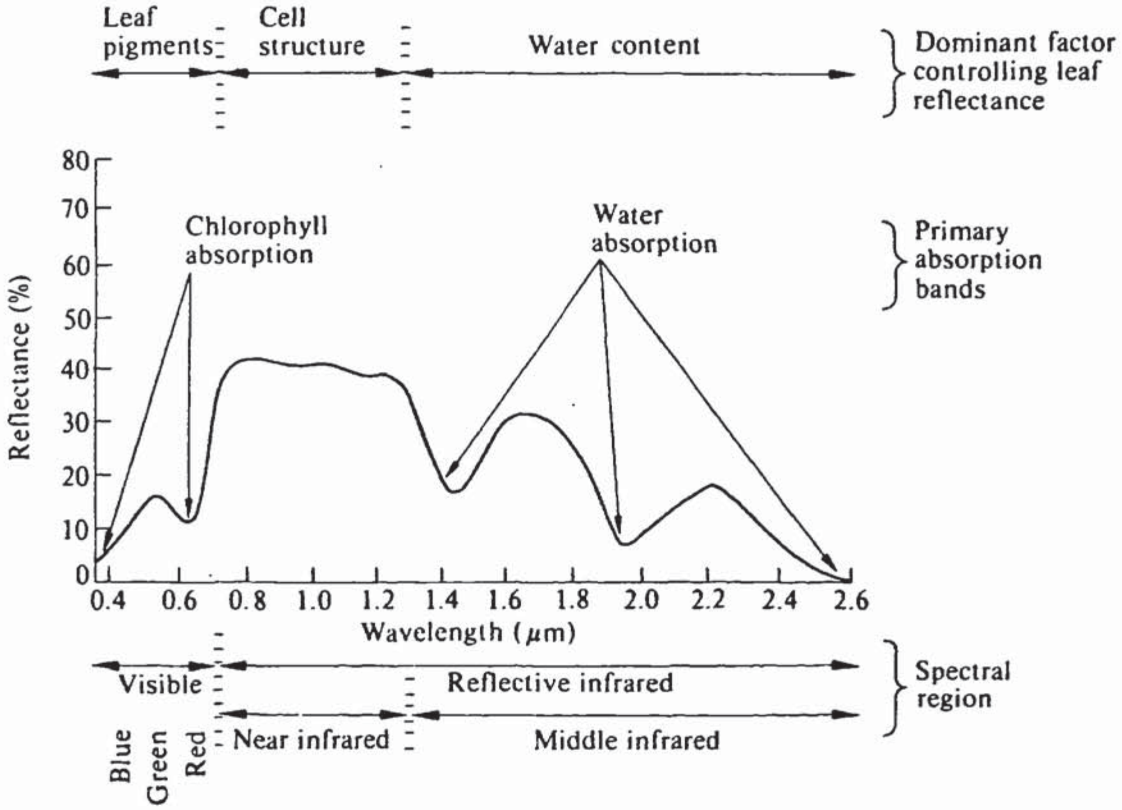


Figure 3.4 Spectral response characteristics of green vegetation (from Swain & Davis, 1978)

3.3.1.1. Visible Wavelengths

Reflectance in the visible wavelengths, i.e. 0.4 - 0.7 μm, is dominated by pigmentation in the plant leaves. The important pigments are the chlorophylls, carotenes, and xanthophylls, the chlorophyll in the leaf usually masking the other pigments. The red / yellow colouration of senescent leaves is due to the loss of chlorophyll, allowing the carotene and xanthophyll pigments to predominate. In addition, if vegetation is subjected to stress, chlorophyll production is reduced, resulting in less absorption and increased reflection of light (Knipling, 1970; Tucker, 1975; Tucker, 1977; Tucker, 1978).

Spectral response in the visible wavelengths (0.35 - 0.70 μm) is characterised by low reflectance and high absorption. A reflectance peak in the green wavelengths, centred at around 0.54 μm, results in the green colour of vegetation. Due to the decreased absorption of radiation, there is a weaker relationship between spectral response and plant material than in the red and blue wavelengths (Tucker, 1978).

3.3.1.2 Near Infrared Wavelengths

Near infrared light is scattered or reflected from plant leaves by refractive index discontinuities (Gausman, 1974) i.e. it is the internal structure of the leaves that largely controls reflectance in this region. The response of leaves in the near infrared is characterised by very high reflectance (45 to 50%), very high transmittance (45 to 50%), and very low absorption (less than 5%) and is considered to be directly sensitive to plant biomass (Tucker, 1978). The overall reflectance of a plant canopy may actually be much higher due to 'additive reflectance' i.e. some of the energy transmitted through the upper layer of leaves is reflected from a lower layer and transmitted back through the upper layer (Swain & Davis, 1978).

3.3.1.3 The Red Edge

The measurement of vegetation reflectance discussed so far utilises broad spectral bands in the order of 100 nm band width. This degree of spectral resolution is adequate for regions of the spectrum where there is a gradual change of reflectance with wavelength. However, vegetation exhibits a rapid increase in reflectance in the transitional area between the far red and the near infrared (Murtha, 1978; Horler *et al* ,1980; Horler *et al* , 1983; Goetz *et al* , 1983). The red edge has been shown to be very sensitive to chlorophyll concentrations in the leaf (Murtha, 1978; Horler *et al*, 1983), and thus may yield information on the phenologic stage and/or state of health of vegetation. However, there are problems in measuring the red edge due to its narrow spectral range and this has restricted its use in the monitoring of vegetation.

3.3.1.4 Mid Infrared Wavelengths

Reflectance in the middle infrared (1.3 to 2.5 μm) is dominated by the absorption of radiation in three major water absorption bands centred near 1.4 μm, 1.9 μm, and 2.7 μm (Swain & Davis, 1978). It is the bands at 1.4 and 1.9 μm that dominate the spectral response of foliage in the middle infrared, resulting in a strong negative correlation between the moisture status of leaves and their reflectance i.e. the greater the moisture content of the leaf, the greater the absorption of incident radiation and the lower the reflectance (Knipling, 1970; Tucker, 1978). This spectral region will discriminate between healthy and stressed vegetation, if the stress is manifested as a difference in foliar moisture content (Lynn, 1984; Everitt *et al*, 1986).

Table 3.1 indicates some of the important spectral regions for monitoring vegetation.

Wavelength (μm)	Utility for Vegetation Monitoring
0.74 - 1.10 (near IR)	Directly sensitive to biomass
0.63 - 0.69 (red)	Directly sensitive to amount of foliar chlorophyll
1.35 - 2.50 (mid IR)	Directly sensitive to foliar water content
0.37 - 0.50 (blue-green)	Directly sensitive to carotinoids and chlorophylls
0.50 - 0.62 (green)	Direct/indirect and slight sensitivity to chlorophyll
0.70 - 0.74 (approx. red edge region)	Indirect and minimal sensitivity to vegetation

Table 3.1 Summary of important spectral regions for monitoring vegetation (from Tucker, 1978)

3.3.2. Spectral Characteristics of Vegetation Canopies

Although it is necessary to understand the reflectance properties of individual leaves, this knowledge in itself does not explain the observed response of vegetation canopies, known as canopy bidirectional reflectance (Knipling, 1970; Colwell, 1974a; Colwell, 1974b; Tucker *et al*, 1980; Curran, 1981; Horler & Barber, 1981; Miller *et al*, 1984; Baret *et al*, 1988). As vegetative canopies are a mixture of leaves, other plant components, background, and shadow, there may be no simple relationship between the hemispherical reflectance of individual leaves and the bidirectional reflectance of the canopy (canopy reflectance). Reflectance from a canopy is considerably less than that from a single leaf because of the attenuation of incident radiation by variations in leaf orientation, shadows and non-foliage background.

Thus the spectral signal received by the sensor will be affected by a combination of variables including factors actually related to the vegetation itself, reflectance characteristics of the soil and other background material, and angular effects. As they are not constant in time or space, these effects will interfere with attempts to extend spectral signatures from a single scene to remote sensing data acquired on different dates or at different locations.

The reflectance of an all-green canopy is largely due to the percentage vegetation cover (Colwell, 1974a; Curran, 1981); however the relationship between plant parameters and spectral response is complex (Table 3.2) For example, a decrease in near infrared and increase in red reflectance of a canopy may be caused by changes in the actual reflectance of leaves as a result of stress to the plant (Gausman *et al*, 1975; Horler & Barber,1981), or it may be due to a decrease in canopy cover, decrease in leaf area index, or leaf wilting (Colwell, 1974b; Horler & Barber, 1981). Baret *et al* (1988) demonstrated that changes in canopy geometry due to leaf wilting could exert a larger effect on the spectral properties of the canopy than concomitant changes in leaf hemispherical reflectance, that is, actual changes in the chlorophyll content, water content or internal structure of the leaves.

Change in Canopy	Possible Cause	Effect on Canopy Reflectance		
		Visible	Near IR	Mid IR
Increase in area of bare soil visible to sensor	(i) temporary wilting (ii) wind blown leaves	increase	decrease	increase
Decrease in canopy cover	(i) increase in cloud cover (ii) high solar angle	increase	little change	increase
Decrease in area of bare soil visible to sensor	(i) lodging of crops (ii) sensor angle	decrease	increase	decrease
Increase in leaf surface moisture	(i) dew (ii) rainfall	little change	decrease	decrease

Table 3.2 Factors that may affect canopy reflectance (adapted from Curran, 1981)

3.3.2.1 Contribution of Background

Attempts to interpret reflectance measurements from vegetated surfaces are hampered by background signals that are combined with the response from the canopy. The influence of soil and other background materials, such as senescent vegetation and shadow, is a function of both the amount of background viewed (and is therefore a function of percent cover and biomass) and the spectral properties of the background itself (Swain & Davis, 1978; Curran, 1981; Horler & Barber, 1981; Jackson *et al*, 1983; Miller *et al* ,1984; Baret *et al*, 1988). For example, the spectral properties of soil are themselves influenced by a number of variables such as soil moisture, texture, surface roughness, organic matter and iron oxide content (Swain & Davis, 1978).

The amount of background viewed depends both on the structure of the canopy, and on angular effects. Changing solar zenith angles result in differing amounts and intensity of shadow being recorded by the sensor (Curran, 1981). A decrease in the amount of shadow may also occur as a result of physical changes to the canopy such as lodging of agricultural crops. For example, Colwell (1974b) recorded in increase of over 50% in red reflectance when a grass canopy was smoothed.

In addition, as the look angle of the sensor varies from the vertical, there is less contribution from background, and more from the vegetation (Curran, 1981). The effect can be minimised by careful flight planning, for example, using sensors with a narrow field of view, and planning the flights such that the target area is located within the central part of the swath.

3.3.2.2 Angular Effects and Shadow

The significance of angular effects to canopy reflectance is ultimately a function of the structure of the canopy and percent ground cover (Colwell, 1974b). Egbert & Ulaby (1972) demonstrated that grass canopies dominated by vertical components showed significant variations in reflectance depending on look angle and solar zenith angle, whereas those with a large proportion of horizontal components appeared to have little variation in reflectance with angular changes (Colwell, 1974b). Also, grass canopies with a high percent cover were found to be less dependant on sun and sensor angles than canopies with low percent cover. This dependence can also be observed in forest canopies, the relationship of reflectance and angular effects being a function of the shape of individual tree crowns (flat-topped or pointed), surface of the forest canopy (smooth or irregular), and the degree of crown closure.

3.3.2.3 Effect of Phenology

As the leaf area and biomass of the canopy increase, there is a progressive and characteristic decrease in reflectance in the visible wavelengths, an increase in the near infrared reflectance, and decrease in middle infrared reflectance (Ahlrichs & Bauer, 1983). These phenologically - related changes are the result of variations in canopy geometry, moisture content, and leaf pigmentation (Ahlrichs & Bauer, 1983).

Tucker & Maxwell (1976) showed that the greatest spectral sensitivity between reflectance and grass canopy variables existed early in the growing season due to there being less heterogeneity in the canopy. Similar conclusions were drawn by Ahlrichs & Bauer (1983) who gave the explanation that the relation between spectral response and measures such as leaf area index, biomass, and plant water content decreases as the crop starts to ripen.

3.3.3 Remote Sensing of Vegetation Damage

3.3.3.1 Vegetation Damage

Murtha (1978) defined forest damage as:

> "any type and intensity of an effect, on one or more trees, produced by an external agent, that temporarily or permanently reduces the financial value, or impairs or removes the biological ability of growth and reproduction, or both".

Biological stress is defined by Levitt (1980) as 'any factor capable of inducing potentially injurious strain in living organisms'. The term in biology usually carries the implication of injury i.e. irreversible or plastic strain (Nilsson, 1983; Murtha, 1982) and is often referred to as the 'damaging agent'. The resulting strain is then known as vegetation damage or injury (Murtha, 1982; Levitt, 1980). In turn, plant injury can be described as changes in the morphology and / or physiology of the plant. Morphological injury is expressed as a change in form or shape e.g. defoliation, breakage of plant parts, cellular collapse (Murtha, 1976; Murtha, 1982; Nilsson, 1983).

Physiological damage is expressed as a deviation from the normal growth and development of the plant (Murtha, 1976; Murtha, 1982). Such damage may include a decrease in photosynthates and deterioration of chloroplasts i.e. chlorosis. The effects are not always immediately visible; however, subsequent changes may occur that emphasise the damage. For example, a stress that interferes with the translocation of water may not result in visible damage until the cells lose turgidity and the plant wilts (Levitt, 1980).

A large number of damaging agents can cause similar injury to vegetation, conversely one single damaging agent may cause a variety of symptoms in the affected plants (Murtha, 1978; Nilsson, 1983; Ciesla *et al*, 1985; Smith, 1988). In order to detect and understand plant injury using remote sensing, an understanding is needed of how a particular stress specifically affects the morphology and physiology both of individual plants, and the canopy as a whole.

Injury can be described as chronic or acute, depending on both the length of time the plant is subjected to the stress, and the intensity of stress (Levitt, 1980). Chronic injury is a result of exposure to a stress at below the threshold value for that stress for a long period of time (Levitt, 1980; Groves, 1989). Acute injury is caused by high concentrations of a pollutant acting over a short time span (Murtha, 1980).

Both types of injury have been recorded in conjunction with landfill gas (Section 2.4.2). The type of injury depends largely on the way in which the gas migrates, small areas of acute injury occurring where gas is moving along discrete pathways and surfacing in high concentrations. Conversely, if the gas is predominantly migrating through the soil micropores, it is likely to be present in lower concentrations, but may still cause damage if migration continues along these pathways for a longer period of time. Due to lack of knowledge of the precise methods of gas migration, and the complexity of the landfill gas / vegetation relationship, it is impossible to state thresholds at which these paramcters start to become important (see Chapter 2).

3.3.3.2 Band Selection for Vegetation Health Monitoring

As previously stated, a specific type of green vegetation has a uniquely varying spectral response as a function of wavelength (Swain & Davis, 1978),the response of a particular plant also varying with the phenology and state of health of the plant. The approach to selecting suitable band combinations should therefore consider the spectral response of the vegetation to the anticipated stress, with a view to selecting the bands which contain maximum information.

The bands chosen should include the wavelengths where vegetation damage is expected to result in spectral changes (Tucker, 1975; Tucker & Maxwell, 1976). The bands which can be expected to yield the most information are those in which the same vegetation-spectral reflectance relationship predominates throughout the waveband. Previous work (Tucker & Maxwell, 1976; Tucker, 1978) has shown that the combination of different relationships within the same band seriously reduces the utility of the band for vegetation monitoring.

The relation of spectral response to plant properties has been discussed in some detail in Section 3.3.2. Based on these relations it would appear likely that any remote sensing study of vegetation should include bands in the blue-green, red, near infrared, and middle infrared regions of the em spectrum. The green wavelengths (0.50 - 0.60 μm) and the transition zone (0.70 - 0.74 μm) would not be expected to yield useful information due to their weak relationship with plant status. The thermal infrared may yield useful information, however, until recently, the spatial resolution of this band has been inferior to that of the other bands, and little has been done to assess its usefulness for vegetation monitoring (DeGloria, 1983)

3.3.3.3 Remote Sensing of Vegetation Damage

The potential of remote sensing techniques to detect or monitor vegetation damage is based on the premise that:

(i) the stressing agent results in some type of damage to the vegetation
(ii) the damage is such that the spectral response of the affected vegetation is qualitatively and quantitatively different to that of healthy vegetation (Knipling, 1970; Murtha, 1978; Hildebrandt, 1980; Smith, 1988) (Figure 3.5).

Figure 3.5 Changes in the spectral response of vegetation with increasing injury (from Murtha, 1978)

In order to relate the inferred vegetation injury to a damaging agent, the remote sensing data should be combined with complementary ground data, either on a point sampling basis, or by comparison with patterns of known occurrence of the stress agent (Vass & van Genderen, 1978; Tucker *et al*, 1980; Nilsson, 1983; Smith, 1988).

In many situations, inferences may be drawn about the causes of injury by relating areas of damage to sources of damage-inducing agents (Barrett & Curtis, 1974; Vick & Handley, 1977; Hildebrandt, 1980; Ciesla & Hildebrandt, 1986). A good example was given by Vick & Handley (1977) who identified the extent of damage to trees and linked this to factory emissions using ground and air surveys. They used two main criteria to identify the cause of damage.; firstly, trees were undamaged prior to building of the factory, and secondly, trees on the upwind side of the factory remained undamaged after factory construction.

It can be appreciated that, due to the number of variables involved, the study of vegetation damage using remote sensing techniques is complex. Accurate identification of stressed areas is most probable if a number of conditions are fulfilled:

(i) stress occurs over a large area,

(ii) the canopy is well developed such that the contribution due to the background is low,

(iii) the symptoms are well developed.

3.3.3.3.1 Spectral Response of Damaged Vegetation

Generally, changes in leaf pigments occur in the visible region, structural characteristics in the near infrared, and emissivity in the mid and far infrared (Evans, 1983). As the plants undergo stress, the chlorophyll deteriorates resulting in less efficient absorption and increased reflection of visible wavelengths (Knipling, 1970). Such increases have been observed both in agricultural studies (Tucker & Maxwell, 1976; Tucker, 1977; Siegal & Goetz, 1977; Tucker, 1979; Horler & Barber, 1981), and in forestry work (Koch & Kritikos, 1984; Kadro, 1985; Kadro, 1986).

Reflectance in the near infrared depends on the cell structure of the leaves, as well as the proportion of green leaf to other canopy components (Kadro, 1984). A reduction in leaf area in the canopy can result in a change in the spectral response due to the decrease of reflectance from healthy green foliage and increased proportion of poorly reflecting branches, shadows and soil background. This may occur without a concomitant change in leaf reflectance (Siegal & Goetz, 1977; Tucker, 1978). The reduction of infrared response tends to be relatively greater than the increase in visible wavelengths because of the effects of cumulative reflection (Knipling, 1970; Siegal & Goetz, 1977; Tucker, 1978; Tucker, 1979; Kritikos *et al*, 1985; Rock *et al*, 1985). In some cases the differences in reflectance have been attributed to changes in leaf orientation (Knipling, 1970).

Although initial work on remote sensing of vegetation utilised colour and colour infrared data, in recent years, sensor developments have enabled data to be collected and analysed from the middle infrared wavelengths. As damaged vegetation usually has a lower leaf water content, a damaged vegetative canopy may show decrease in absorption and increase of reflectance in the mid infrared (Knipling, 1970; Tucker, 1978). This spectral response has been used to detect stressed vegetation (Lynn, 1984; Everitt *et al*, 1986a). In addition, loss of foliage with high moisture content, and the corresponding increase in background contribution, can lead to an increase in mid infrared response (Koch & Kritikos, 1984; Kadro 1985; Kadro, 1986; Kadro & Kuntz, 1986).

Maximum discrimination between healthy and stressed vegetation may be obtained by using a combination of infrared and red wavebands, thus utilising the opposing response to stress in the visible and near infrared regions (Colwell, 1974a; Tucker, 1980; Curran, 1981; Kimes *et al*, 1981; Jackson *et al*, 1983; Kleman & Fagerlund, 1987). Such combinations are known as vegetation indices, and include:

(i) infrared : red ratio,

(ii) normalised difference vegetation index (NDVI = (IR - red) / (IR + red)),

(iii) infrared minus red.

The simple infrared : red ratio is one of the most popular vegetation indices for monitoring stress in crops affected canopies having a lower ratio value. However, for less than 50% cover the ratio is relatively insensitive to variations in plant condition (Jackson, 1983). It is also very sensitive to the inclusion of small amounts of brown biomass and is therefore less useful after senescence (Kleman & Fagerlund, 1987).

3.3.3.3.2 Forest Damage Inventory

Tree decline, in general, has been described as:

> " a continuous recession in health, a disorder or disease, which affects tree growth" (Yuan *et al* , 1988).

Remote sensing has been used for several years for the inventory of forest damage, most studies concentrating on either unspecified forest decline on a regional scale (Holmgren & Wastenson, 1985; Ciesla *et al*, 1985; DeRoover *et al*, 1985; Ciesla & Hildebrandt, 1986; Groves, 1989), or defoliation of spruce and fir by pests (Ashley *et al*, 1976; Talerico *et al*, 1978; McCarthy *et al*, 1982). Some work has also been carried out to investigate the use of remote sensing in monitoring tree damage adjacent to point sources of pollution (Murtha, 1974; Vick & Handley, 1977; Murtha & Trerise, 1977; Carlson, 1978).

Most approaches to forest damage inventory have classified forest health, using a class damage rating system to allocate classes to a number of trees at a sample point (Holmgren & Wastenson, 1985; Ashley *et al*, 1976; Ciesla *et al*, 1985; Ciesla & Hildebrandt, 1986; Schwarzenbach *et al*, 1986). This type of classification may concentrate on percentage defoliation, or may also take into account changes in foliar colour (Ciesla & Hildebrandt, 1986).

The second approach, favoured in the United States, was to concentrate on mortality and top dieback on a sample plot of known size (Vick & Handley, 1977; Ciesla & Hildebrandt, 1986). As most economically-oriented forest surveys are interested in the health of living trees, rather than the number of dead or severely damaged trees, the first approach has tended to be more widely used. The distribution of damage is thought to be strongly affected by the susceptibility of individual trees, apparently healthy trees frequently being found adjacent to those in various stages of decline (Smith, 1988).

(i) Air Photo Interpretation of Forest Damage

Until the recent development of airborne multispectral scanners and aerial video systems, the only remote sensing device available was the photographic camera. Most forestry workers still acknowledge that stereoscopic manual interpretation of colour infrared aerial photos is the best remote sensing system available for assessing forest condition, the technique having been widely used in commercial situations for several years (Hildebrandt, 1980). However, air photo interpretation has several disadvantages, both in terms of maintaining classification accuracy (due to the subjectivity of interpretation procedures, and obtaining consistent film and processing quality), and in terms of the time and cost involved in manual classification.

One of the major disadvantages with air photographs is that variations in tone, both within a single photo due to lens effects (vignetting), and between successive dates of photography, may lead to inaccurate classification results. Vignetting is a problem with all aerial photography and is discussed in numerous texts (Daels & Antrop, 1978; Colwell, 1983; Curran, 1985). Variations between successive dates of photography can be attributed to differences in film and processing quality, making the comparison of photos from separate dates difficult (Holmgren & Wastenson, 1985; Talerico *et al*, 1978; Daels & Antrop, 1978; Ciesla & Hildebrandt, 1986). As a result, damage should be considered as a deviation from a 'standard healthy' tree (Murtha, 1978; Murtha & McClean, 1981; Daels & Antrop, 1978; Nilsson, 1983), the 'standard' tree being a baseline, against which relative damage can be measured.

These problems are offset by the fact that the interpreter is able to include spatial information when carrying out classification; for example, crown damage may be accompanied by loss of foliage from the upper crown, resulting in a 'rough' appearance but without any change in foliar colour. The manual interpreter is easily able to include this in a classification system.

Various scales of photography have been utilised from 1: 1 200 to 1: 20 000. As a general rule, the smaller the scale of photography, the less accurate and more time consuming the analysis (Carlson, 1978; Ciesla *et al* , 1985; Holmgren & Wastenson, 1985). In practice, a balance has to be achieved between the increased cost of obtaining large scale coverage of an area, and the increased difficulties and time concerned with the interpretation of small scale photos (Holmgren & Wastenson; Ciesla *et al*, 1985).

(ii) Computer Classification of Forest Damage

Most work using digital data to survey and classify tree decline has relied on the existence of a difference in spectral response between differently damaged stands or individuals (Figure 3.6 and Table 3.3) (Teillet *et al* , 1981; Kadro, 1984; Ciesla, 1985; Kadro, 1986; Vogelmann & Rock, 1986; Smith, 1988; Westman & Price, 1988). With the wider availability of high resolution data in recent years, attempts have also been made to account for textural changes in the tree crowns (King, 1988; Yuan *et al* , 1988).

Author	Problem	Results
Edwards et al , 1975	Citrus young tree decline	Identified four levels of decline using near and middle infrared bands
Leckie & Gougeon, 1981	Spruce budworm damage in mixed spruce/fir forest	Four levels of damage, using blue, red & near IR Variations due to different hardwood component crown closure confused classification
Koch & Kritikos, 1984	Forest damage detection	Two damage classes identified, shadow classified separately
Beaubien & Laframboise, 1985	Spruce budworm defoliation	No clear defoliation identified - attributed to poor positioning of red band, mixture of coniferous / deciduous trees, variation in crown closure
Baninger, 1986	Geobotanical (metal) induced forest stress	Regressed various spectral bands against soil metal values to identify most useful bands for identifying geobotanical anomalies
Kadro & Kuntz, 1986	Coniferous forest decline	Classified healthy & severely damaged forest stands using 2.5 and 7.5 m resolution MSS data Old dense stands most successful
Vogelmann & Rock, 1986	Spruce/fir forest decline	Used multispectral scanner data to detect, quantify and map forest decline New areas of decline identified
Westman & Price, 1988	Air pollution damage to yellow pine forests foliar injury	Landsat TM & airborne TM data used Natural variations in canopy closure created spectral variation & obscured differences due to

Table 3.3 Examples of previous research on applications of multispectral scanner data to assess forest damage

Figure 3.6 Differences in spectral response of high and low damage forest canopies (from Rock *et al*, 1988)

The spectral reflectance of a single tree crown is dependant on the density and the condition of the foliage; in the event of damage occurring, the foliage may undergo chlorosis, but it may also be lost from the crown. Initial results using multispectral scanner data indicated that damaged and healthy trees and stands were spectrally discriminable, the degree of separation being dependant on the extent and type of damage, and the wavelengths used (Kadro, 1984; Kadro, 1986; Ahern *et al* , 1986).

The spectral response of tree canopies to damage is complex. Based on knowledge of the response of foliage to stress, the expected response would be increased reflectance in the visible and middle infrared wavelengths, and decreased reflectance in the near infrared. However, several studies have demonstrated an increase in infrared reflectance with increasing damage. The reason for this has been associated with the loss of foliage from the crown, and the simultaneous increase in reflectance from the soil or undergrowth (DeRoover *et al* , 1985; Kadro, 1986; Vogelmann & Rock, 1986). For example, Vogelmann & Rock (1986) attributed the increase in near infrared reflectance to the invasion of broad leaved understory as the tree canopy thinned.

It is generally accepted that differences in spectral response become less pronounced as the image resolution diminishes due to the integration of other site variables into the spectral response pattern (Ahern *et al*, 1986; Kadro & Kuntz, 1986; Smith, 1988; Yuan, 1988). In the main, high spatial resolution data (less than 2 m) allows the study of individual crowns and isolation of their spectral responses, coarser resolutions only permitting the investigation of stands or groups of trees (Kadro, 1984; Kadro, 1986; Kadro & Kuntz, 1986; Smith, 1988).

Work using video data in particular, has stressed the importance of textural measures when using high resolution imagery (King, 1988; Yuan, 1988; Yuan *et al*, 1988). Such texture measures were successfully applied to classification of video imagery in cases where textural and spectral changes were occurring concurrently. For example, Yuan *et al* (1988) developed a 'maple decline index', based on the deviation of the spectral and textural response from healthy (reference) trees.

The precise location of spectral bands has also been found to be an important factor in determining the usefulness of multispectral scanner data in forest damage evaluation. Comparison of the MEIS II (multi-detector electro-optical imaging scanner) and Daedalus 1260 scanners by Ahern *et al* (1986) suggested that the superior ability of the MEIS II to detect defoliation was due to the red band being very narrow and well positioned with respect to the chlorophyll absorption minimum at 0.675 μm.

Any spectral changes as a result of damage may be masked by much larger variations caused by mixed stands and degree of crown closure (Ahern *et al*, 1986; Leckie & Gougeon, 1981; Westman & Price, 1988). For these reasons, classification of severe damage affecting many trees has a better chance of success than identification of light or moderate damage. For example, Westman & Price (1988) studied ozone-related foliar injury (chlorosis, necrosis, and some leaf loss) in the field. Whilst the injury was considered to be 'severe' on the scale of foliar damage, there was limited structural damage, and it was insufficient to register as a spectral change above the background variation caused by changes in canopy closure and species composition. This has serious implications, as severely damaged areas are usually well known, and an indication of the onset of decline would be a greater measure of the utility of remote sensing.

3.3.3.3.3 Crop Damage Inventory

As most crops are grown in relatively pure stands of approximately the same age, remote sensing for agricultural monitoring tends to be more straightforward than for forestry purposes (Tucker, 1978). However, there are also difficulties, in that crops usually have a very short phenological cycle, their spectral response varying rapidly as the crop grows and covers increasing amounts of soil (Barrett & Curtis, 1974).

The response of crops to stress is very variable. Symptoms including chlorosis, necrosis, and reduction in plant height, crop cover, or final yield have been recorded in many cases (Jackson & Wallen, 1975; Casalinuovo & Sawan, 1976; DoE, 1988), such injury frequently resulting in a change in spectral response. In some situations, the change in the spectral response of the vegetation was not easily visible to the ground-based observer, but was clearly delineated on colour infrared air photos (Casalinuovo & Sawan, 1976; Ladouceur *et al* , 1986).

Work carried out to investigate crop stress has concentrated on the impact of both biotic factors such as diseases and pathogens (Harney *et al* , 1973; McDonald *et al* , 1972; Jackson & Wallen, 1975; Wallen & Jackson, 1975), and abiotic factors such as water / nutrient stress and soil salinity (Millard *et al* , 1978; Henneberry *et al* , 1979). These studies have mainly been directed towards obtaining spatial information, enabling the interpreter to identify areas of stress within an otherwise 'healthy' field (Meyer & Calpouzos, 1968).

The differences in reflectance characteristics that allow the discrimination of different states of health of vegetation can be related to their leaf and canopy characteristics (Knipling, 1970). However, although there is some amount of agreement in choosing the most informative wavelengths for studying vegetation amount, there is no consensus as to which agronomic variable should be used to represent the actual crop condition. Suggested measurements of vegetation health / amount have included leaf hemispherical reflectance and transmittance, green leaf area index, percentage cover, fresh and dry biomass, leaf water content, chlorophyll content, fraction of leaf chlorosis, plant height, and measurements of plant development (Colwell, 1974a; Tucker, 1977; Tucker, 1978; Tucker *et al* , 1979; Holben *et al* , 1980; Curran, 1980; Curran, 1981; Kimes *et al* , 1981; Ahlrichs & Bauer, 1983; Steven *et al* , 1983). Generally, the reflectance of a green canopy is most highly correlated with green leaf area or green biomass (Tucker *et al*, 1974a; Kimes *et al* , 1981). Due to the difficulty of measuring leaf area index and plant biomass, percent cover has tended to be the preferred measure of vegetation amount (Curran, 1981).

The choice of variables for this project, and the reasoning for their selection, is given in Section 5.2.

Most remote sensing of crop damage has concentrated on visually interpreting the data to identify areas where problems were occurring (Casalinuovo & Sawan, 1976; Gausman *et al*, 1974; Gausman *et al*, 1975; Nixon *et al*, 1983; Nixon *et al*, 1985; Hart *et al*, 1988). Other authors have extracted optical density levels from colour infrared air photos (Jackson & Wallen, 1975; Wallen & Jackson, 1975), or used video data to calculate the mean reflectance of various experimental plots (Ammon *et al*, 1987) (Table 3.4).

Author	Problem	Results
Wallen & Philpotts, 1971	Detection of bacterial blight of field beans	CIR air photos used to estimate percentage of fields affected by blight
Gausman *et al*, 1975	Detection of chloritic (iron deficient) grain sorghum	ERTS-1 satellite data used to identify areas of chlorosis 1.1 ha or larger, within otherwise homogeneous fields
Casalinuovo & Sawan, 1976	Ozone and SO2 damage to potatoes and corn	Resistant strains clearly visible on colour IR air photos
Henneberry *et al*, 1979	Monitoring application of growth regulators	CIR air photos determined effectiveness of application of growth regulators Detected as early as two days after treatment
Ladouceur *et al*, 1986	Crop loss assessment for insurance purposes	CIR air photos used to discriminate three crop damage classes
Ammon *et al* 1987	Detection of moisture & nutrient stress to corn	Multispectral video imagery compared with ground based radiometer data Capable of separating plots with different levels of water, nitrogen, and phosphorus

Table 3.4 Examples of previous research to identify crop damage using remote sensing data

The established method of identifying crop damage has been by manual interpretation of colour infrared air photographs, or more recently, digital imagery (Gausman *et al*, 1975; Casalinuovo & Sawan, 1976; Evans, 1983). In addition, the rapid development of video remote sensing in recent years has led to the investigation of the uses of videography to identify crop injury (Nixon *et al*, 1985; Hart *et al*, 1988; Ammon *et al*, 1987).

Most manual interpretation of remote sensing data has concentrated on identifying the spatial distribution of damaged areas, rather than collecting data on actual areas affected. For example, Casalinuovo & Sawan (1976) identified area of moisture stress, enabling the farmer to correct the situation before the crop was irretrievably damaged. Colour infrared air photos and satellite data were also used in identifying areas of chloritic grain sorghum as a result of iron deficiency (Gausman *et al*, 1974; Gausman *et al*, 1975), the areas of chloritic crop being easily identified by its white appearance on colour infrared imagery. Field work established the fact that the difference between healthy and affected plants could be attributed to chlorosis, the crop cover, plant size, and canopy geometry being essentially the same for all plants.

Evans (1983) highlighted the use of 'indicator' plants in remote sensing surveys i.e. plants which were sensitive to the pollutant being monitored, and expressed this as a change in spectral response . By using such plants, air photos could be used to locate areas of possible stress, and field visits made to these sites (Heck & Heagle, 1973; Harney *et al*, 1973; Oshima, 1974).

Quantitative estimation of crop damage using remote sensing data has been limited. Optical density measurements from infrared aerial photos in conjunction with field data were found to be useful in estimating actual crop losses due bacterial blight of field beans (Jackson & Wallen, 1975; Wallen & Jackson, 1975). Maximum spectral differences between healthy and infected crops were measured as the crop reached maturity, and decreased thereafter. Attempts at automatic classification have been restricted by the fact that additional variation due to angular effects, target variability, and surface variations frequently mask changes related to damage (Duggin & Whitehead, 1983).

3.4 Remote Sensing of Landfill Sites

Remote sensing techniques have been used to solve a number of problems related to landfill sites, including limited applications to monitor landfill gas (Table 3.5).

Problem	Sensor/Product	Remote Sensing Applications
PRE - LANDFILL		
Waste quantities, characteristics,	Project - specific imagery, historic air photos	1. Identification of sources of waste, estimation of types and quantities distribution 2. Changes in trends over time - urban expansion
Site selection and utilisation	Project specific imagery (small scale)	1. Regional geology, and hydrogeology 2. Register of land use - availability of open land; relation to surrounding features; haul distances 3. Waste quantities and types 4. Location of existing excavations
	Project specific (large scale)	1. Local (proposed site) geology, geomorphology, hydrogeology 2. Potential impact of site on local communities 3. Capacity of existing excavations 4. Analysis of vegetation at proposed site
POST - LANDFILL		
Monitoring site filling and restoration	Project specific (large scale)	1. Monitor operational practices 2. Identify areas having escaped restoration 3. Monitor progress of restoration
Environmental impact of waste disposal	Project specific (large scale)	1. Changing water quality 2. Vegetation injury / death on or adjacent to site 3. Aesthetic pollution 4. Destruction of wildlife habitats 5. Spatial inference of risk e.g. proximity to housing
	Thermal imagery	1. Underground fires 2. Leachate pollution in streams

Table 3.5 Possible applications of remote sensing to solid waste disposal (from Garafalo & Wobber, 1974; Anderson, 1980; Coulson & Bridges, 1984)

3.4.1 Site Selection

Remote sensing techniques have been applied for many years to the problems associated with selecting suitable waste disposal sites (Garofalo & Wobber, 1972; Becassio & Redfield, 1979; Ruth *et al*, 1980; Erb *et al*, 1981; Haynes *et al*, 1981; Lyon, 1987). Such work has stressed the use of remote sensing data to interpret regional and site-specific geological and hydrogeological conditions, to provide an initial assessment of the land for landfill operations.

3.4.2 Site History

Remote sensing has been used in a number of situations to help resolve questions regarding the history of landfill sites. Previous studies have included:

(i) delineation of changing site boundaries (Erb *et al*, 1981; Dumbleton, 1983),

(ii) identification of types of waste deposited (Titus, 1983; Stohr *et al*, 1987),

(iii) identification of the existence of completed sites (Amos, 1990),

(iv) monitoring reclamation of completed sites (Anderson, 1980).

In many situations, poor records mean that the actual location, types of waste deposited, and extent of old sites, may be totally unknown. Such knowledge may be particularly useful when attempting to relate an environmental impact to possible sources.

3.4.3 Post-Landfill Impact

Groundwater and surface water pollution due to leachate, and the numerous problems encountered as a consequence of landfill gas migration, have brought to light the fact that burying wastes may have serious environmental repercussions, several years on.

3.4.3.1 Remote Sensing of Leachate

The remote sensing of leachate migration relies on it surfacing at some point, and on the presence of one or more diagnostic features:

(i) Colour anomalies may exist, due to the staining of soil and other surface materials associated with the surface discharge of leachate (Haynes *et al*, 1981). Such colour anomalies have been identified using colour and colour infrared air photo interpretation.

(ii) Damp areas are diagnostic, especially if the increased moisture persists through dry periods, is present at the landfill toe or on side slopes, or exists in conjunction with other features. Moist areas have been identified and associated with leachate breakout using both colour / colour infrared air photos, and thermal imaging (Haynes *et al* , 1981).

(iii) Leachate may induce vegetation injury when present in the root area of plants, and has been observed to result in barren areas, decreased plant numbers, absence of certain species, dead tress, and early senescence (Haynes *et al* , 1981; Lyon, 1987). There may also be a positive stress, for example if the plants are tolerant to the toxins in the leachate, they may thrive due to the increased moisture availability. In addition, if the leachate contains plant nutrients, such as nitrogen, potassium, or phosphorus, the result would be vigorously growing vegetation (Lyon, 1987). The use of vegetation as an additional long-term monitoring approach has been suggested where the cost is justifiable (Ruth *et al*, 1980; Lyon, 1987).

Due to the areas affected by discharge being small or indistinct , there may be difficulties in identifying these on the imagery. In addition, the diagnostic features may not be unique, for example, Haynes*et al* (1981) identified 'leachate staining' on colour infrared air photos. Subsequent field verification attributed many of these areas to changes in cover materials.

Remote sensing can also be utilised to identify or confirm leachate migration pathways. Stohr *et al* (1987) interpreted large scale infrared photos and thermal infrared imagery to locate moisture-holding depressions on a restored site, which allowed drainage into the waste body, and hence eventually into the groundwater system. They also detected lineaments offering the potential for pollutant migration, and related these geological structures to the distribution of contaminated water in wells.

3.4.3.2 Remote Sensing of Landfill Gas

Much less work has been carried out to investigate the role of remote sensing in detecting or monitoring landfill gas migration, largely due to the difficulties in predicting or understanding the migration of gas. Gas migration occurs as part of a dynamic system, and the problems of attributing vegetation damage to the presence of gas are substantial (Section 2.4). Along with the incomplete understanding of the relationship between landfill gas and vegetation damage, this has resulted in an understandable reluctance to commission expensive remote sensing surveys.

Limited work carried out using remotely controlled model aircraft and 35 mm cameras has shown quite promising results (Weltman, 1983; Curran, 1986; Whitelaw, 1986). However, all these studies were qualitative, and involved sites producing very high quantities of gas. Actual details of landfill gas concentrations were sparse, as were any measurements of plant parameters. Curran (1986) stressed that such photos were not suitable for the generation of hypotheses as to the cause or effects of landfill gas migration. However, their use would be in locating areas of methane seepage, with the suspect areas being later tested on the ground.

Due to the fact that landfill gas is produced by an exothermic reaction, gas affected soils may be expected to be warmer than unaffected soils (Section 2.4.1). Further increases in soil temperature may occur as a result of the biological oxidation of methane to carbon dioxide close to the soil surface. Limited work has been conducted to ascertain the use of airborne thermal imaging in verifying the presence of landfill gas (Amos, 1990; Fletcher, 1990). The work identified several areas that exhibited an increase in temperature compared to surrounding soils, all these locations were later confirmed to have high concentrations of landfill gas. However, there were many omission errors, the technique failing to identify all the affected areas.

With the data used in this project, there appeared to be no increase in temperature of the soils associated with high concentrations of gas. Either there was a temperature difference but it was undetectable using the thermal channel, or there was no real difference. The reasons for this are difficult to evaluate, but could be associated with the complexity of the oxidation reaction.

3.5 Summary

Remote sensing tools may have the potential for rapid and accurate assessment of vegetation damage (Talerico *et al*, 1978; Beaubien & Laframboise, 1985; Vogelmann & Rock, 1986). The degree of accuracy that can be expected depends on: the existence of differences in spectral response; the separability of these differences from other variations in the canopy; and the ability of a particular sensor to detect these differences. Direct information about damaging agents is not retrievable using such data; however, much can be inferred by the distribution of the injury, both in space and time.

Although a large amount of work has been carried out to automatically assess forest damage using multispectral scanner or video data, the work is still experimental and has not yet become a widely accepted technique. Initial studies indicated the existence of spectral response differences between healthy and damaged trees; however, these changes were frequently difficult to differentiate from other variations.

High resolution imagery would be expected to have the greatest potential, allowing single tree crowns to be identified, and their spectral response to be isolated. Even with such high resolution imagery, previous studies have indicated that only two or three damage classes are spectrally separable. Combined with the cost of acquiring such high resolution imagery, these factors would be expected to reduce the capacity of multispectral data to be used in studies of large area forest decline. The use of multispectral scanner imagery over smaller areas would have greater potential, particularly if combined with information from air photos.

In contrast, manual air photo interpretation is established as being an efficient means of carrying out forest inventory, large scale stereo photos allowing information about the extent of damage to be extracted on a tree-by -tree basis. The ability to be able to allocate crown damage to a detailed 5-class rating system is unlikely to be paralleled using multispectral scanner data.

Crop inventory is theoretically simplified compared with forest work; within limited areas, crops tend to be at the same phenological stage and are the same species. However, the use of remote sensing for surveying crops has been far less widely reported in the literature.

Remote sensing techniques cannot usually replace ground surveys in the detection and monitoring of vegetation damage. Some type of ground reference data is normally necessary to relate vegetation injury to the damaging agent, and provide a means of estimating the accuracy of the classification result (Ciesla & Hildebrandt, 1986). Instead the techniques are of most use in giving an overview of the damage and facilitating ground work (Knipling, 1970; Ashley *et al* , 1976; Nilsson, 1983; Olson, 1984).

Remote sensing is proposed as a means of obtaining information regarding the migration of landfill gas, as a direct result of its effect on vegetation. The success of such an approach rests on two assumptions:

(i) firstly, landfill gas can be shown to be correlated with vegetation condition,
(ii) the damage is displayed as a change in the spectral response of the plant canopy.

As discussed in Chapter 2, landfill gas has been observed to result in various types of plant injury, predominantly reduction in plant height, chlorosis of the leaves, reduction in crop cover, and eventual death of affected plants. The literature covered in this chapter suggests that many of these symptoms may be detectable using remote sensing techniques. The remainder of this work assesses the use of remote sensing techniques to detect and monitor the migration of landfill gas, as a result of its effect on vegetation.

4 REMOTE SENSING SYSTEMS

The three different systems used for acquiring the imagery used in this study, were briefly introduced in Section 3.1. In order to appreciate the limitations imposed by the different sensors and systems, some of their features are discussed further here. The chapter is not intended as a complete introduction to remote sensing technology. Consequently, as they are extensively covered in the literature, aerial photography and multispectral scanning are not considered in great detail. More emphasis is placed on the development of the aerial video imaging system, and the problems that could affect subsequent analysis.

A summary of the sensors used is given in Table 4.1.

All image processing and spatial analysis was carried out using the Inconsys Image Processing system. The system was developed in-house, and further details may be found in Flach (1989).

4.1 Aerial Photography

Aerial photography was one of the first methods used to obtain data from the air, and even today remains a popular system for collecting remote sensing information. Its popularity is due, in the main, to the availability of air photos, the relatively low cost of acquiring imagery, and the spectral and spatial resolution of the photos.

4.1.1 Aerial Photographic Systems

The information that can be collected by photographic systems is limited by the films available. Four different types of film are commonly used: one-layer black and white, and three-layer colour, both of which may be sensitised to the infrared and visible, or just the visible (Curran, 1985). These are summarised in Table 4.2.

Sensor	Spatial Resolution / Scale	Spectral Resolution
Wild RC8 Film Camera	1 : 2 000 - 1 : 3 000	Visible and near infrared wavelengths
Panasonic Industrial Standard WVP A2E Colour Camera Newvicon Tube	1.6 m	Blue < 0.4 μm Green 0.4 - 0.7 μm Red 0.7 - 0.75 μm
Insight Visions Model 75 Series Newvicon Tube	1.6 m	Infrared 0.69 - 0.9 μm
Daedalus 1268 Opto -mechanical Multispectral scanner	2.0 - 2.5 m IFOV at centre of swath	Band 1 0.42 - 0.45 μm Band 2 0.45 - 0.52 μm Band 3 0.52 - 0.60 μm Band 4 0.605 - 0.63 μm Band 5 0.63 - 0.69 μm Band 6 0.695 - 0.75 μm Band 7 0.76 - 0.90 μm Band 8 0.91 - 1.05 μm Band 9 1.55 - 1.75 μm Band 10 2.08 - 2.35 μm Band 11 8.50 - 13.00μm

Table 4.1 Summary of sensors used in the research

Film Type	Sensitivity	Advantages	Limitations	Cost
Black & white panchromatic	.4 - .7 μm	Good definition & contrast; textural & geometric patterns obvious	Limited number of grey tones distinguishable by eye	Low
Black & white infrared	.4 - .9 μm	Enhancement of vegetation differences; definition of water; haze penetration good	Contrast may be excessive; detail lost in areas of shadow	Low
True colour	.4 - .7 μm	Good contrast and tonal range	Less definition than panchromatic	Interm
False colour	.4 - .9 μm	Enhances vegetation differences & moisture distribution; haze penetration	Lower resolution than colour; difficult to determine exposure	High

Table 4.2 Characteristics of film emulsions used for aerial photography

Black and white panchromatic film has equal sensitivity to all visible wavelengths, but cannot record information in the infrared. The advantages of such photographs include their high tonal contrast, consistent high processing quality, and low cost. However, they cannot detect radiation in the near infrared (and may therefore exclude valuable information about vegetative condition) and, due to the ability of the human eye to discriminate only approximately 16 grey scales, the detection of certain features may be limited.

Black and white infrared emulsion is sensitive up to 0.9 μm; it is used in conjunction with a sharp-cutting filter, such that the visible wavelengths are excluded, and only the 0.7 to 0.9 μm range is recorded. Although more expensive than black and white panchromatic photos, these are capable of providing more contrast between different vegetation types, and also have the advantage of excluding the shorter wavelengths which tend to be affected by atmospheric haze.

Colour and colour infrared (CIR) are more expensive to acquire because of the cost of the film, however, due to the ability of the human eye to perceive colour, they may be of greater use in many surveys.

The sensitivity of infrared film extends into the near infrared (0.7 - 0.9 μm). Used in conjunction with a yellow filter to eliminate blue wavelengths (less than 0.5 μm), this produces photos with the infrared wavelengths represented by red, the red by green, and the green by blue. Although the colours may appear confusing to an untrained observer, due to the high reflectance of vegetation in the near infrared, this type of film produces far better discrimination of differences in crop type or condition. In addition, as a result of the elimination of the shorter wavelengths, the effects of atmospheric haze are reduced.

Problems are frequently encountered with the use of CIR photos due to the rapid decrease in speed of the infrared-sensitive layer with age (Fritz, 1967). This may result in a difference in colour balance between different sets of photos, and can confuse attempts to extend results over large areas, or comparison of photography from different dates.

A further difficulty is presented by the optics of the camera, which cause a reduction in the amount of light reaching the outer edges of the film i.e. vignetting. Both these problems, and ways in which to minimise them, are dealt with in numerous texts (e.g. Fritz, 1967; Eastman Kodak Co., 1978; Colwell, 1983). As they did not present a problem in the context of the present research, they are not discussed further here.

Traditionally, air photos are acquired by means of a mapping camera, producing large format (23 x 23 cm), vertical prints or diapositives. These have very high resolution and geometric fidelity. The timing of the photography ensures that there is a 60% overlap along the flight path. Subsequently, a stereoscope may be used to gain a three-dimensional perspective of the scene.

Further descriptions of the methodology involved in acquiring and interpreting air photos in general may be found in any of the references given above, and the use of CIR photos specifically for vegetation damage monitoring is discussed in Section 3.3.3.

4.1.2 Flight Details

Several sets of air photos (both colour infrared and black and white panchromatic) were obtained for the project. The flight details are given in Table 4.3.

Date / Time	Site	Flight altitude	Imagery / sensor
6 July 1988 / 11.00	Ware	900 m	ATM Colour IR aerial photos
6 Sep 1988 / 11.30	Ware, Panshanger	Approx 1000 m	Colour IR aerial photos
31 March 1989 / 13.00	Ware, Panshanger	800 m	ATM B/W aerial photos
15 June 1989 / 18.00	Ware, Panshanger	Approx. 300 m	Colour and B/W video imagery
22 July 1989 / 09.21	Panshanger	800 m	ATM B/W aerial photos

Table 4.3 Flight Summaries

In order to prevent confusion when integrating the field and remote sensing data, the imagery acquired on the 31 March 1989 is referred to throughout the thesis as 'April' data.

4.2 Video Remote Sensing

Concomitant with the increasing use of remote sensing techniques in the scientific community, came a realisation of the need for techniques that could provide near real time information for the cost-effective interpretation of vegetation condition. Partly in response to this need, video remote sensing has been proposed and investigated by many workers, with the eventual aim of supplementing or replacing more traditional methods (Meisner & Lindstrom, 1985; Richardson *et al* , 1985; Toomey, 1985; Vlcek & King, 1985; King, 1988; Flach, 1989). The rapid development of increasingly high quality video cameras and recorders has aided this progression in recent years, with the result that modern video systems are now being considered as viable alternatives for low cost multispectral photographic systems.

This section outlines the initial development of such a system for the monitoring of vegetation stress in the landfill environment.

4.2.1 Video System Components

The video system comprised a number of components, including the cameras, tape recorders and monitors used to collect the data, and framegrabbers and decoders to process and analyse the acquired data (Figure 4.1). The following sections outline the hardware used in the acquisition of the aerial video data for this project. Different set ups have been used by other authors, and the reader is directed to any of the references for additional details on these.

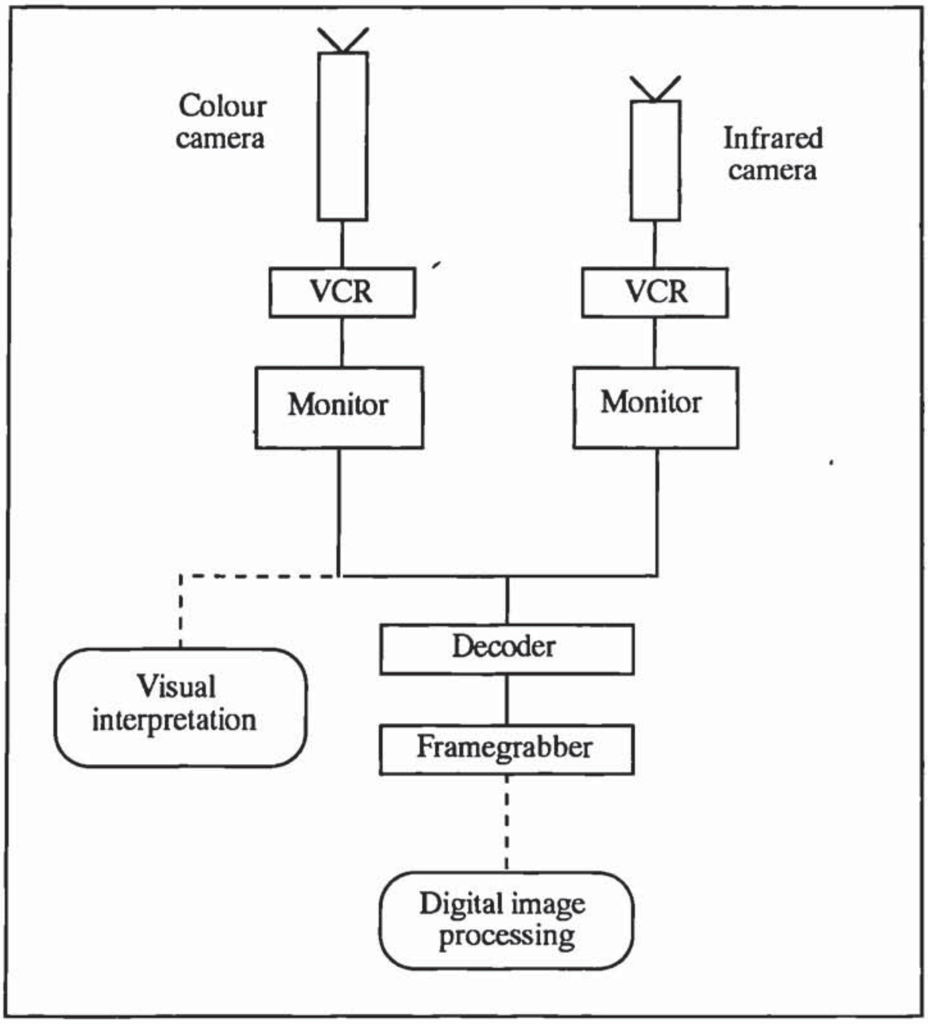


Figure 4.1 Airborne video set-up used

4.2.1.1 Cameras

Two tube cameras were utilised, one being a colour camera, and the other a monochrome camera, with a Newvicon tube sensitive to the near infrared; in this way four wavebands of data were collected i.e. near infrared, red, green, and blue (see

Table 4.1). Both cameras utilised Newvicon tubes, although the infrared response of the colour camera was restricted due to the inclusion of a 0.75 μm cut-off filter within the camera.

The critical component of a tube camera is the vidicon tube, as it is this that converts the incoming light to an analogue signal. Together with the image display tube, this controls the quality of the system to a greater extent than any other single component (White, 1979). The tube includes an element covered with a photo-conductive material, contained within a gas or vacuum (White, 1979; Slater, 1980; Flach, 1989). The camera lens focuses incoming light onto the element, which is then scanned by an electron beam. This detects and records the intensity of light as amplitude on an analogue signal. Spatial and spectral resolution of the entire system is ultimately controlled by the sensitivity of the photo-conductive material used in the tube (Section 4.2.3), although the resolution may be seriously modified by other components of the video system.

The lenses used were 12.5 mm; this focal length is equivalent to a 50 mm lens used for still photography.

4.2.1.2 Video Recorder

The main prerequisite for the recorder used in airborne surveys is that it is robust and portable i.e. it must be light and able to be powered by battery or the internal electrical system of the plane. The Panasonic NV 180 VHS recorders used were both home standard, and capable of capturing the signal at a resolution of approximately 220 lines.

In terms of spatial resolution, the recorder is the 'weak' link in most video recording systems. Until recently, home standard recorders, such as the one used, were only capable of recording between 180 and 220 lines, compared with 350 using a U-matic machine.

4.2.1.3 Framegrabber and Decoder

For the digital display and analysis of video imagery, it was necessary to convert the analogue signal to digital values. This was carried out by means of a framegrabbing card which accepted either a monochrome, or separate red, green, and blue signals, as well as a synchronisation signal. The card digitised the incoming signal to produce an array of 768 pixels per line, with 576 lines

The image (or frame) comprises two interlaced fields; one being the even lines of the frame, the other the odd. The software used allowed the option of grabbing interlaced or non-interlaced signals. Unless imagery is acquired with a shuttered camera, interlaced images are likely to show image motion, caused by the movement of the aircraft between alternate fields. As such cameras were not used, the non-interlaced option was utilised.

As described above, with the colour camera, the signals were encoded to give a composite. Prior to framegrabbing, the composite colour signal had to be split (or decoded) into its individual components. This procedure was carried out by inputting the composite signal to a PAL decoder, the decoded signal then being input to the framegrabber.

4.2.1.4 Video Signals

There are two video line standards in existence; these contain information on the combined or total luminance levels, and the synchronisation for the interlacing of odd and even fields (Toomey, 1985; Flach, 1989). The normal UK standard is the CCIR standard. Using this standard, a field (half frame) is produced every 1/50th second (determined by the mains frequency), the two fields then being interlaced to produce a frame.

In addition, in colour systems, to maintain compatibility with monochrome signals, the separate signals received from the vidicon tubes are encoded to give a composite output from the camera using the PAL (Phase Alternation Line) standard. Unfortunately, a result of the encoding is the reduction in amplitude of each signal, and consequently a large amount of spectral information may be lost.

4.2.2 Video System Characteristics

4.2.2.1 Geometric Characteristics

The geometric characteristics of the video imaging system were influenced by a number of factors including, the resolution capabilities of the components, flying height, and the lenses used.

The spatial resolution of imagery has been defined as "the number of individual picture elements that can be distinguished in one horizontal scan line, usually expressed as the number of vertical lines" (Heckel, 1987). The theoretical minimum ground pixel size detected by the camera can be simply calculated using similar triangles, with the field of view in the horizontal and vertical dimensions being determined from the focal length, sensor dimensions, and flight altitude. For this data, the minimum pixel size was 0.7 m.

In practice, the actual spatial resolution of the system was controlled by several variables, including the camera tube, video recorder, frame-grabber, and monitor being used to display the images. With the set up used, the lowest resolution factor was the video recorder (approximately 220 lines), and so this controlled the resolution of the data.

There are several possible sources of geometric distortions in video imagery including the tube itself, lens effects, and registration of images from different cameras. Tube cameras are subject to distortions resulting from the curved imaging surface, electron beam scanning non-linearities, and instabilities over time (Toomey, 1985; Heckel, 1987; King, 1988). For example, the frequently quoted spatial resolution of specific tubes is measured at the centre of the image, and is much lower at the edges (Heckel, 1987).

Although video cameras are not designed with high geometric fidelity in mind, work by King (1988) indicated that the small apertures and long focal length lenses used for aerial videograhy tended to minimise geometric distortions in the data.

For many practical applications of video imagery, coregistration of several frames would be required, allowing a mosaiced image of the area of interest to be generated, and digital image processing to be carried out. Although the standard polynomial-based approach to correction of the invidual frames would be appropriate (see Section

4.3), the overall geometric fidelity of the mosaic would not be expected to be high. The mosaicing procedure, and estimates of the geometric accuracy of the final mosaics, are given in Section 4.3.

4.2.2.2 Radiometric Characteristics

Two aspects of the radiometric characteristics of video data were investigated - system noise and image shading. If the characteristics of these could be understood, a means of reducing their effect on image quality could be devised.

Noise is "any unwanted signal or disturbance in an image" (Schowengerdt, 1983). Here 'system noise' refers to the constantly fluctuating output from the vidicon target when it is irradiated with a steady level of flux (Slater, 1980). The amount of noise limits the accuracy with which a certain output can be expected to be measured, and also limits the ability to discriminate differing levels of input. That is, a high level of noise could be expected to place a limiting effect on the accuracy of image interpretation.

System noise frequently results from defects in the sensor structure, and may be temporally random, varying from one frame to another (Heckel, 1987; King, 1988). In addition, due to the manufacturing process, there are often residual particles of metal and chemicals within the tube; these loose particles can land on and damage the photoconductor surface, resulting in 'dead spots' on the reproduced image (Heckel, 1987). This could be a particular problem if care was not taken with the cameras in transit.

In order to evaluate the noise characteristics of the digitised video imagery, the system was assembled as for normal image acquisition in a standard photographic dark room, with the camera lenses adjacent to the dark room wall. In this way, all light was excluded from the system, and analysis of the images would reveal any radiometric distortions that were unrelated to lens effects, varying illumination levels, etc.

The output from the cameras was recorded and digitised following the same procedure as described in Section 4.2.4. The grabbed images were spectrally enhanced using a median autolinear contrast stretch. In this way, small variations could be visually observed, and their pattern determined.

The image statistics are given in Table 4.4. The histograms of the individual bands were all positively skewed and narrow, indicating that although the majority of the pixel values were close to zero, in all channels there were a number of abnormally high values.

	Infrared	Red	Green	Blue
mean	87.8	14.0	4.4	4.7
s.d.	2.02	3.37	0.78	4.33
minimum	81	5	3	0
maximum	95	29	9	31

Table 4.4 Image statistics for the 'dark room' image.

Visual examination of the enhanced colour images revealed diagonal striping from the bottom left corner to the upper right corner of the image. The striping was thought to be a result of the way in which the incoming radiation was filtered into its individual components within the camera.

Examination of the infrared image revealed a high average pixel intensity of 87.8; it was assumed that the high values were due either to the inclusion of background illumination within the tube (see White, 1979), or to a gain setting within the infrared camera. Although this would not affect relative variation within images, it restricted the radiometric range of the camera, and future work should attempt to identify and correct the cause of the offset .

It was found that the pixel values of the infrared noise image decreased gradually from the top to the bottom of the image, although the variation was not very large in magnitude. The statistics for individual channels indicated the high level of noise within the red and blue bands, and the relatively low level for the green band.

Various means of reducing noise were considered, including band ratio/subtraction, averaging consecutive frames, and spatial filtering. As the noise was not constant between frames, the first two alternatives would not be expected to provide any improvement. Therefore, only the use of spatial filters was investigated.

Previous work had highlighted the use of meanal, rather than modal or median filters (King, 1988; Slater, 1980; Maxwell, 1977), the latter filters tending to polarise the noise data in a bimodal distribution, and resulting in an overall increase in the noise in the image. King (1988) stated that six applications of a 3 x 3 meanal filter reduced noise to 16% of its original value. However, with aerial imagery the consequent loss of information would also seriously reduce the image utility. The effects of filtering were assessed by subjecting the grey card image firstly to a single, and then to a second, 3 x 3 meanal filter.

As shown in Table 4.5, the reduction in variance within the images was significant after application of a single 3 x 3 meanal filter. Further application of the filter reduced variation fractionally. It was considered that the additional reduction in noise associated with the second filter would not be sufficient to overcome the increased problems caused by reduction in resolution and increased boundary effects.

Filter	Infrared		Red		Green		Blue	
	mean	sd	mean	sd	mean	sd	mean	sd
none	170.2	3.03	186.6	8.74	121.2	4.37	196.5	12.34
1 3x3	169.5	2.71	186.1	7.49	120.8	3.62	196.1	11.69
2 3x3	169.1	2.68	185.6	7.42	120.3	3.60	195.6	11.63

Table 4.5 Effects of filtering 'grey card' images using a 3 x 3 meanal filter

Even assuming there was no contribution to the output signal from system noise, a surface of uniform radiance would not be expected to produce a uniform irradiance on the imaging surface due to lens effects. Usually, spectral response is greatest at the centre of the image, decreasing with off centre angles. This effect is termed 'image shading' in video technology (King, 1988; Slater, 1980), and can be compared to vignetting in aerial photography.

As the degree of shading is related to the aperture used, and the scene illumination, it is preferable to acquire image shading correction data at the time of the flight (King, 1988; King & Vlcek, 1988). However, this data was unavailable, and, in order to examine lens geometry effects, images were recorded of a Kodak Standard Grey Card under daylight conditions. The same camera settings were used as at the time of flight. The resulting images were then digitised and subjected to a median autolinear contrast stretch, and the overall variation in pixel brightness values visually examined.

Assessment of the enhanced images indicated that only the infrared data was subject to image shading. However, this was not expected to create a serious problem to image interpretation as the overall range of pixel values of the image was only 179 to 185.

Image shading was not evident on the colour camera images. However, the general reflectance pattern varied across the image for different bands, and appeared to be somewhat random in nature; minimum reflectance occurring in the bottom left corner in the red and green bands, and in the lower right hand corner in the blue band. The channels worst affected by this variation were again the red and blue.

Due to the low range of variation in brightness values across the reference images, corrections for image shading were not applied to the aerial data. Techniques to carry out such corrections are given in King (1988) and Kliman (1988).

4.2.2.3 Spectral Resolution

The spectral resolution of video cameras is controlled by the construction of the tube, specifically the target. The spectral resolution of different vidicon tubes is shown in Figure 4.2. The Newvicon tubes used in both cameras are sensitive up to a cut-off value of approximately 1.0 μm, maximum spectral response occurring at 0.775 μm. As noted in Section 4.2.1.1, the response of the colour camera was restricted by the inclusion of a 0.75 μm cut-off filter within the camera.

The spectral response of the monochrome infrared camera was further modified by using a Wratten 89b filter to exclude wavelengths less than 0.69 μm.

4.2.3 Video Methodology

The first step of processing the data involved digitising the video imagery. The approximate flight lines were identified by interactively playing back the recorded imagery and marking the locations on a 1:50 000 OS map of the area, whilst noting the position on the video tape (as indicated by the tape counter). The flight lines could then be modified on a 1:2 500 OS plan to more accurately represent the path of the aircraft.

Figure 4.2 Spectral resolution of video tubes (from Meisner, 1985)

Having accurately identified the flight paths the required sections of the tape were played through the PAL decoder, the non-interlaced fields then being grabbed to produce a 24 bit colour image.

Much of the intended work covered areas of up to 1.5 km by 0.5 km; as the area covered by individual frames was approximately 350 m by 350 m, it was necessary to consider the best way to piece together the individual video 'frames'. The original strategy was to select ground control points (GCP's) on the 1 : 2 500 OS map and the video imagery, and to coregister the individual video frames to the map coordinates. However, due to the small area covered by each frame, and the relatively featureless areas frequently being imaged, this had to be abandoned; there were simply not enough identifiable points within each frame.

The eventual procedure selected coregistered 2 to 4 video frames, adjacent frames having approximately 50% overlap. This ensured that sufficient GCP's could be identified in adjacent images. The frames were coregistered by selecting up to 8 GCP's between adjacent frames, and carrying out a nearest neighbour transformation. The transformation matrices were saved to file such that all the colour bands could be subjected to the same geometric rectification. After transformation, each individual frame was written to an image data file, gradually building up a composite image. The next stage was to register the composite image to the geometrically corrected ATM image, using the same techniques described above. The resultant 'geometrically correct' image was again saved to file. The process was repeated as many times as necessary to construct a video mosaic of the sites.

Examination of the video mosaics revealed that severe radiometric distortion existed between frames, and that this was extreme enough to prevent any useful automatic classification of the mosaics. Consequently, it was decided to carry out histogram matching of adjacent images, to assess if any improvement could be achieved. This technique examined the statistics from the areas of overlap between two adjacent images, and adjusted the means and standard deviations of the images such that their cumulative histograms were similar.

The procedure involved coregistering two images using the previously calculated geometric transformation matrices. The histogram matching algorithm then examined the statistics in the area of overlap, and calculated the transformation required to match the histograms. The radiometric characteristics of the entire images were transformed, and the two frames combined. The frames were added individually, until the mosaic had been constructed. Visual examination of the imagery showed much less variation between adjacent frames.

Due to the need to select images with approximately 50% overlap, up to 14 separate images were grabbed for each site, and each component band. It can be appreciated that the procedure described required a substantial amount of computer memory. In this case, the memory was provided by utilising optical discs; however, this prerequisite could place restrictions on the general use of video remote sensing in many situations.

The whole process of mosaicing video images was tedious and time consuming. If enough well spaced GCP's were not (or could not be) identified, the resulting transformation was useless, and much time had to be spent selecting suitable control points. Despite the amount of time spent carefully choosing registration points, the end result showed that the infrared mosaic was not accurately registered to the colour mosaics, and therefore a further transformation had to be carried out to correct this.

In the light of the above comments, the geometric accuracy of the video imagery was not considered to be high. As an indication of the overall accuracy, the root mean square (RMS) error was calculated for a number of points at each site using the following formula:

$$RMS_{error} = (x - x_{orig})^2 + (y - y_{orig})^2$$

where x and y are the actual pixel locations on the image (in terms of BNG coordinates), and x_{orig} and y_{orig} are the theoretical (accurate) BNG coordinates.

The average RMS error was 2.55 and 4.04 pixels for the Panshanger and Ware mosaics respectively. The greater error at the Ware site was a reflection of the lack of identifiable GCP's at this location.

4.2.4 Flight Planning

When planning the video survey, two opposing factors had to be taken into account - resolution and coverage. Because of the noise inherent in the system, large scale imagery was required to offset the effects of poor resolving power. This was particularly important for the woodland damage survey, due to the need to identify individual crowns. However, to acquire suitably large scale imagery, it was necessary to reduce the swath width to 350 m (see Section 4.2.2). The effects of such a narrow strip of imagery were not fully appreciated until attempts were made to mosaic the imagery, and the lack of suitable GCPs became apparent (see Section 4.2.3). In addition, the sites could not be covered by a single run, and both sites required two overpasses.

Further practical considerations follow on from this, mainly the increasing importance of aircraft movement at enhanced resolutions, combined with the greater turbulence at low altitudes. In addition, as plane height decreased, the problems of navigation increased, with problems being experienced in accurately overflying the area of interest; at the Ware site, this resulted in part of the area being missed.

It can therefore be appreciated that many factors have to be considered, beyond the simple decision of the required resolution. The relative importance of each factor will vary according the the application, and each case must be evaluated on its own merits.

The video imagery was acquired using a Cessna 172 single engined aircraft. The cameras were mounted vertically in a specially modified door (Civil Aviation Authority approved), loaned by the Institute of Hydrology. The door had been fitted with a special camera housing, providing the cameras with a vertical view of the ground from the outside of the plane, whilst allowing access to them from within. To assist in maintaining a near vertical view angle, the housing included a pivoted gantry which was able to swing freely. The entire door was fixed to the aircraft by means of a lock and two split pins; thus removal and fitting of the door was relatively simple.

Flight details are shown in Table 4.3.

4.3 Airborne Thematic Mapper Imaging

4.3.1 ATM Imaging System

The Daedalus AADS 1268 Airborne Thematic Mapper (ATM) is an eleven band digital system, seven of the wavebands covering the same spectral ranges as the Thematic Mapper carried by Landsat (see Table 4.1). The system comprises a scan-head, spectrometer, digitiser, operator console, thermal reference source system, and magnetic tape recording system. Although the system will not be described in detail here, to comprehend the geometric problems associated with this type of imagery, it is important to have some understanding of the way in which such line scanners operate.

Essentially, an optical-mechanical system scans the target one line at a time, the radiation passing through optics which establish the instantaneous field of view i.e. the size of individual pixels. The radiation is then dispersed using filters and prisms, and the individual wavebands directed to appropriate detectors. The foreward motion of the aircraft, and the scan rate are such that each scan line includes the ground surface immediately beyond the previous scan line. In this way, a digital image is built up of successive scan lines (Figure 4.3).

4.3.2 ATM Imagery

4.3.2.1 Geometric Characteristics

The ground resolution of the data is inextricably linked to the velocity/height ratio of the aircraft and the scan rate of the scanning mirror. The platform velocity is controlled by the ability of the plane, and the scan rate by the instrumentation. In this case, all other variables being fixed, the controlling factor on the spatial resolution of the data was the altitude of the plane.

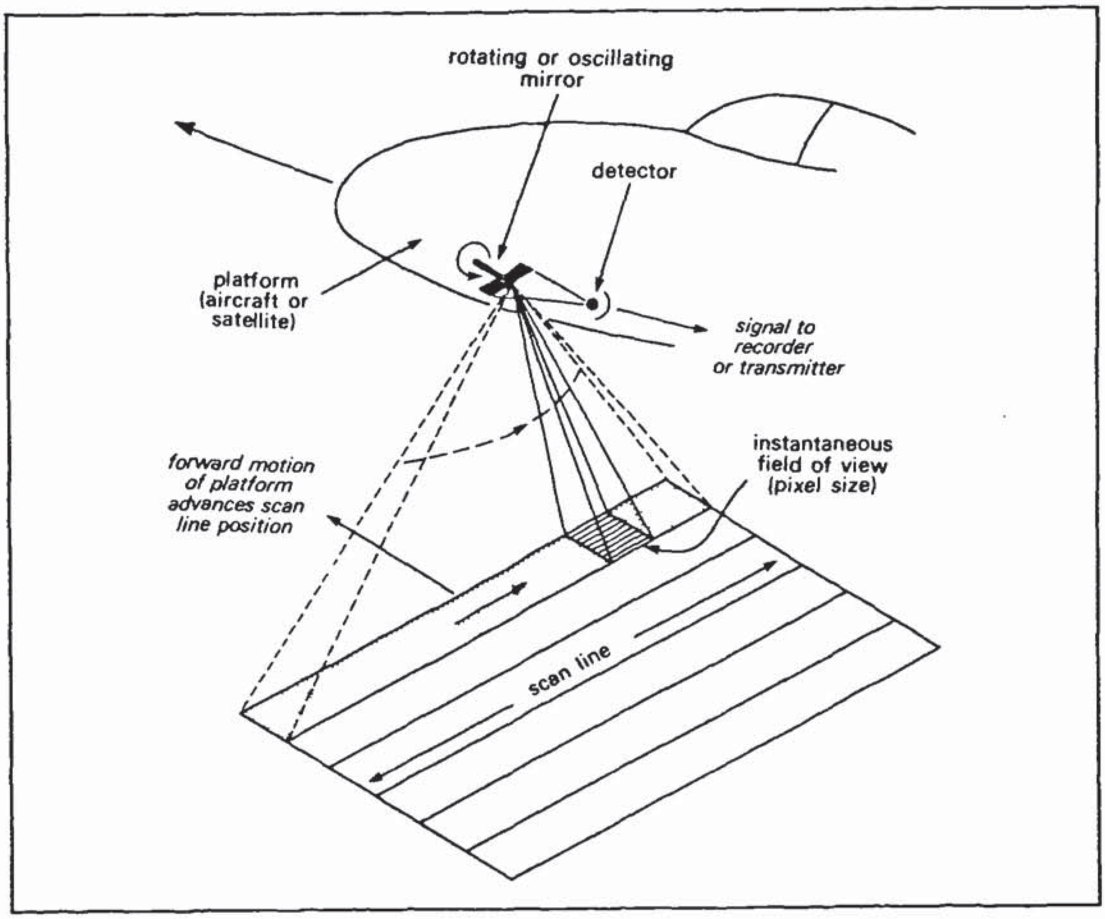


Figure 4.3 Multispectral scanner data collection along a flight line

Geometric distortions occurred as a result of aircraft movement (roll, pitch, yaw. drift, and altitude/attitude changes), changes in ground resolution element size at different scan angles, and overscanning / underscanning when the rotation speed of the scanner mirror was incorrectly set for the speed and altitude of the plane. Scan angle effects were reduced by ensuring that areas of interest were aligned along the centre of the flight lines. Problems due to aircraft movement were more difficult to correct.

Geometric correction of digital imagery is usually carried out using ground control points to calculate a polynomial equation, the method assuming that the relationship between the GCP's is representative of the distortion over the whole image (see Section 3.1.1.1). The polynomial-based approach works well as long as the internal geometric distortion of the data is minimal; that is, the image is effectively a plane surface that can be tilted and rotated to fit the reference surface. However, due to the way in which a line scanner collects data, there may often be high frequency (i.e. localised) distortions affecting small areas of the image. In such data, polynomial-based geometric correction fails to adequately model the real situation (Roy *et al*, 1989; Devereux *et al*, 1990; Harrison & Garg, 1990).

In order to overcome the problems specific to airborne scanner imagery, a software package was developed at Cambridge University based on Delaunay tessellation of triangles (Roy *et al*, 1989; Devereux *et al*, 1990). The theory of the method is that localised distortion is modelled by constructing a grid of triangles through the GCPs in image and map space, with the GCP's acting as nodes of the triangles. Each individual image space triangle is then corrected individually for the localised distortion within its boundary, image pixels being resampled to a new image pixel position based on a simple linear transform.

Because the GCP's are not averaged over the whole image to achieve a global transformation, each GCP has a much more significant effect on the correction of the imagery, but only within a nearby area. Therefore, any errors at the GCP collection step are not averaged, and result in localised inaccurate modelling of the distortion.

Up to 30 GCP's were collected for each image, ensuring that sufficient points were selected along boundaries, at discontinuities, within areas of obvious distortion, and around the edges of the areas of interest.

All points that could be accurately identified on both the images and the reference maps were used to calculate the transformation. As a result, it was not possible to calculate the accuracy of the resultant transformed image, and the assumption had to be made that the outcome was a close representation of the true situation. This problem has been experienced by other workers (Roy *et al*, 1989), who suggested using a stereo zoom transferscope and aerial photos to plot new GCPs onto the reference map.

4.3.2.2 Spectral Characteristics

The Daedalus 1268 multispectral scanner utilised 11 bands of data, ranging from the visible blue to the thermal infrared (Table 4.1). The original selection of bands was based on consideration of their relation to the spectral characteristics of vegetation and other ground features (Townshend *et al*, 1988), and thus the sensor was considered to be particularly appropriate for this type of application.

4.3.2.3 Radiometric Characteristics

In order to adequately utilise the full 0 - 255 pixel intensity range, when the data was collected, the gain on each of the scanner's channels was set to one of five settings (Wilson, 1986). For certain applications, for example the study of interband relationships, this would require calibration of the data. However, as relative differences, rather than absolute radiance values were being used, it was not considered necessary to carry out such correction.

4.3.3 Flight Summaries

Two separate sets of imagery were collected for each site as a part of the NERC Airborne Remote Sensing Campaigns. The flight details are given in Table 4.3.

4.4 Summary

The above chapter has outlined the pertinent issues related to the imaging systems used in this project. Both black and white panchromatic, and colour infrared aerial photos were utilised, their major value being to provide reference data for the video and multispectral scanner interpretations.

Although the video imagery was initially attractive in terms of cost, radiometric and geometric problems with the imagery were anticipated to limit its use. In addition, if mosaicing of frames was necessary to provide complete cover of a site, the costs and time involved in processing the data would increase substantially.

The ATM data was considered to be superior to the video, insofar as spectral resolution was concerned. However, the cost of acquiring such imagery would be considerable.

The systems each have their own advantages and drawbacks; their relative utility would be expected to vary according to the information requirements. The following chapters describe the ways in which the systems were used at two specific sites.

5 PANSHANGER ESTATE

5.1 Introduction

The Panshanger site had accepted domestic refuse for several years before being restored to agriculture in 1982. Throughout the following years, the crops growing on the restored site showed symptoms of stress, with areas being generally unhealthy and chloritic. The poor growth was originally attributed to the effects of respreading of soils associated with the restoration procedure; however, subsequent gas monitoring suggested the influence of landfill gas.

The purposes of the research at this site were:

(i) To explain the relationship between observed crop condition and gas concentration in the near surface soils. Initial analysis showed a poor correlation, and discriminant analysis was carried out to assess the contribution of both gas and soil variables to the relationship.

(ii) Subsequently, to assess the possibilities of using discriminant analysis to predict the combination of environmental variables likely to result in a change in spectral response of the crop canopy. The variation in vegetation condition as a result of the environmental variables across the site could then be displayed in the form of a thematic map.

(iii) By using multi-temporal data, examine the changes in the above relationships through the growing season.

The remote sensing data available for the study is shown in Table 5.1.

Sensor and Data Type	Date	Scale / Resolution
Daedalus 1268 Airborne Thematic Mapper	April 1989	2m
Wild RC8 Camera Black & white panchromatic photos	April 1989	1 : 2 000
Insight Monochrome Infrared Video Camera	June 1989	1.6 m
Panasonic WVP-A2E Colour Video	June 1989	1.6 m
Wild RC8 Camera Black & white panchromatic photos	July 1989	1 : 2 000

Table 5.1 Remote sensing data for the Panshanger site

5.1.1 Site History

The Panshanger Estate is located to the north of the A414, 6km to the east of Hatfield, and 4km west of Hertford. The estate totals 440 ha in size, comprising approximately equal proportions of agricultural land and woodland. The drift geology is similar to much of the area, with the sequence being lower gravel, intermediate clay, and upper hoggin underlain by Cretaceous Chalk bedrock.

Three areas within the Estate had been worked for sand and gravel (Figure 5.1). Areas A (2.2 ha) and B (4.7 ha) were worked to a depth of approximately 12 m to the middle clay in the early 1970's. Area A was restored to a level below original ground level, and was re-afforested in 1982.

Area B was worked for sand and gravels in 1975 to 1976. A thin clay lining was created around the sides of the quarry using some of the middle clay, the area then being filled with domestic waste. A domed profile was achieved, and the site finished by capping with a clay cap before replacing overburden and topsoil. The area was restored to permanent grassland and has been maintained as such.

Area C (16.6 ha) was the last part of the Estate to be worked, abstraction taking place between 1972 and 1976. Again, deposits were removed to a depth of 12 m and a partial seal was achieved around the edges of the site using part of the middle clay. At the eastern end of the site an earth wall was constructed using clay and reject hoggin, such that an area of approximately 2.4 ha was separated from the rest of the site. This small area was left unfilled with the eventual aim of creating a farm pond, the pond was never created and the area now supports rough vegetation and shrubs.

Filling of the main part of area C commenced in four stages from west to east, each stage being separated by north-south earth walls constructed using clay from the base of the site and reject hoggin. Household refuse was used as fill with locally obtained inert waste being employed for intermediate cover. Filling commenced in 1977, and was finished in 1982, the overall profile being slightly domed, and grading down to the east. Each cell was finished with a 0.6 m thick clay cap to reduce rainwater infiltration, followed by 0.6 m of subsoil, and 0.2 m of topsoil. To enhance drainage, land drains were installed to a depth of 0.75 m after restoration of the soil profile.

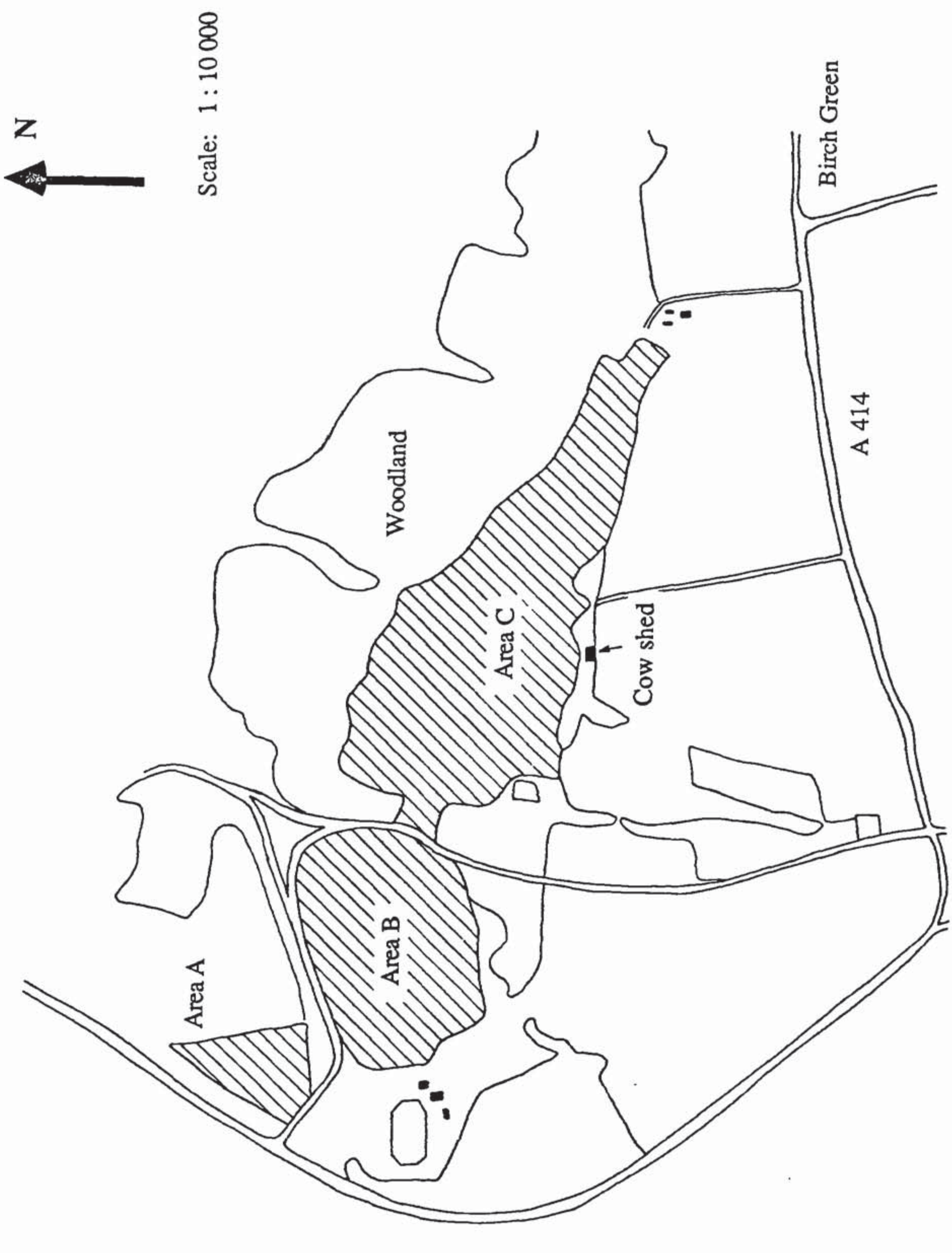


Figure 5.1 Site plan of the Panshanger Estate

In the spring of 1983 a 0.6 ha plot in the west end of the site was established as a trial area, with Grade 1 soils being imported from adjacent agricultural land. The original intention was to observe whether improved yields could be obtained from higher grade soils in comparison with the original soils, although the trial was not followed up.

After reinstatement, various crops were grown including winter barley, winter oil seed rape, winter wheat, and grass. In the early years following restoration crops tended to be poor in terms of yield. This was felt to be due to poor soil conditions associated with the replacement of the soil profile. In 1984 oil seed rape and winter barley grown on the site were showing chlorosis and stunted growth. This was attributed to nitrogen deficiency. Plates 5.1 and 5.2 illustrate examples of crop chlorosis and the poor soil conditions at the site.

5.1.2 Landfill Gas History

The first evidence of landfill gas at the Panshanger site (Area C) was recorded in March 1984 when a detailed survey was carried out to determine the quality of restored soils (reports held at M J Carter Assoc.). The survey involved digging pits by hand across the site and obtaining soil profiles to a depth of 1m. In eight of the twenty seven profiles, putrescible tip material was reached and anaerobic conditions were evident. It was suggested that methane generation from the underlying refuse was starting to affect the soils and could result in damage to the crops.

In March 1986 regular monitoring of area C commenced with the installation of 24 permanent gas monitoring standpipes to a depth of 1m; a further 10 being added in June 1986 (Figure 5.2). Monitoring of gas levels in the standpipes throughout 1986 showed great variation, both spatially and temporally, maximum concentrations of 2 000 ppm being recorded in standpipe 27 in June, and over 10 000 ppm in standpipe 28 in September. The surveys also recorded the presence of gas in ditches adjacent to the site, illustrating the venting of methane from the site in this way.

Overall, the pathways for gas migration appeared to be random, both spatially and temporally. Due to this, it was considered that the monitoring programme was probably not giving a representative indication of gas levels across the field, and should be replaced by a more general ground survey using a more sensitive gas meter.

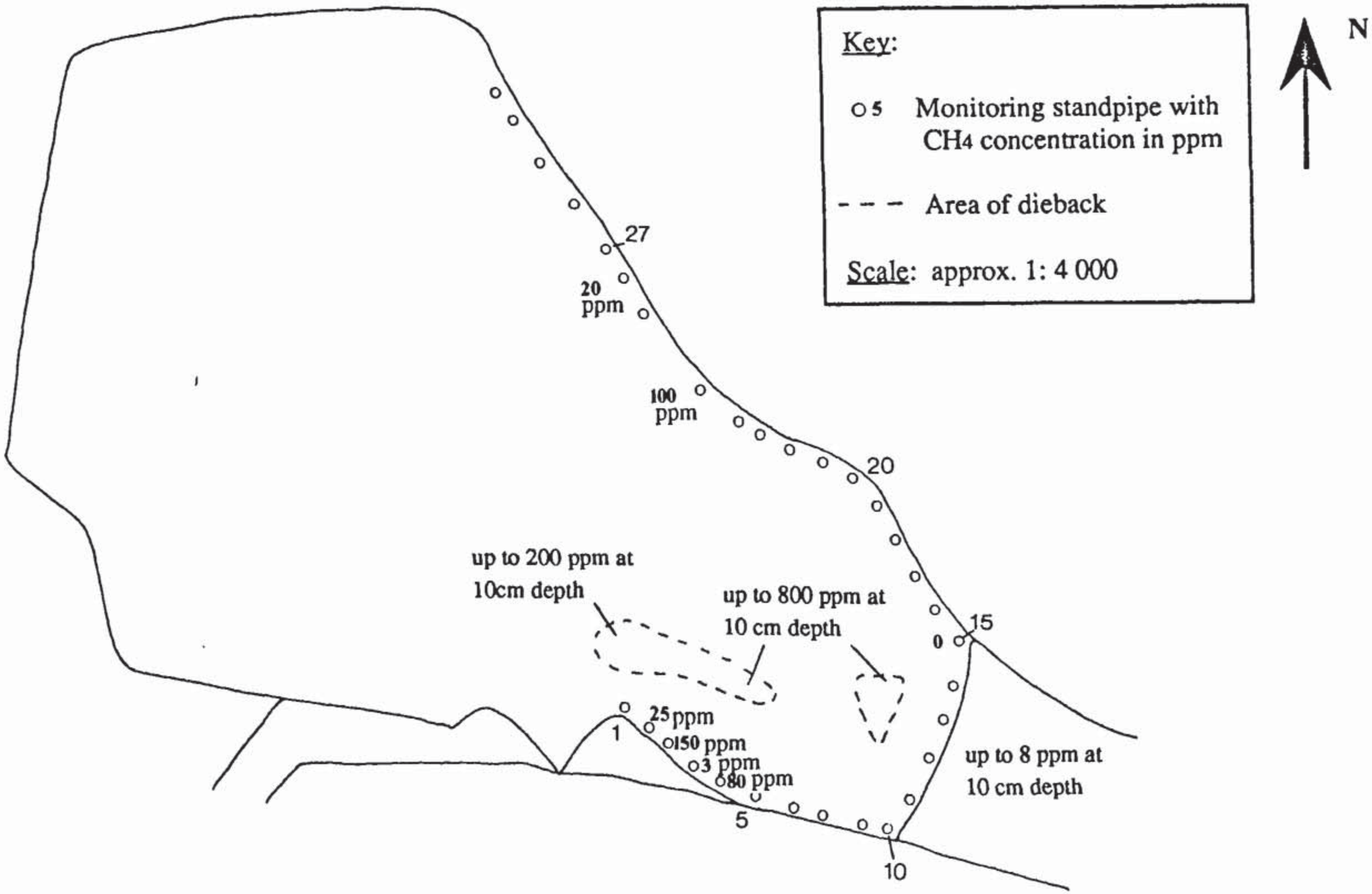


Figure 5.2 Location of monitoring standpipes and results of routine monitoring survey, October 1986

Plate 5.1 Chlorosis of crop at Panshanger site, Autumn 1987

Plate 5.2 Poor soil conditions and waste at surface, Panshanger site

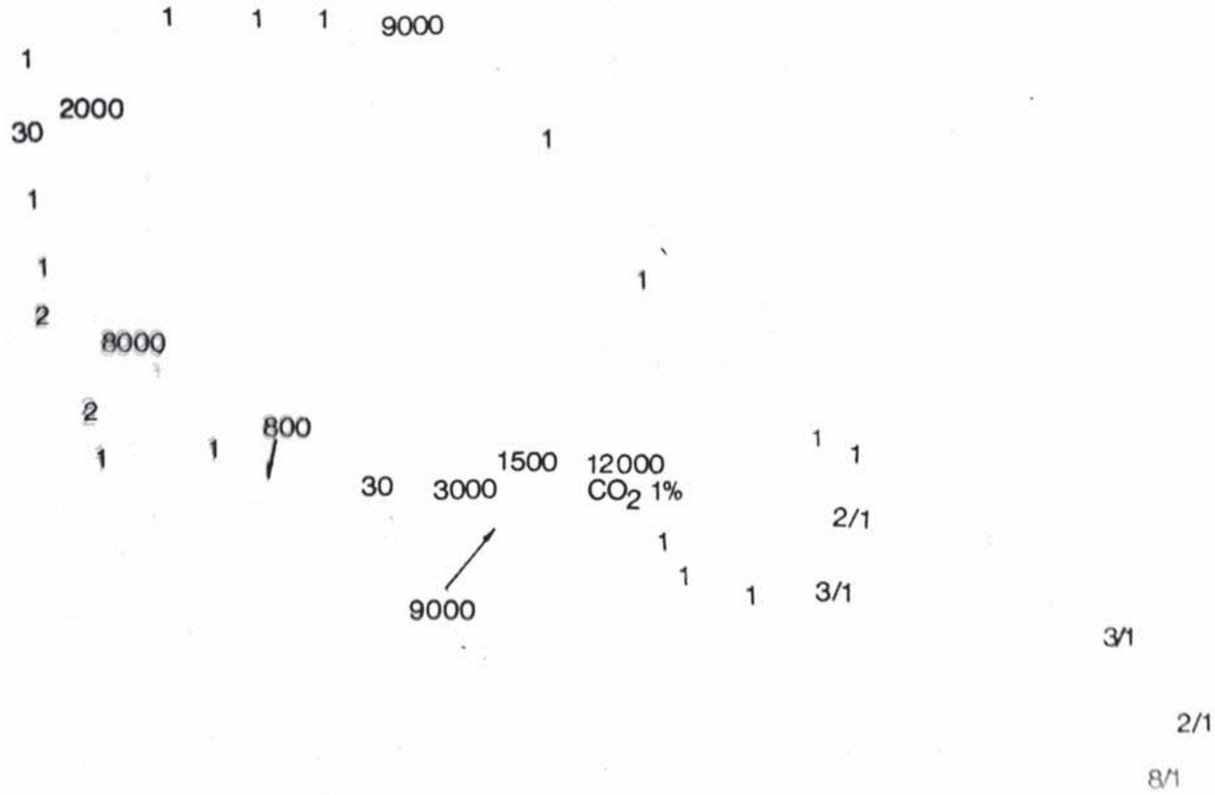
Regular monitoring of both areas B and C (by M J Carter Assoc) continued in 1988, methane concentrations being measured at ground surface and subsurface. The subsurface measurements were made by driving a spike into the ground to a depth of 30/40 cm and measuring the concentration of methane in the hole immediately after withdrawal of the spike.

Results of monitoring surveys in 1988 were ambiguous, gas concentrations being inconsistent from one survey to the next. The temporal and spatial variation in gas concentration is illustrated by Figure 5.3, showing the results of 2 surveys carried out to routinely monitor for gas migration at the site. Continued monthly monitoring through 1989 revealed notable differences between surveys, in particular the locations at which significant methane concentrations were recorded. Two locations tended to consistently give high levels of methane in the subsurface. The first was on the southern boundary of area C, close to the disused ox shed (see Figure 5.1), the second being along the line of the settlement fissure at the western perimeter of area B.

Additional monitoring was carried out during 1989 in conjunction with the remote sensing surveys being flown during this period. Again, the recorded gas concentrations varied both temporally and spatially (Figure 5.4). The results of these surveys, and the subsequent statistical analyses, are discussed in more detail in Section 5.4.

The results of the surveys illustrated the problems likely to be encountered in monitoring for landfill gas, the dynamic nature of gas generation and migration, resulting in fluctuating gas concentrations at the depths to which monitoring was undertaken. It was considered that these fluctuations could be due to the differing atmospheric conditions and soil moisture status between different dates, which in turn affected emission rates and migration pathways (see Section 2.3). In addition, due to the clayey nature of the soil, gas was liable to be migrating, in part, along discrete pathways. In such a situation, the majority of measurements would be low due to the failure to intercept a migration pathway. If a pathway was intercepted, it would result in an anomalous high reading. Despite the difficulties in measuring consistent concentrations between dates, the monitoring did confirm the generation of large quantities of gas.

18 10 89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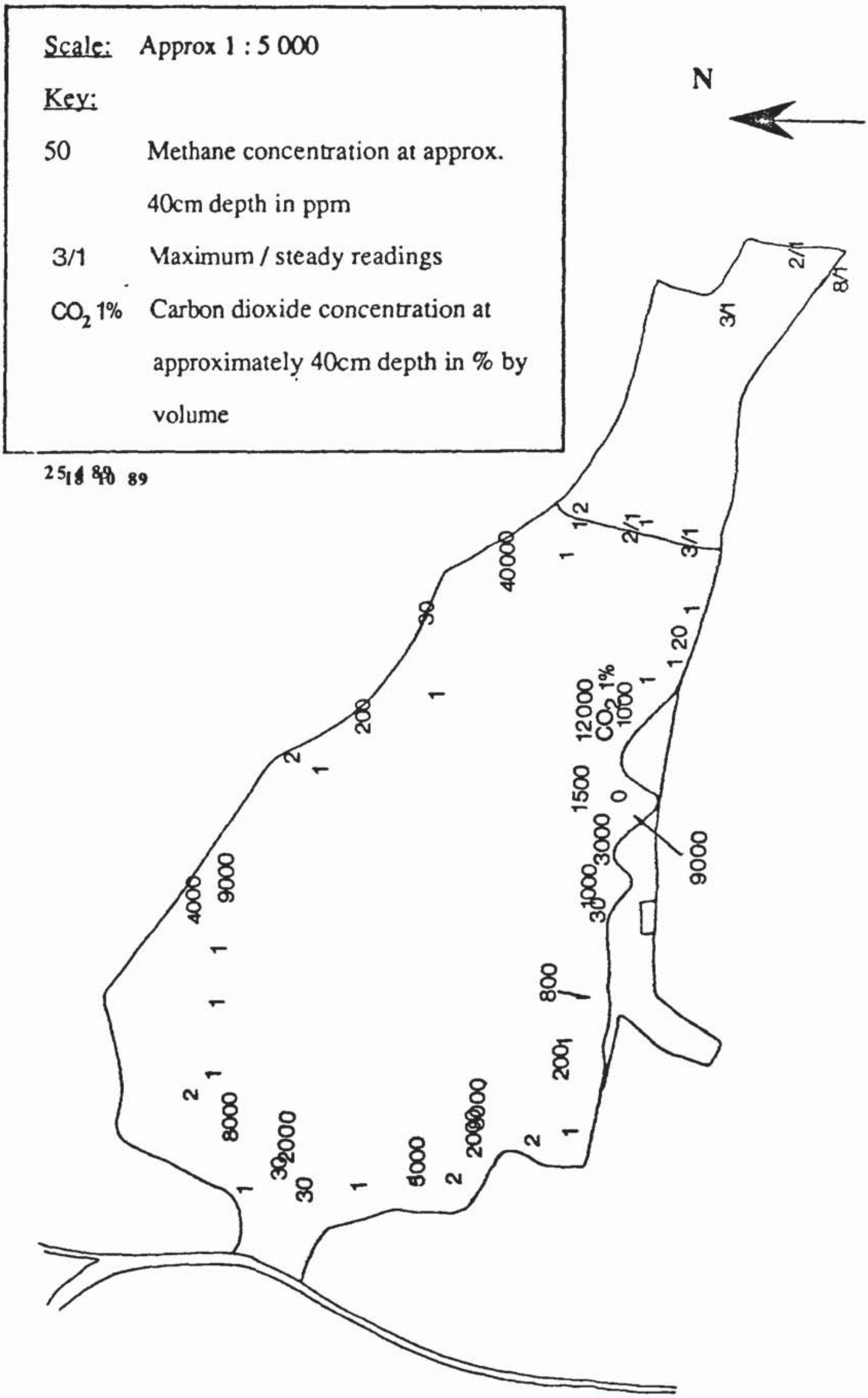

Figure 5.3 Subsurface methane concentrations recorded by M J Carter Assoc. as part of regular site monitoring visits

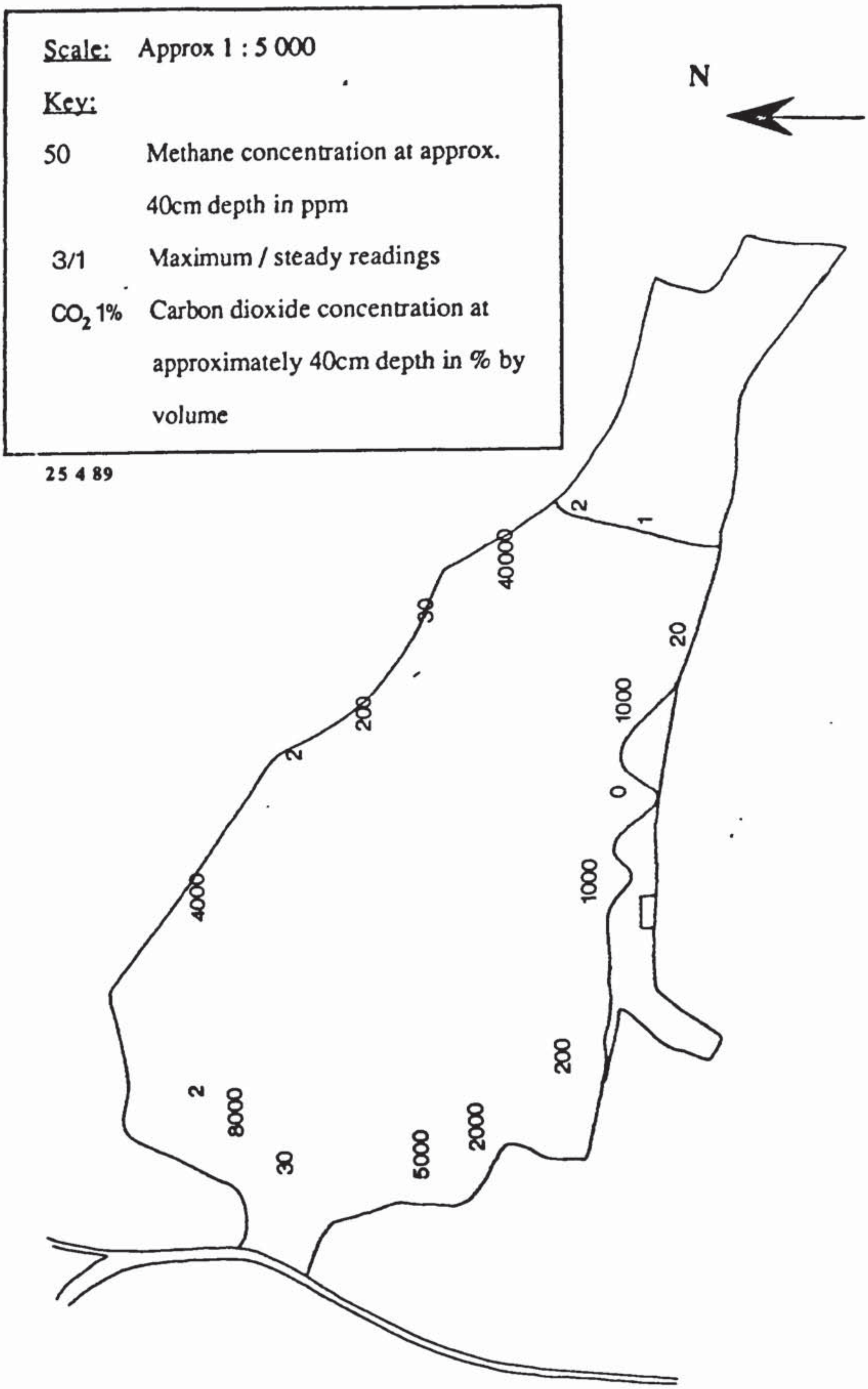

Figure 5.3 Subsurface methane concentrations recorded by M J Carter Assoc. as part of regular site monitoring visits

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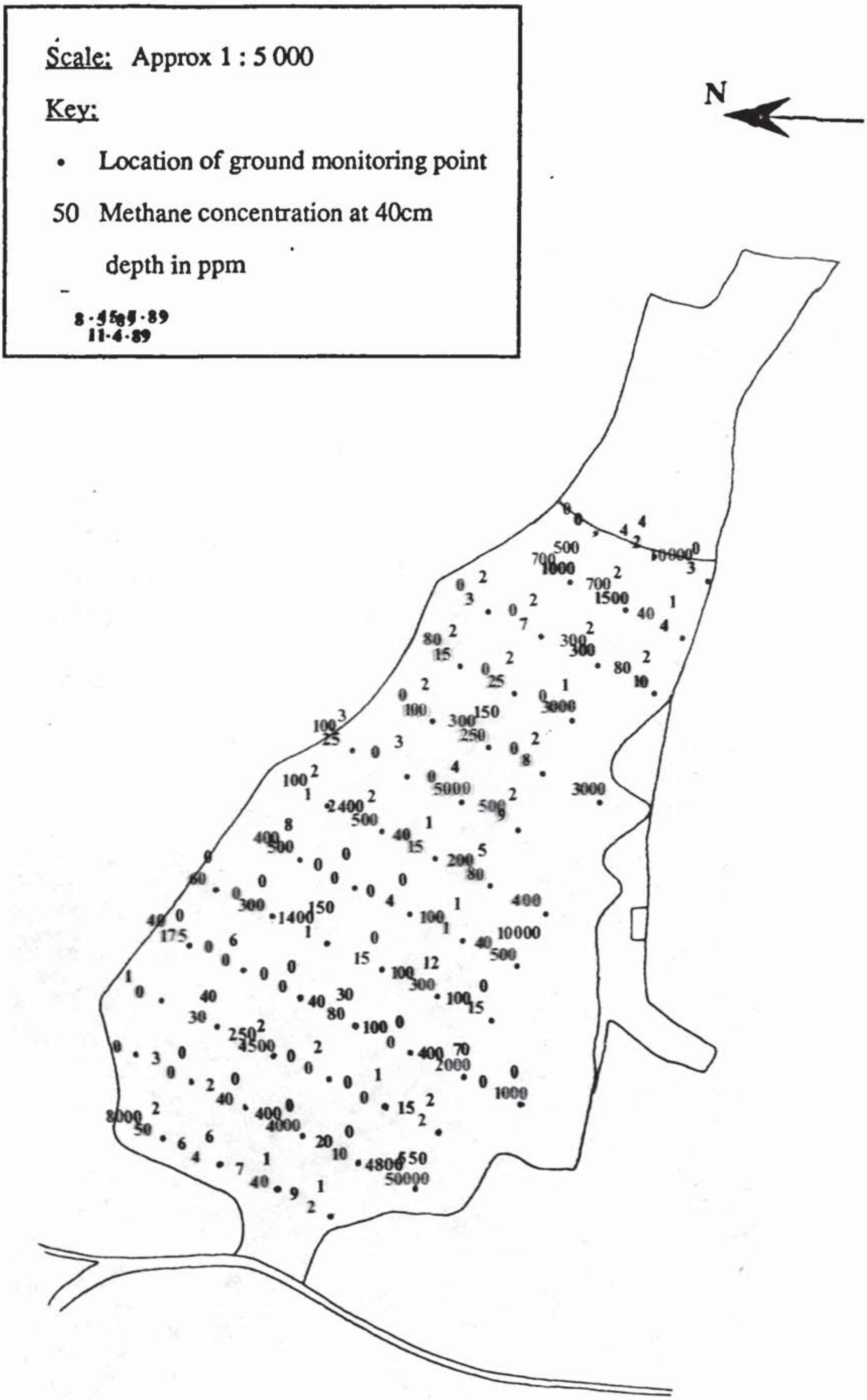

Figure 5.4 Subsurface methane concentrations recorded on monthly visits to Panshanger site

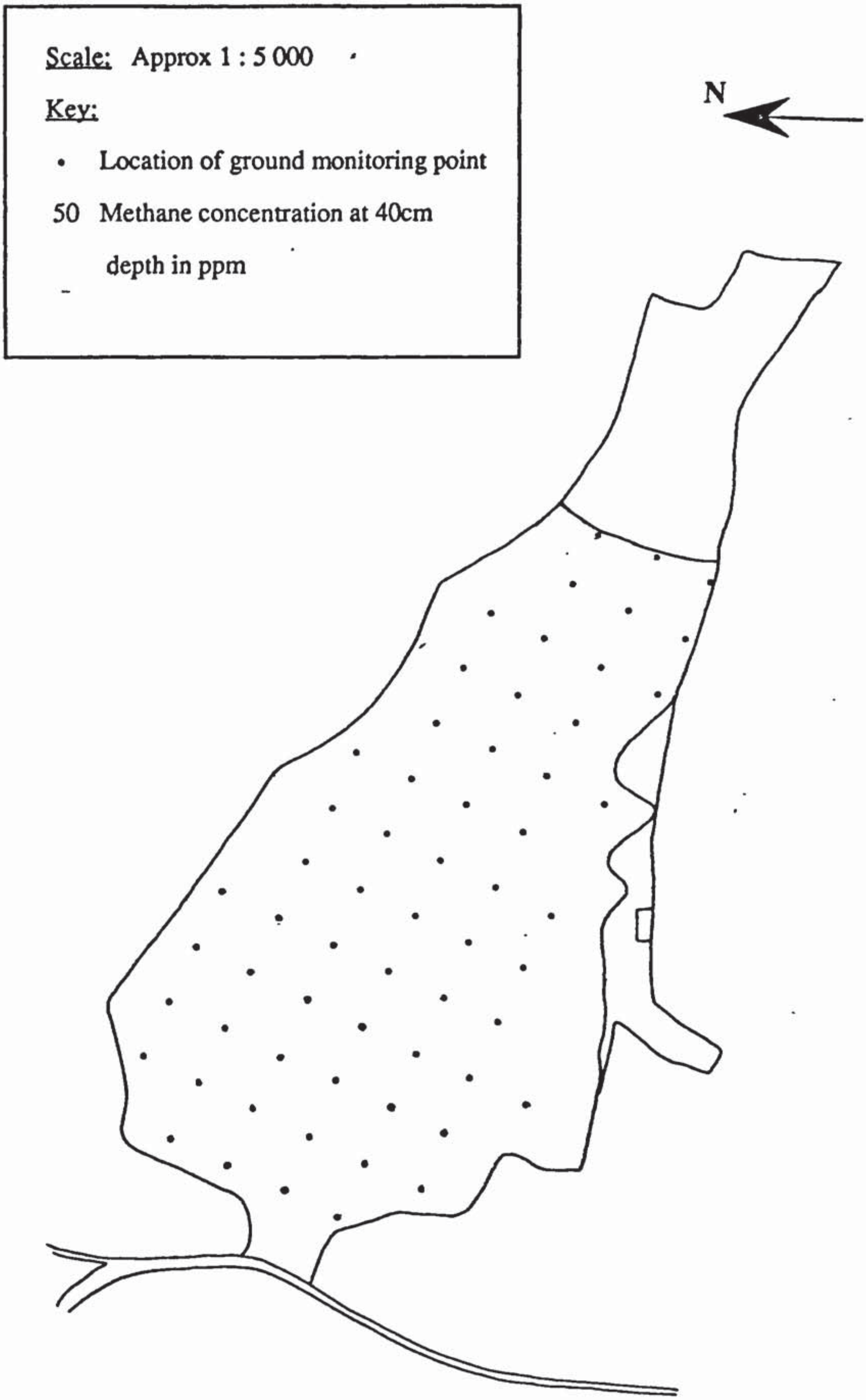

Figure 5.4 Subsurface methane concentrations recorded on monthly visits to Panshanger site

5.1.3 Risk Factors

As can be seen on Figure 5.1, there were two groups of properties possibly at risk from the migration of landfill gas. The first were the properties to the east of area C, and to the north of Birch Green. Low levels of methane at the surface were recorded in this area, 2 ppm being detected in June 1989. The other area considered to be at risk were the properties to the west of area B as these were located only 40 m from the settlement fissure at the western end of the site. It was not known whether landfill gas was migrating at depth from this site; routine near-surface monitoring in the vicinity of the properties detected minimal levels of methane (maximum 8 ppm).

A further risk was the potential for flash fires to occur at the ground surface when stubble burning as a result of ignition of methane venting at the ground surface. Thus, it was recommended that the lighting of fires and stubble burning close to the site was carefully controlled or avoided altogether.

5.1.4 Vegetation Damage

Areas of crop chlorosis were identified throughout 1986 and 1987, many of the areas being spatially related to the location of land drains. Overall it appeared that gas generated in the site was being vented through the surface, causing damage to the crops growing on the site. This problem was likely to be at its worst during dry weather when fractures and pores in the soil profile were open, allowing for the free movement of gas. During wet weather, when permeability of the cover soils decreased, the gas was being encouraged to move laterally through in situ gravel and the land drains eventually venting at the site perimeter.

Two problems were expected to hinder the identification of a relationship between landfill gas and vegetation injury at this site. In clayey soils, macropores would provide pathways for rapid movement of the gas, and the probability of actually intercepting a migration pathway was very low. If the pathway was intercepted, the gas would be moving very rapidly and at high concentrations and the distribution of vegetation damage would be over a limited area. Because of this, its detection would be very difficult, either from the ground or air. Conversely, in soils with a higher sand content, the gas would affect larger areas of vegetation, but at lower concentrations.

These points serve to highlight many of the obstacles faced when investigating the effects of landfill gas on crop health. The ways in which the problems were overcome or minimised are explained further in Section 5.2.

5.2 Sampling Procedure

As access to the site was readily available, a detailed ground based survey was planned and carried out. There were two broad objectives to be considered when designing the field sampling procedure. Firstly, as the overall aims of the project involved examining the relationship between landfill gas and vegetation health, the sampling procedure was designed such that the statistical analysis of the relationship between biological and environmental parameters could be carried out. Secondly, data was required for the training and testing of the remote sensing imagery.

These two approaches were not complimentary. As highlighted by Barnsley & Curran (1990), ecological and remote sensing studies have different data requirements, ecological investigations requiring information at the level of individual plants or communities, and remote sensing surveys integrating information over a much wider area. The eventual sampling scheme was a compromise between the different aims.

Ultimately, the controlling factors were:

(i) the time and cost involved in sample collection,
(ii) the ability to geographically relate the sample points to locations on the remote sensing imagery,
(ii) the requirement for the collection of samples for statistical analysis,
(iv) the ability of the author to assess relevant variables, and the replicability of the techniques by other relatively inexperienced personnel,
(v) physical and political access to site.

The major constraints on sampling design are summarised in Table 5.2.

5.2.1 Sampling for Determination of the Landfill Gas / Plant Relationship

The ecology of soils affected by landfill gas, and the relation with growth of vegetation on these soils, is extremely complex. A number of variables directly and indirectly affect plant health, and usually cannot be considered in isolation. The sampling was designed to collect information on as many of these variables as practically possible, with the aim

Statistical Requirements	Gas Sampling Requirements	Remote Sensing Requirements
SPATIAL CONSIDERATIONS		
Random sampling Required sample size for tests to be significant Control of variables unrelated to impact	Grid sampling - grid from 10 to 100 m Representative distribution of sample points Location of site in relation to sensitive areas	Scale of sampling - depends on resolution of data Positive identification of sites
TEMPORAL CONSIDERATIONS		
	Transient nature of gas requires frequent monitoring Different effects of gas at different stages of phenology	Crop phenology may change rapidly

Table 5.2 Constraints on sampling design

of identifying the factor, or combination of factors, responsible for vegetation injury at the Panshanger site. Only the actual landfill site was sampled. Even so, there was considerable variation in soil moisture, pH, and texture, and these became predictor variables in subsequent statistical analysis.

Due to the difficulty of accurately locating random sample points, sampling was carried out on a permanent grid. Provided the grid was chosen without prior knowledge of the site, this would fulfill random sampling requirements. Grid points were spaced at 50m, the separation being constrained by the size of the site, and the time available.

5.2.2 Sampling for Ground Reference Data

Two factors controlled sampling design for the ground reference data. Firstly, the plant variables selected had to be expected to respond to the presence of landfill gas by causing a change in the spectral response of the plant canopy, secondly, the size of sample units had to be considered.

Small sample units are not generally recommended when collecting ground reference data for remote sensing surveys due to inadequate representation of ground conditions, and problems with accurately locating the reference points. However, time and practical considerations restricted measurement of plant parameters to a 0.5 m square quadrat. To minimise the problems caused by using small sample areas, the homogeneity of the cover at each grid point was assessed (see Table 5.3). Any points failing the criteria were excluded from use as ground reference data.

Characteristic	Allowable Variability
Surface Cover	Distribution of cover types must be spatially uniform throughout the site
Aspect	Site must have no more than 22.5% variation from the dominant aspect
Slope Angle	No more than 25% variation from dominant slope angle for no more than 20% of the area

Table 5.3 Criteria for assessing site homogeneity (from Justice & Townshend, 1981).

5.2.3 Sample Scheme

The eventual scheme used a grid with points separated by 50m, a total of 61 grid points being specified. The grid was laid out using standard surveying equipment, with the intersections marked with pegs.

For each point, several plant and environmental variables were recorded. The variables were partitioned into two sets, the first containing the biological variables, the second including the environmental parameters expected to relate in an explanatory manner to the biological variables.

Although there is agreement about useful spectral bands for monitoring vegetation parameters, there is little consensus about the agronomic variables that should be used as ground reference data to train and test the remote sensing data (Section 3.3.2). The main requirements were (i) that the variables used should be sensitive to the stressing agent, and (ii) that the resultant damage should be shown as a change in the spectral response pattern.

The reported effects of landfill gas on vegetation have included chlorosis, necrosis, reduction in height or yield, and eventual dieback of the plants concerned (Section 2.4.2). Relating this diversity of symptoms to a single spectral response was not expected to be straightforward.

The variables finally chosen were:

(i) plant height, recorded as the average height of up to 20 individuals within a 0.5m quadrat,

(ii) percent crop cover, estimated by eye within a 0.5m quadrat,

(iii) percent weed cover,

(iv) visible damage.

For each survey, any chlorosis or necrosis of the leaves was observed, noting the severity and extent of such damage. The qualitative record was then converted to an interval scale according to the constraints shown in Table 5.4.

		Chlorosis		
		Light/Absent	Moderate	Severe
	Light	0	1	2
Necrosis	Moderate	0	2	3
	Severe	1	3	3

Table 5.4 Crop condition rating key

The environmental variables recorded were methane, oxygen and carbon dioxide concentrations, soil moisture (gravimetric method, British Standards Institution, 1975), soil pH (colorimetric method, British Standards Institution, 1975), and field soil texture (Fitzpatrick, 1980).

Maximum and steady landfill gas concentrations were measured at 40 cm depth, after removal of a soil sample by hand auger. Maximum gas concentrations occurred as a result of the accumulation of gas in the subsurface, augering a hole provided a rapid escape route for the gas. The steady reading gave an indication of the rate at which the gas was actually migrating through the subsurface. As the maximum gas concentration was an indication of the quantity of gas likely to be present in the root zone of the plants, this measure was used in the statistical analysis of the relationship between plant health and landfill gas.

Due to the many problems associated with physical measurement of landfill gas concentrations, the lack of gas on a single monitoring survey was not considered to be proof of the absence of gas. Therefore,the maximum recorded gas concentration on any of the surveys was used. In this way, the presence of gas at a particular location on any one of the surveys, served as an indication that gas was potentially present.

Although carbon dioxide is also an important component of landfill gas, and may be more important in terms of causing injury to vegetation, high concentrations of this gas were invariably accompanied by high levels of methane. As the Gastec used for monitoring methane was more accurate and reliable than the carbon dioxide meter, methane concentration was chosen as the indicator of the presence of landfill gas (see Appendix 1 for details of the gas monitoring equipment used).

Finally, previous discussion with the farmer had disclosed that certain parts of the site had not been sown due to waterlogging at the time of drilling. Thus, locations with no crop cover due to failure of the crop could not be distinguished from those that had simply not been sown. For this reason, all grid points with no crop cover were excluded from the analyses relating crop condition to the environmental variables.

Field data acquired on these surveys is given in Appendix 2.

5.3 Discriminant Analysis

The relationships between crop variables, soil conditions, landfill gas, and the spectral response of the crop canopy, were anticipated to be complex. Statistical analysis of the field data failed to unambiguously identify a direct relationship between landfill gas and crop damage. Multivariate analysis was therefore carried out, to identify the environmental variables influencing crop health. A second analysis was then undertaken to investigate the effects of the environmental variables on the spectral response of the crop canopy, and the relative importance of the variables in combination with each other.

Discriminant analysis is used as a technique to statistically distinguish between two or more groups. In order to separate the groups, the analyst selects a number of 'discriminating' variables which measure the characteristics that are expected to cause differences in group membership. A linear combination of discriminating variables is formed that maximises group separation:

$$D_i = d_{i1} Z_1 + d_{i2} Z_2 + \dots + d_{ip} Z_p + \dots + d_{in} Z_n \qquad \text{Equation 5.1}$$

where D_i is the score on the discriminant function, i, d_{ip} is the weighting coefficient on the p discriminating variable for the 'ith' function, and the Z's are the standardised values of the p discriminating variables used in the analysis. Group membership is assigned to individual cases based on their 'D' values. The maximum number of functions that can be derived is either one less than the number of groups, or equal to the number of discriminating variables, whichever is the less.

The analysis proceeds with the extraction of the first function, the discriminant scores being evaluated such that maximum separation of the groups occurs within the function. The second discriminant function is then extracted, again creating maximum separation of the groups, with the proviso that the function is orthogonal to, i.e. uncorrelated with, the first. The process continues until all the possible functions have been extracted, each discriminant function being orthogonal to those previously extracted. The contribution of each discriminant function to the overall separation of the groups is assessed by Wilks' Lambda.

After derivation of the functions, discriminant analysis can be used in 2 ways:

(i) Analysis of data. By examining the various statistics generated, it is possible to assess the degree to which each function contributes to group separation, and also identify the discriminating variables that contribute most to the differentiation of the groups. The statistics involved are explained, with reference to a specific example, in Section 5.4.1.

(ii) Classification of data. If a group of variables can be identified that provides good discrimination for cases with known group membership, the functions can be used to predict the group membership of unknown cases. A separate linear combination of the discriminating variables is calculated for each case, the case then being assigned to the group to which it has the highest probability of belonging based on its discriminant score. Further details of the methodology involved in classification are given in Nie *et al* (1975)

The ability of the discriminant functions to adequately separate groups can be assessed by classifying the original set of cases, and calculating the number that are correctly classified.

It is important to realise that the functions discriminate between real differences in an optimal way. If the groups are not separable using the chosen discriminating variables, this 'optimal way' may still not be very good, and the functions are not significant. A discriminator may not be significant for a number of reasons - there may be a real difference between populations, but they are so close that the discriminator is not effective; sample size may not be large enough; or the parent populations may be identical, any discriminant function being illusory (Kendall, 1980).

Despite the similarities of discriminant analysis to multivariate linear regression, with this technique the grouping variable should not be thought of as the 'dependant' variable - the relationship may be in either direction. That is, although the group categories may be defined as being dependant on the discriminating variables, other situations may specify the values on the discriminating variables as being dependant upon the groups (Klecka, 1986).

Further details of the actual mathematics and procedures involved can be found in several references (Nie *et al*, 1975; Kendall, 1980; Klecka, 1986).

In order to assist in understanding discriminant analysis, the procedure is explained with reference to a specific example, that is, the relationship between crop height and environmental variables for the April data. The detailed statistics for all other analyses are given in Appendix 3, and only the pertinent results discussed in this chapter.

5.4 Relationship between Crop Condition and Environmental Variables

Previous work has had a very subjective approach to the problems of landfill gas- related vegetation injury. Most research has concentrated on situations with very high concentration of gas and the associated acute vegetation injury (Leone *et al*, 1977a; Arthur *et al,* 1981; Flower *et al*, 1981; Arthur *et al*, 1985), with little investigation of the contribution of different environmental stresses in the situation where long term, chronic injury was occurring. At this site, the levels of gas in the subsurface were relatively low, and the situation was complicated by the variability of soil characteristics and settlement of the cap across the site.

Initially, the field data was examined to assess the linear correlation between landfill gas and crop variables. No such relationship could be identified. There could be several reasons for this, including failure to actually detect gas with the sampling technique used, temporal changes in gas migration pathways and rates, or crop failure due other causes.

Assuming that landfill gas was (at least in part) responsible for poor plant health, and that the recorded gas concentrations were representative of the actual concentrations in the area, the reasons for the lack of association could be explained by one of two hypotheses:

(i) for the crops to be damaged by landfill gas, they must already be pre-disposed to injury as a result of other environmental factors or disease,

(ii) crop damage would only occur as a result of a combination of factors acting simultaneously.

It would be impossible to decide which hypothesis represented the true situation using the field data collected. However, the use of discriminant analysis should establish whether either represented the true situation. Therefore, discriminant analysis was carried out in order to establish the combination of environmental variables responsible for crop damage, and in particular to assess the relative importance of landfill gas in combination with the other variables.

5.4.1 Discriminant Analysis

One of the the most frequently reported symptoms of damage caused by landfill gas was a reduction in plant height. As this was also the least subjective measurement of crop condition, it was used as the grouping variable.

As explained earlier, it was decided to use maximum methane concentration recorded on any date as the measure of landfill gas concentration. Examination of the data revealed a very wide range of gas concentrations, represented by a positively skewed distribution. The concentration data were transformed to approximate a normal distribution by taking logs of the data values. The discriminating variables used were then the log of maximum methane concentration (LNCH4); soil moisture (MOIST); pH (PH); and soil texture (TEXT).

Discriminant analysis was carried out for each individual survey, and the results examined to assess if any combination of soil and gas variables could reasonably account for the variation in crop condition. The results, and intermediate statistics, for the first analysis are described in some detail here. The detailed statistics for all other analyses are shown in Appendix 3; only the results are now discussed.

Three height classes were defined, ranging from class 1, representing tall, 'healthy' plants, to class 3, exemplifying small, poorly growing crop. Discriminant analysis was carried out to assess the ability of the environmental variables to account for class membership.

5.4.1.1 Importance of the Discriminant Functions

The first discriminant function is the weighted composite of scores of the discriminating variables, which maximally discriminates between all the groups (Bennett & Bowers, 1976). The second function is the weighted composite which next best separates the groups, and is uncorrelated with (orthogonal to) the first. In this way groups that are not well differentiated by the first function may be separated using the second. The process continues until the maximum possible number of functions has been extracted, the number being restricted to either one less than the number of groups, or equal to the number of discriminating variables (whichever is the less).

The results for the first analysis are shown in Table 5.5 (a). The right hand side of the table indicates the amount of discriminatory information actually in the data, prior to removal of any functions, and then as each successive function was extracted. Wilks' lambda is a measure of the proportion of the variance contained in the discriminant scores, that is not explained by differences between the groups i.e. a small value of lambda prior to removal of a function, indicates the data in that function is able to separate the groups well. It is converted to a chi-square statistic, and the associated significance level calculated. In this way, it is possible to estimate the probability of obtaining that value of chi-square (and hence lambda) purely due to sampling variability. A large increase in lambda after removal of a function infers a large amount of discriminatory information existed in the removed function, and little remains in the data.

In Table 5.5 (a), Wilks' Lambda was 0.541 prior to removal of the first function, corresponding to a chi-square of 16.295, and a significance level of 0.038. This indicated reasonable ability of the variables to separate the groups, the separation being statistically significant. Much of the available discriminating information was contained within the first function, as indicated by the increase of lambda to 0.869 after removal of this function.

An estimation of group separability is given by the eigenvalue associated with each function. Large eigenvalues (greater than 0.4) indicate 'good' functions (Nie *et al*, 1975). Associated with the eigenvalues are the percentage variance and the cannonical correlation coefficient attributed to the function, the cannonical correlation being a measure of the degree of the association between the discriminant scores and the groups.

Thus the left hand side of Table 5.5 (a) denoted the relative importance of each function in overall group separation. From Table 5.5 (a) it was possible to infer that the first function, with an eigenvalue of 0.608 had reasonable ability to separate the groups. As expected, the second function was less efficient (eigenvalue of 0.150), however it still contained nearly 20% of the variance, and should still have a contribution to group separation.

If the group separability is not uniform, for example, if one group is very well discriminated, but the others are close, the resulting eigenvalue may be deceptively large. Such confusion may be minimised by examining the separation of group centroids, (Table 5.5 (b) and Figure 5.5). The group centroid is the mean value of each function for each group i.e. the average location of a case from that group in discriminant space. Comparison of the group means on each function indicates the separation of the groups in that dimension, and may reveal unequal group separation in a function. Figure 5.5 shows the plot of the groups and their centroids for the data, with the first two functions defining the axes. From this, it can be seen that all three classes were reasonably separated in the first function, the second function also being important in discriminating classes 2 and 3.

5.4.1.2 Importance of the Discriminating Variables

The discriminant function coefficients represent the relative contribution of each standardised variable to the discriminant functions, and are calculated such that they maximise the differences between the groups in discriminant function scores. The score on the variable is then multiplied by the respective discriminant function coefficient and the results totalled to give that case's discriminant function score.

The variables are standardised to remove the effects of differing means and standard deviations in the predicting variables. If this was not performed, variables with small standard deviations would tend to have larger coefficients, and hence the comparison of discriminating variables would be difficult.

When attempting to assess the relative importance of each variable, it should be noted that the coefficients are calculated according to the combination of discriminating variables providing maximum separation i.e. their contributions generally cannot be considered as being independent. Also, each successive function contains considerably less discriminatory information than the preceding one. Therefore the magnitude of the discriminant function coefficient for a variable should be considered in conjunction with the amount of information contained within that function.

From Table 5.5 (b) it can be deduced that MOIST, LNCH4, and PH were all important contributors to group separation in the first function, with coefficients of -1.866, 1.295, and 1.805 respectively. The variable having greatest contribution to the second function was TEXT (0.934). As the second function contained nearly 20% of the discriminating information, the contribution of this variable to overall group separation was still likely to be important.

A greater understanding of the analysis results can be gained by examining the scatterplot showing the distribution of cases on each function (Figure 5.5). This confirms the decrease in HEIGHT from class 1 to 3 (class 1 representing healthy vegetation, class 3 being poor) was associated with increasing scores on function 1. As this function was represented by positive contributions from LNCH4 and PH, and negative from MOIST, it was inferred that, decreased height (represented by increasing class) was a result of increased values of LNCH4 and PH, and decreased MOIST.

For each case the value of the discriminant function is calculated, and the Pearson correlation coefficient between the score and the original variables is calculated. This gives a measure of the contribution of the discriminating variables to the discriminant functions. Separate correlations are computed for each group, and the results combined to give the pooled within-groups correlation coefficients for each variable. A low coefficient indicates the data should be treated with caution, as it infers a large degree of variation in the data. Again, care should be exercised when interpreting the coefficients, as correlations between the discriminating variables affect the magnitude of the correlation with the functions.

From Table 5.5 (b), it can be seen that none of the variables were strongly correlated with the first function, further emphasising the lack of a strong relationship between the variables and plant height at this time.

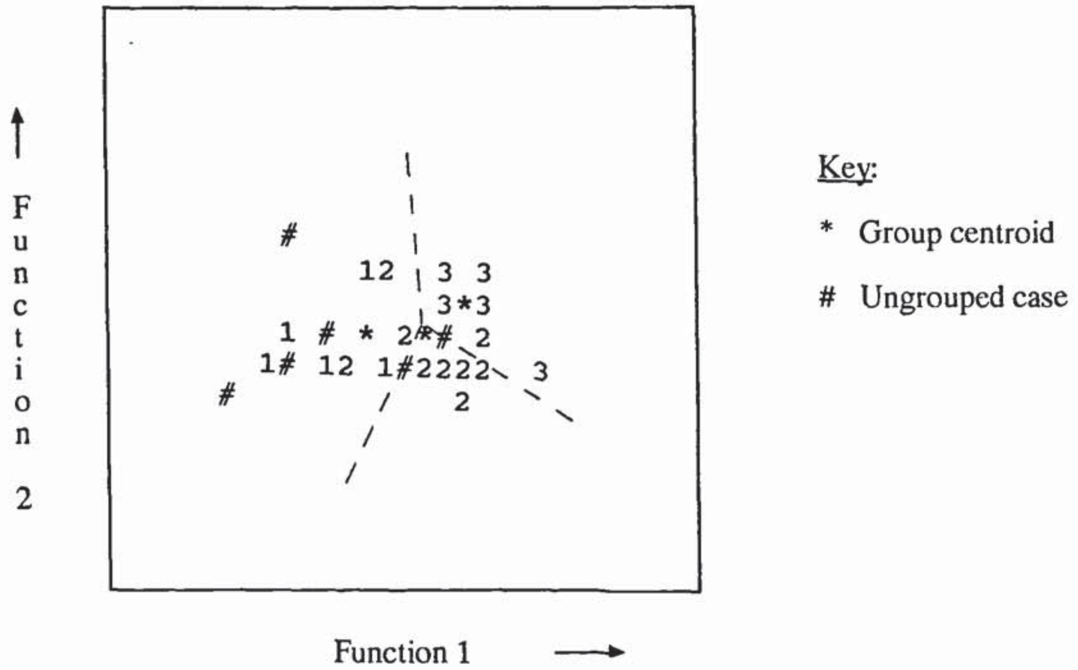

Figure 5.5 Environmental variables grouped on HEIGHT, all groups scatterplot for April data

5.4.1.3 Prediction of Class Membership

The ability of the variables to account for differences in plant height could be gauged by calculating the number of cases that were classified correctly, that is, the cases where the soil and gas variables could be used to accurately assign individual cases to their height classes.

Table 5.6 showed that, overall, the environmental variables could predict HEIGHT in nearly 71% of cases. Closer examination of the results indicated that the healthy crop was least accurately predicted using these variables (57%), whilst membership of classes 2 and 3 was predicted in 75% of cases.

Fcn	Eigenval	% Var	Cum %	Canon Corr	After Fcn	Wilks' Lambda	Chi Square	DF	Signif
					: 0	.5407	16.295	8	.0384
1	.6078	80.17	80.17	.6148	: 1	.8693	3.711	3	.2944
2	.1503	19.83	100.00	.3615	:				

Table 5.5 (a) Canonical discriminant functions, environmental variables grouped on HEIGHT, April data

Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
LNCH4	1.295	-0.143
MOIST	-1.866	0.149
PH	1.805	-0.016
TEXT	0.338	0.934

Pooled-within-groups Correlations between Discriminating Variables and Canonical Discriminant Functions

	FUNC 1	FUNC 2
MOIST	-0.345	0.226
TEXT	0.094	0.985
LNCH4	0.252	-0.354
PH	-0.001	0.303

Canonical Discriminant Functions at Group Means (Group Centroids)

GROUP	FUNC 1	FUNC 2
1	-1.278	0.249
2	0.156	-0.348
3	0.807	0.479

Table 5.5 (b) Discriminant function coefficients and additional statistics, environmental variables grouped on HEIGHT, April data

		Actual Group Membership		
		Group 1	Group 2	Group 3
Predicted Group	Group 1	4 (57.1%)	2 (12.5%)	1 (12.5%)
	Group 2	2 (28.6%)	12 (75.0%)	1 (12.5%)
	Group 3	1 (14.3%)	2 (12.5%)	6 (75.0%)
		Overall Classification Accuracy 70.97%		

Table 5.6 Accuracy of predicting HEIGHT using environmental variables

5.4.2 Results

5.4.2.1 April

Analysis of the April data revealed that most of the discrimination of height classes was explained using two functions. Examination of Table 5.5, in conjunction with the all-groups scatterplot (Figure 5.5), indicated the decrease in plant height could be attributed to the combined effects of increasing PH, LNCH4, and decreasing MOIST. TEXT contributed mainly to separation of classes 2 and 3, and had most effect in the second function. The results indicated that all the variables were operating in combination to limit crop height, although none of the variables were very well correlated with the functions. This was attributed to the early stage in the phenology of the crop; at this point, the plants were sensitive to any environmental disturbance, and a slight variation in any one of the variables could result in a relatively large effect on plant health.

The ability of the environmental variables to account for the observed differences in crop height was assessed by comparing predicted with actual class membership (Table 5.6). The analysis yielded an accuracy of 70.97% i.e. in over 70% of cases, the discriminant functions could be used to accurately predict crop condition (based on plant height) using the measured environmental variables.

5.4.2.2 May

Remote sensing data had not been acquired during May; however, field work had been carried out as in the preceding month, and this was again used to assess the relationship between plant health and the environmental variables.

It was not possible to account for differences in plant height based on the environmental variables (Table A3.1). The high Wilks' lambda of 0.7072 (significance level of 0.33) indicated that much of the discriminating ability within the data was due to sample error. The degree of confusion in the data was revealed both in the scatterplot (Figure 5.6), and in the prediction accuracy results (Table A3.2), overall classification accuracy being only 55%.

Despite the discouraging results, the intermediate statistics were examined to assess which of the variables were contributing to the small amount of group separation. As with the April data, a decrease in HEIGHT was associated with a combination of increasing LNCH4 and PH, and decreased MOIST, all these variables being similarly weighted in the first function.

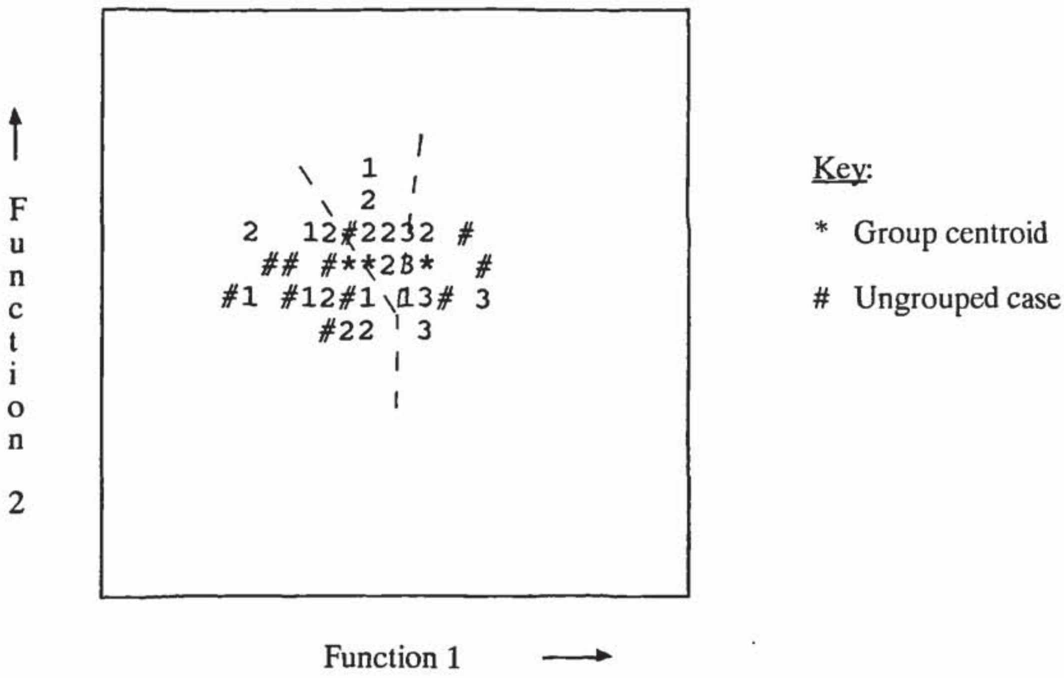

Figure 5.6 Environmental variables grouped on HEIGHT, all groups scatterplot for May data

5.4.2.3 June

At the time of the June survey, weather conditions had been hot and dry for a prolonged spell. Consequently, severe problems were encountered when augering for soil samples, and it was not possible to obtain either soil or gas data.

5.4.2.4 July

The strongest relation between plant height, and the soil and gas parameters was obtained for the July data (Table A3.3 and Figure 5.7). Most of the separation of groups was accounted for in the first function, which was largely controlled by an increase in LNCH4 and PH, combined with a decrease in MOIST, the contribution from LNCH4 being proportionally greater than in previous months.

The usefulness of the variables in predicting class membership were confirmed when they were able to accurately predict 76.7% of cases, the third class again being identified correctly most frequently (88 %) (Table A3.4).

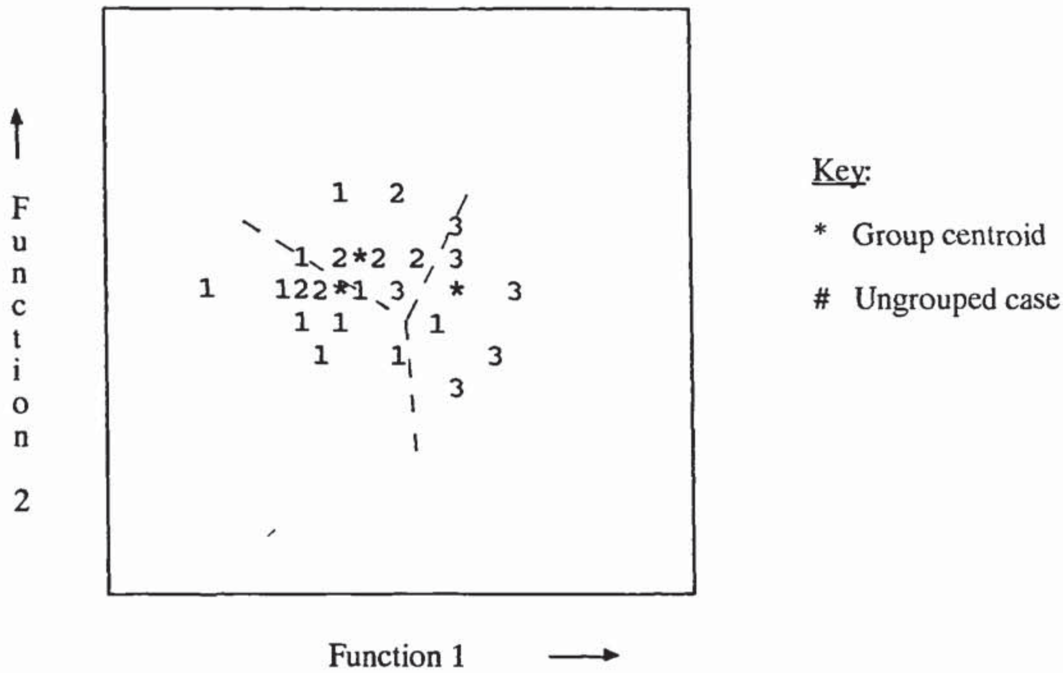

Figure 5.7 Environmental variables grouped on HEIGHT, all groups scatterplot for July data

5.4.3 Summary

The above results showed that a relationship between plant height and environmental variables existed, the association strengthening through the growing season. Early in the phenological stage of the crop, there was not a strong correlation between the variables. This was interpreted as being due to the fact that the plants were at a sensitive stage of growth, and slight variations in any of the controlling factors were enough to cause a relatively large effect on the individual plants.

By July, plant height was much more strongly influenced by the combination of environmental variables. That is, the crop required a larger change in the variables for plant height to be affected. As the predictor variables were varying with each other, a change in magnitude of one variable was influenced, or had an influence on, the others. The result was a strengthening of the relationship between the environmental variables and crop height.

A second point that became apparent from analysis of the data, was the comparative influence of methane on plant height as the season progressed. Although the environmental variables could not be considered in isolation, the relative weighting of methane (compared to the soil variables) increased with increasing crop maturity.

At this site, crop condition was being influenced by a number of interdependent factors. It was not possible to define any single variable as having an influence on plant growth. However, the differences in crop condition, as indicated by plant height, could be attributed to a combination of soil and gas variables, the strength of the relationship, and the relative importance of methane concentration, strengthening with crop maturity. These results concur with previous investigations (Rys & Johns, 1986; DoE, 1988), which suggested the differences in plant height between plots affected and unaffected by landfill gas, increased with time.

The reasons for lack of a stronger relation between crop height and gas concentration were felt to be two-fold:

(i) The affected plants were growing on the restored landfill cap. That is, even in the absence of landfill gas, the intrinsic heterogeneity of the soil would be expected to result in variations in crop condition. In addition, the variability of the soil caused a complex system of migration pathways resulting in gas migration paths changing both spatially and temporally across the site.

(ii) Much of the damage was expressed as a general decrease in crop health, rather than acute injury. This was thought to be mainly due to the relatively low concentrations of gas, combined with the inconsistency of migration pathways. As a result, high concentrations of gas were unlikely to be in the root zone for any length of time, and acute vegetation injury did not result.

In addition, the exclusion of areas of bare soil meant that any areas of dieback were not included in the analyses. This resulted in the loss of valuable information from the investigation.

5.5 Relationship between Spectral Response and Environmental Variables

Having identified a relationship between the environmental variables and crop height, the effect of the same variables on the spectral response of the crop canopy was investigated. Crop health classes were defined based on the spectral response of the canopy. Discriminant analysis was carried out, firstly to identify the agronomic variables, and secondly the environmental variables, influencing spectral response. Finally, the April and July images were classified, assigning class membership according to the near infrared : red ratio value of individual pixels. With an understanding of the relationship between spectral response and the environmental variables, it was possible to infer changes in the environmental variables.

5.5.1 Spectral Response and Crop Condition

The initial analysis aimed to identify the combination of agronomic variables having maximum effect on the recorded spectral response.

Using the digital mapping facility on the image processing system, a representative grid locating the ground sampling points, was copied onto the overlay planes. Reference points in the field were located on the image, a transformation matrix was derived, and the grid rotated to the ATM image. Any ground reference points that were located in heterogeneous areas were excluded from the following procedures. By using only grid points located within homogeneous areas, there would be better tolerance to any minor positional errors associated with the grid location.

For the April and July data, the infrared and red images were subjected to a 3 x 3 meanal filter to reduce local high frequency variation, and the value of the infrared : red ratio calculated for each viable grid point. The infrared : red ratio was chosen as the grouping variable in preference to a single spectral band, as it was expected to provide greater spectral discrimination between healthy and damaged crops (see Section 3.3.3). A similar procedure was carried out for the June data, except that, due to problems experienced with the infrared data, the red reflectance values were used.

The variables available to be used to predict spectral response were percent crop cover (COVER), plant height (HEIGHT), visible damage (DAM), and percent weed cover (WEED).

5.5.1.1 April

ATM imagery and black and white panchromatic air photos of the Panshanger site had been acquired on 31st March 1989 (Table 5.1). Field data was collected approximately two weeks later (13th April 1989). Although not desirable, the time lapse was not considered to be critical as the survey was concerned with the spatial distribution of crop health, rather than an absolute measure of crop condition.

Four classes were defined based on differences in the canopy spectral response; these included three crop condition classes ranging from healthy to unhealthy (1 to 3), and a bare soil class (class 4). Increasing plant health (as expressed by enhanced plant height and cover), was represented by higher values of the infrared : red ratio. Statistical analysis indicated that, in combination with the other variables, HEIGHT had the strongest influence on the spectral response of the canopy, for classes 1 to 3 (Table A3.5). The contribution from weed accounted for most of the separation between the crop and soil classes. From Figure 5.8, discrimination of this class can be seen to be largely accounted for by the second function, which was in turn strongly controlled by a decrease in weed cover.

Overall classification accuracy was 65% (Table A3.6), with the 'soil' class being classified most accurately (83%). Classes 1 and 2 were predicted with 62.5% and 60% respectively, class 3 being the worst at 54%. These results emphasise the spectral separation of soil from crop, and the difficulties that may be encountered in distinguishing different crop classes.

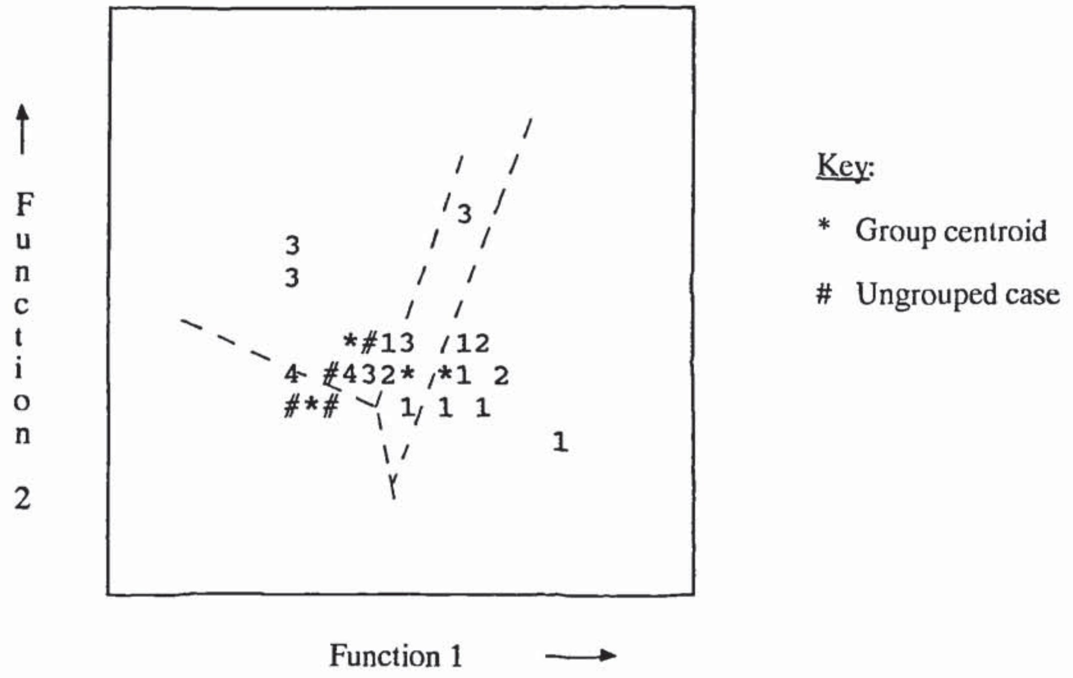

Figure 5.8 Agronomic variables grouped on B7B5 (infrared : red ratio), all groups scatterplot for April data

5.5.1.2 June

Due to the problems experienced in obtaining gas and soil samples during June, there was little benefit to be gained from analysing the relation between spectral response and the environmental variables. However, the ability of the video data to predict ground cover conditions was analysed, such information being valuable to gauge the usefulness of thè data for future analyses.

Colour and black and white infrared video imagery of the site was acquired on 15 June 1989. Field work had been carried out between 10 and 12 June 1989. Preprocessing of the video data was carried out, and a mosaic constructed from the frames (Plate 5.3).

At this point, the problems caused by radiometric variation between frames became apparent. Due to the automatic gain of the cameras, the varying illumination from the ground surface had resulted in radiometric differences between frames. The majority of variation between adjacent frames was reduced by histogram matching (Section 4.2.3). However, with the infrared imagery, this appeared to result in a gradual reduction in brightness levels from the east end of the site to the west.

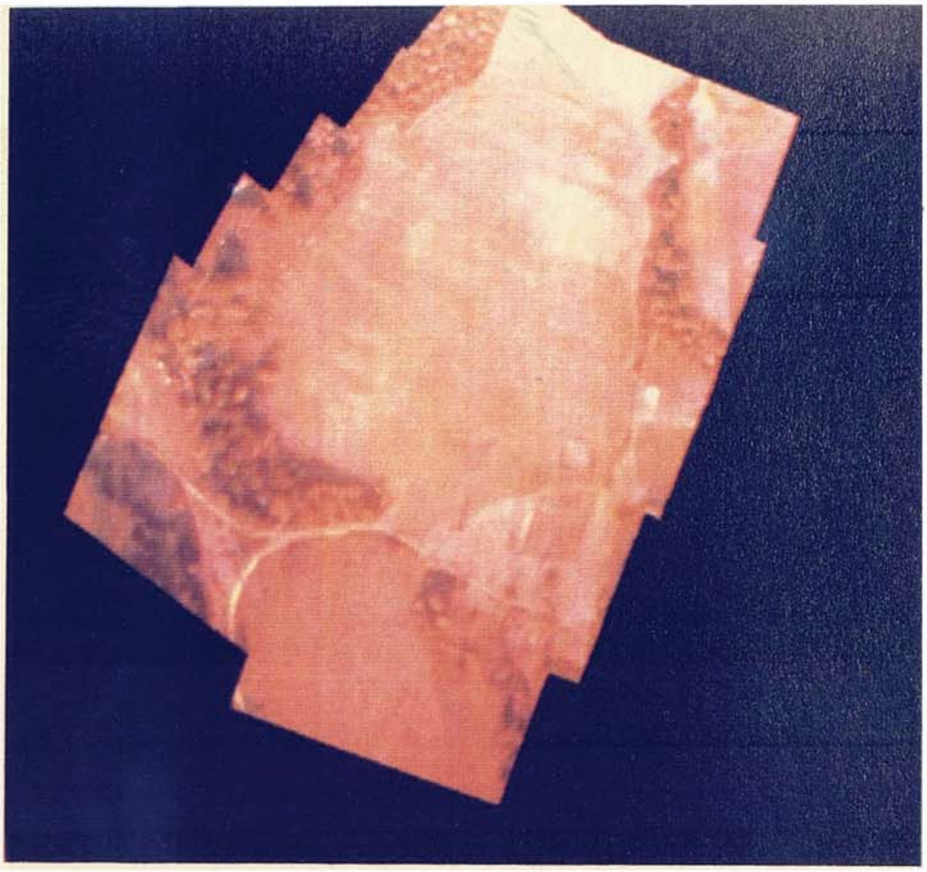

Plate 5.3 True colour video mosaic of Panshanger site, June 1989

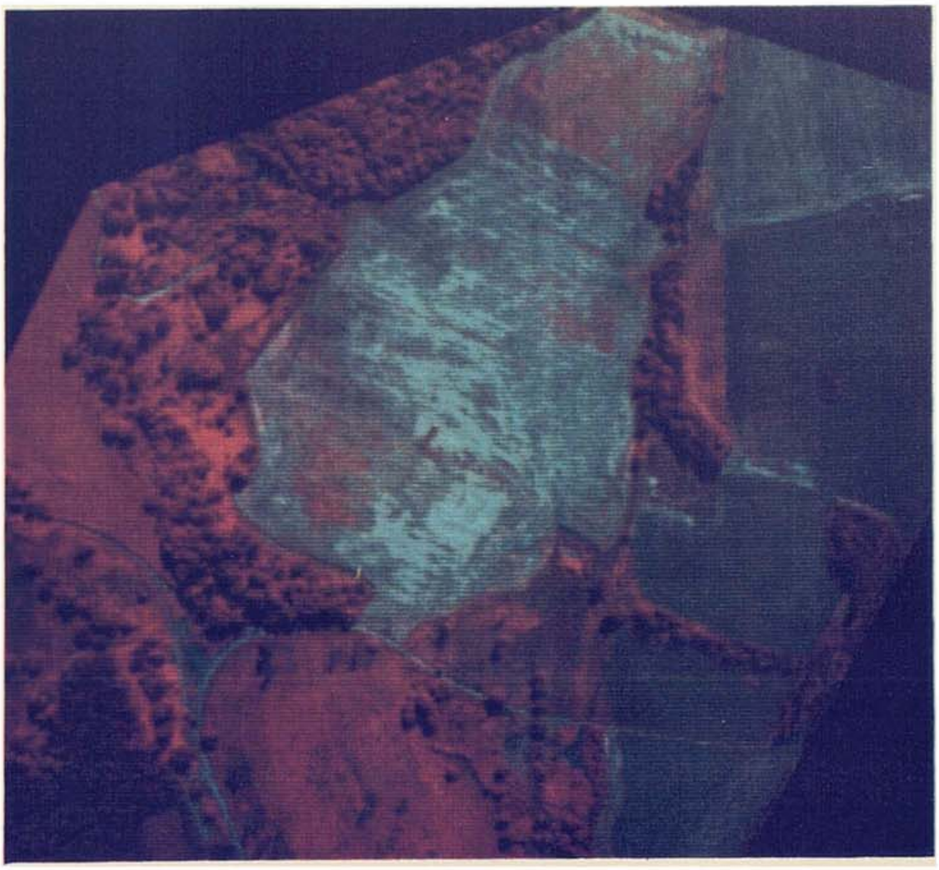

Plate 5.4 False colour composite, Panshanger site, July 1989 ATM data

Band ratioing of the infrared and red bands to reduce illumination variation was considered. However, this would only be successful if the individual frames were perfectly registered, and the between-frame, and within-frame, variation was similar for different bands. These criteria could not be satisfied due to the imagery being obtained using different cameras, and the use of the infrared mosaic was anticipated to be restricted.

The ground reference grid was rotated to fit the mosaic in the same way as described in Section 5.4, and infrared, red, green, and blue reflectance values extracted for use in further analysis.

As a test of the quality of the infrared video data, the Pearson correlation coefficient between infrared and red values was calculated. As explained in Section 3.3, generally the infrared reflectance would be expected to decrease or show little change as visible reflectance increased with decreasing crop health. The calculated correlation coefficient between the two instead showed a strong positive relation (0.4098).

The correlation of the infrared and visible bands was further emphasised by examination of the correlation coefficients associated with the plant variables and spectral response (Table 5.7). All the coefficients were negative, signifying that an increase in any of the plant variables resulted in a decrease in reflectance. Whereas this was expected in visible wavelengths, it would not normally be expected in the near infrared.

	RED	IR	HEIGHT	COVER	WEED
RED	1.0000				
IR	0.4098	1.0000			
HEIGHT	-0.1506	-0.3731	1.0000		
COVER	-0.0938	-0.1619	0.6853	1.0000	
WEED	-0.4637	0.0221	-0.1533	-0.1486	1.0000

Table 5.7 Correlations between spectral response and plant variables, June video data

Due to the above considerations, the red reflectance was chosen as the grouping variable, and three classes were defined. Class 3 included very low crop cover / bare soil, classes 1 and 2 roughly representing 'healthy' and 'unhealthy' crop. Various proportions of weed were included in all classes.

For each grid point, the value of the red reflectance was extracted, and discriminant analysis carried out to assess the extent to which the spectral response could be predicted using the agronomic variables. Almost all the variation contained within the discriminating variables could be allocated to the first discriminant function, that is, a linear combination of the discriminating variables could be used to predict the spectral response (Table A3.7 and Figure 5.9). The most important discriminating variable was again identified as HEIGHT. The prediction accuracy was 60% (Table A3.8), indicating that, despite the data problems, there was a reasonable relationship between the ground cover type and the reflectance values.

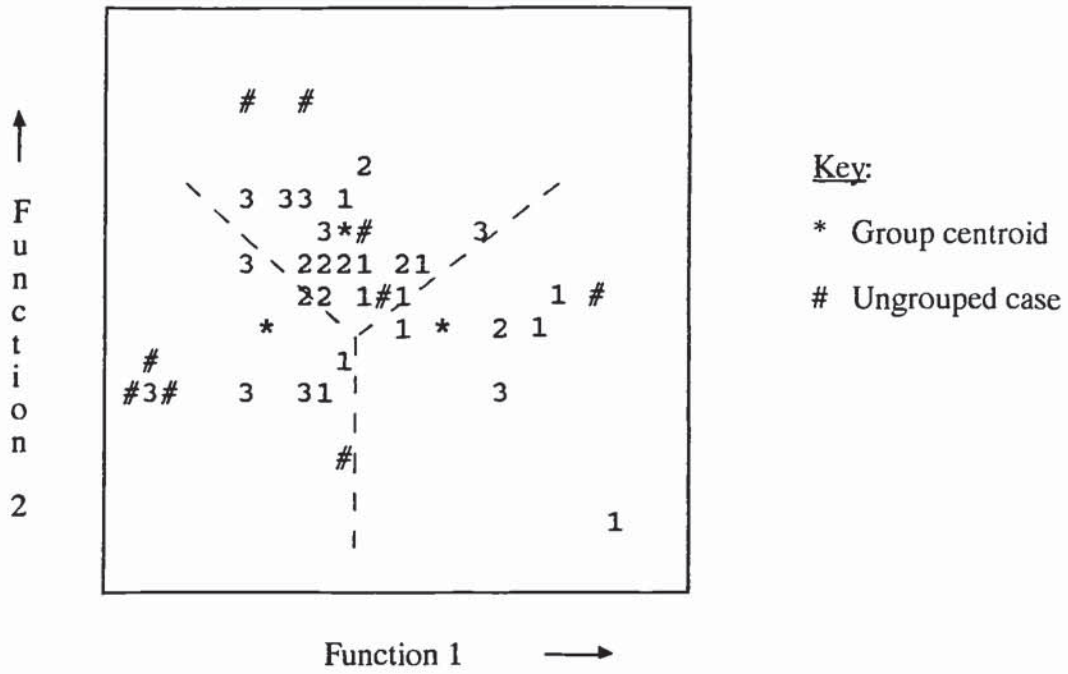

Figure 5.9 Agronomic variables grouped on red reflectance, all groups scatterplot for June data

5.5.1.3 July

A second set of airborne multispectral scanner data was obtained on 22 July 1989 (Plate 5.4). Once again, the imagery was geometrically corrected (Section 4.3.4), and the ground reference grid rotated to fit the image.

Field work on the 15 and 16 July 1989 had shown the crop to be senescent, there also being several areas of 'lodging' caused by wind damage to the rye. Inspection of the infrared : red ratio values for each grid point revealed that the ratio was low for 'healthy' vegetation and highest for areas dominated by weed, soil also having a high value. This suggested the crop was not reflecting highly in the near infrared, and crop condition would not be expected to be related to spectral response (see Section 3.2.2.4).

Discriminant analysis revealed that the spectral response of the canopy was strongly controlled by the contribution from HEIGHT, combined with WEED (Table A3.9). The increasing contribution from WEED was due to the fact that these areas were still actively growing, and therefore strongly reflecting in the infrared wavelengths.

As with the April data, the scatter plot of the predicted classes showed the good separation of class 3 (soil) from classes 1 and 2 (healthy and unhealthy crop) (Figure 5.10). This was confirmed by calculation of the prediction accuracy for the analysis (Table A3.10). Class 3, dominated by bare soil and weed, was reasonably well discriminated (72%), as was class 2 (77%). Class 1 was most confused (56%), much of this class being attributed to class 2.

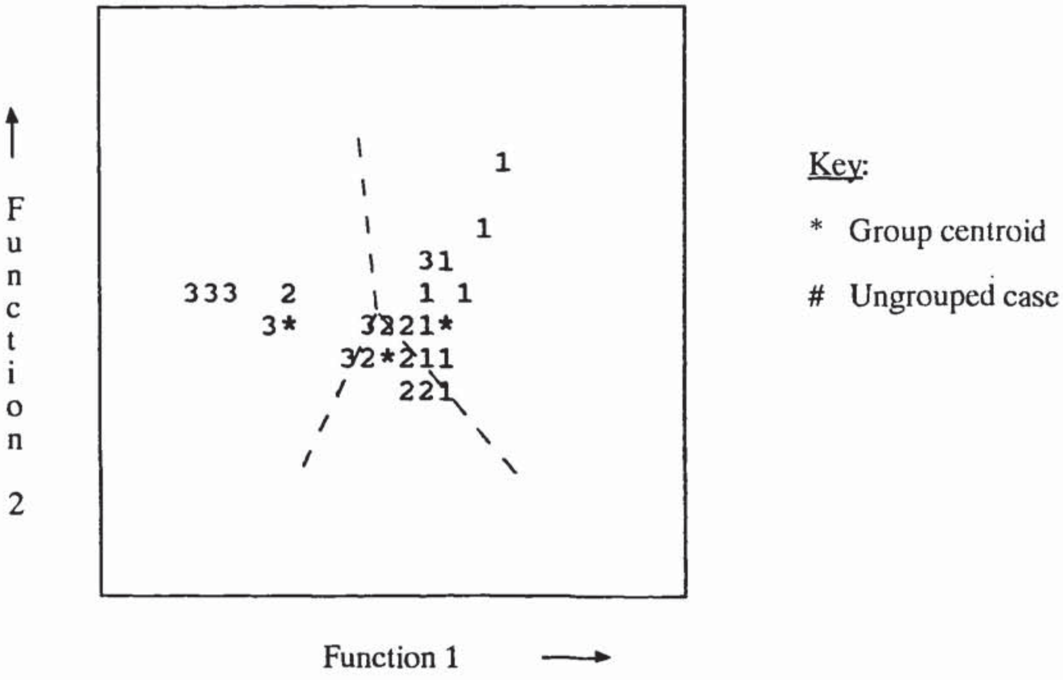

Figure 5.10 Agronomic variables grouped on B7B5 (infrared : red ratio), all groups scatterplot for July data

From this it could be interpreted that areas of predominantly soil and weed, could be spectrally discriminated from areas with crop cover. The main source of confusion was caused by the similarity of spectral response for different crop condition classes, a fact that would be expected due the senescent state of the crop.

5.5.1.4 Summary

Overall, HEIGHT was identified as the variable having maximum influence on separation of the spectral classes, although it could not alone account for class separation. The strength of the relationship between HEIGHT and spectral class could be explained by the fact that taller plants would have greater green leaf area, and would be expected to be more vigorously growing than smaller specimens. The contribution from WEED tended to increase as HEIGHT decreased. This was interpreted as being due to the increased proportion of weed plants in areas where competition from crop was reduced, particularly towards the end of the growing season.

5.5.2 Relationship between Spectral Response and Environmental Variables

Reasonable success had been achieved in correlating spectral response with the crop variables, and also in relating plant height to the measured environmental variables. Further analyses were carried out to appraise the extent to which spectral response could be related to the environmental variables. The infrared : red ratio was again used as grouping variable, being divided into the same groups as had been used in the previous analyses. For reasons explained in Section 5.2, any points with zero crop cover were assigned missing value labels.

5.5.2.1 April

Although the discriminant analysis for the spring data indicated that the environmental variables had some influence on the spectral response, the discriminating information was not significant (significance level of 0.124). Figure 5.11 shows the large spread of cases around the group centroids and helps to explain the lack of significance of the discriminant functions. The statistics (Table A3.11) indicated that an increase in the infrared : red ratio (implying improved crop health) was affected by increased MOIST and PH, and decreasing LNCH4. i.e. increased crop health, as shown by higher values of the infrared : red ratio, was accompanied by lower methane concentrations, and heightened MOIST and PH.

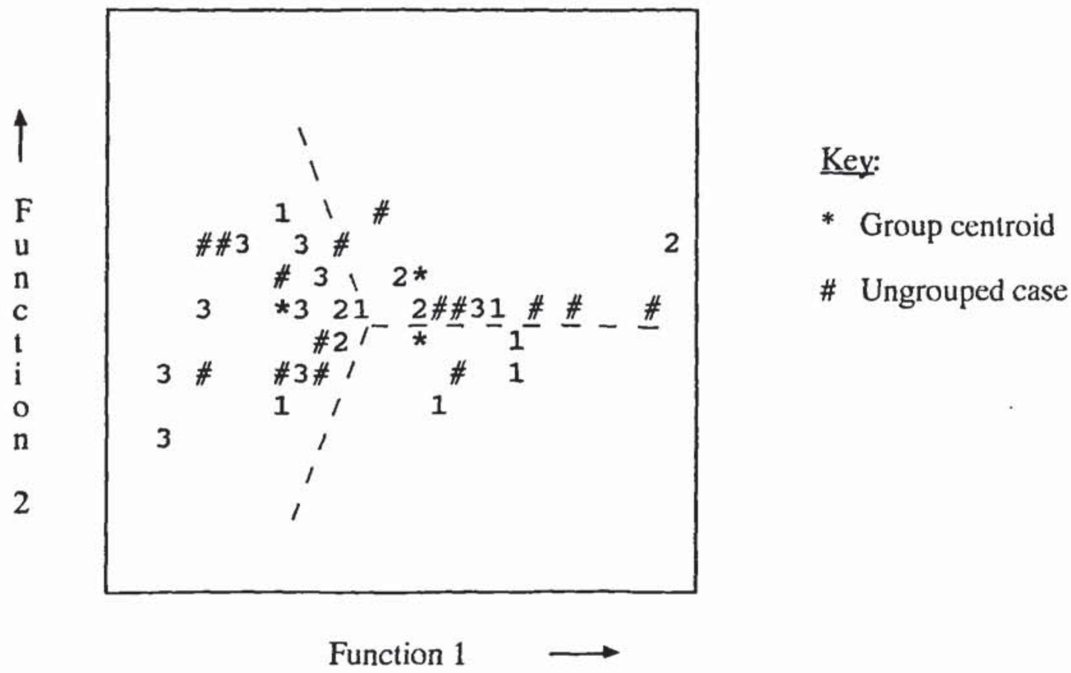

Figure 5.11 Environmental variables grouped on B7B5 (infrared : red ratio), all groups scatterplot for April data

The overall prediction of spectral class using the environmental variables was 64% (Table A3.12), although class 2 (sickly crop) was only correctly classified in 38% of cases, and was confused with both classes 1 and 3.

The similarity between this, and the relationship established between environmental variables and plant height, should be noted. It indicates that the impact of environmental variables on HEIGHT, had a consequent effect on the spectral response of the canopy. Again, the large amount of variability within the data suggested the sensitivity of the spectral response to small changes in soil moisture or methane concentrations.

The notable difference between this and the previous analysis was the fact that increasing PH now appeared to have a positive effect on plant health, compared to its negative contribution to plant height. Examination of the class statistics showed that the range of pH values for the classes was relatively small (6.95 to 7 25), and suggested that the changes in pH might not be significant. Further work would be required to identify the precise role of pH within the relationship.

5.5.2.2 July

Again, the strongest relationship between crop health and the environmental variables was attained at the end of the growing season (Table A3.13). Considerable spectral separability was provided by the environmental variables, as indicated by the low value of Wilks' lambda (0.385 at a 1% significance level). The improved ability of the environmental variables to account for the spectral response is shown by the close grouping of the cases in Figure 5.12, and the prediction accuracy of 74% (Table A3.14). All members of class 3 were correctly identified (5 cases), virtually all the confusion existing between classes 1 and 2.

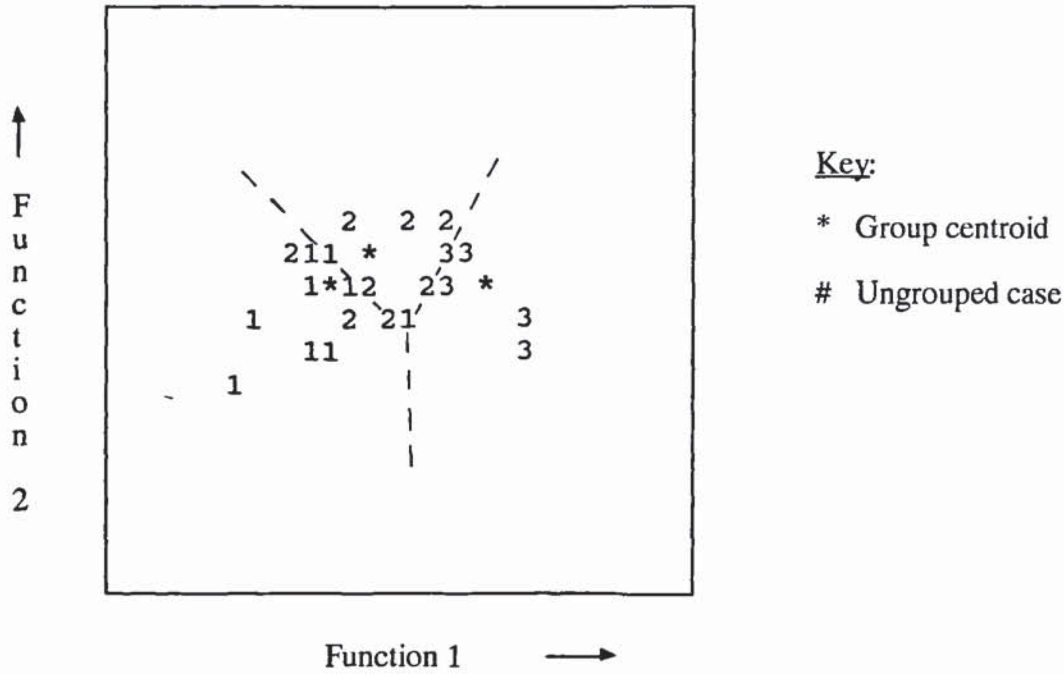

Figure 5.12 Environmental variables grouped on B7B5 (infrared : red ratio), all groups scatterplot for July data

This analysis indicated that no single environmental variable was exerting a proportionally large influence on group separation. Consideration of the statistics and Figure 5.12, indicated the increase in infrared : red ratio could be attributed to increased methane and decreased soil moisture, in combination with an increase in the clay content of the soil, and decreased pH.

This implied that, even more than for the April data, there was no single variable that could account for the changes in spectral reflection of the canopy. However, the variables in combination were exerting considerable influence on the perceived response.

5.5.2.3 Summary

Analyses of the relation between the spectral response and the environmental variables again indicated the increasingly strong relationship between the environmental variables and crop health, as the crop approached maturity. However, LNCH4 was comparatively less important as the crop matured, with all the variables having a similar contribution to group separation. Overall, the results indicated that the spectral response of the canopy could be related to the measured environmental variables, the association being most powerful as the crop approached senescence.

The results were generally similar to those using HEIGHT to group the environmental variables, indicating the impact of the variables on plant height had a consequent effect on the spectral response of the vegetation. This bears out the underlying assumptions of this approach - that the effects of gas on vegetation could be detected as differences in vegetation spectral response. The results would be more positive if a stronger relationship between landfill gas and plant height could have been identified.

5.6 Image Classification

One of the aims of research at this site had been to produce a classification of the site, the classes representing areas where specific concentrations of gas could be expected. However, this would rely on a direct link between spectral response and landfill gas concentration, a relation which was disproved early in the analysis. Instead, multivariate analyses established that spectral response could be predicted with reasonable accuracy using a combination of gas and soil variables.

By defining the environmental variables as being dependant on the spectral response, it would be possible to use discriminant analysis to predict values for the gas and soil variables from the spectral response. However, this would produce an apparent level of accuracy that could easily be mis-interpreted, and instead the results were used to indicate areas where high gas concentrations would be most probable.

To aid in this, the site was classified by assigning a class to each pixel, based on the value of the pixel (i.e. density slicing), the same grouping being assigned as in the statistical analyses. The classification enabled rapid assessment of vegetation condition across the site and, when combined with the discriminant analysis results, provided an indication of the areas most likely to be at risk from landfill gas.

Thematic maps were produced in this way for April and July data, using the near infrared : red ratio image (Figures 5.13 and 5.15). Due to problems with the June data, it had not been possible to establish any relationship between environmental variables and spectral response. However, the red reflectance had been shown to be correlated with the agronomic variables, and classification of the video data was carried out to show the variation in vegetation condition across the site (Figure 5.14).

The differences between classification results do not represent temporal changes in crop condition, each analysis was specific to the data for that month, and consequently the results from different dates cannot be directly compared. Instead, the thematic maps represent the spectral groups that are best separated by the environmental variables for that date. As the environmental variables provided optimum separation of spectral groups for the July data, these results provide the most reliable indication of landfill gas. However, the importance of the remaining environmental variables cannot be ignored, and care should be exercised when attempting to draw simple conclusions from such data.

In practice, these results could be used to indicate areas that could be affected by landfill gas. If these locations were in the vicinity of housing or other 'risky' areas, or if compensation for crop loss was sought, ground work would be required to back up the results from the remote sensing survey. They would also enable monitoring to be concentrated in areas apparently being affected by high concentrations of landfill gas.

5.7 Conclusions

Initially, the Panshanger site had been investigated to demonstrate the use of remote sensing to detect and monitor the presence of landfill gas in the near-surface soil. However, due to site conditions, the underlying assumption -that landfill gas and vegetation health were simply correlated - could not be established. However, discriminant analysis showed that, in combination, the soil and gas variables had an influence on plant health. Further analyses indicated that a relationship between landfill gas and spectral response did exist, again provided that soil characteristics were included in the model. The two sets of analyses revealed similar relationships between the grouping variables (either plant height or spectral response) and the discriminating variables (LNCH4, MOIST, TEXT, and PH). This was attributed to the fact that HEIGHT was affected by the environmental variables, and was also the crop variable most strongly affecting spectral response of the canopy.

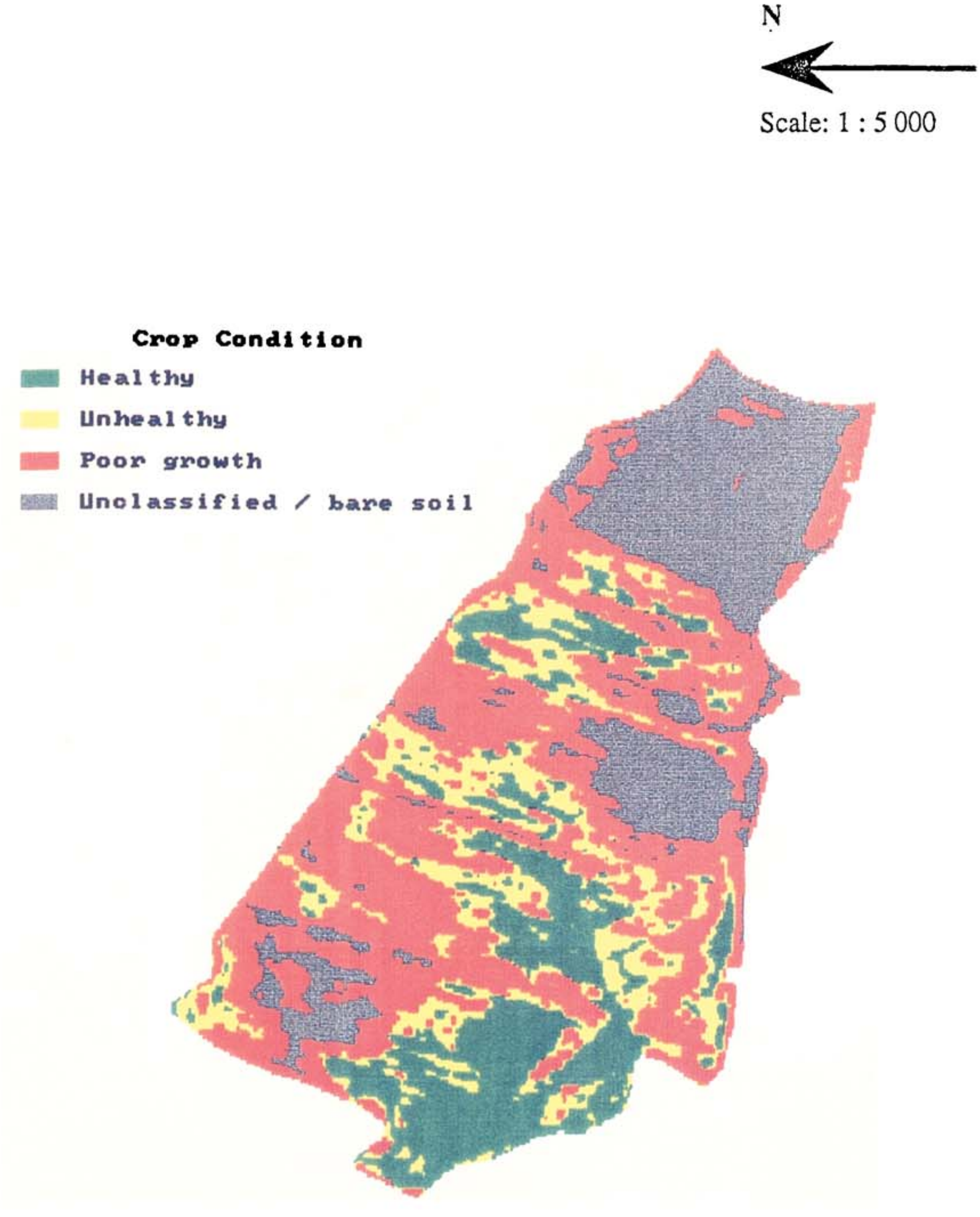

Figure 5.13 Classification of Panshanger site, April 1989, ATM data

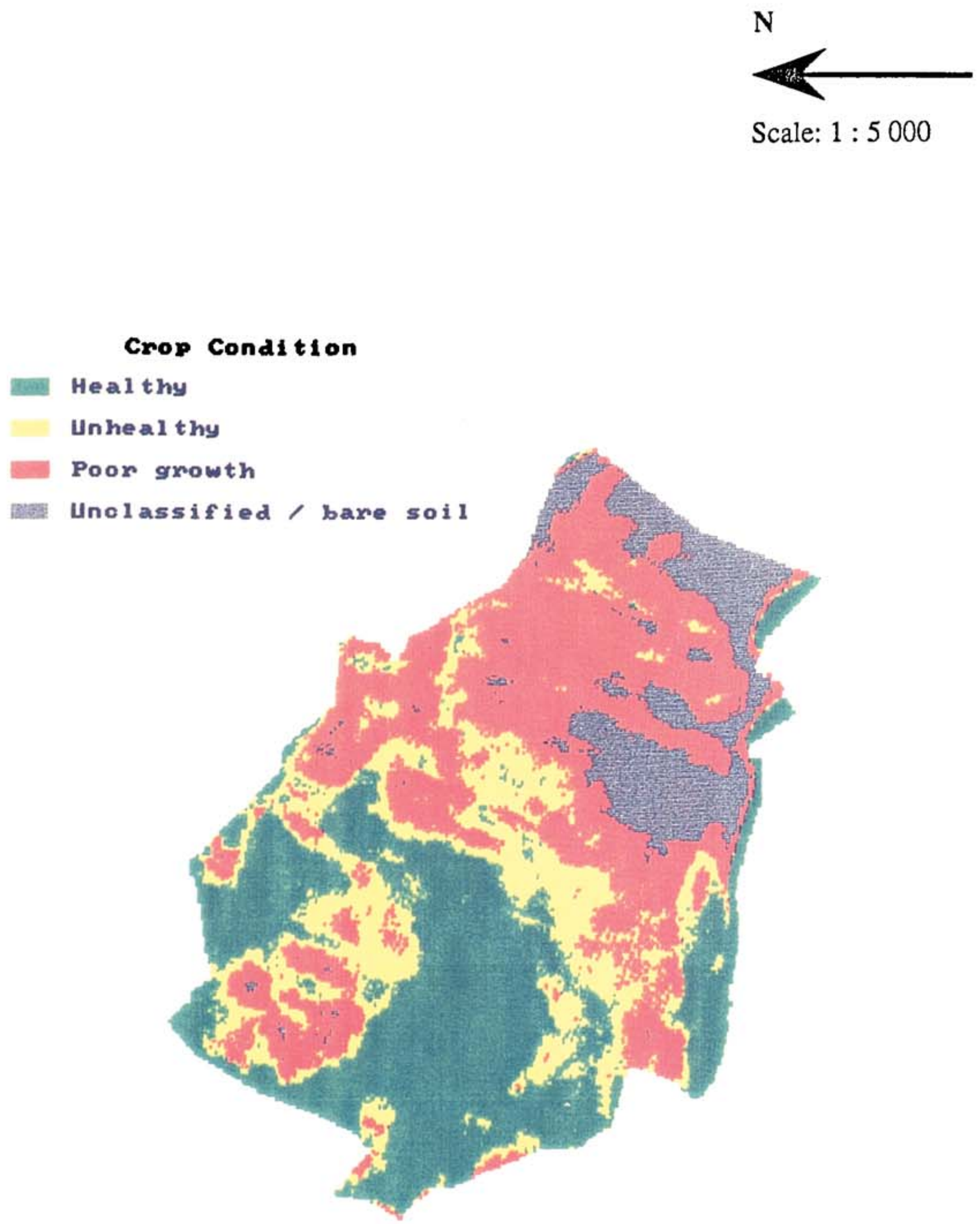

Figure 5.14 Classification of Panshanger site, June 1989, video data

N

Scale: 1 : 5 000

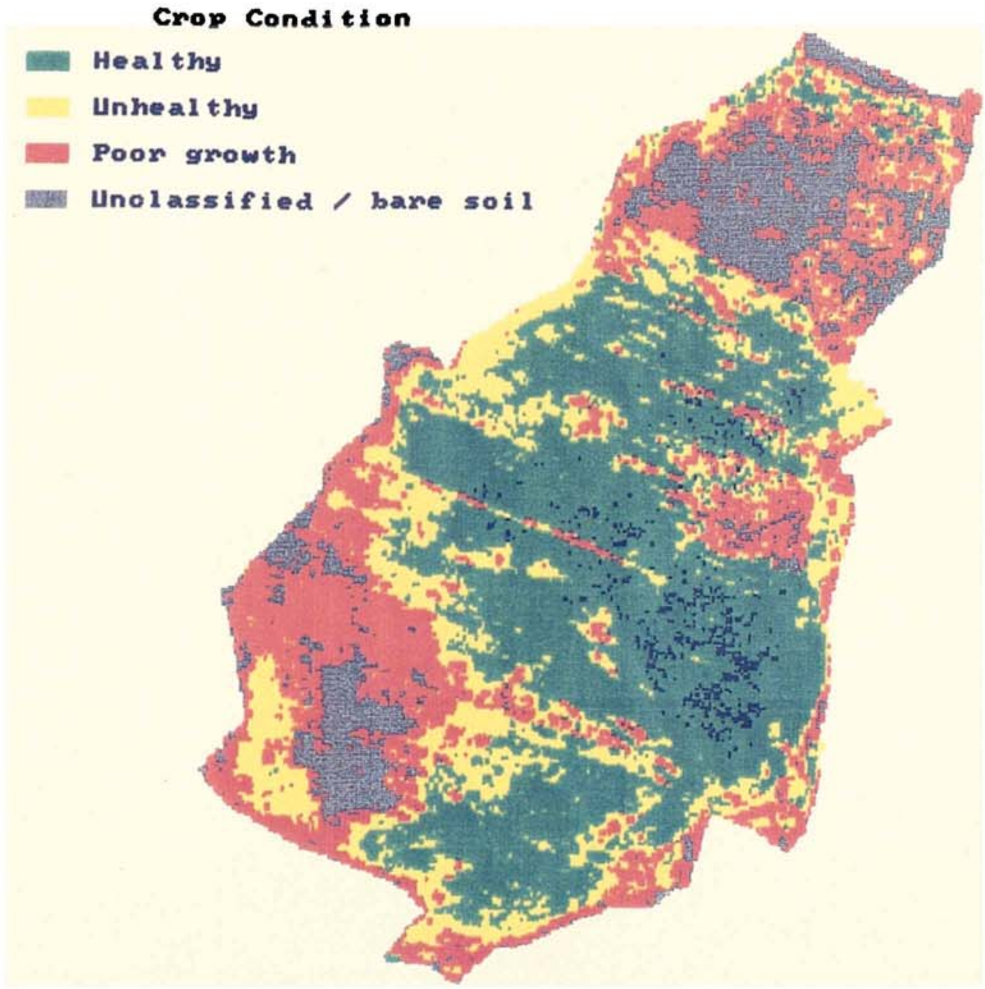

Figure 5.15 Classification of Panshanger site, July 1989, ATM data

From the analyses, it was inferred that LNCH4 was the variable contributing most to differences in HEIGHT. However, when the effect of the environmental variables on spectral response was analysed, it was much more the combination of soil and gas variables that were responsible for group differences.

In addition, the contribution of PH changed for the two sets of analyses. Whereas positive changes had resulted in a decrease in HEIGHT, increases in PH were observed to be associated with an improvement in crop condition as indicated by the spectral response As the differences between classes were only small, they were more likely to be attributable to the changes in the relationship between LNCH4 and MOIST, rather than 'real' differences in the spectral response / environmental variable relation.

The most noticeable temporal effect was the increased intensity of the above relationships as the plants approached maturity. The stronger association between the environmental variables and spectral response of the crop canopy was due to the combined effects of an increase in intensity of the relationship between crop condition and the environmental variables, and between spectral response and the agronomic variables. The first of these was attributed to the sensitivity of crop plants early in the growing season, with slight variations in any of the variables exerting considerable influence on plant condition. When considering the practical application of remote sensing, this has important implications for the timing of surveys, success being less likely if the crop is at an early stage of growth.

Discriminant analysis was shown to be an effective tool for examining the complex relationships between plant, environmental, and spectral parameters at the Panshanger site. The reasons for the lack of a stronger relationship between plant health and landfill gas were attributed to a number of factors:

(i) The variable quantities of landfill gas were causing chronic, rather than acute, injury to the plants. Damage appeared to be a general decline in crop health, evidenced by reduction in height and cover.

(ii) Variable soil conditions existed across the site, due mainly to respreading of the soils during restoration of the site. This not only affected crop condition at various locations, but also exerted an influence on the migration of gas through the restored soils.

(iii) As a result of decomposition of the wastes, the original surface of the cap had settled in places, and these parts of the site tended to become waterlogged. Lack of competition from crop plants in these areas meant that weed had tended to invade, confusing the spectral response of the canopy.

(iv) The exclusion of areas with no crop cover was felt to bias the results. If these areas had been sown, but the crop had not germinated due to high concentrations of gas, removing such data from the analyses would be expected to weaken any relationship between landfill gas and vegetation health. In addition, the farmer had avoided these locations because of the waterlogged soils; the data could not therefore be expected to represent the true range of soil moisture across the site.

The practical application of the results in this situation are somewhat limited, due to the lack of a straightforward relationship between methane and plant health. The image classification identified areas with a particular spectral response, and an understanding of the environmental variables could then be interpreted from the results of the discriminant analysis. In such situations, rather than stating that vegetation damage was being caused by landfill gas, the plant injury, and its associated effect on spectral response of the canopy, should be treated as an indication that landfill gas could be present.

6 WARE QUARRY

6.1 Introduction

The Ware Quarry site is situated approximately one kilometre to the north west of the town of Ware in Hertfordshire. As for much of Hertfordshire, the geology of the area is characterised by sand and gravel deposits overlying the Upper Chalk, covered by up to 2m of boulder clay. For many years, these glacial deposits were quarried for their sand and gravel component, landfilling with domestic waste being initiated in 1967.

Damage to crop and trees to the south of the site was noted in 1985, and became progressively worse over the following years. Landfill gas monitoring confirmed that the damage was likely to be as a result of the migration of gas. In 1989, a gas abstraction system was installed in order to prevent migration, subsequent monitoring confirming the success of the installation.

This chapter outlines the investigation of damage to both crops and trees in the vicinity of the site using remote sensing, combined with limited ground reference data. As landfill gas had been established as the cause of vegetation injury and dieback, the work concentrated on the use of remote sensing to investigate several features of the site. The aims of the work were to assess:

(i) damage to the crops and woodland area, both in terms of the extent of damage, and in terms of severity using remote sensing data,
(ii) the spatial relationship of crop damage and soil type,
(iii) temporal changes in crop health related to landfill gas,
(iv) the relative utility of airborne video and ATM data to detect tree and crop damage.

The remote sensing data available included two sets of colour infrared aerial photographs, ATM data, and video.data (Table 6.1).

6.1.1 Site History

Landfilling of the area known as Gentleman's Field proceeded in 1967, to be followed by the Middle Field area in 1974. Work in this area progressed from the south west end of the strip, adjacent to Garrett's Wood, towards the A602 in the north east (Figure 6.1).

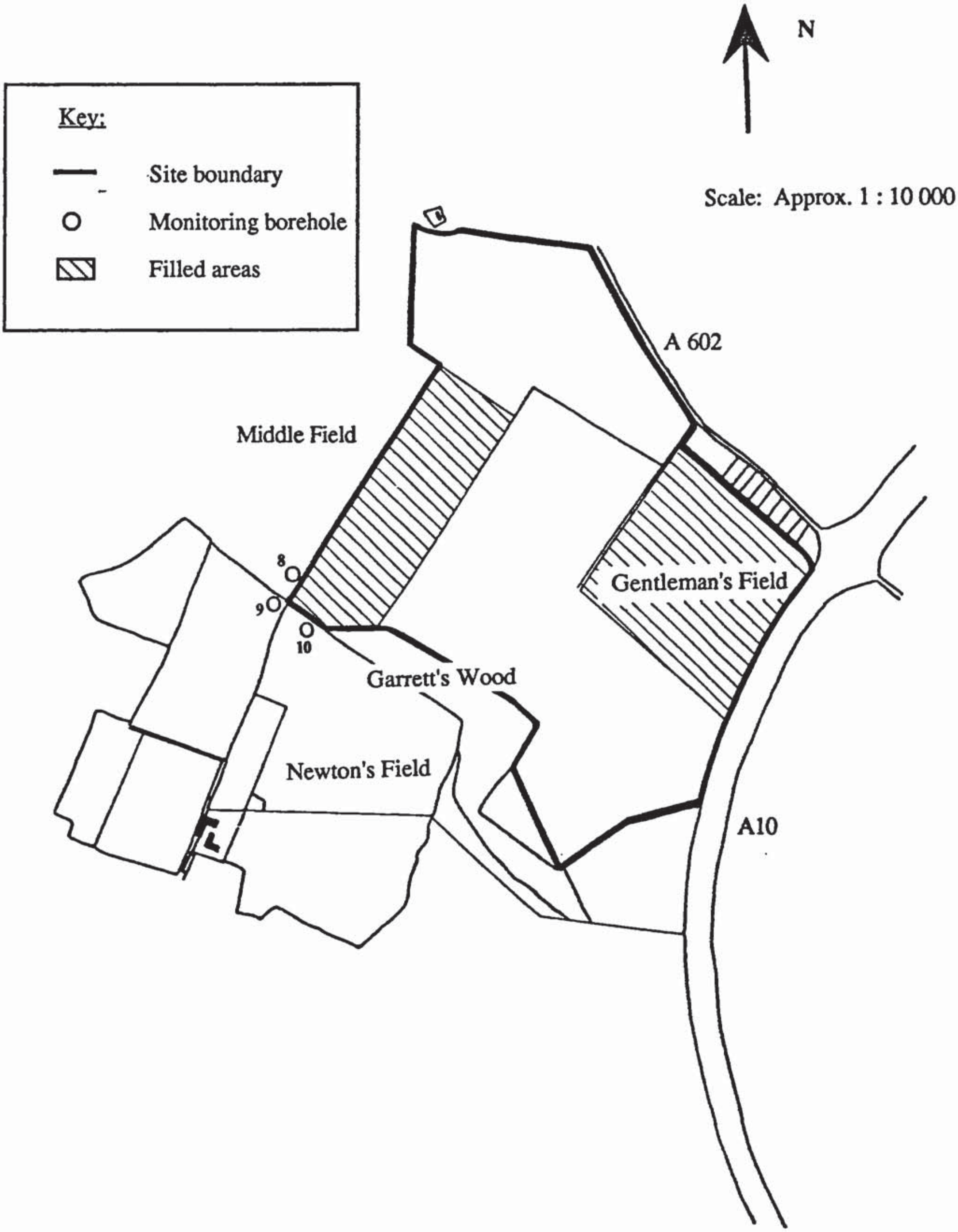

Figure 6.1 Site plan of Ware Quarry

Sensor and Data Type	Date	Scale / Resolution	Use
Wild RC8 Camera Colour infrared 23 x 23 cm photos	July 1988 September 1988	1 : 3 000 1 : 2 500	Woodland
Daedalus 1268 Multispectral Scanner	July 1988	2.5 m	Woodland
Wild RC8 Camera Black & white panchromatic photos	April 1989	1 : 2 000	Crop
Insight Monochrome Infrared Video Camera	June 1989	1.6 m	Crop
Panasonic WVP-A2E Colour Video	June 1989	1.6 m	Crop

Table 6.1 Remote sensing data for the Ware Quarry site

Both these plots were completed and restored to grass in 1984 - 85. Although gas migration problems have occurred to the north of Gentleman's Field, this work is concerned with the effects of gas migrating from the Middle Field area.

Site licensing allowed for the deposit of "domestic refuse and industrial waste", the disposal company being required to "ensure the complete restoration of the land to agricultural use". As with many old sanitary landfill sites, at the time of filling and restoration, no provision was made to allow for the possible migration of landfill gas. Subsequently, there have been several problems associated with the lateral movement of gas from the site.

6.1.2 Landfill Gas History

The first recorded incidence of lateral migration of landfill gas from Middle Field was in 1984 when 54% methane by volume was recorded in permanent monitoring boreholes in the field to the north west of the site. Occasional measurement of gas levels over the next 18 months recorded methane concentrations in the range 37 to 64 % by volume. In early 1986, monitoring of the methane levels in the boreholes to the south west of the site commenced (see Figure 6.1). By the end of 1986, monthly monitoring of all these boreholes had confirmed gas was migrating to the farm land both to the north west and the south east. Recorded gas concentrations in borehole 9 were consistently high. Those in boreholes 8 and 10 showed much more fluctuation, but were predominantly above the lower explosive limit (Table 6.2 and Figure 6.2).

	Methane concentration (% by volume)		
Date	Borehole 8	Borehole 9	Borehole 10
1/86	48	66	8
2/86	13	55	15
3/86	7	61	17
4/86	21	60	
5/86	22	60	
6/86	22	54	0.2
7/86	31	57	0.4
8/86	0.8	60	0.3
9/86	20	56	1.3
10/86	0	53	0.2
12/86	0	63	0
1/87	59	65	0
2/87	59	67	0
4/87	24	57	flooded
5/87	22	63	flooded
7/87	flooded	55	flooded
9/87	14	60	flooded
10/87	flooded	49	flooded
11/87	44	63	0
12/87	60	42	0
1/88	53	60	0
2/88	57	11	0
3/88	50	54	0
4/88	19	40	flooded
5/88	20	33	flooded
6/88	30	0.2	flooded
5/89	29	flooded	flooded
6/89	47% LEL	41% LEL	flooded
7/89	13% LEL	40	flooded

Table 6.2 Methane concentrations in permanent sampling boreholes, 1986 (LEL is approximately 5 to 15% mthane by volume)

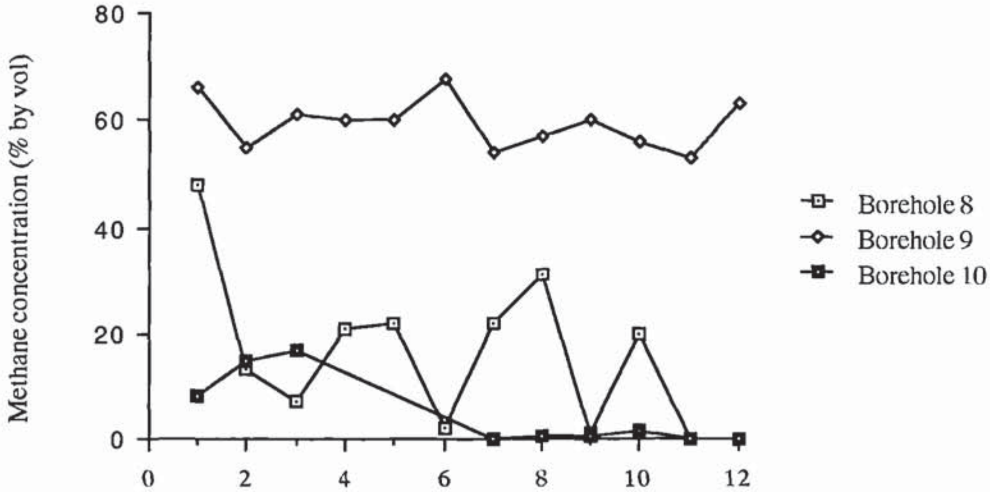

Figure 6.2 Methane concentration data from permanent sampling boreholes, 1986

6.1.3 Vegetation Damage

In March 1985, several instances of damage to vegetation were noted, including:

(i) death of a section of hedgerow on the north west site boundary
(ii) leafless branches on many of the trees in Garrett's Wood (Plate 6.1)
(iii) damage to the crops on the farm land to the north west of the site (Plate 6.2).

It was suggested that the most likely cause of the damage was migration of methane from the site. This problem was considered likely to worsen following the proposed restoration of the Middle Field area. Restoration of the area commenced in 1986, and by the summer of that year was complete, the area producing a good crop of grass and barley. Although this was proof of the successful restoration, it also underlined the relative impermeability of the cap, a fact which would almost certainly increase the lateral migration of gas.

At the same time several instances of vegetation damage were noted, both to crops in the fields to the north west and south west of Middle Field, and further damage to the trees at the northern end of Garrett's Wood. Further signs of deterioration to the woodland were again noted in October 1986.

In December 1986, at the request of the tenant farming the area to the south west of Middle Field, a brief survey of gas levels in the field and in Garrett's Wood was carried out. The survey involved point measurements of gas concentrations at 40 cm depth, and indicated methane concentrations of 16 - 18 % in the root zone of a large area of chloritic crop approximately 200 m from the northern boundary of the field. Conversely there was no detectable methane in the root zone of apparently healthy crop in the same area. Methane levels of up to 3000 ppm were also recorded at ground level in the vicinity of severely damaged trees at the northern end of Garrett's Wood.

6.1.4 Remedial Measures

By 1987, the gas levels in the soils of the land adjacent to Middle Field were considered to be unacceptable. The migration of gas was causing vegetation damage both to crops and to the trees in Garrett's Wood. Although of lesser economic importance, the damage to the woodland was considered to be more significant due to the dead trees being an emotive sight.

Plate 6.1 Dead trees at north western end of Garrett's Wood, July 1990

Plate 6.2 Chlorosis and dieback of crop at Ware Quarry site, Autumn 1987

In view of these problems, some means of minimising the migration of gas from the site was considered necessary. The initial intention was to construct a simple cut-off trench to allow passive venting of the gas. However, it was thought that this would probably not be sufficient to safeguard the trees; it would also not be sufficient to satisfy the County Council. Instead, the decision was made to install perforated collection pipes within trenches, the gas then being directed to a central flare stack. This would also allow for the eventual development of a gas abstraction system.

Such a system was installed and became operational in 1989. Monitoring surveys carried out the following year failed to detect significant concentrations of gas, and the system was considered to be successful.

6.2 Garrett's Wood

6.2.1 Introduction

For several years poor growth of ash trees in Garrett's Wood, to the south west of the Ware Quarry site had been noted (see Figure 6.3). In particular, the trees at the northern end of the woodland, i.e. those adjacent to the Middle Field area, had a 'very straggled appearance' with many dead trees (see Plate 6.1). High concentrations of landfill gas had been measured in the soil in the vicinity of the affected trees and in the permanent monitoring boreholes on several occasions, and the presence of gas was unanimously agreed to be the cause of the damage. Although the gas was not posing an immediate risk to property, or creating an economic problem, the appearance of dead and dying trees was considered to be an emotive, and immediately obvious, sight. Consequently, the damage to the wood was considered to be a relatively serious and pressing problem.

The remote sensing survey was carried out to provide an overview of the status of the woodland, delineating the extent and severity of damage to individual trees. The initial assessment used air photo interpretation to produce a crown condition map; this was then used to assess the results of analysis of the video and ATM data

The methodology comprised carrying out manual classification of colour infrared air photos to assign a crown condition rating to individual crowns, the resulting crown condition map then being used as ground reference data for classification of the digital data. As the different data sources were acquired on different dates, the exact comparison of different sensors and interpretation techniques was not possible. Instead, the eventual aim was the identification of an overall pattern of damage, with 'damage'

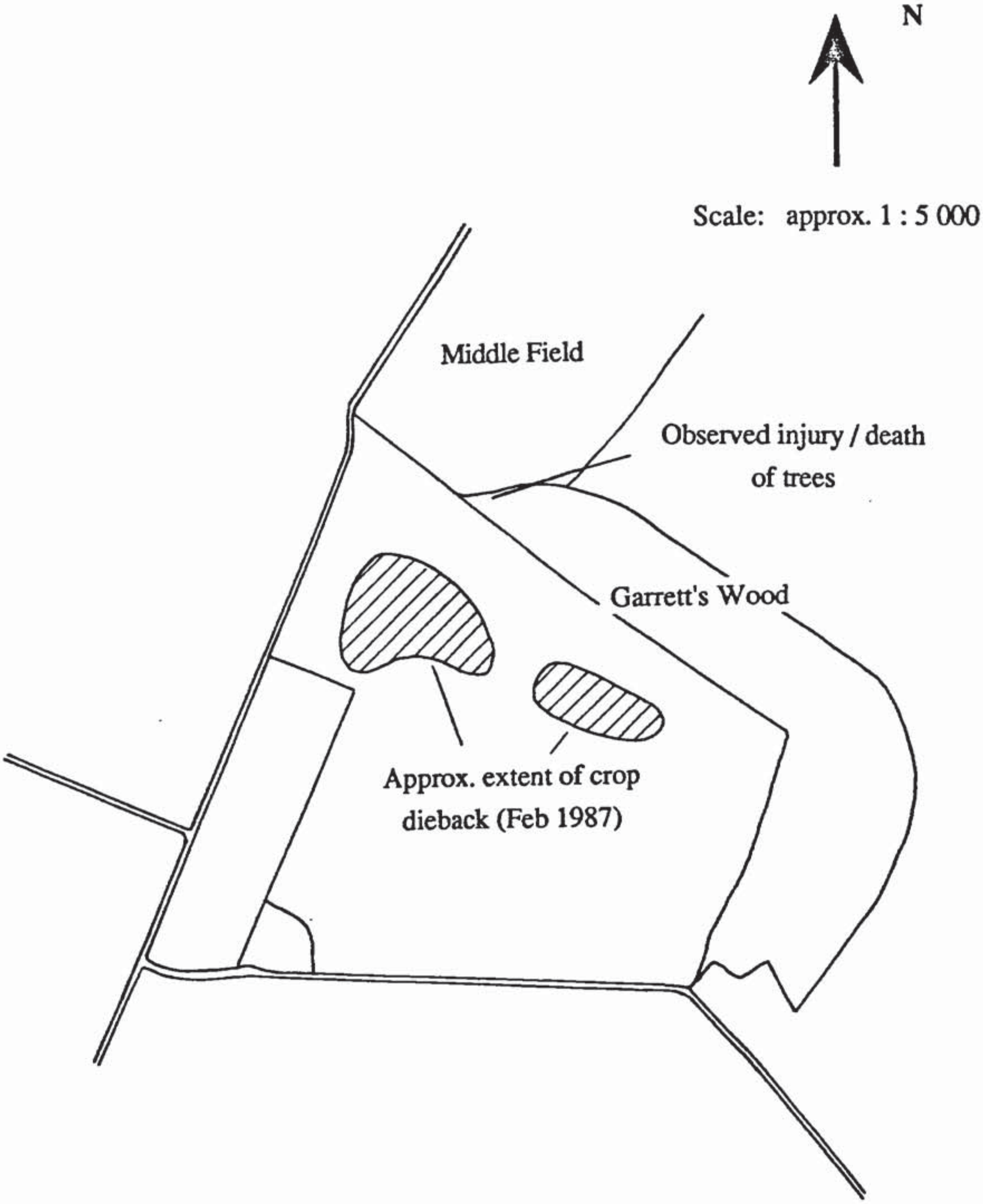

Figure 6.3 Observed injury to crop and woodland, February 1987

being taken as the deviation of crown condition from known healthy individuals (see Murtha & McLean, 1981).

6.2.2 Colour Infrared Air Photo Interpretation

Colour infrared air photo interpretation has been an accepted means of carrying out forest damage surveys for many years (Section 3.3.3). These surveys have shown that symptoms of tree decline can be readily interpreted from colour infrared air photos, with inventories being carried out up to 15 times more quickly than with ground survey (Goossens *et al* , 1984).

6.2.2.1 Photo interpretation Keys

Photo interpretation keys are guidelines to assist in the identification of photographic features. There are two types of keys, the simplest being a selective key whereby the photo-interpreter identifies a particular crown and, referring to a list of descriptive features, selects the attributes that best describe the crown. The second type of key is a dichotomous key, consisting of a number of decision trees, with the interpreter being lead through several descriptions until the correct classification is reached (Murtha, 1972).

Although much has been written on the damage symptoms of softwood species and their interpretation on colour infrared air photos (Meyer *et al* , 1985; Holmgren & Wastenson, 1985), limited work has been carried out regarding the development of interpretation keys for hardwoods. Ciesla *et al* (1985) examined symptoms of damage, and the resultant effects on the tree crowns, for a number of northern hardwood species. In addition, photo-interpretation keys were developed for beech as a part of a multi-national project known as Sansilva (Schwarzenbach, 1986; Groves, 1989). Using this work, a photo-interpretation key was developed to describe five states of health for the trees in Garrett's Wood (Table 6.3). This classification system was later simplified to allow for the automatic interpretation of the digital imagery (see Section 6.2.3).

6.2.2.2 Sampling procedure

In the assessment of crown damage, it is important to decide whether the required information is related to forest area or individual crowns (Murtha, 1978; Smith, 1988). Various sampling procedures have been described to evaluate patterns of damage to tree crowns, including:

(i) overlaying a grid and either assigning a damage rating to the crowns, or estimating the percent cover of crowns, within a specified area adjacent to each node (Schowengerdt, 1983; Smith, 1988; Groves, 1989).

(ii) random sampling across area using pre-defined sized blocks (Daels & Antrop, 1978; Smith, 1988)

(iii) development of a tree crown map and assigning a damage rating to each individual crown (Smith, 1988).

Due to the distribution of damage, with healthy individuals often being located adjacent to unhealthy trees, the small area under study, and the high resolution of the data, it was desirable and possible to carry out classification on a crown - by - crown basis.

Class	Foliage Colour	General Description
1 Healthy	Homogeneous deep pink / magenta	Irregular crown perimeter Inner crown and branches not visible
2 Light dam	Paler pink - red Some mottling / 'flagging'	Some loss of foliage from crown perimeter
3 Mod dam	Uneven colouring, lighter pink hue, pale 'flags' of acute chlorosis	Increasing loss of foliage from crown, ends of branches visible
4 Severe dam	Pale pink, may be increased proportion of pale flags	Sparse crown, inner crown may be clearly visible
5 Dead	Grey - white	Skeleton

Table 6.3 Photo interpretation key for manual classification of tree crown condition using colour infrared air photos

6.2.2.3 Classification

The tree crown map was developed using the 1 : 2 500 scale September 1988 air photos. An initial attempt was made to define crown outlines using a zoom transferscope (Bausch & Lomb, 40 x magnification); however, loss of stereo viewing using this method meant that many tree crowns were difficult to isolate. Therefore use was made of an Old Delft Scanning Stereoscope (ODSS III) with 4.5x magnification. Due to the tendency of hardwood crowns to have irregular perimeters and a dense canopy, there were problems even using this stereoscope, and creating the crown outline plan was time consuming and tedious. The tree crown outlines were traced onto an acetate overlay which was subsequently photocopied and enlarged to produce the final tree crown map.

The crown condition rating system described in Section 6.2.2.1 was used in conjunction with the June 1988 colour infrared air photos, to assign a damage rating to each individual crown, producing a crown condition map for the woodland (Figure 6.4). This map was intended to serve two purposes - firstly it gave a crown condition rating for each individual tree in the wood, and showed the distribution of damage. Its second purpose was to provide ground reference data for the following analysis of the digital imagery.

It has been stated that for air photos to be successfully used as ground reference data, they should be of an appropriate scale, and the different classes should be easily distinguishable (Townshend & Justice, 1980). In addition, the photos should be collected synchronous with the data being compared.

As the video data had been collected 12 months after the air photos, the assumption had to be made that the relative spectral response of the tree crowns had not altered to any great extent. This was considered to be a reasonable assumption for two main reasons. Firstly both sets of data were collected at the same time of year, thus any relative changes due to premature senescence would be minimised. Also, as damage had been noted as occurring to the same groups of trees for several years, it seemed unlikely that a major alteration in migration pathway would occur between the two dates of imagery.

As formal accuracy checking of damage distribution was not possible at the time of acquisition of photography, a later site visit was carried out. This indicated a good correspondence between tree damage visible from the ground, and manual air photo interpretation results.

Later attempts to classify the digital imagery revealed a lack of textural information in the data, and problems identifying small crowns. For these reasons, it was decided to simplify the tree crown classification in two ways. Firstly, the air photo-interpretation key was rationalised to include only three classes - healthy/light damage, moderate damage, and severe damage/dead (see Table 6.4), the classification being weighted toward spectral changes in the tree crowns but also taking into account significant alterations in texture. Secondly, in order to aid crown identification on the digital imagery, small, close growing crowns with the same damage rating were amalgamated into a single 'crown'.

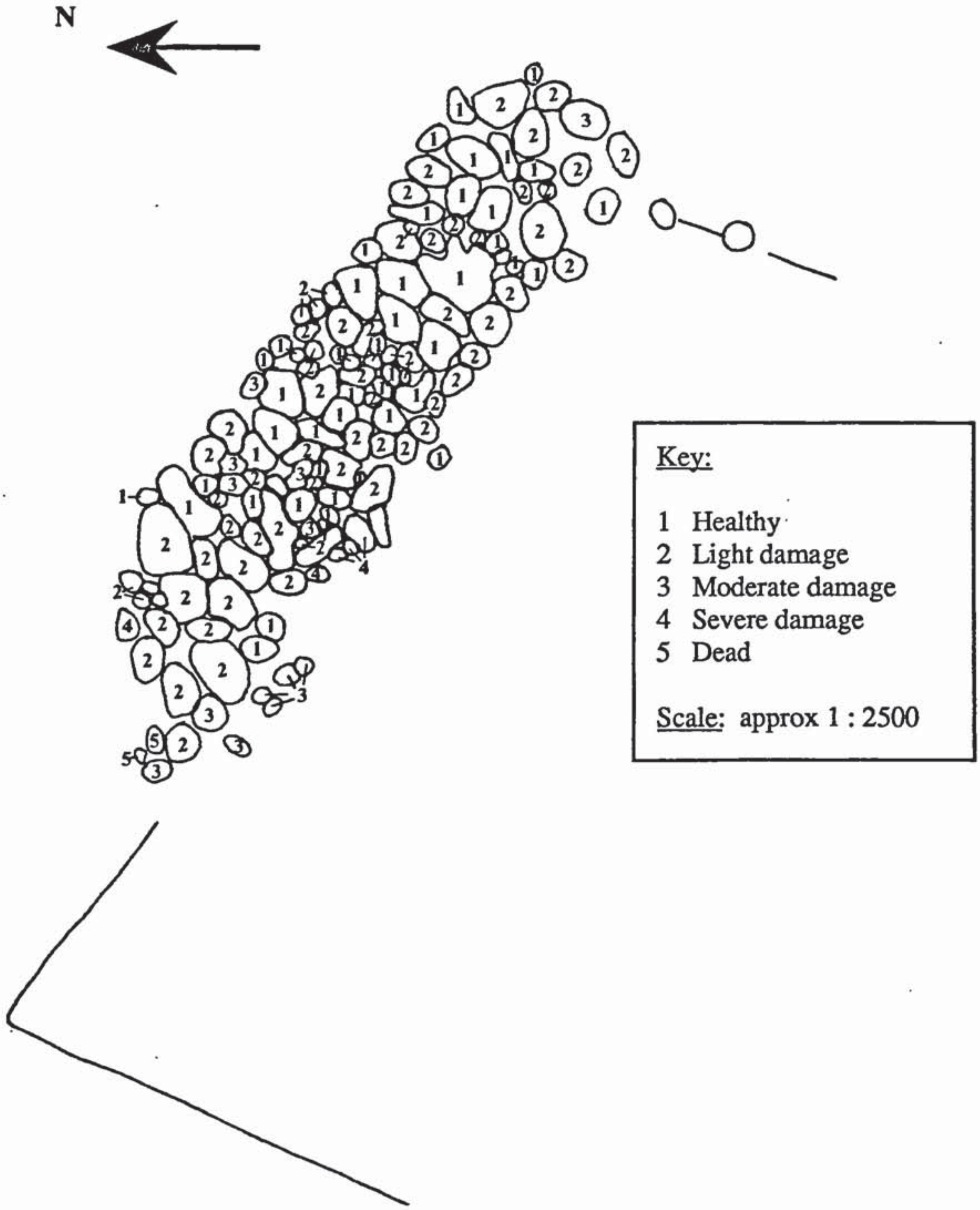

Figure 6.4 5 class crown condition map from colour infrared air photo interpretation

In his way, a second crown condition map was produced, and used as ground reference data for training and testing the classification of the digital data (Figure 6.5).

Class	Description	Characteristics
1	Healthy	Magenta / deep pink colour No obvious defoliation
2	Slight / moderate damage	Pink hue, may be paler flags or areas of discolouration
3	Severe damage	Pale pink - white hue, may have noticeable defoliation

Table 6.4 Simplified photo interpretation key

6.2.3 April ATM Data

As the main concern was with the identification of damaged individuals, and the delineation of the overall pattern of damage, it was not considered necessary to use the geometrically corrected imagery. Consequently, full resolution ATM images were used for both the manual interpretation, and computer classification of the data. The higher resolution imagery assisted in the identification of crowns, and decreased the influence of boundary effects on classification.

6.2.3.1 Manual Interpretation of Damage

The three bands initially used in the classification were selected based on theoretical considerations, and combinations suggested in the literature. As discussed in Section 3.2.3 the individual regions of the electromagnetic spectrum that would be expected to be most useful were the blue-green (0.37 - 0.50 μm), the red (0.63 - 0.69 μm), the near infrared (0.74 - 1.10 μm), and the middle infrared (1.35 - 2.50 μm).

Previous forest inventory work had suggested several band combinations, most of these including one band from each of the visible, near infrared, and middle infrared regions of the electromagnetic spectrum (Leckie & Gougeon, 1981; DeGloria, 1984; Nelson *et al* , 1984; Sheffield, 1985; Townshend *et al*, 1988; Vogelmann & Rock, 1988).

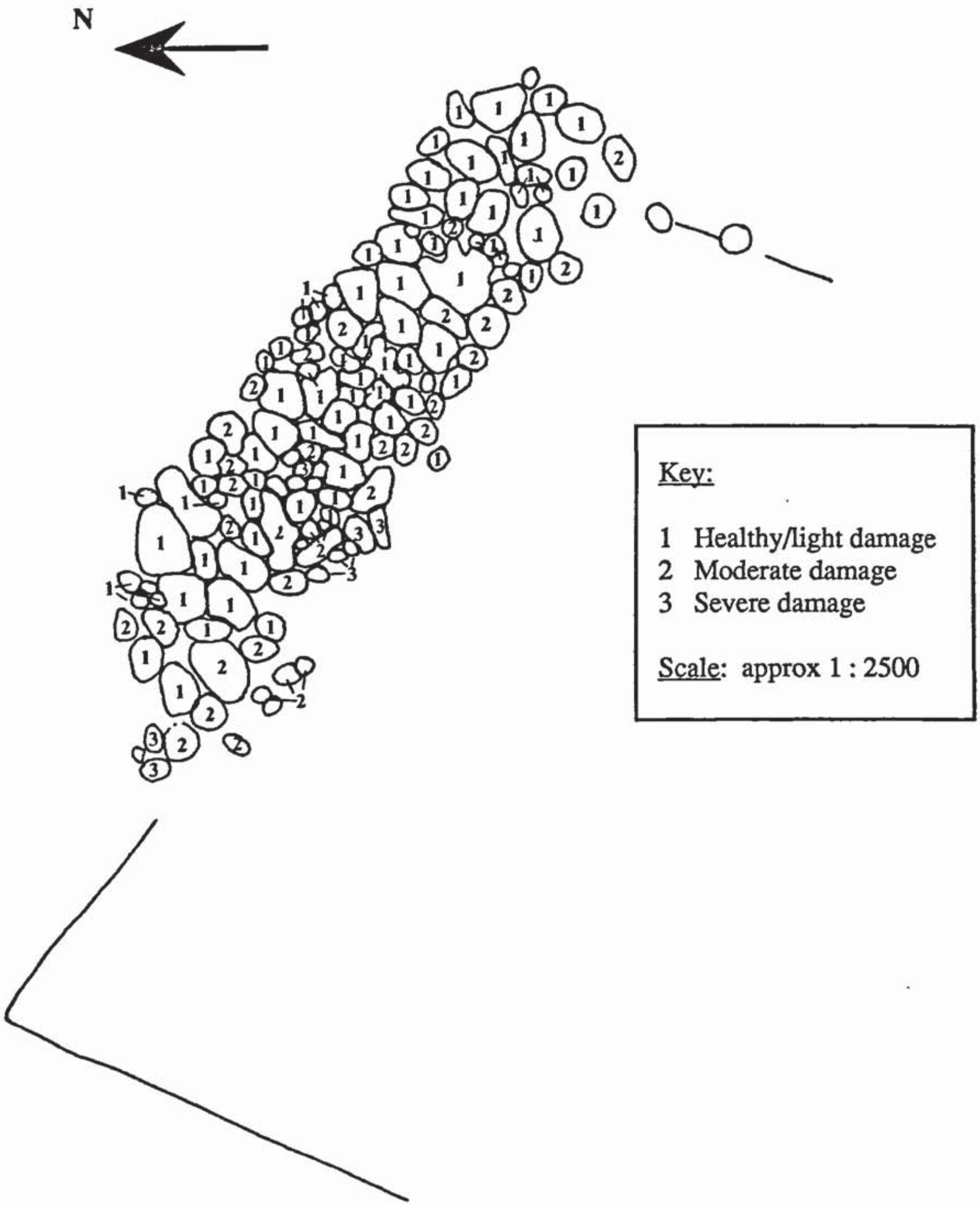

Figure 6.5 3 class crown condition map from colour infrared air photo interpretation

Three different composite images were initially examined to identify the combination which firstly enabled the identification of individual tree crowns, and secondly showed good contrast between the crowns. The bands used were:

(i) B10/B7, B7, B3;
(ii) B10, B7, B3;
(iii) B10, B5, B3.

Each composite image was visually examined to determine the optimum combination for visual interpretation. In order to enhance variation between the crowns, the wood was masked off, and a median autolinear contrast stretch applied. Ultimately, the B10, B5, B3 combination was selected as providing maximum discrimination of the crowns, and manual classification was carried out.

In order to carry out manual classification, a photo-interpretation key specific to the imagery was developed. The key was developed by defining damage as a deviation from the 'standard, normal tree' (Murtha & McClean, 1981). As there were no visible differences in texture of crowns, the key was based solely on spectral changes. On this composite, healthy crowns appeared dark magenta to green in colour, moderate damage was represented by paler colours, frequently with a bluish hue, and severely damaged crowns were very pale to near-white.

Using the revised photo-interpretation key and tree crown map, a crown condition map was produced, and the accuracy tested against the crown classification of the air photo interpretation procedure. The results indicated good correspondence between the classes identified on the air photos, and those on the multispectral scanner imagery, overall accuracy being calculated as nearly 84% (Table 6.5). The major source of confusion was between healthy and moderately damaged trees, approximately 43% of moderately damaged trees being identified as healthy i.e.the differences between healthy and moderately damaged crowns were difficult to identify on the ATM imagery. Severely damaged trees were identified unambiguously, indicating their distinct spectral response.

6.2.3.2 Supervised Classification of ATM Data

Classification of the ATM data was carried out according to the procedure described in Section 3.2.3.3. Manual interpretation of the imagery had indicated the relative ease of identifying training crowns using the B10, B5, B3 false colour composite. However, some crowns would be represented by as few as 15 pixels. Due to the influence of

True (Air Photo) Class				
		Class 1	Class 2	Class 3
Predicted Class	Class 1	37 (0.925)	12 (0.430)	0 (0.000)
	Class 2	3 (0.175)	16 (0.570)	0 (0.000)
	Class 3	0 (0.000)	0 (0.000)	5 (1.000)
Overall Accuracy 83.5 %				

Table 6.5 Accuracy of manual classification of ATM false colour composite

boundary effects, such small crowns were avoided for the purposes of training the classifier.

Over 50 tree crowns were identified on both the crown condition map and the imagery. These were randomly divided into two sets, one containing training crowns, the other representing test crowns. The composite image was displayed, the woodland masked, and a median autolinear contrast enhancement applied. Training crowns were identified and delineated. The training crowns were then saved as an overlay file, and the procedure repeated for the test crowns.

The class statistics were extracted and examined (Table 6.6 and Figure 6.6). The expected effect of increasing damage on spectral response would be an increase in reflectance in visible wavelengths, and a decrease, or no change, in the near infrared (Section 3.3.3). In addition, infrared : red band ratios would be expected to be lower for stressed vegetation than for healthy plants.

The majority of results corresponded with the anticipated spectral response, with two notable exceptions. Band 1 (blue) showed an increase, then a decrease in reflectance with increasing damage, and the spectral response of different classes in Band 9 barely altered. In both cases, this was considered to be a consequence of noise in the image, a view highlighted by the large variance within the classes.

Several authors have emphasised the importance of spatial information i.e. texture, when using high resolution data (Smith, 1988; Yuan, 1988). If texture is assumed to be represented by variance (Yuan, 1988), then large differences between class variances would indicate that texture changes were occurring as a result of injury to the tree crown.

In order to assess the relative importance of texture changes in the classification of the woodland, the images were visually examined; this revealed little discernible difference in texture between crowns from different classes. In addition, the class statistics showed that there was significant variation between the means of the classes, and little difference between their respective variance. This suggested that classification on a purely spectral basis could be successful.

	Class Statistics (mean and standard deviation)		
Band	Class 1	Class 2	Class 3
1	31.8 3.7	32.3 3.8	31.2 4.7
2	30.2 1.1	31.5 1.2	32.3 1.2
3	34.5 1.3	36.4 1.5	37.6 1.5
4	23.1 0.6	24.0 0.7	24.8 0.7
5	34.5 1.2	35.9 1.3	36.8 1.2
6	40.4 3.1	40.0 3.1	36.4 3.7
7	43.4 3.9	41.8 3.8	36.2 4.8
8	47.8 3.8	46.2 3.6	41.2 4.5
9	37.5 3.2	37.8 3.4	37.6 3.3
10	30.1 1.3	30.8 1.5	32.2 1.6

Table 6.6 Training area statistics for classification of Garrett's Wood, July 1988 ATM data

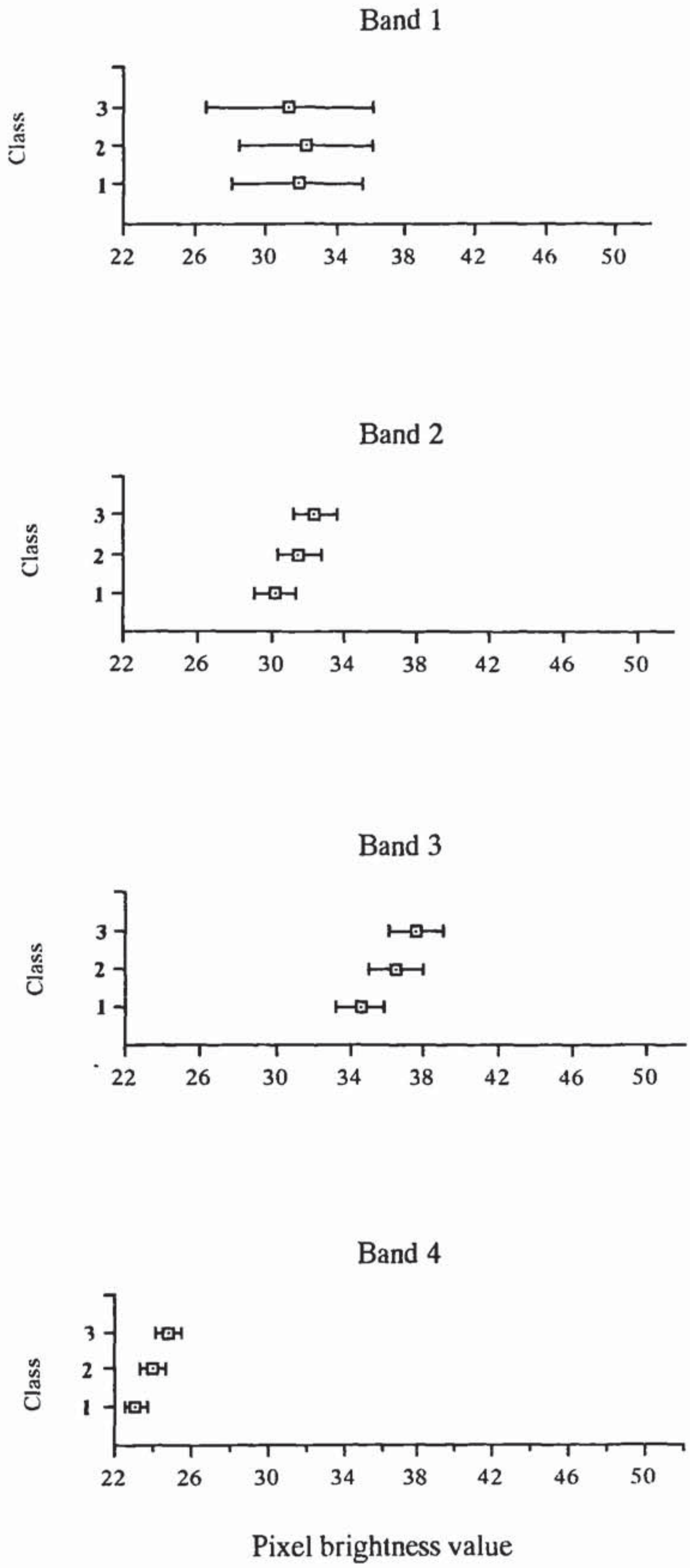

Figure 6.6a Training area spectral plots for Garrett's Wood, July 1988 ATM data (mean value ± one standard deviation)

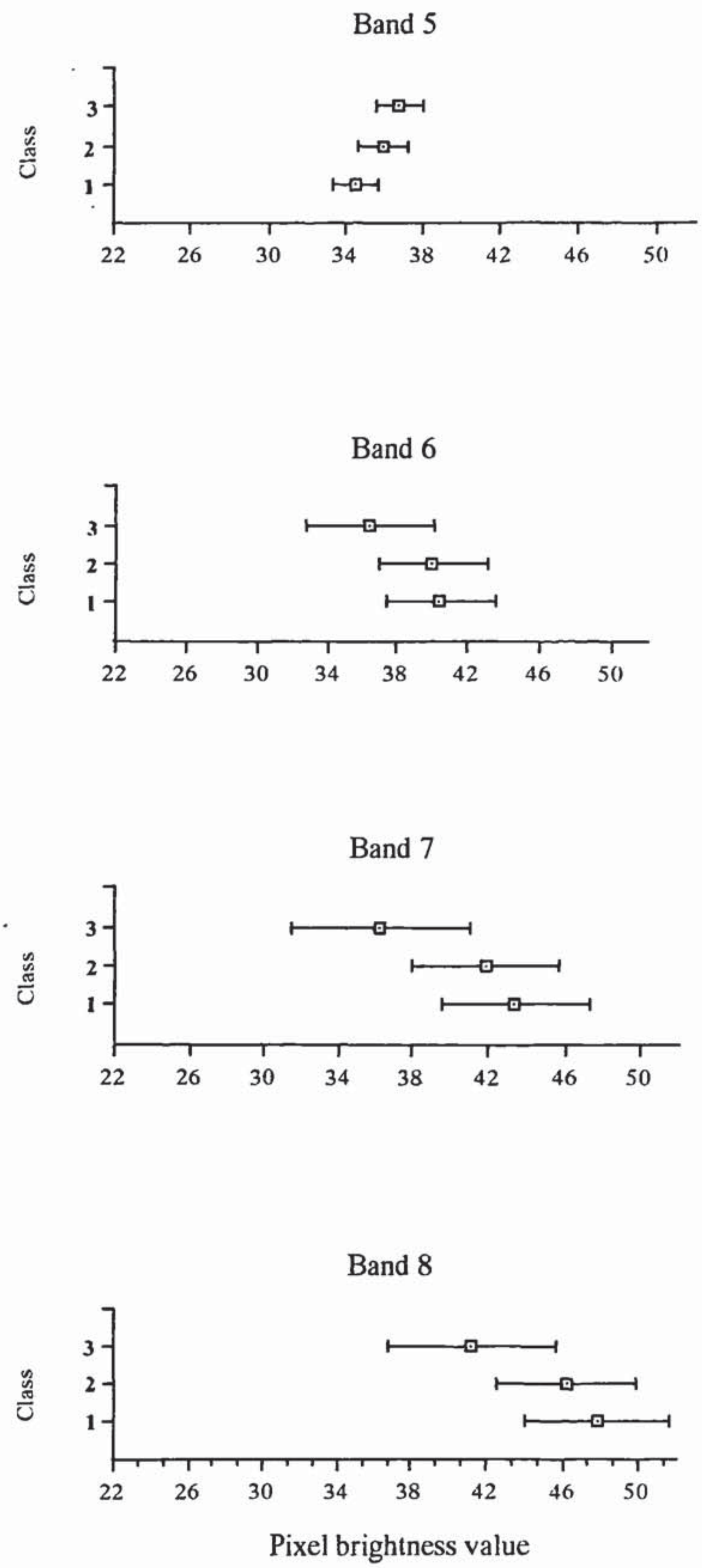

Figure 6.6b Training area spectral plots for Garrett's Wood, July 1988 ATM data (mean value ± one standard deviation)

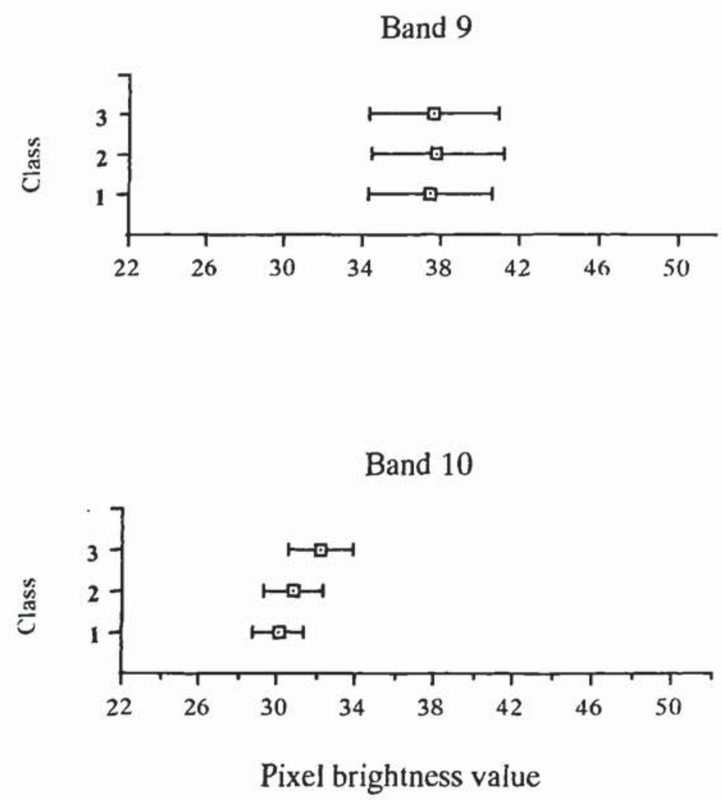

Figure 6.6c Training area spectral plots for Garrett's Wood, July 1988 ATM data (mean value ± one standard deviation)

(i) Band Selection For Classification

Although waveband selection results are highly data and application dependant, the overall pattern that emerged from the literature was the usefulness of a middle infrared, near infrared, visible band combination. Class separability was assessed for the bands within each spectral region, in order to select the bands providing maximum spectral discrimination. The method used to assess class separation in each waveband involved calculation of the F-ratios for each waveband (Ebdon, 1983).

This approach was based on the premise that, if the groups had been defined at random from a common population variation within groups would be approximately the same as the variation between them, both being a reflection of the overall variation within the population. Any difference would be due to sampling error. However, if the groups were taken from different populations, this would not be expected, since the variation within each group is a reflection of the variation within the particular population from which it was drawn. Thus, by calculating the ratio of between groups variance to within groups variance (the F-ratio), it was possible to evaluate the relative utility of individual bands to spectrally separate the groups.

Analysis of variance was carried out using the training area statistics, in order to identify the wavebands in which the classes were spectrally most separable. The optimum bands within each spectral region were selected based on the magnitude of their associated F-ratio (Table 6.7).

ATM Band	F-ratio
NDVI	433
3 (green)	181
4 (red)	158
2 (blue-green)	125
7 (near infrared)	81
8 (near infrared)	74
10 (middle infrared)	61

Table 6.7 F-ratios calculated for ATM data

Examination of these values revealed several facts, firstly that the bands in which classes were most separable were those which were sensitive to changes in plant pigments (i.e. changes in foliar pigmentation, rather than differences in canopy structure or foliar water content) were being identified. Neither Band 1 nor Band 9 could be identified as contributing any information to class separability, a fact that had been apparent when initially examining the class statistics. As was expected, Band 6, the 'transition zone' between the strong chlorophyll absorption of the visible bands and the high reflectance of the near infrared (Tucker, 1978), contributed less to class separability than either the visible or near infrared bands.

Two band combinations were examined for the purposes of classifying the woodland. The first was the recommended middle infrared, near infrared, visible combination, the optimum bands within each spectral region being identified as bands 10, 7, and 3 (see Plate 6.3). In addition, the false colour composite (bands 7, 4 and 3) was assessed. Class statistics were examined for the training areas, and the interband relationships examined to assess the degree of correlation between the bands, and hence the degree of data redundancy. The band combinations were used to classify the woodland, and the classification results tested to assess their ability to classify different damage classes.

Plate 6.3 Garrett's Wood, ATM band 10, 7, 3 composite, July 1988

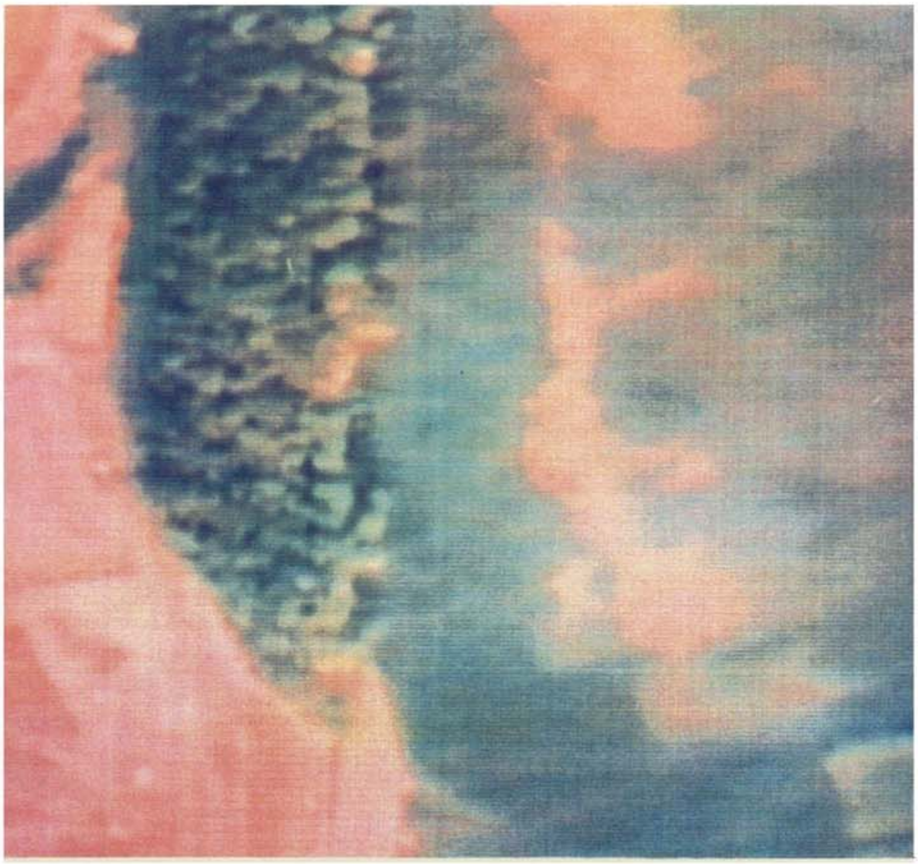

Plate 6.4 Garrett's Wood, video true colour image, June 1989

(ii) Image Classification

The maximum likelihood and minimum distance classifiers were both used to classify the imagery. The minimum distance classifier provided poor results, and only the maximum likelihood results are discussed further.

The possible benefits of filtering the image data were considered. The degree of improvement would be a trade off between the variability within the class training areas, and the number of boundary pixels maximum gain being achieved with large, heterogeneous training areas (Section 3.2.2). The resolution of the ATM data resulted in the training crowns frequently being small in size (as few as 20 pixels), and relatively homogeneous (standard deviation of up to 4 pixel values). Filtering was therefore not considered likely to contribute to classification accuracy.

The effects of shadow on classification accuracy were also considered. Koch & Kritikos (1984) reported that, unless shadow was classified as a separate class, it was assigned to the 'severe' damage class. This response would be expected if defoliation was the major symptom of damage; as defoliation level increased, there would be a concurrent increase in contribution from 'within crown' shadow. In this way the overall spectral response of damaged crowns would become dominated by shadow.

This work experienced the opposite effect, with shadow being mapped as 'healthy' crown. This was thought to be due to the fact that the damage caused by the landfill gas was being expressed mainly as chlorosis, with little defoliation until the damage was extreme. Thus, Class 1, having low reflectance in the visible and middle infrared wavebands, was spectrally closest to shadow. In order to simplify the interpretation of the results, the shadowed areas were first masked off.

6.2.3.3 ATM Classification Results

The classification accuracy was calculated for the resultant thematic maps by comparison with the test crowns (Section 6.2.3.2). Using the maximum likelihood classifier (95% probability threshold) similar classification results were obtained for the different band combinations, the false colour composite fractionally achieving the best overall accuracy at 69.7%.

Individual classes exhibited minimal variation in classification accuracy between the different band combinations. As the middle infrared, near infrared, visible composite resulted in a comparable overall accuracy to the false colour composite (69.6%), and class 2 was marginally better classified, this combination was chosen to be used in further analyses. As shown in Table 6.8, classification accuracy for individual classes varied widely, class 3 (severely damaged) being identified accurately most often (89%), and class 2 (moderate damage) least frequently (50%). The resultant thematic map is shown in Figure 6.7. These results are consistent with those achieved by the manual interpretation of the imagery, with classes 1 and 2 again being frequently confused with each other.

		Air Photo Class		
		Class 1	Class 2	Class 3
Predicted Class	Class 1	192 (0.70)	123 (0.33)	0 (0.00)
	Class 2	62 (0.23)	186 (0.50)	7 (0.11)
	Class 3	21 (0.08)	63 (0.17)	57 (0.89)
Overall Accuracy 69.63 %				

Table 6.8 Accuracy of maximum likelihood classification of Garrett's Wood, July 1988 ATM data (bands 10, 7, and 3)

While the above results give an indication of the accuracy of the classification, they do not give any estimate of the level of confidence in the results. To determine the degree to which reliance could be placed on the classification results, 95% confidence limits were calculated for each damage class (Jensen, 1986):

$$p = p\sim \pm [\, 1.96\sqrt{(p\sim)(q\sim)/n} \;+\; 50/n\,]$$

where: p = actual class accuracy expressed as a percent,

p~ = percent of class calculated as being accurately classified (the number of pixels correctly identified divided by the total number of pixels),

q~ = 100 - p~,

n = number of pixels in the class.

The results are summarised in Table 6.9.

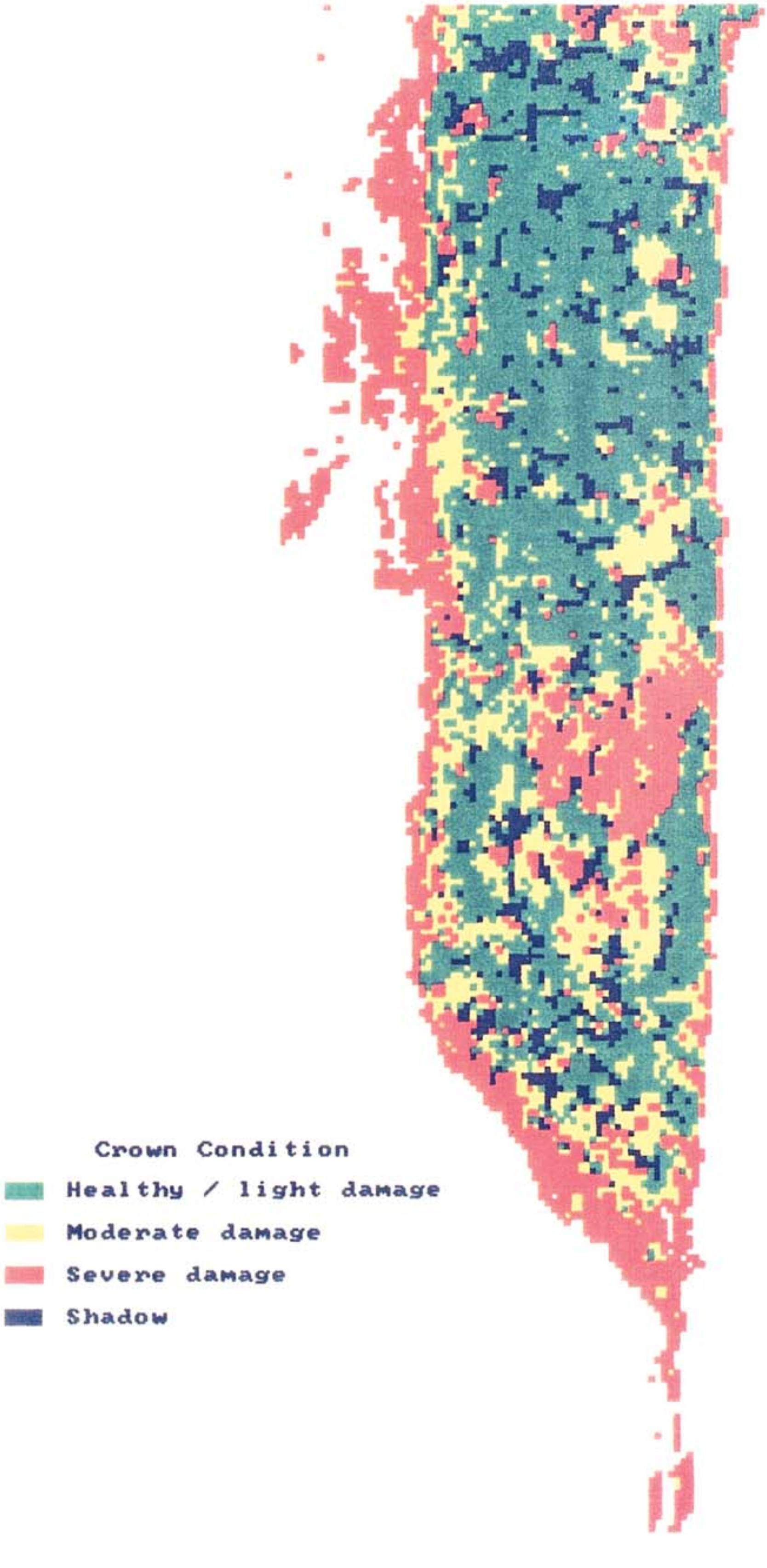

Figure 6.7 Supervised classification of Garrett's Wood, July 1988 ATM data

Class correct	Pixels of pixels	Number	% Correct limits	95% Confidence
1 (healthy/light dam)	192	275	70	64.4 - 75.6
2 (moderate damage)	186	372	50	44.8 - 55.2
3 (severe damage)	57	64	89	80.6 - 97.5
Overall map accuracy	435	711	69.6	66.2 - 73.1

Table 6.9 Confidence limits for classification of Garrett's Wood (July 1988)

6.2.4 June Video Data

The documented use of video data to assess forest and woodland characteristics has been rather limited, with much of the work concentrating on visual interpretation of imagery. The following section describes, firstly the manual interpretation of the video data to appraise tree crown damage, and then proceeds to the digital classification of the data on a crown - by - crown basis.

As with the ATM data, full resolution video images were used in the analysis (see Plate 6.4). The entire woodland area could be located in the centre of a single video frame, and thus mosaicing was not required. This presented the opportunity to carry out classification on 'raw' video data that had not been repeatedly geometrically warped and subjected to radiometric modifications.

6.2.4.1 Manual Interpretation of Damage

Initial examination of the video images did not offer much hope for the successful classification of tree crown damage. As a consequence of the low sun angle at the time of image acquisition, there was extensive shadow along the long northern edge of the wood and within the woodland. After examination of the statistics for individual crowns, it became apparent that crowns on the sunlight side of the wood had a higher reflectance than those on the shaded side. In addition, the images were very noisy, effectively ruling out any possibility of using texture measures in the classification. These factors served to confuse the identification of individual crowns and the comparison of tree crown status throughout the analysis. Identification of individual crowns was facilitated by digitising the tree crown map, and registering the digital map to the image.

Display of the true colour image underlined the lack of texture within the crowns, many being blurred and indistinct. Thus, further analysis involved use of the false colour composite image. As the infrared and visible bands had been obtained with different cameras, this involved warping the infrared image to one of the visible bands.

Compared to the true colour image, the false colour composite showed less variation, both within individual crowns, and between crowns. This was thought to be due to the exclusion of the 'noisy' blue band, and resulted in greater ease of interpretation. The resulting image was displayed and a manual interpretation key specific to the image was developed as for the ATM imagery.

Manual interpretation was carried out on a crown - by - crown basis. If the individual crowns could not be clearly distinguished but their crown condition appeared similar, a damage rating was given to a group of trees.

The results showed that, in contrast to the manual interpretation of the ATM imagery, the moderate damage class was most accurately identified (83%), an overall accuracy of 71% being achieved (Table 6.10). There was still a great deal of confusion between classes 1 and 2, but with the main mis-classification being identification of class 1 as being class 2, rather than the reverse.

		Air Photo Class		
		Class 1	Class 2	Class 3
Predicted Class	Class 1	17 (0.72)	4 (0.17)	0 (0.00)
	Class 2	7 (0.29)	19 (0.83)	2 (0.40)
	Class 3	0 (0.00)	0 (0.00)	3 (0.60)
Overall Accuracy 71.48 %				

Table 6.10 Accuracy of manual classification of the video false colour composite

6.2.4.2 Video Supervised Classification

Again, supervised classification was carried out as described in Section 3.2.3.3. As the imagery had undergone minimal geometric alteration, and there were none of the problems associated with mosaicing, the emphasis was to investigate whether airborne video data could produce similar (or better) results to those achieved using the ATM imagery.

Due to the low sun angle, crown location was judged to have an important effect on the spectral response of individual crowns. In order to evaluate the scale of this problem, statistics for 54 crowns were collected and examined. Although the results suggested that crown location did have an effect on reflectance, it was difficult to use the information quantitatively.

Wherever possible, the same crowns as had been utilised to train and test the ATM imagery were used again. The main exceptions were crowns that could not be confidently identified, or those with anomalous means or standard deviations. After copying the digital crown map onto the true colour image, the training areas were delineated, ensuring that only definite crown areas were used and boundary pixels were avoided. The process was repeated for the test crowns, and both sets of data saved to overlay files.

In an attempt to reduce the problems of shadow, the infrared and red bands were ratioed. However, although this appeared to reduce the effects of shadow, it also eliminated much of the discriminating information between different crown condition classes as shown by the F-ratio (see Table 6.12).

Inspection of the class statistics revealed deviations from the anticipated responses (Table 6.11 and Figure 6.8). As was expected, reflectance in the red band increased with increasing damage, and the infrared : red and the NDVI both decreased. However, the blue, green and near infrared bands all exhibited an increase between class 1 and class 2, and a decrease (although not of the same magnitude) from class 2 to class 3.

In the near infrared, tree crown damage would normally be expected to result in a decrease in reflectance of individual leaves, although due to defoliation and the increased contribution from the understory, the overall response of the canopy might be expected to increase (Section 3.3.3.3). As explained in Section 6.2.3, the damage to the trees in Garrett's Wood was expressed as chlorosis, defoliation only occurring in extreme cases (i.e. at the northern end of the wood). Therefore, the spectral response to damage was anticipated to be a decrease in the infrared reflectance. Whilst this appeared to account for the difference between classes 2 and 3, there was an increase from class 1 to 2. Examination of the class histograms for the training data indicated there was little spectral separation between any of the classes in this waveband.

The variance within individual crowns was also examined to assess if textural changes could account for the spectral response. However, most crowns showed relatively similar within-crown variation, anomalous high values occasionally existing within all crown condition classes. For these reasons, the infrared band was not expected to be able to contribute to class separation.

The class statistics for the red band exhibited the anticipated spectral response to increasing damage, and examination of the histograms revealed normal distributions. However, it was evident from the histograms, that confusion would be likely to occur between classes 1 and 2. Histograms for both the green and blue bands again showed normal distributions, but also showed the confusion that was likely to occur between classes 1 and 3 as a result of their similar means.

	Class Statistics (mean and standard deviation)		
Band	Class 1	Class 2	Class 3
Infrared	207.7 19.0	219.1 19.1	211.4 15.2
Red	169.5 7.0	178.9 10.4	184.9 6.9
Green	121.4 6.1	128.8 6.7	125.1 4.2
Blue	135.4 7.8	142.1 9.5	136.5 5.2

Table 6.11 Training area statistics for classification of Garrett's Wood, June 1989 video data

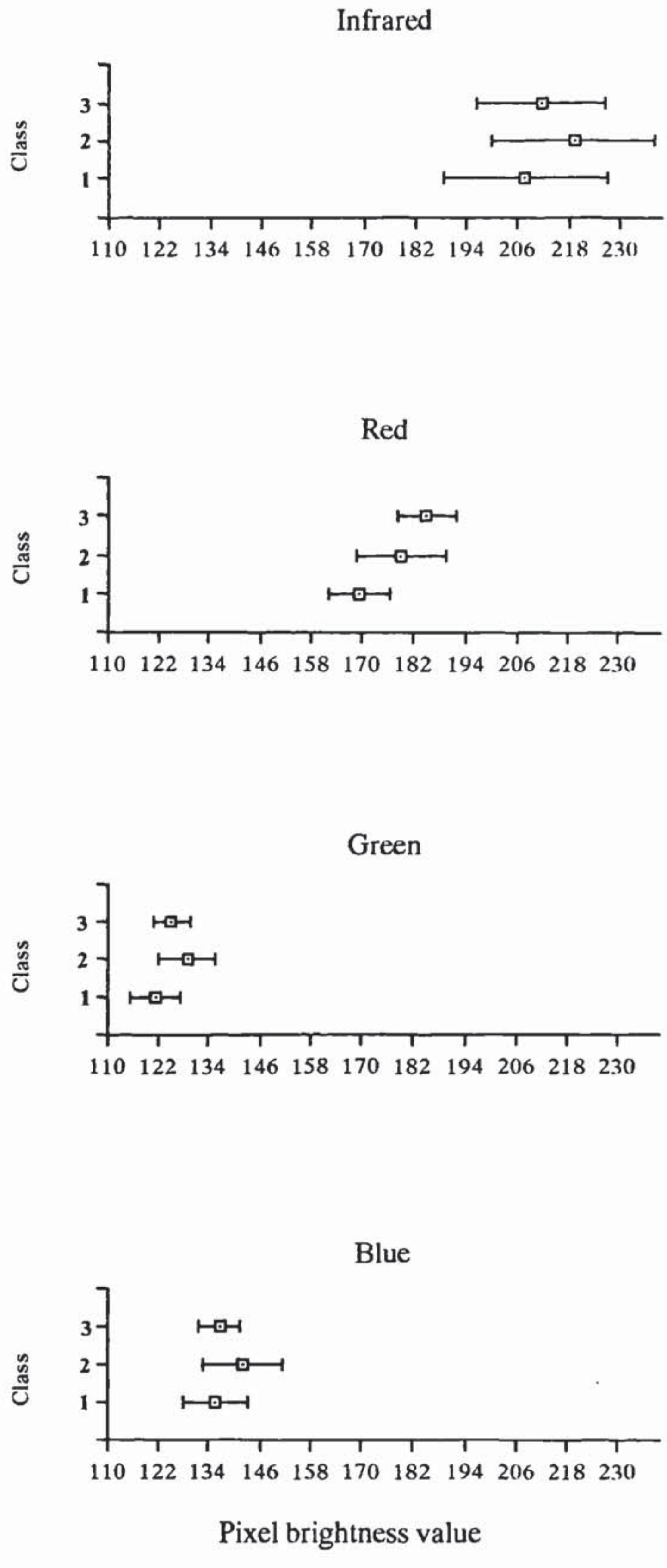

Figure 6.8 Training area spectral plots for Garrett's Wood, June 1989 video data (mean value +/- one standard deviation)

The reason for the uncharacteristic spectral response in the green and blue bands could not be explained, particularly when compared with the 'normal' spectral characteristics of the red band. Without this, the green and blue response might have been attributed to unrepresentative crowns, or the effects of the low illumination angle at the time of the flight. It was also noted that the crowns used to test the classification result showed a similar response.

Two synthetic bands, the NDVI and infrared : red ratio, were also calculated. Normally, these bands would be expected to enhance spectral differences between healthy and unhealthy crowns; a second benefit being the reduction of shading effects. However, examination of the class histograms showed bi-modal distributions and poor class separation, and the bands were not used any further.

Class separation in the four natural and two synthetic bands was assessed by analysis of variance (Section 5.4.3). The F-ratios (Table 6.12) inferred the red and green bands to be very useful in discriminating the crown condition classes (F-ratios of 553 and 457 respectively). Not remarkably, the infrared band alone ranked lowest. On the basis of the class statistics and the F-ratios, it seemed unlikely that the infrared band could offer any contribution to class separability, and only the true colour image was considered any further.

Video Band	F-ratio
Red	553
Green	457
Blue	212
NDVI	164
Infrared / red	68
Infrared	63

Table 6.12 F - ratios calculated for video data

The merits of filtering high resolution data, in order to reduce target variability, were outlined in Section 3.2.2. As the training areas were relatively large, and were also quite heterogeneous, the use of low pass filters was considered to have the potential to effectively reduce target variability (as a consequence of both scene noise and system noise). Thus, the images were subjected to a 3 x 3 meanal filter prior to classification.

Again, in the absence of a shadow class, much of the woodland in shade was classified as healthy. Therefore the use of a shadow mask was examined, with the green band being used to define the thresholds. A threshold value of the mean pixel brightness value of class 1 minus two standard deviations was considered likely to mask off the majority of the shadow whilst not excluding any crown pixels.

6.2.4.3 Video Classification Results

The classification accuracies were calculated for both classification algorithms. Whilst overall classification accuracy showed little difference for the different algorithms used, considerable variation occurred in the classification of individual damage classes, particularly class 2. The most successful result used the minimum distance classifier (threshold of 40) to classify the true colour image, and produced an overall accuracy of 68.75% (Table 6.13 and Figure 6.9). As before, class 2 was worst classified (55%), virtually all the confusion being with class 1. Severely damaged trees were again most accurately identified (79%).

		Air Photo Class		
		Class 1	Class 2	Class 3
Predicted Class	Class 1	1012 (0.67)	586 (0.42)	8 (0.04)
	Class 2	406 (0.27)	768 (0.55)	33 (0.17)
	Class 3	86 (0.06)	35 (0.03)	154 (0.79)
Overall Accuracy 67.18 %				

Table 6.13 Accuracy of minimum distance classification of Garrett's Wood, June 1989 true colour video data

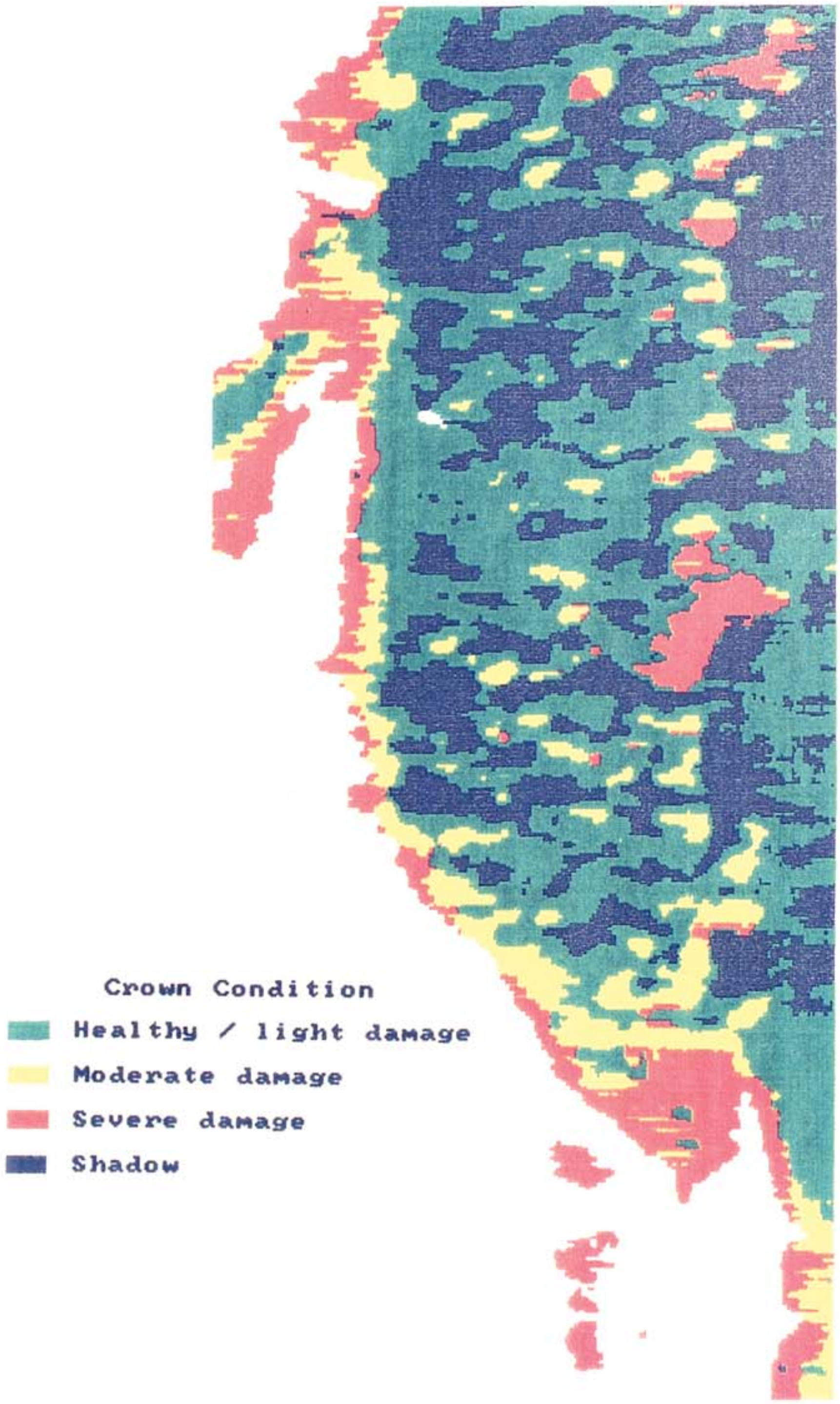

Figure 6.9 Supervised classification of Garrett's Wood, June 1989 video data

The confidence limits to indicate overall map accuracy were again calculated, as shown in Table 6.14.

Class correct	Pixels of pixels	Number	% Correct limits	95% Confidence
1 (healthy/light dam)	1012	1504	67	64.6 - 69.4
2 (moderate damage)	768	1389	55	52.3 - 57.7
3 (severe damage)	154	195	79	73.0 - 85.0
Overall map accuracy	1934	3088	67.2	65.5 - 68.9

Table 6.14 Confidence limits for classification of Garrett's Wood (June 1989 video data)

One of the benefits of using the true colour image, rather than the false colour composite, was the fact that the three bands were perfectly geometrically co-registered. Therefore, problems caused by inaccurate registration of the infrared to the visible images, and consequent inclusion of boundary pixels in training areas, were avoided. Use of the colour imagery could also represent a substantial saving in time in a practical situation.

As the problem of shadow was inherent in the imagery, and little could be done to compensate for it, image processing was carried out on the entire woodland area. As with the ATM data, this resulted in the allocation of most shaded areas to the 'healthy crown' class, and to reduce confusion, a mask was applied to exclude shadow.

Visual examination of the classification result indicated that the overall pattern of damage was similar to that on the air-photo crown condition map. That is, there was a concentration of moderately damaged crowns in the north-western end of the wood, a group of severely damaged trees on the southern edge, and a aggregation of healthy crowns in the south-eastern end of the wood.

6.2.5 Summary

Overall, the results emphasised the spectral separability of severely damaged crowns from moderately damaged or healthy ones. However, considerable confusion arose between 'moderate damage' and 'healthy' classes, a large proportion of the intermediate class being assigned to the healthy class (Figure 6.10). Manual interpretation of the imagery had been carried out to assess if the differences in crown condition identified on the colour infrared air photos could also be visually identified on the digital imagery, and to compare this approach with automatic classification. Results of the classification of the ATM imagery was similar in both cases, with manual classification being a more rapid procedure. Manual classification of the video imagery initially suggested this data provided superior separation of the moderate damage class; however, supervised classification failed to confirm this.

With the high resolution data used, two, or even three, damage classes could exist within a single crown. For this reason, the results are evaluated somewhat unfairly by comparing a pixel - by - pixel classification against manual interpretation procedures that assigned a single damage class to each crown. For example, crowns classified as moderately or severely damaged frequently had a border of 'healthy' pixels (see Figure 6.9). It was not possible to assess if these 'borders' were actually part of the tree crown, or areas of shadow.

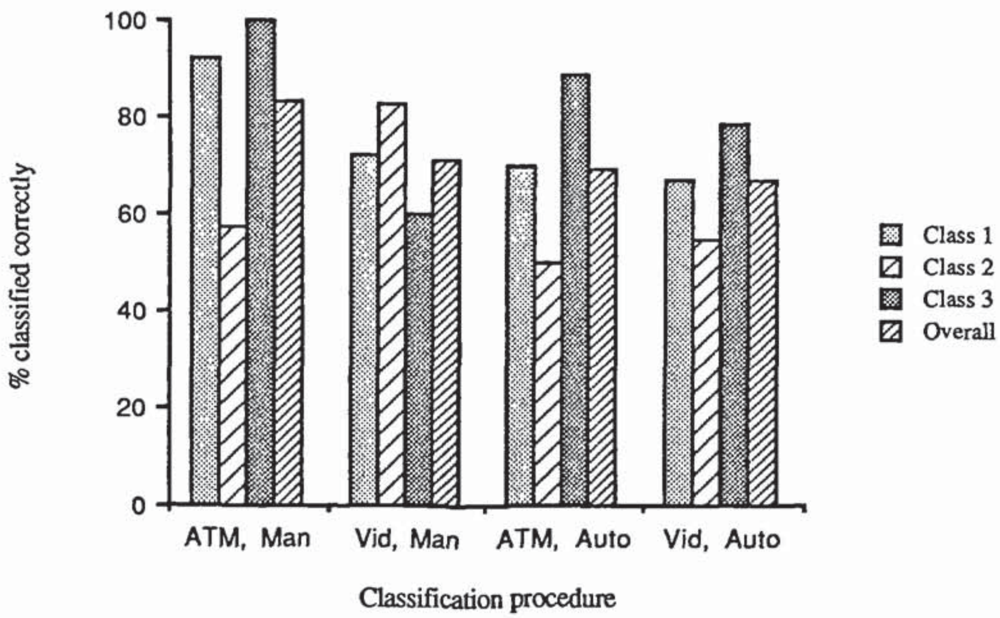

Figure 6.10 Comparison of accuracy of different approaches to classification of Garrett's Wood

The dead trees at the north-west end of the wood were correctly identified as severely damaged/dead on both sets of data, despite the fact that it was impossible to identify these by eye on either ATM or video images. The only explanation that seemed plausible was the fact that background in this area was almost entirely covered by undergrowth, and that the spectral response of this was similar to severely damaged crowns. That is, the fact that the trees were correctly classified was entirely fortuitous, rather than being due to valid identification.

Analysis of both ATM and video data yielded similar results. The main difference was in classification of severely damaged crowns, the ATM data classifying this group with 89% accuracy. However, on the whole, the differences between the video and ATM results were minor, with the confidence intervals for both sensors overlapping (see Tables 6.9 and 6.14).

The similarity of results achieved using the different sensors reinforced the assumption that relative changes in crown condition had not occurred between dates. Considering the poor quality of the video images, the similarity between the results was also somewhat surprising. Such results indicate that, under better conditions of illumination, and using superior equipment (see Section 7.2), video imaging could prove to be a realistic technique to be used for this type of application, and might yield superior results to those obtained using the ATM data.

6.3 Crop Damage

6.3.1 Introduction

For several years, the farmer working the land to the south of Garrett's Wood had noted increasingly severe damage to crops, to the extent that certain areas of the field were totally unable to support crop growth. The existence of the landfill site initially raised suspicions that landfill gas could be the cause, a fact that was confirmed by spot measurements of landfill gas, and later, readings from permanent monitoring boreholes (Section 6.1) (Reports held at Pioneer Aggregates, Herts).

As the injury to the crop was acute, the discrimination of different 'crop condition' classes was expected to be relatively straightforward, and the remote sensing data was analysed to assess its contribution to:

(i) Gain an understanding of the spatial distribution of crop injury, and hence the extent of migration of the gas, by visual examination of the imagery.

(ii) Obtain estimates of the areal extent of crop damage. This information in itself could be useful in compensatory settlements. In future, the inclusion of actual crop growth parameters from field investigations, would enable more accurate prediction of the extent of crop loss.

(iii) Gain an understanding of the interrelations between landfill gas, soil type, and vegetation damage based on spatial relationships (Section 6.4.2).

As shown in Table 6.1, the data had been collected on two dates, and so the possibility also existed to monitor temporal changes of crop injury. However, as two different sensors had been used, change detection could only yield qualitative information.

6.3.2 April ATM Data

6.3.2.1 Manual Interpretation of Damage

The imagery was initially examined to qualitatively assess the spatial extent of damage to the crops growing in Newton's field. Whilst this was not intended to result in quantitative measurements of areas damaged, the manual interpretation of imagery provided a rapid overview of the extent of damage.

The black and white panchromatic air photos were stereoscopically viewed using a Wild 3x magnification stereoscope. Three distinct crop condition classes could be quickly and easily delineated; these being areas of dieback, chloritic crop (highly reflecting), and 'healthy' crop. The healthy crop exhibited a smooth, homogeneous surface across the field, the stressed areas showing much more variation.

Spatially, stereoscopic examination revealed a broad strip of chloritic crop alongside the edge of the wood. However the worst damage occurred immediately along the edge of this strip, with areas of complete dieback gradually reducing with distance away from the wood (see Plate 6.5). Outlines of dieback, chlorosis, and healthy crop were traced onto acetate overlays, and the approximate areal extent of individual cover types calculated using a Hewlett Packard 9874A Digitizer as a planimeter.

Visual interpretation of the ATM data was carried out to assess the ease with which the same crop condition classes could be identified. Initially, a middle infrared, near infrared, visible composite (bands 10, 7, and 3) was used. After application of an autolinear stretch to the agricultural area, regions of dieback and chloritic vegetation could be very clearly delineated in contrast with the healthy vegetation. However, visual discrimination of complete dieback and chloritic vegetation was difficult.

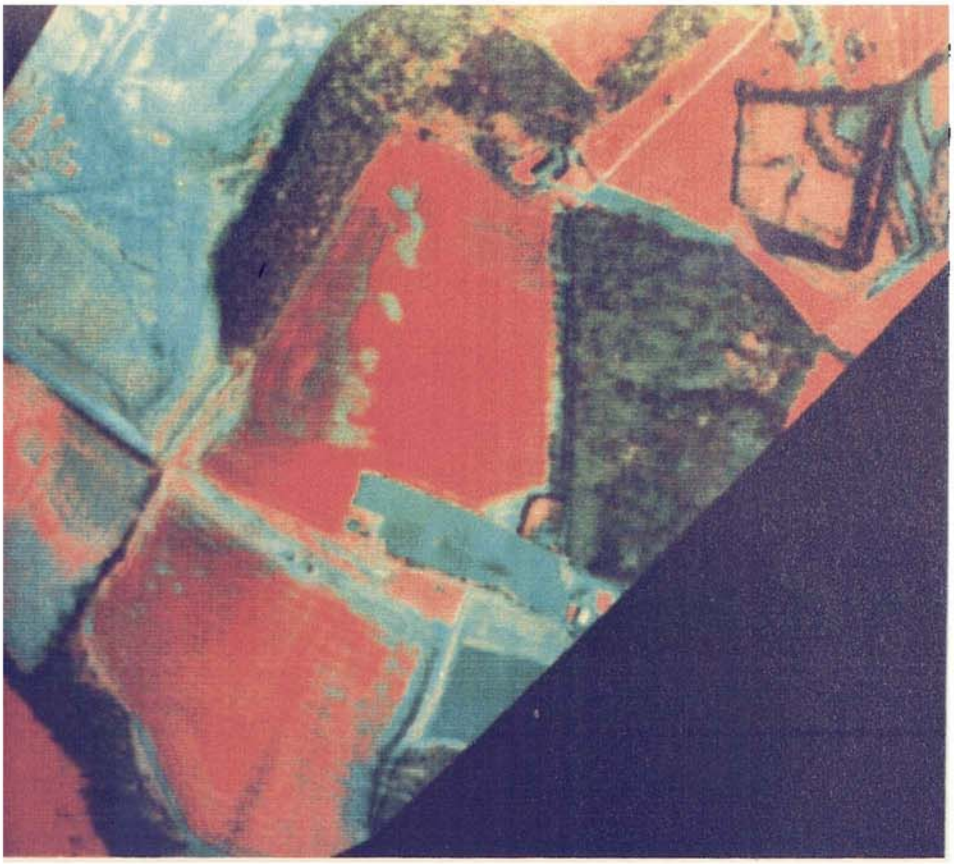

Plate 6.5 ATM false colour composite showing areas of damaged crop, Ware Quarry, April 1989

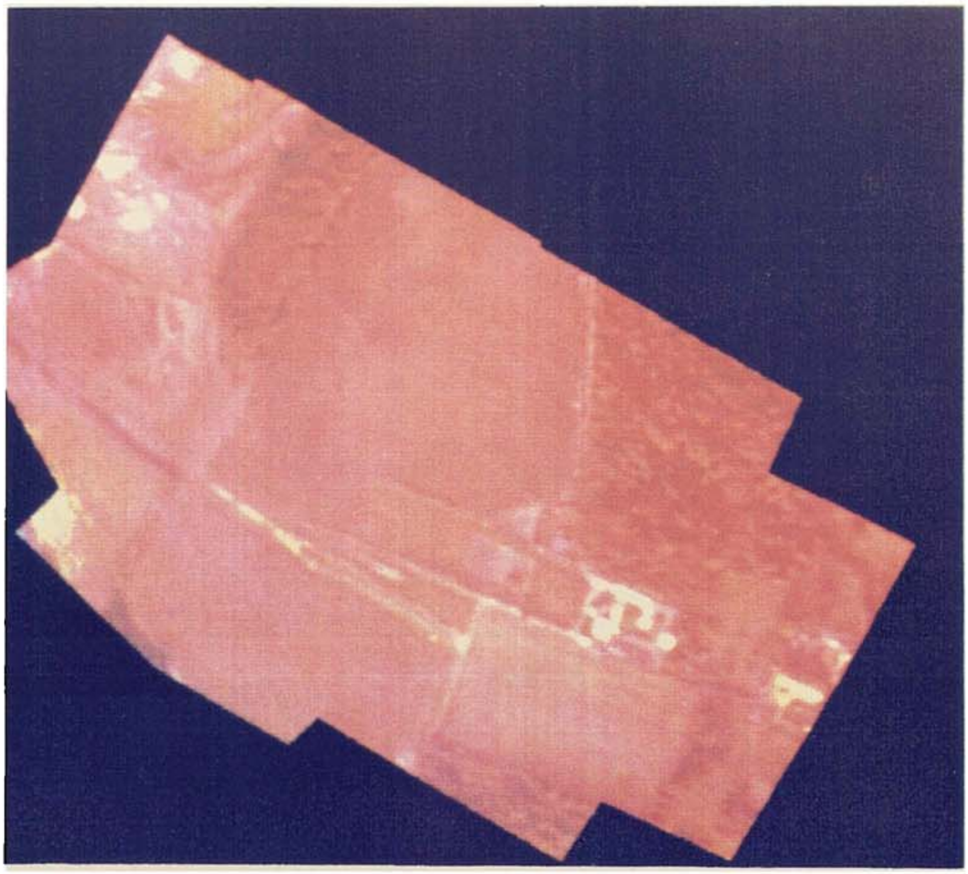

Plate 6.6 Crop damage at Ware Quarry, video true colour composite, June 1989

As a result, the same procedures were applied to a false colour composite image (bands 7, 5, and 4). This image enabled easy and rapid delineation of the three principal cover types, the areas of dieback appearing bright cyan, chloritic vegetation having an increased red contribution, and healthy vegetation appearing red/magenta (Plate 6.5).

6.3.2.2 Unsupervised Classification

The false colour composite had proved most useful to visually distinguish between the different crop condition classes, and was subsequently used in the automatic classification procedures. Unsupervised clustering of the agricultural area identified 3 classes, and these were used to classify the image. The result clearly distinguished the three previously identified crop classes (Figure 6.11), the class statistics are shown in Table 6.15.

	Class Statistics (mean and standard deviation)		
	Healthy	Chloritic	Dieback
Band 7	97.8 5.8	79.0 5.5	71.6 4.0
Band 4	52.2 1.3	55.3 2.2	65.2 4.0
Band 3	62.9 1.4	67.4 2.4	78.0 4.2

Table 6.15 Class statistics as a result of unsupervised classification of crop damage, April 1989 ATM false colour composite

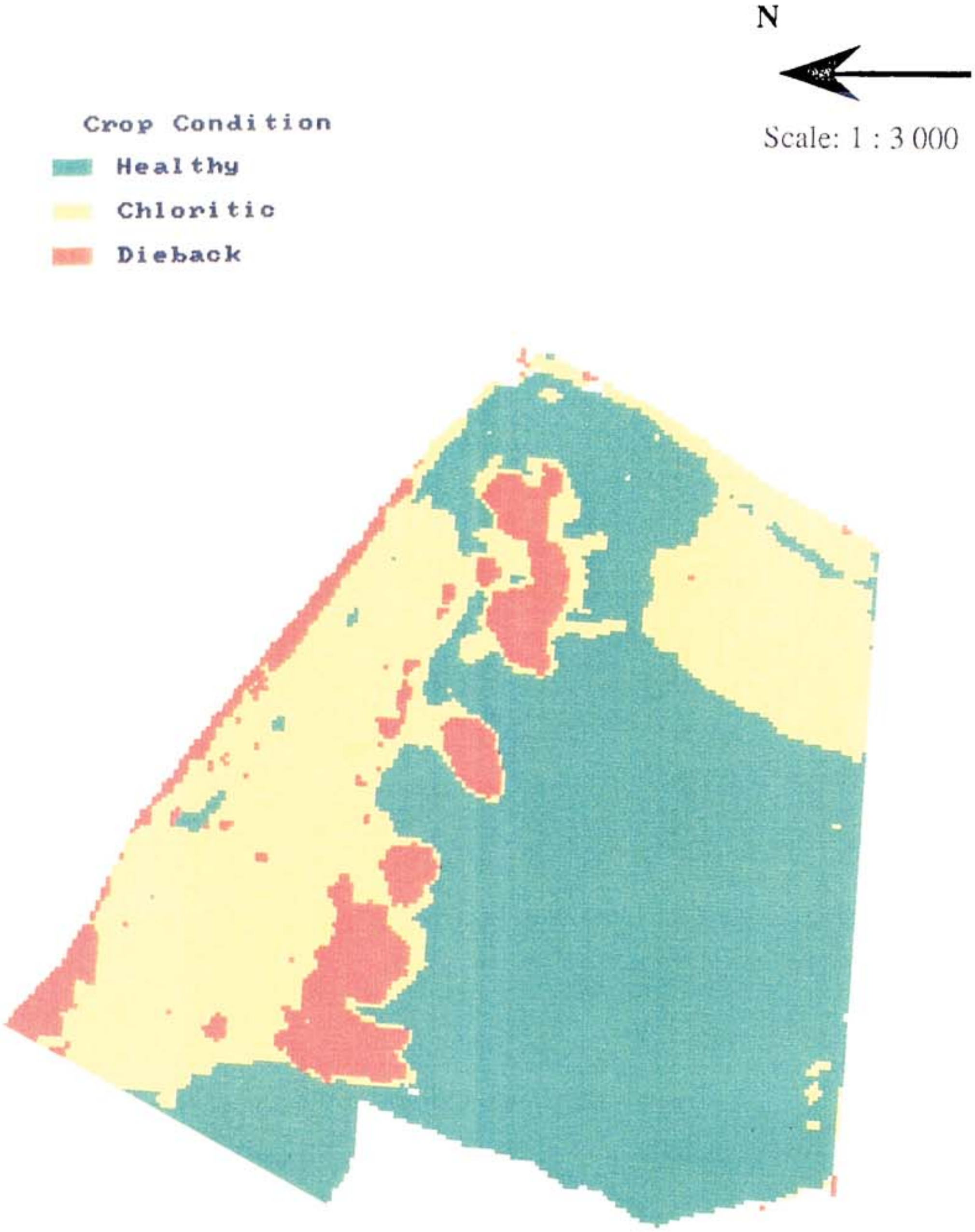

Figure 6.11 Unsupervised classification of agricultural area, Ware Quarry, April 1989, ATM data.

6.3.2.3 Supervised Classification

Supervised classification of the agricultural areas was also carried out. Training areas representing the three ground cover types were identified on the air photos, and used to train the false colour image. The class statistics showed the classes to be very well separable, with the infrared response decreasing, and the visible response increasing, as crop damage increased. The class statistics were very similar to those obtained from the unsupervised clustering of the data. Calculation of the F-ratios for each band suggested excellent separation of the class statistics for all bands, and the false colour composite was once again selected for use in classification.

Due to the excellent class separability, it was considered that the minimum distance classifier would be as accurate, and much more rapid than, the maximum likelihood, and this was used with a threshold value of 10.

The resulting classification showed a very similar distribution of damage as for the unsupervised approach. With the additional time required to carry out supervised classification, there was little advantage to be gained from this procedure.

6.3.2.4 ATM Classification Results

From the classification result (Figure 6.11), the pattern of dieback and chlorosis within the field could be assessed. Chlorosis was idenitfied in three areas:

(i) the major chloritic area was a long strip adjacent to the woodland, gradually extending in width towards the western end of the field,
(ii) a further area showing chlorosis was observed in the south eastern corner of the field,
(iii) finally, the crops in the close vicinity of the areas of dieback exhibited chlorosis, gradually giving way to healthy crop with distance away from the dieback. These areas were not immediately obvious on the air photos, but were identified after they had been highlighted by the computer classification.

With the limited field data available, there was little point in attempting a quantitative assessment of crop loss. For comparative purposes, the percentage cover of each crop 'condition' class was estimated (Figure 6.12). The different approaches produced similar results, although the unsupervised classfifcation identified less chloritic vegetation than either of the alternatives. The difficulty in manually delineating small areas of dieback within chloritic regions, explained the underestimation of this class by air photo interpretation.

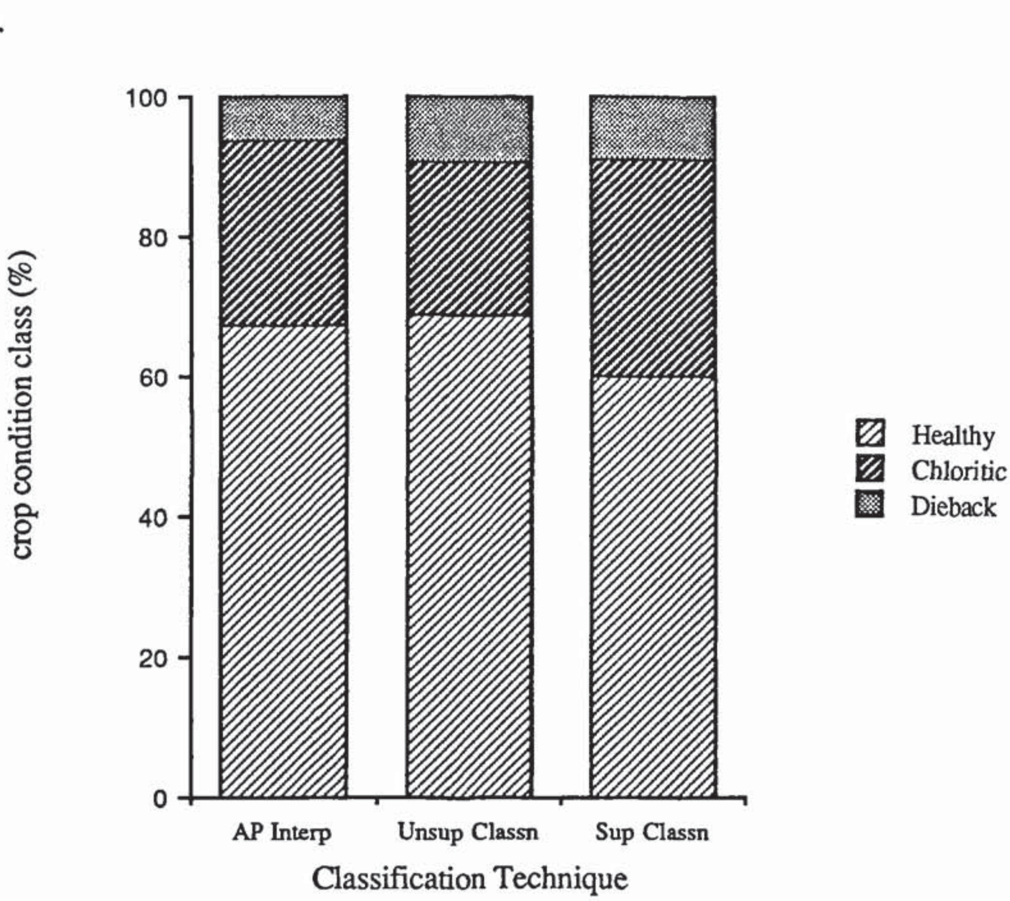

Figure 6.12 Results from classification of crop damage at Ware using air photo interpretation, and unsupervised and supervised classification of ATM data

6.3.3 June Video Data

Video data was acquired in June 1989 (Table 6.1). Due to mis-alignment of the flight path, the eastern end of the field had not been covered; however, as the majority of crop damage was in the centre and western parts of the field, this was not considered to be detrimental to image interpretation.

As described in Section 4.2.3, individual video frames had been coregistered and warped to fit the geometrically corrected ATM imagery, to form a mosaic (Plate 6.6). Despite careful coregistration of frames, the lack of appropriate GCP's had caused several problems in the mosaicing procedure. Display of the infrared and visible mosaics showed they were not perfectly registered, and a further nearest neighbour transformation was carried out.

6.3.3.1 Manual Interpretation of Damage

Initial analysis examined the false colour composite, comprising the infrared band coregistered to the green and red channels of the colour camera. A mask was drawn to delineate only the area of interest, and an autolinear contrast stretch applied.

Variations in radiometric levels between frames was still evident, despite carrying out histogram matching when constructing the mosaics. Contrast enhancement of the mosaic emphasised the variation between frames, to the extent that any visual interpretation was meaningless. Further analysis was carried out on the raw data.

On the false colour composite the areas of dieback could be delineated, appearing bright cyan in colour; chloritic vegetation appeared greenish-blue, and healthy crop reddish-purple. Overall visual interpretation of the video imagery was difficult; although areas of dieback could be identified, more subtle variations in spectral response were masked by radiometric variations between frames.

Display of the true colour video composite showed much less between - frame variation. However, the chloritic areas identified on the April data were much less spectrally separable from the healthy vegetation. Although healthy vegetation was still very variable, it appeared dominantly green, with the chloritic areas having a slightly bluish hue, and the areas of dieback appearing pale pink to white.

6.3.3.2 Unsupervised Classification

Unsupervised clustering of the false colour composite identified 12 clusters within the area. The majority of these had less than 10 pixels, and only the first three clusters were used in the classification. The resultant classification identified areas of healthy and chloritic crop, and regions of complete dieback, similar to those specified using the ATM data. The class statistics (Table 6.16) again emphasised the dubious quality of the infrared video data, there being a significant increase in reflectance accompanying increased chlorosis. However, from the statistics, it was apparent that the visible bands were not able to separate these classes to any great degree, and so the class discrimination relied almost entirely on the infrared band.

Unsupervised clustering of the true colour image failed to make any distinction between the areas previously identified as chloritic and healthy crop. In consideration of the statistics shown in Table 6.16, this was not unexpected. Clustering did identify two main spectral groups, one representing dieback and the other healthy / chloritic crop.

	Class Statistics (mean and standard deviation)		
	Healthy	Chloritic	Dieback
Infrared	146.7 8.0	165.6 7.1	140.0 10.7
Red	167.9 5.9	166.0 5.6	187.4 8.6
Green	112.1 4.4	115.0 4.1	118.8 3.9

Table 6.16 Class statistics as a result of unsupervised classification of crop condition, June 1989 video false colour composite

6.3.3.3 Video Classification Results

Manual examination of the video imagery was disappointing; although areas of dieback could be identified, discrimination of chloritic crop was difficult due to the radiometric variation between frames in the mosaic.

Unsupervised classification of the false colour image revealed a similar distribution of crop injury to that observed on the ATM imagery, although chlorosis was not as extensive as on the April imagery. Classification of the true colour image failed to identify 'chloritic' areas.

There were three possibilities to explain the inability to detect the chloritic crop using the colour imagery:

(i) Firstly, there was a real difference between healthy and chloritic crop, but due to the problems inherent with the sensor, the colour camera was not able to detect the subtle variations in the visible wavelengths. Conversely, the infrared camera, sensing further in the near infrared, was able to perceive the slight differences in crop condition.

(ii) The stressed crop had recovered.

(iii) With maturity, the spectral response of healthy and chloritic crop became similar (Ahlrichs & Bauer, 1983).

In reality, these factors were probably operating in combination. However, due to doubts about the quality of the infrared video data, further analyses used the result of the true colour classification.

6.4 Association of Vegetation Damage and Soil Type

Discussion with the farmer, and examination of soil maps, had indicated a change in soil type across the field, with the clayey, impermeable soils of the Hanslope Association giving way to the sandy loam of the St Albans Series (Jarvis *et al* , 1984). The soil map for the area indicated there was a change in soil type along the western edge of the field. However, the farmer expressed the view that the change occurred along an east-west line, and this was confirmed by field texture assessment of soil samples.

6.4.1 Soil Mapping

Remote sensing techniques have been used for many years to map the distribution of different soil types (Hoffer, 1978; Fitzpatrick, 1980; Brink *et al* , 1982; Colwell, 1983). The spectral reflectance of soils is dominated by several different, but often closely interrelated soil properties, including soil texture, soil moisture, surface roughness, organic matter, and iron oxide content of the soil. The surface roughness, organic matter, and iron oxide content of the soil were not expected to vary to a great extent across the field, and it was hypothesized that the variation in reflectance was mainly a consequence of a change in soil texture.

As ATM data was available for summer 1988, at which time there was no vegetative cover, it was possible to carry out a classification of the two main soil types at the Ware site. Previous work indicated that there was no particular waveband region likely to be superior to any other in the discrimination of soil types, therefore the wavebands showing greatest variation across the area were assumed to contain most information. Bands 7, 5 and 2, were selected to carry out an unsupervised classification, and quickly produced a 'soil map' representing the distribution of the two soil types. The validity of the map was confirmed by field sampling.

6.4.2 Association of Crop Damage and Soil Type

The distribution of crop damage across the area of interest could be visually related to the change in soil types. In order to assess the relationship in greater detail, the unsupervised crop condition map derived from the ATM data (6.3.2.2) was combined with the 'soil map'. The two sets of data were of slightly different resolution, and so a transformation matrix was derived to coregister the summer 1988 image to the spring 1989 image. Several GCP's were selected, the transformation carried out, and the transformation matrix saved to file. After modal filtering of the 'soil' and 'crop' maps to reduce high frequency variation, the transformation matrix was used to coregister the two classifications.

The two overlays were then combined using Spatial Analysis routines within the Iconoclast system, each pixel being assigned to a new class according to its class membership on both the parent images. That is, six new classes were developed, dependent on the pixel belonging to sand or clay in the soil classification, and healthy, chloritic or dieback on the crop classification.

A similar procedure was carried out using the results of the video classification; as only two classes had been identified, the combined image contained four new classes.

6.4.3 Results

Classification of the April data confirmed the spatial relationship between soil type and vegetation damage in the area of interest (Figure 6.13). The majority of the area was classified as healthy vegetation on sandy soil type, or chloritic vegetation on clayey soil.

Originally, crop stress adjacent to the woodland had been attributed to low concentrations of gas in the subsurface. However, the clayey area in the south east corner of the field also supported chloritic vegetation, indicating the majority of the chlorosis could be related to the clay soil type, rather than due to the presence of landfill gas. Further chlorosis on the sand (represented by cyan in Figure 6.13), was almost invariably associated with areas of dieback, forming a 'halo' around each region. This was interpreted as being due to low concentrations of gas in the root zone of the crop. The pale green areas indicate healthy crop growth on clay type soil, and probably represent small, discontinuous clayey patches of soil within the sand.

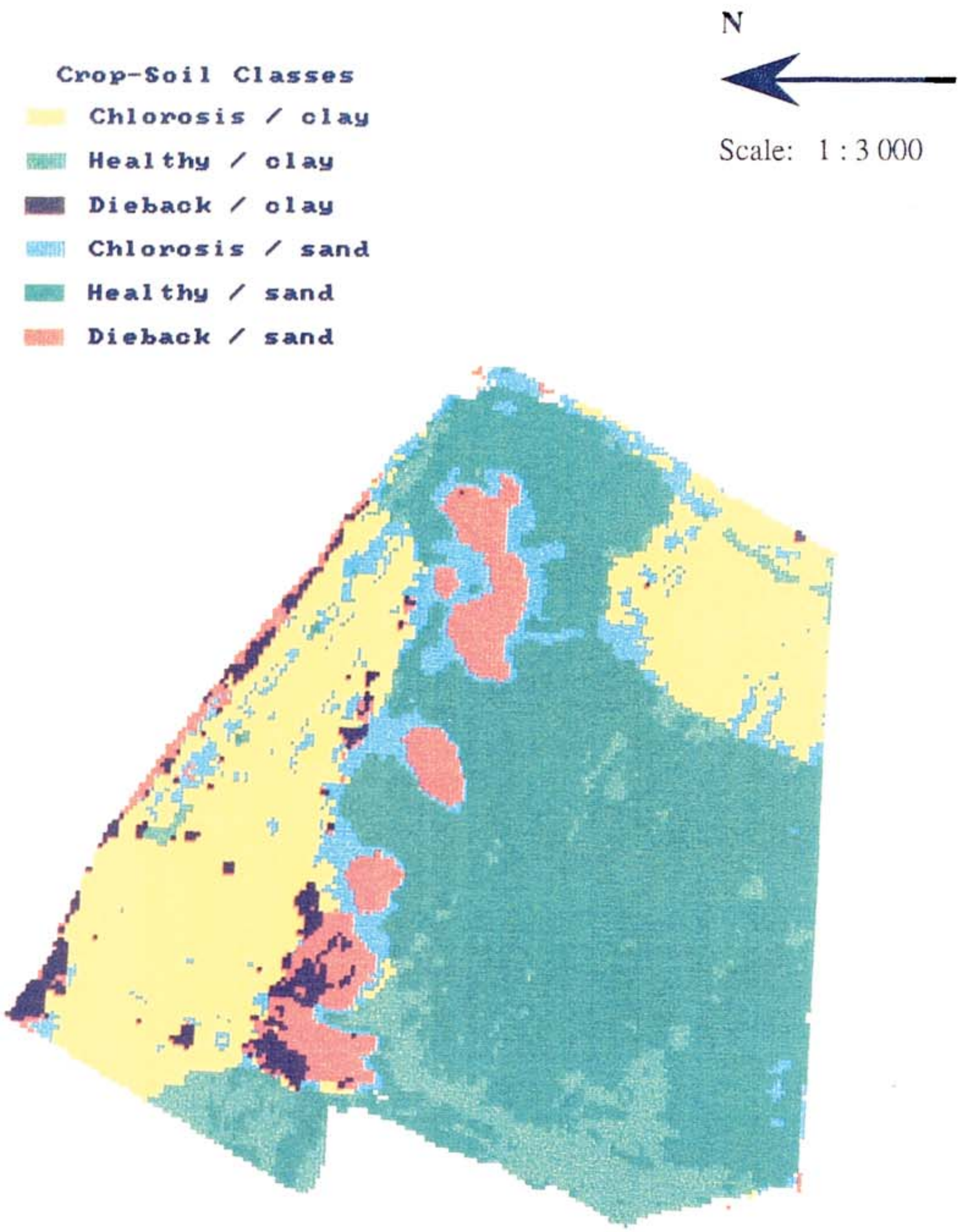

Figure 6.13 Combined soil and crop classification, April 1989, ATM data

The farmer had reported that gas was surfacing close to the boundary of the two soil types, and this was confirmed by point measurements of gas concentrations (Section 6.1.3). This was reinforced by the classification results which indicated that virtually all dieback occurred on the sand within a few metres of the soil boundary. These areas of dieback were surrounded to a greater or lesser extent, by chloritic vegetation.

As described in Section 6.3.3, chloritic and healthy crop could not be reliably discriminated with the video data, and only 'healthy' and 'dieback' areas had been classified. From the combined classification, it was possible to observe increased areas of dieback, in particular the dieback having extended onto the clay soil adjacent to the soil boundary (Figure 6.14).

6.5 Temporal Changes in Crop Condition

Accurate comparison of crop condition between the two dates was not possible due to the different sensors used. Visual comparison of the two sets of imagery indicated that the overall area of chloritic vegetation appeared to have contracted, although areas of dieback had increased. In particular, the chloritic haloes around patches of dieback had either deteriorated to bare soil, or recovered sufficiently to be identified as healthy crop. These changes were attributed to real differences in crop condition, although the interpretation was confused by the different sensors being used.

Although the distribution of dieback on the video classification exhibited a similar pattern to that on the April data, the areas of dieback towards the eastern end of the field appeared to have moved further to the east. As this was unlikely to be due to real changes in crop condition (from 'dieback' to 'healthy' and vica versa), it was attributed to the geometric inaccuracy of the video mosaic. This reinforced the fact that video imagery would find limited use for applications requiring geometric accuracy, although a substantial amount of information could still be gained from spatial relations.

In view of the absence of ground reference data, and the doubts about the quality of the video imagery, attempts to derive estimates of temporal changes in crop condition were not made. Even without the problems of radiometric variation between frames, temporal analysis would have been confused by differences in sun elevation and azimuth, and atmospheric conditions.

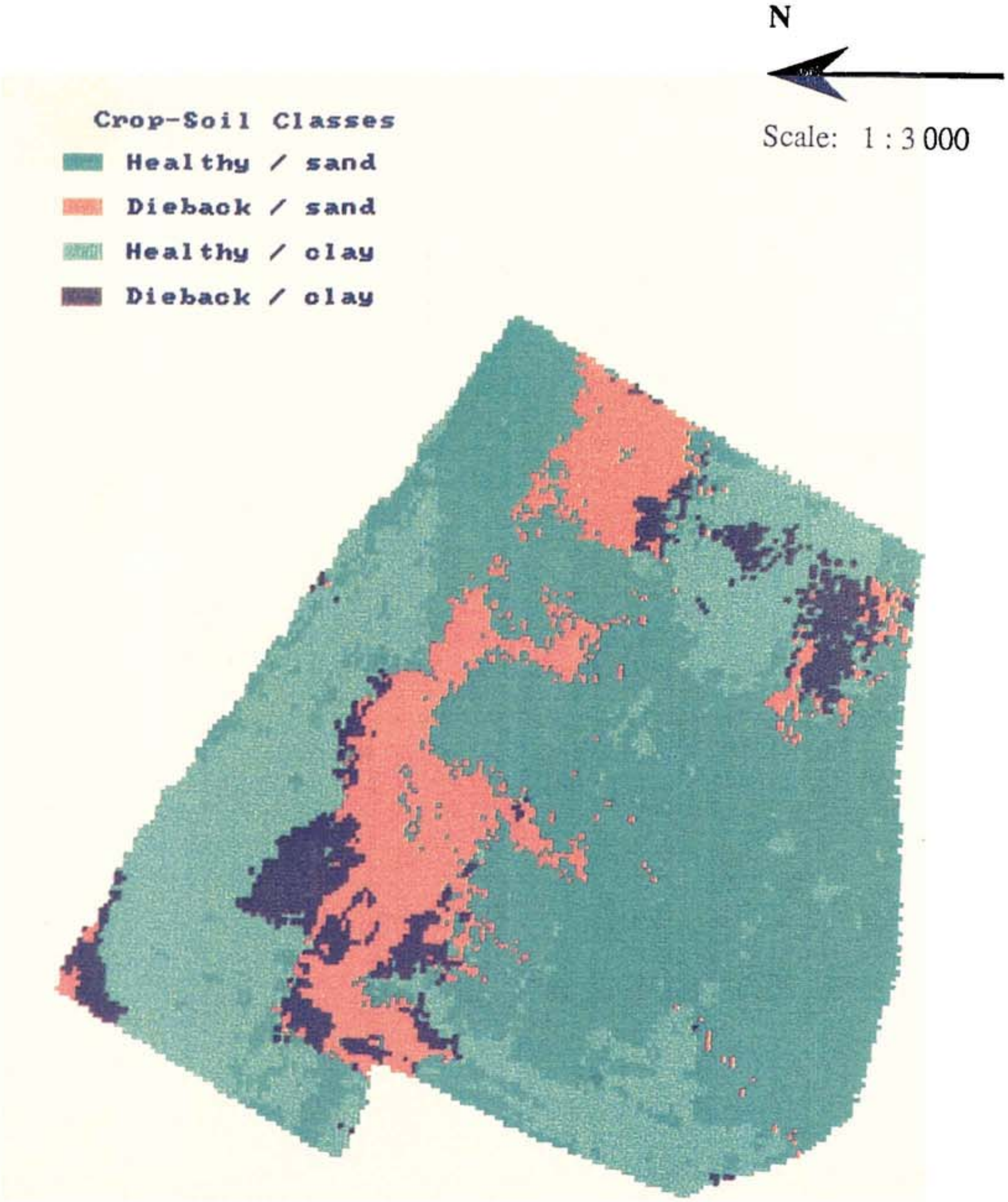

Figure 6.14 Combined soil and crop classification, June 1989, video data

6.6 Conclusions

Study of gas-related vegetation damage at the Ware site revealed a number of points. In contrast with previous studies, most of which concentrated on air pollution damage, the injury to the tree crowns in Garrett's Wood was dominated by spectral changes - that is, chlorosis, as opposed to loss of foliage. Manual classification of the colour infrared air photos produced a crown condition map showing the distribution of crown injury in the wood. This was then used as reference data for the manual and digital classification of the digital imagery. The choice of automatic or manual classification, in this case, had little difference on classification accuracy; the manual interpretation of the video and ATM imagery showed that the changes in crown condition observed on the air photos could also be visually identified on the digital imagery.

With all analyses, maximum confusion occurred between healthy and moderate damage classes, class 3 (severe damage) being consistently well identified. Classification of the video data produced comparable results to the ATM imagery, suggesting that the superior spectral resolution provided by the multispectral scanner added little information in this case.

Due to the separability of crop condition classes at the site, unsupervised classification routines provided a rapid means of delineating injury and estimating the areal extent of the three classes. The success of the unsupervised approach, and the similarity with the results of supervised classification, indicated that the additional time required to carry out the latter was unneccesary.

The combined soil / crop classification suggested that gas was migrating beneath the clayey soil and surfacing in concentrations high enough to cause chlorosis and dieback of vegetation as the clay content of the soil decreased, and permeability to the gas increased. The discrete areas of damaged vegetation close to the boundary, indicated the gas was moving along well defined pathways under the clay, and surfacing in high concentrations over relatively small areas. Chlorosis of vegetation adjacent to the woodland was also originally attributed to gas damage; however study of the combined classification indicated this could be due to the clayey soil type.

In this case, classes were well separable, and, in combination with soil map it was possible to deduce which areas of chlorosis could be due to soil type, and which could be attributed to the effects of landfill gas. Such a result could be highly valuable in the assessment of compensation payments.

Despite the use of different sensors, which prevented quantitative evaluation of temporal changes in crop condition, a marked decrease in the extent of chloritic crop was observed as the plants approached maturity. However, the chloritic 'haloes' surrounding areas of dieback had deteriorated and were identified as 'dieback'. Precise temporal comparisons were not attempted because of the difficulties caused by using different sensors.

The similarity of results for the two remote sensing systems was surprising, particularly considering the uncertain quality of the video data. Unfortunately, the lack of ground reference or air photo data for the June survey prevented firm conclusions from being drawn as to whether the temporal changes were due to real differences in crop condition, or as a result of problems specific to the video imagery.

Nevertheless, the possible utilisation of video data was highlighted. The optimum application would be one that could make use of a single frame of data and didn't require geometric precision, such as the classification of the woodland area. In this way, the geometric and radiometric drawbacks of mosaicing the images could be avoided.

7 DISCUSSION

In the following chapter, some of the problems likely to be encountered in the remote sensing of landfills are discussed with reference to the problems experienced at the Panshanger and Ware sites. Based on the studies, a number of applications of remote sensing are outlined, and a possible methodology for integrating ground survey and remote sensing data suggested.

The second part of the chapter brings the different techniques into perspective regarding their practical use, cost, accuracy, and reliability of results. It also outlines some of the areas, in which, improvements may be expected in future studies, either as a result of refinements to the procedures used, or because of development of new techniques or equipment.

7.1 Summary of Research

Remote sensing can be an effective technique for measuring environmental impact, by observing the effect of the impact on biological indicators (McCarthy, 1972). This research used remote sensing specifically to detect environmental impact caused by migrating landfill gas. The approach to each site was defined by a combination of factors, including the data available, severity of vegetation damage, possible complicating factors, and ease of access.

Due to the disturbed soil conditions and complex migration patterns at the Panshanger site, much of the work was concerned with identification of the relationship between vegetation health and landfill gas. The only means of relating the variables to each other was by utilising multivariate statistics, and including soil parameters within the model. This approach enabled the identification of a relationship, initially between the environmental variables and vegetation height, and also between these variables and spectral response. Subsequently, cover type maps of the site were produced, based on the spectral response of the ground cover. These maps could then be used in combination with the statistical results, to rapidly assess areas at risk.

In contrast, at the Ware site high concentrations of gas were affecting vegetation on undisturbed land, and the relation between landfill gas and plant injury was readily established. At this site remote sensing data was used to assess the extent and severity of damage, its relation to soil type, and any temporal changes in crop condition. In addition, it was possible to compare the utility of the ATM and airborne video data for woodland classification.

Both sites indicated the increasing impact of gas on crop health as the growing season progressed. At the Panshanger site, this was expressed by the increasing evidence of the relation between the environmental variables and plant height (or spectral response). At the Ware site, crop dieback extended in area between the April and June surveys. This has relevance when planning a remote sensing survey, there being a greater opportunity to detect gas-related damage later in the season.

Future work is required to gain a more comprehensive understanding of the way, in which, landfill gas affects plant growth. In particular:

(i) the concentrations (order of magnitude) at which gas has a detectable effect on plant health,
(ii) the length of time plants must be exposed before the gas affects health,
(iii) the effects on different species and at various stages of phenology.

The general lack of understanding about the landfill gas / plant health relationship was felt to be due, in part, to the failure to account for many of the variables affecting the vegetation. If utilised in future research, discriminant analysis could enhance understanding of the complex relationship, and hence lead to greater confidence in the proposed techniques.

7.2 Practical Integration of Remote Sensing and Ground Survey

The drawbacks of ground-based monitoring have been discussed in detail, and the possibility of using remote sensing to overcome many of these has been outlined (Section 2.5). Remote sensing cannot be considered as an alternative to ground survey, but rather the two techniques should be integrated in a way that optimises their individual advantages, and minimises their disadvantages (Table 7.1). That is, the spatial and temporal information available from remote sensing data, should be utilised in a way that reduces field work requirements.

Ground Survey	Remote Sensing Survey
Disadvantages	
1. Difficulties in obtaining accurate measurements due to fluctuating levels of gas and changing migration pathways 2. No spatial perspective 3. Physical / political access	1. Relies on the existence of a relationship between landfill gas and perceived spectral response 2. Cannot estimate gas concentrations 3. Will always require fieldwork to confirm presence of gas
Advantages	
1. Quantitative measurement of gas (required to satisfy waste disposal authorities and legislative requirements)	1. May identify previously unknown areas 2. May be able to infer information from spatial relations, use as a planning tool 3. Quick and unobtrusive method 4. Spatial estimates of damage 5. Marginal costs to survey additional sites would be low

Table 7.1 Advantages and disadvantages of remote sensing and ground based surveys

As stated by Lindenlaub & Davis (1978):

> "The ultimate success of a project is determined by whether or not the user is better able to to solve the problem, or make better earth resource management decisions as a result of the information supplied through analysis of remote sensing data."

It should always be borne in mind that the end point of any monitoring exercise is not the collection of data, but the resolving of a practical problem, within the landfill situation, in a rational and cost-effective manner. Any remote sensing survey should focus on assessing possible impacts and risks to local structures, and identify pathways in order to assist effective siting of migration prevention systems and monitoring schemes.

Due to the wide range of remote sensors and techniques available, and the diversity of problems facing the landfill site operator, it may prove difficult to determine whether or not remote sensing technology can be applied in a cost-effective manner. The design of an integrated approach should consider a number of factors, including the resources available to collect and process the data, the type of data required, and the frequency of data collection.

Depending on the application, ground sampling would still be required for one or more reasons:

(i) initially to establish the relationship between landfill gas and vegetation damage,
(ii) to confirm the relationship between vegetation damage and spectral response,
(iii) to confirm landfill gas concentrations at locations suggested by interpretation of the imagery,
(iv) to confirm the relationships were still viable if periodic monitoring was being undertaken, and to verify any additional areas apparently suffering from the effects of landfill gas.

7.2.1 Application of Remote Sensing to Landfill Gas Monitoring

In order to highlight the practical application of remote sensing, it is important to identify situations where remote sensing could realistically be used by a site operator as an information source. The techniques may be of use prior to fieldwork:

(i) To assess variation across the site, and hence identify unhealthy areas of vegetation. This type of non-specific survey would enable subsequent fieldwork to be concentrated in anomalous areas. However, the risk that gas could be present but was not affecting vegetation should always be considered, and the survey supplemented with additional information.
(ii) After an initial desk study, remote sensing could be used to gather specific spatial information in order to identify locations where gas would be expected to surface, for example, the edges of old sites, or geological / soil boundaries.
(iii) Remote sensing could provide the opportunity for the rapid coverage of many sites, giving an indication of potentially troublesome areas on a regional scale.

However, due to the complexity of the landfill gas / vegetation relationship, in most cases it would be necessary to undertake detailed field work prior to instigating a remote sensing survey. The aim of such field work would be to establish the nature of the relationship between landfill gas and the observed vegetation damage. If the analyses revealed a weak relationship, or one that was complicated by other factors, the benefit to be gained from a remote sensing survey would be limited. For example, at the

Panshanger site, the interrelation of the gas and soil variables meant that landfill gas could not uniquely be established as the cause of decline in vegetation health. In a practical situation the information provided would not be considered sufficient to merit commissioning a remote sensing survey.

If a significant correlation could be established between gas and vegetation health, remote sensing could be successfully integrated with field work in a number of ways:

(i) In the initial identification of further stressed areas, unknown from field work. This would be of particular use in surveying large sites, or those with access problems (either political or physical). Such surveys could also identify problems occurring beyond site boundaries, and help overcome the 'blindfold' attitude of many site operators.

(ii) To gain an understanding of the observed measurements of landfill gas by inference from the spatial distribution of vegetation damage. For example, anomalously high gas concentrations might be recorded along old site boundaries, at geological contacts, or above field drains. The perspective gained from an airborne platform would aid an understanding of these problems, and facilitate the appropriate location of monitoring boreholes.

(iii) To use the data as a baseline, against which to monitor change. That is, by comparison with known areas of high landfill gas, infer possible changes in the extent of migration, or identify new locations of vegetation damage.

(iv) To rapidly estimate the extent of damage to agricultural areas for crop loss assessment, and subsequent compensation settlements.

All remote sensing surveys are limited by the lack of knowledge concerning the levels of gas required to result in a visible effect on vegetation ('trigger levels'). Greater understanding is only likely to be provided after extensive field investigations, taking into account different combinations and concentrations of gases, various species of vegetation, and the effects of phenology. In addition, this work has underlined the importance of soil variables; it is felt that unless these are included in such models, the relation between landfill gas and plant health will remain ambiguous.. Until the relationship can be defined with greater precision, there is a large void in the information provided by such surveys, which will hinder their acceptance by landfill site operators.

Although the surveys accurately identified severely damaged vegetation, they also revealed the confusion between the spectral response of healthy and moderately damage classes. The mis-identification was due both to healthy vegetation being classified as moderately damaged, and vica versa. In the first case (commission errors), this would result in unnecessary field work. However, the failure to identify damaged vegetation (ommission errors) could have more serious consequences, and will further limit the practical application of remote sensing.

The success of remote sensing surveys would be most probable if the relationship between landfill gas and the spectral response was relatively simple. That is when:

(i) high concentrations of gas were affecting the vegetation, with severe vegetation damage resulting,
(ii) the vegetation cover was homogeneous,
(iii) the vegetation species was susceptible to landfill gas,
(iv) other environmental variables, such as soil moisture and texture, were relatively constant across the site.

7.2.2 Suggested Methodology

A possible methodology for the integration of remote sensing and ground data is suggested (Figure 7.1). This is only a guideline; in reality, the infinite number of possible situations prevents the definition of a rigorous methodology.

The potential of remote sensing systems to be used for landfill monitoring will rest ultimately both on costs, and proof of their accuracy and reliability for the defined purpose. This can only be provided after surveys have been carried out and shown to be successful.

7.3 Economics of Remote Sensing

The economics of information gathering can be divided into the elements of costs and benefits (Watkins, 1978), the benefit of the data in this case being represented by the possible reduction in field work that could be afforded by using remote sensing techniques. In practice, benefits are much more difficult to estimate than costs; due to the difficulties in defining a single approach to the problem, the calculation of a 'benefit-cost' as a result of the reduction in sampling requirements was not possible. However, the relevant features of the different systems, and the way in which they could affect the practical application of remote sensing, is briefly discussed.

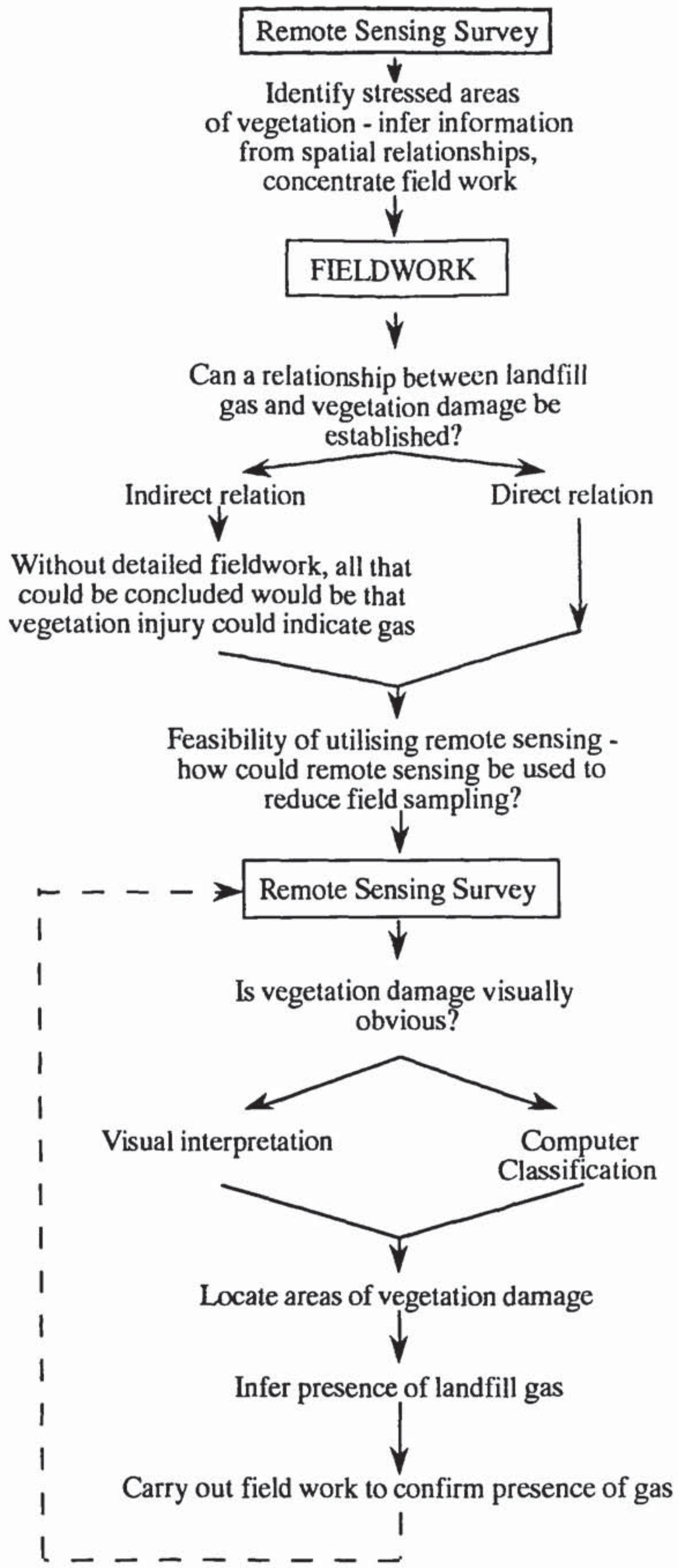

Figure 7.1 Possible approach to integrating remote sensing and ground survey to monitor landfill gas migration

Costs of remote sensing surveys include not only the costs of acquiring the data, but also the associated preprocessing and processing expenditure. The least expensive data source could result in being the most expensive (and / or the least accurate) overall system, due to processing requirements. For example, although the cost of acquiring the video data was very low, the mosaicing requirements almost doubled the time required to process the imagery.

Although only three remote sensing systems have been investigated in this project, there are numerous sensors and platforms available to acquire remote sensing data. In practice, it would be necessary to assess the relative utility of each system, and select the method which would satisfy the project requirements in the most cost-effective manner.

Table 7.2 attempts to give a guide as to the time and costs involved in the different types of survey. The table should be interpreted with consideration of the following points:

(i) The figures in Table 7.2 are based on the time and costs involved in acquiring and interpreting the data for the Panshanger and Ware sites. The relative utility of different remote sensing techniques will vary according to the site in question and the purpose of the survey.
(ii) As stated in Section 7.2, remote sensing cannot be used in isolation from ground surveys; rather it should be used in conjunction with such surveys to optimise the benefits of each, and reduce the overall costs of surveying the site.
(iii) The costs are based on the work being carried out by trained personnel.
(iv) The figures do not take into account the hire or purchase of equipment which could represent a substantial proportion of the costs. The equipment required is listed at the end of each section.
(v) The cost (per site) of flying for all airborne surveys is affected by a number of factors including: transit times from the aircraft base; number of sites covered on a single flight; and cost of fuel. For these reasons, it is difficult to obtain general estimates of flying costs.
(vi) The figures concerning the interpretation of the digital data do not take into account the additional costs of air photo interpretation, the results of which were required for the classification of this data
(vii) The cost of acquisition of the ATM imagery is based on the actual cost to the NERC - commercial rates would be much higher.

Procedure	Time	Cost / site
GROUND SURVEY		
General monitoring for landfill gas (ground survey, interpretation of results)	8 hours	£400 - £500
Equipment required	Gas monitoring equipment	
AIRBORNE VIDEO		
Flight	30 minutes plus transit	£50 / hour
Preprocessing (location of flight lines, decoding, frame-grabbing, mosaicing, geometric registration)	8 hours	
Manual interpretation of vegetation damage	2 - 4 hours	
Computer classification (unsupervised)	10 minutes	
Computer classification (supervised - definition of training areas, classification, accuracy testing)	8 hours	
Interpretation of classification results	1 hour	
Total cost of processing @ £50 / hour	19 - 21 hours	£1 000
Equipment required	Airborne platform Video camera, recorder, monitor Image processing system, decoder, framegrabber	
N.b. the costs of carrying out a video survey would be substantially reduced if the area of interest could be covered by a single frame, and mosaicing could be avoided.		
AIRBORNE THEMATIC MAPPER		
Flight and imagery (approximate)		£1 000 / site
Preprocessing (reading of data on CCT to PC, geometric correction)		£500 / site
Manual interpretation of vegetation damage	2 - 4 hours	
Computer classification (unsupervised)	10 minutes	
Computer classification (supervised - definition of training areas, classification, accuracy testing)	8 hours	
Interpretation of classification results	1 hour	
Total cost of processing @ £50 / hour	11 - 13 hours	£600
Equipment required	Airborne platform Multispectral scanner Access to tape reader, image processing system	
AERIAL PHOTOGRAPHY		
Flight and photographs		£450
Manual interpretation (delineation of tree crown map, tree crown classification)	20 hours	£1 000
Equipment required	Stereoscope	

Table 7.2 Costs of ground and remote sensing surveys

Air photo interpretation is one of the few aspects of remote sensing that is routinely used in a practical situation. Photos are usually of high geometric quality, with very high spatial resolution. However, the relatively high cost of acquiring large format air photos, especially for the small areas under consideration, is likely to hinder its widespread use for monitoring landfill gas migration.

Video imagery is attractive due to the convenience of data acquisition, low cost, and the immediate availability of imagery. As such, the technique has the potential to be readily incorporated within a monitoring programme. However, if it is necessary to mosaic frames together to provide complete cover of a site for computer classification, the processing costs would escalate, while accuracy decreased. For this reason, the technique is most likely to be applicable for small areas, where minimal mosaicing would be required. Alternatively, visual examination of video could provide useful information for initial site assessment.

The problems of mosaicing frames should not be underestimated. The lack of clearly identifiable ground control points at many sites hinders the process, and the results are frequently far from geometrically accurate. In addition, radiometric variation between frames may impair classification of the data.

A further problem with the video data acquired for this project concerned the data from the infrared camera; the sensor appeared to be recording more in the red than the infrared, and the data quality was treated with some caution. The colour camera also used a Newvicon tube, although this had a cut-off filter fitted to exclude wavelengths greater than 0.75μm. It is suggested that future work may benefit from using only the colour camera, with the understanding that the 'red' response actually includes near infrared information.

Whereas the Airborne thematic mapper (ATM) data was spectrally superior to the video, the classification results at the Ware site did not show any significant improvements in accuracy. The high cost of the data, and the slow turn-around time, suggested it is unlikely to find practical utilisation.

7.4 Future Potential of Remote Sensing Systems

The relative utility of different techniques, can be expected to change according to technical developments of the hardware and processing techniques.

7.4.1 Air Photography

One aspect of aerial photography that has not yet been considered in this work, is small format aerial photography. Although the small format air photos produced would not provide high geometric accuracy, they could yield valuable information relating to the spatial distribution of vegetation damage, and therefore find use in the general reconnaissance of sites prior to field work. A further advantage of this type of photography is that, due to the small size of the cameras, they may be carried on board remotely controlled aircraft, further reducing the costs of the survey. The use of such techniques for investigation of relatively small sites has been proposed by several authors (Weltman, 1983; Whitelaw, 1986; Curran, 1986).

A second platform that could be considered would be a helium-filled balloon. This method has been used in a number of site investigations (Williams & Aitkenhead, 1989; Fletcher, 1990), and has the advantage of providing a relatively stable platform, that can be easily positioned.

7.4.2 Videography

Video remote sensing has the potential to provide valuable, real-time data, at very low cost. However, numerous problems were encountered with the imagery used in this project which restricted its use. Such complications could be broadly divided into those associated with the equipment used, and drawbacks with the methodology.

7.4.2.1 Hardware

Several factors could improve the quality of imagery collected by future surveys:

(i) The resolution of the cameras were approximately 375 lines vertically (colour camera), or 550 lines (infrared camera), and digitisation of the signal produced an array of 768 pixels per line, against 576 lines (Toomey, 1985; Flach, 1989). As the resolution of the recorder was only 220 lines, it became obvious that the elimination of this component could lead to significant improvements in the information available. An alternative would be the use of superior recording equipment, such as Super VHS (325 lines) or U-matic (350).

(ii) Despite debate about the comparative merits of tube and CCD cameras (Section 4.2), CCD cameras are generally accepted to suffer less from the effects of vibration, and have a better response in the near infrared region. Therefore, better image quality could be expected using these, as opposed to tube, cameras.

(iii) The use of shuttered video cameras would enable the acquisition of large scale images, without the problems associated with image motion.

(iv) Much useful information can be collected in narrow wavebands by using appropriate filters. (Nixon *et al*, 1985; King & Vlcek, 1988). However, this would require the acquisition of several cameras, and the capability to mount these cameras in correct alignment in an aircraft.

(v) Loss of resolution could be reduced by by-passing the recorder altogether, and recording directly to the hard disc of a PC carried on board a light aircraft. Such a procedure would substantially improve the utility of the system. However, due to the large memory requirement for storing the image data, flights would have to be carefully planned.

7.4.2.2 Methodology

Several drawbacks to video imaging only became apparent when image processing was undertaken. Some of these could be overcome with planning, others are less easily solved. Most of the problems were due to mosaicing of video frames, with the associated radiometric and geometric problems (Section 4.2.3). There is no foreseeable way to avoid this problem; acquiring imagery at a scale such that the entire target areas were covered by a single video frame, would result in unacceptable levels of resolution for most projects.

Some of the ways in which the utility of the video imagery could be improved are given below:

(i) Due to the lack of well defined GCP's in many of the frames, registration of frames to each other was frequently difficult. The development of pattern matching procedures would help to overcome this problem to a large extent, and would also significantly reduce the time required to process the imagery. However, it would also require more sophisticated image processing capabilities.

(ii) There were frequently substantial differences in overall image brightness levels between adjacent frames used to form the video mosaic. If this could be prevented, many of the radiometric problems associated with mosaicing would be avoided.

(iii) The imagery was collected in late afternoon, with extensive shadowing occurring due to the low sun angle. This was a particular problem when attempting to classify the woodland, and one that could easily be avoided.

(iv) Synchronisation of the signals from different cameras would enable more effective use of the infrared imagery.

Despite the disadvantages, video imaging is a rapid and convenient method of acquiring remote sensing data. Many of the above points could be easily implemented, and would greatly enhance the utility of the system used.

7.4.3 Airborne Multispectral Scanning

The practical utility of airborne multispectral scanner imagery for many applications has been limited, due in large to the problems of geometric distortion (Section 4.3.2.1). Much work has been applied to solving such problems, and has resulted in the development of correction routines based on Delauney triangulation. These procedures have gone a long way to overcoming localised geometric distortions, although there are still drawbacks, mainly due to the accurate location of GCP's. On-going research at the NERC is attempting to develop a system to systematically correct geometric errors using an in-flight system to account for variations in plane altitude and attitude.

A further disadvantage with this type of imagery, was the time between the overflight and the actual acquisition of the data, in this case approximately three months. Such a time lapse would prevent the use of such data for the rapid assessment of sites.

Finally, whereas it would be possible to visually interpret the video data and air photos without particularly sophisticated instruments, the analysis of the multispectral scanner data requires extensive computer back up and image preprocessing capabilities, further removing this type of data from the landfill operator.

7.4.4 Technological Advances

Rapid technological advances in the near future could dramatically affect the utility of remote sensing. The development of digital photography has implications for the future use of aerial photography (Lippman, 1990), with a high resolution digital version of each photograph stored on computer disc. Rapid progress is also being made to develop high definition television, the present standard of 525 lines being replaced by up to 1250 lines.

Generally, for the same costs, computing power can be expected to double every two years, and, as the costs of such systems drops, their integration into remote sensing approaches may be anticipated.. The implications for the practical application of remote sensing are enormous, as changes in costs of ground-based monitoring are not likely to follow a similar trend.

7.5 Summary

There is considerable scope to utilise remote sensing techniques in the monitoring of landfill gas migration. The main decision is not whether to use remote sensing or ground survey, but rather what combination of the approaches, and which sensor to use to provide maximum information. It is impossible to define a single approach, due to the variability of sites, time limitations, budgetary constraints, available facilities, etc., and each site must be evaluated on its own merits.

It is anticipated that the remote sensing approach would be most useful where spatial relations, rather than absolute geometric accuracy, were important, for example at the Ware site. Restricting the application of remote sensing to such situations would enhance the utility of the data, and reduce the costs of processing, as geometric correction would not be required.

Considering the similarity of results attained with the video and ATM data at the Ware site, the high spectral resolution available with the latter would appear to be redundant. In view of the high cost of such data, and the facilities required for processing, it is unlikely to find wide application in the monitoring of landfills.

Future developments, particularly in the field of video technology, are expected to augment the cost-effectiveness of remote sensing data. As the costs of processing reduce, and the accuracy of results increase, such techniques should find increasing favour among the landfill technical community.

In more general terms, the incorporation of remote sensing data, ground sampling information, general purpose maps as well as specific thematic maps within a geographical information system would greatly enhance the usefulness of all forms of information to the landfill site manager. The development of such an integrated approach can only be encouraged.

8 CONCLUSIONS

Whenever biodegradable material is placed in the anaerobic environment of a landfill site, landfill gas will be produced. It should therefore be assumed that all landfill sites accepting domestic waste, plus many others licensed to take 'inert' waste, are capable of generating landfill gas. Without proper management, the gas poses a substantial threat, and appropriate measures should be taken to prevent its migration to areas considered to be sensitive.

The basic requirement for effective management of landfill gas is the satisfactory measurement of gas in the subsurface in the proximity of the site. By virtue of the way in which it is produced and migrates, the gas is transient in character. In the near-surface soils, migration occurs along pathways offering least resistance - some of which are themselves transitory - at varying rates, depending on climatic conditions and the rate at which the gas is being produced. Consequently, the absence of gas on a single monitoring visit can not be considered to be proof of the absence of gas.

It can therefore be appreciated that the accurate measurement of landfill gas can create many problems for the site operator. The actual physical measurement of landfill gas is endowed with a number of deficiencies, which hinder the effective interpretation of the sampling results. In addition, financial, time, and access considerations, may place constraints on the extent of ground sampling.

Some of these drawbacks could be overcome by approaching monitoring from a different stand-point, that is, by examining the impact of gas, rather than measuring the actual physical concentration. Possibilities that have been investigated by other workers have included assaying microbiological populations or concentrations of reduced iron and manganese in soils affected by gas. The approach followed in this research was the analysis of vegetation health, expressed as a visible alteration in physiology or morphology of plants growing on gas affected soils. It should be stressed that these techniques can not give any indication of gas migrating at depth. However, they could provide valuable information concerning the presence of gas in the near-surface soils, possibly a considerable distance from the point of generation.

Following review of the literature, two contrasting sites were investigated. These differed in terms of the degree of damage, types of vegetation affected, concentrations of landfill gas, and homogeneity of the areas of interest. Both studies provided a great deal of information, which assisted in the definition of a possible methodology for combining ground-based and remote sensing approaches.

8.1 Effects of Landfill Gas on Vegetation

It was shown that landfill gas in the root zone of vegetation could result in a change in plant condition. However, as with any biological system, the relationship is frequently indirect, and invariably complex. As stated by Valiela (1984):

> "No form of study or analysis will allow certain (or even near certain) impact prediction for most systems. There will be residual or major uncertainties in all situations as a result of biological complexity and the unknown nature of impact interactions."

Study of the literature reinforced this view. Despite the widely held conviction that landfill gas was detrimental to plant health, the complexity of the landfill gas - vegetation - soil relationship defied any attempt to accurately identify the association, or predict the concentrations and combinations of gases that could be expected to result in vegetation injury. This lack of knowledge will inhibit the practical application of remote sensing techniques, as it is not possible to state a concentration at which vegetation damage may be expected to occur.

Fieldwork at the Panshanger site further underlined the complexity of the situation - although landfill gas was affecting vegetation health, the variability in soil characteristics masked the relationship. Discriminant analysis was used to investigate the combination of gas and soil variables that were affecting plant health. The results underlined the usefulness of this technique, and indicated that a combination of gas and soil parameters could be used to predict vegetation condition.

The importance of the soil variables in the relationship was attributed either to the fact that landfill gas would only affect vegetation if the plants were predisposed to injury, or the effects of landfill gas were only significant when operating in combination with soil parameters. These results suggested that the failure to identify a relation between landfill gas and vegetation health in previous research, was probably due to the inability to incorporate soil variables within models. Discriminant analysis provides the capability to explain differences in plant health as a result of several environmental variables acting in combination; it could therefore prove to be a useful technique for future work.

The literature had also suggested that the effects of landfill gas on vegetation varied according to plant phenology. This was confirmed by this work; analyses of the

Panshanger data not only revealed a stronger relationship between plant height and the environmental variables as the growing season progressed, but also indicated the increasing importance of landfill gas in the relation. The relation was also confirmed by interpretation of the Ware site imagery. At this site, areas of chlorosis associated with landfill gas degenerated to dieback over the growing season, whereas chloritic plants associated with the clay soil type showed improved health.

Due to waterlogging of parts of the Panshanger site, several areas had not been sown, and were not included in the statistical analyses. The exclusion of areas with no crop cover was felt to bias the results in two ways:

(i) Areas of dieback could not be distinguished from areas not sown. These regions would be expected to have the strongest relationship with landfill gas, and their omission from the analyses was expected to reduce the strength of the relation.
(ii) As the areas excluded were those with the highest soil moisture values, the contribution of this variable to the relation would be affected.

The fact that a relationship could be established in spite of these drawbacks was particularly encouraging, and it was felt that further work on a less complex site could yield a more clearly defined relation.

8.2 Remote Sensing of Vegetation Injury

The approach to the remote sensing surveys at the two sites was affected by the data available, severity of vegetation injury, effects of other site variables, and ease of access. At the Panshanger site, the relationship between landfill gas and crop condition was not clear. Analyses of field data indicated that plant height was influenced by a combination of gas concentration and soil data. The remote sensing data was then used to carry out further analyses to determine the relation between crop properties and spectral response, and consequently between spectral response and the environmental variables.

Again, when compared with the analysis of plant health and environmental variables, the strength of the relationship between spectral response and the environmental variables increased as the crop approached maturity. However, the relative importance of landfill gas was reduced, the soil variables all having much greater weight. This indicated that, while gas concentration was the dominant variable affecting plant height, the soil variables exerted a greater influence on the overall condition of the crop canopy. The thematic maps produced could be used in conjunction with the results of analyses to assess the way in which the environmental variables varies across the site.

Vegetation damage related to landfill gas had been reported at the Ware site for many years. The remote sensing survey attempted to assess the extent of damage, the relation with soil variables, and temporal changes in vegetation condition. Many of the trees in Garrett's Wood exhibited signs of injury, the northern end of the wood being particularly severely affected. The remote sensing data showed that injury was clearly expressed as a spectral change in the tree crown. That is, the perceived response to landfill gas was chlorosis, rather than defoliation or change in the morphology of the crown. Photo interpretation of the colour infrared air photos produced a crown condition map, and subsequent classification of the digital imagery was carried out using the air photo-interpretation as reference data. The results showed that severely chloritic crowns were consistently well identified; however, healthy and moderately damaged vegetation was frequently confused. The consistency of these results for different sensors indicated that there were real difficulties in separating healthy and moderate damage classes.

The land to the south of the wood also had a long history of landfill gas - related crop injury, and areas of damaged crop could be clearly delineated from healthy vegetation using the remote sensing data. The distribution of injury was appeared to be largely associated with changes in soil type. By combining the soil and crop damage classification results, it was possible to identify chlorosis that was occurring as a result of soil type, and separate this from chlorosis caused by landfill gas.

Both sites illustrated the importance of soil type and conditions when relating landfill gas to plant injury. Changes in soil characteristics may be a hindrance to accurate identification of a relationship, for example at the Panshanger site. In contrast, knowledge of the change in soil type at the Ware site assisted in identifying the relationship.

8.3 Potential of Remote Sensing

One of the major advantages of remote sensing surveys is that large areas can be surveyed rapidly, and data acquired from otherwise inaccessible locations. However, the lack of an unambiguous relation between landfill gas and vegetation injury in most cases would prevent such surveys from providing a direct estimate of landfill gas concentrations in the subsurface. Instead, a combination of ground-based and aerial approaches could provide optimum information regarding landfill gas migration.

The potential of remote sensing techniques to be used to solve problems related to landfill gas will depend on the individual situation. Factors that could affect the outcome of the survey include:

(i) the degree to which vegetation damage can be related to landfill gas; that is, the severity of damage to vegetation, homogeneity of vegetation cover, homogeneity of soil cover,
(ii) the areal extent of vegetation damage,
(iii) the sensors used.

These factors act in combination, firstly to affect the possibility of detecting vegetation damage using remote sensing, and secondly to attribute this to the presence of landfill gas. Remote sensing could be expected to accurately identify landfill gas when as many of the variables involved in the relationship as possible were controlled; for example, high concentrations of landfill gas were affecting a homogeneous crop canopy, the injury being expressed as severe chlorosis or dieback. Unfortunately, this 'ideal' situation very rarely occurs.

Therefore, consideration was given to ways in which remote sensing and ground-based monitoring surveys could be combined. The optimal method of integrating the two approaches would involve initial field sampling to establish the relationship between landfill gas and the spectral response of the vegetation. Remote sensing could then be used to identify additional areas of damage and monitor changes in gas migration patterns. A second important application would be the use of airborne survey to rapidly assess site conditions, prior to detailed site investigations.

Although these were identified as the situations in which remote sensing could be used to best advantage, several other possible applications were also detailed (Section 7.4).

8.4 Costs and Benefits

It was not possible to calculate a benefit-cost of integrating remote sensing and field data, due to the variability of individual situations, and the difficulties of attributing a value to the benefits gained. Chapter 7 highlights the benefits, and gives an indication of the costs of surveys; it is left to the landfill operator to assess the benefit-cost for individual situations.

In addition, the different sensing systems were compared in order to assess the cost-effectiveness of alternative sensors for this type of application. Analysis of injury to the woodland at the Ware site provided an opportunity to compare the accuracy of classification using ATM and video imagery. The results of the analyses were similar in terms of accuracy, and it was concluded that when single video frames could be used there would be little benefit to be gained from the superior spectral resolution of the ATM data.

In terms of costs, the acquisition and processing of airborne thematic mapper data may be prohibitive, and preventing the use of such imagery in many projects. A further barrier to the practical application of this imagery, would be the time lapse between overflight and the production of the digital imagery.

In contrast, aerial video could provide very low cost, and timely, data, in a form that could be either subjected to visual interpretation, or digitised and automatic classification carried out. As such, the technique would be particularly useful as part of a reconnaissance survey. It is suggested that such systems could prove to be most cost-effective if mosaicing of frames was kept to a minimum, or avoided altogether. In addition, several changes could be made, to either improve the methodology or the system used, that would be expected to enhance the quality of the data in future surveys.

Although quantitative comparison between the two types of digital imagery was not possible due to temporal differences, the results suggested that the superior radiometric and spectral resolution of the ATM imagery were not necessary for this application.

8.5 Summary

The traditional means of detecting near-surface migration of landfill gas from sites has been by point sampling and direct measurement of gas concentrations. However, the problems of obtaining accurate gas concentration data are considerable, and the results of such surveys must be interpreted with care. Remote sensing was investigated as a means of detecting and monitoring the migration of landfill gas in soils adjacent to completed landfills. The techniques were not suggested to substitute present methods of monitoring, but to supplement them. The degree to which ground sampling requirements could be reduced would be expected to vary according to specific site conditions.

At the Panshanger site, gas was migrating vertically upwards through the cap, and the variable soil conditions across the site complicated the analyses. Such factors hindered attempts to detect or monitor landfill gas, and prevented identification of a decisive relationship between landfill gas and vegetation health. Nonetheless, it was possible to establish a relationship between landfill gas and soil parameters, and spectral response, and the imagery was used to produce thematic maps representing the distribution of gas and soil variables across the site.

In contrast, plant injury at the Ware site was confirmed as being due to the lateral migration of landfill gas, the gas migrating in high concentrations along well established pathways. The use of multi-temporal remote sensing data enabled the confirmation of the extent of vegetation injury, the identification of the spatial relationship between soil type and gas parameters, and observation of temporal changes in plant condition.

It can be appreciated that remote sensing to detect or monitor landfill gas migration, actually relies on two dynamic, and difficult to quantify, systems: the gas / plant, and the vegetation / sensor systems. The techniques would be anticipated to be successful where the underlying relationship between vegetation damage and high gas concentration was relatively easy to establish. That is, in situations where there were high gas concentrations, homogeneous vegetative cover, and predictable variations in soil characteristics. The results of this research cannot be taken to represent conditions at other sites; each site will have particular soil, gas, and vegetation conditions, and any survey carried out is specific to that site.

In conclusion, remote sensing techniques may not necessarily define areas of chlorosis or dieback with perfect geometric accuracy, nor do they provide accurate crop statistics. However, it combines extensive spatial and land cover type information, in a way that no other approach does, and so has the potential to fill a void in information provided by ground-based surveys.

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APPENDIX 1

GAS MONITORING EQUIPMENT

GasTec

Manufacturer:	Research Instruments
Type of device:	Flame ionisation detector
Sensitivity:	1 to 10 000 ppm methane
Comments:	Calibrated for methane, but will monitor any flammable gas i.e. presence of solvents or petrol vapour will be recorded.

Gascoseeker

Manufacturer:	GMI
Type of device:	Catalytic oxidation detector
Sensitivity:	0.5% LEL to 100% by volume methane in air
Comments:	Measures oxidation of gas, therefore minimum of 10% oxygen must be present. Will respond to any combustible gas, including hydrogen generated in early stages of waste decomposition. Catalyst in detector is susceptible to poisioning by trace constituents of landfill gas. Also records oxygen.

Carbon dioxide meter

Manufacturer:	GMI
Type of device:	Infrared detector
Sensitvity:	0.5 to 100% carbon dioxide by volume
Commments:	Measures energy absoption at wavelength specific to carbon dioxide.

APPENDIX 2

FIELD DATA - PANSHANGER SITE

APRIL 1989

Loc	COVER (%)	HEIGHT (cm)	WEED (%)	DAM	CH4MAX (ppm)	CH4 Steady (ppm)	CH4 Surface (ppm)	PH	MOIST (% by wt)	TEXT	B7B5
B2	0	0	20		3	1	0	6.50	17.80	1	
B3	0	0	0		2	0	0	6.50	20.17	2	0.81
B4	0	0	0		0	0	0	6.50	19.18	2	0.75
C2	5	16.75	75		4	1	0	7.00	23.29	4	0.91
C3	0	0	0		1500	80	0	7.25	24.39	1	0.72
C4	0	0	0		1000	2	0	7.25	22.56	1	0.83
D2	10	19.3	5		10	3	3	6.50	20.07	1	0.88
D3	0	0	0		300	1	0	6.50	22.36	1	0.72
D4	0	0	0		7	1	0	7.00	24.35	1	0.73
D5	0	0	60		3	2	0	6.50	22.98	1	0.86
E3	0	0	0		3000	60	4	6.75	21.38	1	0.73
E4	0	0	0		25	6	4	7.00	20.26	1	0.74
E5	0	0	15		15	5	5	8.00	23.55	1	0.77
F2	5	13.2	0		3000	1000	5	7.00	26.65	1	0.79
F3*	5	17.6	0		8	3	2	7.50	22.68	1	1.25
F4	10	24.0	0		250	9	2	7.00	22.50	1	0.92
F5	15	20.9	10		100	20	8	7.50	21.88	1	1.01
G3	0	0	0		9	3	2	7.00	23.26	1	0.74
G4*	10	22.1	0		5000	50	2	6.50	21.95	1	1.15
G6*	30	24.6	15	1	25	0	0	7.00	23.02	1	1.05
H2	0	0	0		400	3	0	7.00	20.85	1	0.73
H3	0	0	0		80	2	0	7.75	20.82	1	0.74
H4*	30	30.6	0	1	15	1	0	8.00	21.91	1	0.86
H5	5	12.6	5		500	7	0	7.00	20.88	1	0.81
H6	5	7.9	15		1	1	0	7.00	20.15	3	1.03
I3	10	20.3	0		1	0	0	7.00	16.82	1	0.78
I4	75	35.6	0		4	0	0	7.50	22.40	1	1.23
I5	15	23.8	0		0	0	0	7.50	21.13	4	1.12
I6	10	21.5	5		500	25	0	7.50	23.22	1	0.79
J2	10	19.8	5		15	1	0	7.00	19.91	1	1.07
J3	20	20.0	5		300	20	0	7.50	20.02	1	1.09
J4	40	31.1	0		15	1	0	7.00	19.30	1	1.32
J5*	10	15.6	10	1	1	1	0	7.00	23.29	1	0.86
J6	20	17.9	5		300	25	1	8.00	26.13	4	1.04
J7	5	6.3	0		60	3	0	7.50	22.84	4	
K1	5	16.4	5		1000	6	0	7.00	21.09	2	1.29
K2*	15	18.9	0		2000	50	0	7.50	19.93	2	1.31
K3	100	42.3	0	1	0	0	0	7.00	22.24	2	1.63
K4	10	14.6	5		80	1	0	7.00	23.40	2	1.20
K5	5	11.5	5		0	0	0	7.00	17.46	3	1.04
K6	10	13.8	10		0	0	0	6.50	14.70	3	0.97
K7	0	0	75		175	8	0	7.00	20.26	2	0.88
L2	50	30.8	10		2	0	0	7.50	18.85	2	1.37
L3*	5	22.5	25		0	0	0	7.00	27.81	2	1.14
L4	50	30.9	20	1	0	0	0	7.00	22.96	1	1.03
L5	5	9.6	10		4500	80	0	7.25	19.96	1	0.90
L6	5	9.5	5		30	20	0	7.00	17.42	6	0.97
L7	0	0	5		0	0	0	7.25	18.78	1	0.96
M2	50	25.5	20	2	50000	12500	100	6.00	33.28	2	1.04
M3	50	35.4	20		10	0	0	7.50	25.27	4	1.70
M4	25	17.1	10	2	4000	50	0	7.00	23.46	1	1.28
M5	10	11.7	5		40	0	0	7.50	19.43	4	0.79

M6	0	0	5		0	0	0	7.25	26.16	4	0.77
M7	15	15.9	5	1	0	0	0	7.25	20.07	2	0.92
N3	10	21.8	5		2	0	0	7.00	17.05	2	1.53
N4	40	20.4	5		40	2	0	7.00	20.48	2	1.20
N5	20	15.3		1	4	0	0	7.50	18.61	2	1.46
N6	0	0			50	1	0	8.00	11.10	2	0.98
N7	10	13.8			800	250	0	6.50	17.18	2	1.06

* indicates grid point failed criteria for site homogeneity (Table 5.3) and was excluded from analysis

Climatic conditions at time of survey:

Barometric pressure:	1001 mbars
Wind:	north westerly light breeze
Weather:	dry, high cloud, 19^0c

MAY 1989

Loc	COVER (%)	HEIGHT (cm)	WEED (%)	DAM	CH4MAX (ppm)	CH4 Steady (ppm)	CH4 Surface (ppm)	PH	MOIST (% by wt)
B2	0	0			10000	30	20	6.00	13.4
B3	0	0			4	0	0	7.00	16.5
B4	0	0			0	0	0	6.50	16.8
C2	10	48.2	80		40	0	0	6.50	20.9
C3	0	0			700	150	0	7.25	19.7
C4	0	0			700	200	1	6.75	18.6
D2	10	54.0	10		80	0	0	7.00	17.7
D3	0	0			300	0	0	8.00	21.3
D4	0	0			0	0	0	8.00	22.0
D5	0	0	70		0	0	0	7.00	19.8
E3	0	0			0	0	0	7.50	17.5
E4	0	0			0	0	0	7.25	20.5
E5	0	0	50		80	20	0	7.50	18.2
F3*	10	40.5	5	1	0	0	0	8.00	19.2
F4	15	60.9	5		300	40	0	8.00	19.4
F5	15	72.9	10		0	0	0	7.50	18.9
G3	0	0			500	80	0	8.00	20.9
G4*	15	51.6			0	0	0	8.00	20.2
G5	50	60.0			0	0	0	8.00	19.1
G6*	30	41.4	10	1	100	40	0	8.00	23.0
H3	0	0			200	0	0	8.50	21.5
H4*	30	58.5		2	40	0	0	8.00	19.8
H5	5	28.0	5		2400	360	40	8.00	23.1
H6	15	31.1	40		100	40	0	8.00	17.5
I2	15	43.8	10		40	0	0	8.00	17.7
I3	15	41.1	5		100	40	0	8.00	22.1
I4	80	98.1			0	0	0	8.00	19.6
I5	30	62.1	5		0	0	0	7.25	18.4
I6	20	53.5	10		400	200	0	8.00	19.4
J2	20	45.9			100	40	0	8.00	20.7
J3	25	59.1	5		100	0	0	8.00	20.5
J5*	15	32.3			1400	0	0	8.00	20.1
J6	20	47.1	15		0	0	0	8.00	19.9
K1	10	28.7	5		0	0	0	7.25	17.7
K2*	30	55.3	5	1	400	0	0	7.25	19.7
K3	100	97.6			100	0	0	7.00	18.8
K4	30	44.6	15		40	0	0	6.50	21.8
K5	30	40.9	5		0	0	0	6.75	15.7
K6	50	53.2	5		0	0	0	6.75	15.1
K7	0	0	90		40	0	0	8.00	16.1
L2	60	84.0	30	2	15	3	0	7.50	16.6
L3*	5	77.1	90		0	0	0	7.50	16.6
L4	50	74.5	20		0	0	0	7.50	21.0
L5	5	26.4	10		250	20	0	7.50	14.7
L7	5	38.5	10		1	0	0	7.50	14.6
M2	60	63.7	20		4800	1600	500	6.50	21.3
M3	90	81.4			20	2	1	7.75	23.2
M4	20	47.5	5		400	20	0	7.50	21.4
M5	25	34.6			2	0	0	7.50	16.2
M6	0	0	5		3	0	0	8.00	20.8
N3	50	43.1		1	9	3	2	7.00	14.8
N4	70	65.4			7	5	0	7.00	16.5
N6	0	0	10		8000	200	3	7.50	17.0

* indicates grid point failed criteria for site homogeneity (Table 5.3) and was excluded from analysis

Climatic conditions at time of survey:

Barometric pressure:	1012 mbars, falling
Wind:	north westerly light breeze
Weather:	dry, high cloud, 17^{0}c

JUNE 1989

Loc	COVER (%)	HEIGHT (cm)	WEED (%)	DAM	RED
B2	0	0	10		
B3	0	0	10		
B4	0	0	60		
C2	10	173.1	90		
C3	0	0			
C4	0	0			
D3	0	0	5		
D4	0	0			
D5	0	0	100		
E3	0	0			255
E4	0	0	5		247
E5	0	0	80		247
F3*	10	157.3			253
F4	10	143.2		1	249
F5	50	174.8	10		227
G3	0	0			254
G4*	5	128.5			251
G5	30	175.8		1	242
G6*	30	164.5		1	226
H2	0	0			254
H3	0	0			254
H4*	30	157.5		1	251
H5	5	102.7	10	1	244
H6	5	114.3	25		219
I2	15	97.3		1	238
I3	15	146.2		1	237
I4	75	178.8		2	225
I5	15	173.3		2	220
I6	15	156.8	5	2	223
J2	10	138.7		2	226
J3	20	121.8	5	1	217
J4	50	149.0		2	217
J5*	15	126.0	30		216
J6	25	157.3	20	2	220
J7	0	0			234
K1	10	109.2	20		220
K2*	15	159.2	5	2	212
K3	100	171.8		1	207
K4	20	147.4	10		199
K5	15	150.0	15	1	206
K6	30	121.0	40	1	221
K7	0	0	100		201
L2	60	185.0	20	1	209
L3*	40	208.3	60		188
L4	50	182.5	50	1	192
L5	5	118.0	25		217
L6	5	95.2	30		214
M2	50	142.0		2	187
M3	50	181.5	60	1	177
M4	25	136.8	20		196
M5	20	150.7	70	1	227
M6	0	0	50		232
M7	30	164.2	5	2	206
N3	25	135.3	20	1	203
N4	30	143.2	10	1	210
N5	30	111.7			192
N6	5	137.3	30		216

* indicates grid point failed criteria for site homogeneity (Table 5.3) and was excluded from analysis

Climatic conditions at time of survey:

Barometric pressure:	998 mbars
Wind:	westerly light breeze
Weather:	dry, sunny, 24^0c

JULY 1989

Loc	COVER	HEIGHT	WEED	CH4MAX	CH4 Steady	CH4 Surface	PH	MOIST	B7B9
	(%)	(cm)	(%)	(ppm)	(ppm)	(ppm)		(% by wt)	
B2	0	0		0	0	0	5.75	9.39	
B3	0	0		4	1	1	6.75	12.24	1.12
C2	5	181		1	0	0	6.00	10.68	1.02
C3	0	0		2	1	0	7.50	16.10	1.03
C4	0	0	40	500	10	1	7.50	17.90	1.07
D2	10	184		2	0	0	7.00	9.69	0.84
D3	0	0		2	1	1	7.25	18.87	1.07
D4	0	0	60	2	1	1	8.00	23.18	1.19
D5	0	0	100	2	1	0	6.50	11.00	0.91
E3	0	0		1	0	0	7.25	13.82	1.02
E4	0	0		2	0	0	8.00	15.85	1.33
E5	0	0	80	2	1	0	7.50	11.59	1.04
F3*	5	177		2	0	0	7.50	11.48	0.75
F4	10	148		150	5	0	7.75	16.62	0.81
F5	15	186		2	1	1	7.50	13.16	0.74
G3	0	0	10	2	0	0	7.50	18.15	0.78
G4*	5	127		4	1	0	7.00	16.23	0.78
G5		180		3	1	0	7.75	15.25	0.74
G6*	30	125		3	0	0	8.00	17.48	0.78
H3	0	0	30	5	1	0	7.75	16.59	0.95
H4*	30	141		1	0	0	8.00	17.82	0.79
H5	5	120	10	2	0	0	8.00	20.45	0.82
H6	5	122	25	2	0	0	8.00	10.85	0.78
I2	20	129		10000	10000	20	7.50	17.81	0.71
I3	15	156		1	0	5	7.50	15.10	0.71
I4	75	182		0	0	0	7.50	15.37	0.73
I5	15	167		0	0	0	7.50	15.89	0.72
I6	10	155		8	1	0	8.00	16.39	0.71
J2	10	139		0	0	0	8.00	19.87	0.70
J3	20	140		12	0	0	8.00	11.93	0.70
J4	40	174		0	0	0	7.00	14.58	0.71
J5*	10	131	30	150	25	0	8.00	16.09	0.80
J6	20	156	20	0	0	0	8.00	18.91	0.84
J7	5	0	30	0	0	0	8.00	17.81	1.06
K1	5	165	20	0	0	0	7.25	12.52	0.82
K2*	15	149		70	20	0	8.00	14.38	0.71
K3	100	178		0	0	0	7.00	14.59	0.72
K4	10	182	10	30	15	2	7.00	14.10	0.77
K5	5	150	15	0	0	0	7.00	11.02	0.78
K6	10	146	40	6	1	0	7.00	11.69	0.82
K7	0	0	100	0	0	1	7.50	12.19	1.18
L2	50	171	20	2	1	0	7.00	14.87	0.72
L3*	5	211		1	0	0	7.50	16.05	0.76
L4	50	183	50	2	1	4	7.00	19.06	0.77
L5	5	120	25	2	1	1	7.25	10.08	1.02
L6	5	115	30	40	8	0	7.25	9.68	1.05
M2	50	122		550	100	1500	6.50	14.90	0.98
M3	50	202	50	0	0	0	7.75	17.51	0.76
M4	25	174	20	0	0	0	7.00	22.19	0.76
M5	10	158	70	0	0	0	7.25	12.61	1.30
M6	0	0	50	0	0	0	8.00	10.10	1.29
N3	10	157	20	1	0	0	7.00	13.26	0.78
N4	40	175	10	1	0	0	7.25	12.50	0.88
N5	20	145		6	5	4	7.75	13.36	0.77
N6	0	146	30	2	2	2	7.75	13.00	0.85

* indicates grid point failed criteria for site homogeneity (Table 5.3) and was excluded from analysis

Climatic conditions at time of survey:

Barometric pressure:	997 mbars, rising
Wind:	westerly light breeze
Weather:	dry, sunny, 22^0c

Field variables used in discriminant analysis:

Biological variables

COVER	% crop cover estimated by eye within a 0.5m quadrat
HEIGHT	average vlaue for up to 20 plants within a 0.5m quadrat
WEED	% weed cover estimated by eye within a 0.5m quadrat
DAM	visible damage to foliage, assigned a quantitative rating, 1to 3 (see Table 5.4)

Environmental variables

LNCH4	log of maximum recorded methane concentration at 40cm depth at each sample point
MOIST	soil moisture of sample from 40cm depth, calculated using the gravimetric method (British Satndards Institution, 1975)
PH	soil pH of sample from 40cm depth, calculated using the colourmetric method (British Satndards Institution, 1975)
TEXT	field texture, assigned a quantitative rating: clay 1 silty clay 2 sandy clay 3 clayey silt / silt 4 clayey sand 5

Spectral variables

B7B5	band 7 : band 5 (near infrared : red) ratio, ATM data
RED	red reflectance values, video data

APPENDIX 3

DISCRIMINANT ANALYSIS

Table A3.1 HEIGHT vs Environmental Variables, May Data

Canonical Discriminant Functions

Fcn	Eigenval	% Var	Cum %	Canon Corr	After Fcn	Wilks' Lambda	Chi Square	DF	Signif
					: 0	.7072	9.180	8	.3273
1	.4027	98.03	98.03	.5358	: 1	.9920	.213	3	.9754
2	.0081	1.97	100.00	.0896	:				

Standardised Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
LNCH4	0.839	0.623
MOIST	-0.835	0.649
PH	0.620	0.061
TEXT	0.381	0.139

Pooled-within-groups Correlations between Discriminating Variables and Canonical Discriminant Functions

	FUNC 1	FUNC 2
PH	0.298	0.186
MOIST	-0.482	0.827
LNCH4	0.455	0.764
TEXT	0.080	-0.173

Canonical Discriminant Functions at Group Means (Group Centroids)

GROUP	FUNC 1	FUNC 2
1	-0.570	-0.106
2	-0.157	0.085
3	1.068	-0.046

Table A3.2 Classification Results

		Actual Group Membership		
		Group 1	Group 2	Group 3
	Group 1	6 (66.7%)	7 (46.7%)	0 (0%)
Predicted	Group 2	2 (22.2%)	5 (33.3%)	1 (14.3%)
Group	Group 3	1 (11.1%)	3 (20. 0%)	6 (85.7%)
Overall Classification Accuracy 54.84%				

Table A3.3 HEIGHT vs Environmental Variables, July Data

Canonical Discriminant Functions

Fcn	Eigenval	% Var	Cum %	Canon Corr	After Fcn	Wilks' Lambda	Chi Square	DF	Signif
					: 0	.372	25.216	8	.0014
1	1.304	88.66	88.66	.7523	: 1	.8571	3.932	3	.2689
2	.167	11.34	100.00	.3780	:				

Standardised Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
LNCH4	1.034	-0.265
MOIST	-0.731	0.230
PH	0.605	0.837
TEXT	0.132	0.533

Pooled-within-groups Correlations between Discriminating Variables and Canonical Discriminant Functions

	FUNC 1	FUNC 2
LNCH4	0.661	-0.348
PH	0.311	0.795
TEXT	-0.078	0.355
MOIST	-0.189	0.229

Canonical Discriminant Functions at Group Means (Group Centroids)

GROUP	FUNC 1	FUNC 2
1	-0.855	-0.279
2	-0.253	0.636
3	1.749	-0.147

Table A3.4 Classification Results

		Actual Group Membership		
		Group 1	Group 2	Group 3
	Group 1	11 (78.6%)	3 (37.5%)	0 (0.0%)
Predicted	Group 2	2 (14.3%)	5 (62.5%)	1 (12.5%)
Group	Group 3	1 (7.1%)	0 (0.0%)	7 (87.5%)
Overall Classification Accuracy 76.67%				

Table A3.5 B7B5 (infrared : red Ratio) vs Agronomic Variables, April data

Canonical Discriminant Functions

Fcn	Eigenval	% Var	Cum %	Canon Corr	After Fcn	Wilks' Lambda	Chi Square	DF	Signif
					: 0	.3401	40.984	12	.0000
1	1.2083	78.77	78.77	.7397	: 1	.7510	10.879	6	.0922
2	.3070	20.01	98.78	.4847	: 2	.9816	.704	2	.7032
3	.0187	1.22	100.00	.1355	:				

N.B. Only first two functions used in further analysis

Standardised Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
HEIGHT	0.744	0.741
COVER	0.217	-0.689
WEED	-0.035	0.906
DAM	0.322	-0.083

Pooled-within-groups Correlations between Discriminating Variables and Canonical Discriminant Functions

	FUNC 1	FUNC 2
HEIGHT	0.917	0.156
COVER	0.831	-0.192
DAM	0.418	-0.141
WEED	-0.080	0.818

Canonical Discriminant Functions at Group Means (Group Centroids)

GROUP	FUNC 1	FUNC 2
1	1.737	-0.274
2	0.674	0.109
3	-0.597	0.687
4	-1.073	-0.653

Table A3.6 Classification Results

		Actual Group Membership			
		Group 1	Group 2	Group 3	Group 4
Predicted Group	Group 1	5 (62.5%)	2 (20.0%)	0 (0.0%)	0 (0.0%)
	Group 2	3 (37.5%)	6 (60.0%)	3 (23.1%)	2 (16.7%)
	Group 3	0 (0.0%)	2 (20.0%)	7 (53.8%)	1 (20.0%)
	Group 4	0 (0.0%)	0 (0.0%)	3 (23.1%)	10 (83.3%)
Overall Classification Accuracy 65.12%					

Table A3.7 RED vs Agronomic Variables, June data

Canonical Discriminant Functions

Fcn	Eigenval	% Var	Cum %	Canon Corr	After Fcn	Wilks' Lambda	Chi Square	DF	Signif
					: 0	.5078	20.672	8	.0081
1	.8826	95.03	95.03	.6847	: 1	.9559	1.376	3	.7112
2	.0461	4.97	100.00	.2100	:				

Standardised Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
HEIGHT	0.868	0.196
COVER	0.224	-0.805
WEED	0.464	-0.173
DAM	0.011	0.883

Pooled-within-groups Correlations between Discriminating Variables and Canonical Discriminant Functions

	FUNC 1	FUNC 2
HEIGHT	0.875	0.238
COVER	0.615	-0.341
DAM	0.408	0.710
WEED	0.213	-0.296

Canonical Discriminant Functions at Group Means (Group Centroids)

GROUP	FUNC 1	FUNC 2
1	0.933	-0.245
2	0.461	0.264
3	-1.143	-0.055

Table A3.8 Classification Results

		Actual Group Membership		
		Group 1	Group 2	Group 3
	Group 1	5 (50.0%)	4 (33.3%)	1 (7.7%)
Predicted	Group 2	4 (40.0%)	8 (66.7%)	4 (30.8%)
Group	Group 3	1 (10.0%)	0 (0.0%)	8 (61.5%)
Overall Classification Accuracy 60.00%				

Table A3.9 B7B5 (infrared : red ratio) vs Agronomic Variables, July Data

Canonical Discriminant Functions

Fcn	Eigenval	% Var	Cum %	Canon Corr	After Fcn	Wilks' Lambda	Chi Square	DF	Signif
					: 0	.3170	49.395	6	.0000
1	1.8318	94.15	94.15	.8043	: 1	.8978	4.635	2	.0985
2	.1138	5.85	100.00	.3197	:				

Standardised Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
HEIGHT	0.875	-0.697
COVER	0.253	1.065
WEED	-0.530	0.131

Pooled-within-groups Correlations between Discriminating Variables and Canonical Discriminant Functions

	FUNC 1	FUNC 2
HEIGHT	0.823	-0.225
WEED	-0.256	0.008
COVER	0.570	0.791

Canonical Discriminant Functions at Group Means (Group Centroids)

GROUP	FUNC 1	FUNC 2
1	1.483	0.264
2	0.337	-0.521
3	-1.562	0.142

Table A3.10 Classification Results

		Actual Group Membership		
		Group 1	Group 2	Group 3
	Group 1	9 (56.3%)	1 (7.7%)	1 (5.6%)
Predicted	Group 2	7 (43.8%)	10 (76.9%)	4 (22.2%)
Group	Group 3	0 (0.0%)	2 (15.4%)	13 (72.2%)
		Overall Classification Accuracy 68.09%		

Table A3.11 B7B5 (infrared : red ratio) vs Environmental Variables, April Data

Canonical Discriminant Functions

Fcn	Eigenval	% Var	Cum %	Canon Corr	After Fcn	Wilks' Lambda	Chi Square	DF	Signif
					: 0	.5831	12.675	8	.1235
1	.5372	82.29	82.29	.5912	: 1	.8964	2.571	3	.4625
2	.1156	17.71	100.00	.3219	:				

Standardised Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
LNCH4	-0.632	0.640
MOIST	0.985	0.574
PH	0.853	-0.142
TEXT	0.285	0.004

Pooled-within-groups Correlations between Discriminating Variables and Canonical Discriminant Functions

	FUNC 1	FUNC 2
PH	0.370	-0.316
TEXT	0.305	-0.119
MOIST	0.418	0.803
LNCH4	-0.295	0.773

Canonical Discriminant Functions at Group Means (Group Centroids)

GROUP	FUNC 1	FUNC 2
1	0.616	-0.420
2	0.584	0.430
3	-0.800	-0.007

Table A3.12 Classification Results

		Actual Group Membership		
		Group 1	Group 2	Group 3
Predicted	Group 1	5 (62.5%)	2 (25.0%)	0 (0.0%)
Group	Group 2	1 (12.5%)	3 (37.5%)	2 (16.7%)
	Group 3	2 (25.0%)	3 (37.5%)	10 (83.3%)
Overall Classification Accuracy 64.29%				

Table A3.13 B7B5 (infrared : red ratio) vs Environmental Variables, July Data

Canonical Discriminant Functions

Fcn	Eigenval	% Var	Cum %	Canon Corr	After Fcn	Wilks' Lambda	Chi Square	DF	Signif
					: 0	.3846	25.323	8	.0014
1	1.2705	89.74	89.74	.7480	: 1	.8732	3.593	3	.3089
2	.1452	10.26	100.00	.3561	:				

Standardised Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
LNCH4	0.958	0.390
MOIST	-0.746	-0.337
PH	-0.495	0.884
TEXT	0.680	0.304

Pooled-within-groups Correlations between Discriminating Variables and Canonical Discriminant Functions

	FUNC 1	FUNC 2
MOIST	-0.423	-0.088
TEXT	0.364	0.073
PH	-0.397	0.917
LNCH4	0.251	0.353

Canonical Discriminant Functions at Group Means (Group Centroids)

GROUP	FUNC 1	FUNC 2
1	-0.806	-0.256
2	0.068	0.488
3	2.270	-0.305

Table A3.14 Classification Results

		Actual Group Membership		
		Group 1	Group 2	Group 3
	Group 1	11 (73.3%)	3 (27.3%)	0 (0.0%)
Predicted	Group 2	4 (26.7%)	7 (63.6%)	0 (0.0%)
Group	Group 3	0 (0.0%)	1 (9.1%)	5 (100 %)
Overall Classification Accuracy 74.19%				