THE APPLICATION OF REMOTE SENSING IN THE ASSESSMENT OF PIPELINE CONSTRUCTION AND OIL SPILL IMPACTS ON FARMLAND IN GLENGARRY COUNTY, ONTARIO

by

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'We need authority that shall be jealous of the land, intolerant of its waste and defilement. All the world over there seems to be little conscience of this duty that man owes to the land, that he shall hand it on at least unimpaired to his successors.'

Sir Daniel Hall
1941
(cited in Bradshaw and Chadwick, 1980, p. 244)

Abstract

The construction of oil pipelines results in direct impact to the land. The objectives of this study were twofold: to assess the effects of pipeline construction and oil spillage to farmland in southeastern Ontario; and, to evaluate the extent to which remote sensing could be used in this assessment. The pipeline was constructed in 1975 and the spillage occurred in 1978. Results indicate that the right-of-way is still characterized by increased bulk density and pH levels, and decreased soil organic matter and crop yields relative to adjacent sites. Corn yields on the area affected by the oil spill were highly variable, with common patches of zero growth. The area has clearly not been restored to its original state of productivity.

The application of remotely sensed data was shown to be of some value in detecting, quantifying and recording these impacts. Archival aerial photography was used to examine pre-construction ground conditions. The analysis of large scale colour infrared (CIR) photography was found to be the best method of acquiring data relating to stress on vegetation resulting from the pipeline construction and oil spillage. MEIS (multi-detector electro-optical imaging scanner) imagery provided little additional information.

Résumé

La construction d'oléoducs affecte directement les terres. Cette étude se penche sur les effets causés par l'installation d'un pipeline et par un déversement d'huile, dans une région du sud-est de l'Ontario. L'oléoduc a été construit en 1975 et le déversement d'huile a eu lieu en 1978. Des analyses démontrent que les sols du droit de passage demeurent caractérisés par une densité apparente et un pH élevés, ainsi que par un contenu en matière organique et des rendements de culture diminués, par rapport à des sites adjacents. Les récoltes de mais à l'intérieur de la zone affectée par la fuite d'huile étaient très variables et plusieurs endroits ne présentaient aucune croissance. De toute évidence, la productivité de cette zone n'a pas été restaurée.

L'utilisation de la télédétection est valable afin de détecter, quantifier et enregistrer ces impacts. L'état du terrain précédant la construction de l'oléoduc a été examiné à l'aide d'images aériennes tirées d'archives. L'analyse de photographies infrarouge couleur à grande échelle s'est avérée comme étant la meilleure méthode d'acquisition de données relatives au stress exercé sur la végétation par l'installation de l'oléoduc et par le déversement d'huile. Les données MEIS (balayeur optoélectronique à barette) ont fourni peu de renseignements additionnels.

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I am grateful to Mr. G. Stadelmann of Glengarry County, Ontario, for his interest in the project and for allowing the research to be carried out on his property. It is hoped that rural landowners will derive some benefit from this examination of impacts due to pipelining.

Finally, I wish to thank my family and friends for their patience and support. Special thanks to S. Paul, E. Paul and S. Lipsey for making otherwise solitary fieldwork much more enjoyable.

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Table of Contents:

List of Tables:

List of Figures: * = photo + = grey scale plot

List of Figures: (continued)

chapter 1

INTRODUCTION

1.1 THE PROBLEM ADDRESSED

Soil degradation is a "result of one or more processes which lessen the current and/or potential capability of soil to produce (quantitatively and/or qualitatively) goods or services" (FAO, 1977). It is a subject of global concern. The stresses placed upon the land resource by increasing population, exploitive technology and the pursuit of economic growth contribute to degradative processes in varying degrees of severity throughout the world. Land degradation places at risk the very basis of our means of food production, and such threats must not be taken lightly. A general qualitative assessment of land degradation in the agricultural regions of Canada was prepared by Coote et al.(1981) and there has been increasing concern regarding land degradation and the need for conservation. Strategy statements have been presented by Agriculture Canada (Whelan, 1984) and the Agriculture Institute of Canada (AIC, 1985) before committees of the Senate (see Sparrow, 1984) and House of Commons respectively. They call for a halt to further degradation and encourage conservation and rehabilitation of our land resource.

Oil pipelines, an essential lifeline of our energy-dependent society, represent a specific hazard for the land through which they pass. There are two areas of concern: the impacts resulting from the pipeline construction *per se* and the more serious impacts that can occur in the event of oil spillage. Until recently, attention given to these impacts has been directed to areas where the concentration of oil production is greatest. Areas in Alberta, Canada's largest oil-producing province, and in the North have received the most attention (see Rowell, 1975, 1977; Toogood and McGill, 1977; McGill and Bergstrom, 1983). This is understandable in view of the magnitude of the hydrocarbon exploration and production facilities in these areas and the fragility and susceptibility of the northern ecosystems to long-term environmental impacts. However, it is important to realize that the farmlands of Eastern Canada are far from being immune to these hazards. Concern for specific ecosystems, such as the northern tundra or the coastal zones is justifiable: Canada's sensitive areas must be protected to ensure their continued viability. However, the effects of oil spillage along the thousands of kilometers of oil pipeline in Southern Canada must not be ignored. Inland spills rarely attract the public attention that is given to marine spills since they have a less visible impact on physical and biological resources and are usually on private, rural property. Nonetheless, the impacts resulting from construction and spillage are very real and may significantly affect soil productivity and, most importantly, crop yields.

This study has two objectives: firstly, to ascertain to what extent impacts to certain soil and crop parameters can be found on agricultural land affected by oil pipeline construction and oil spillage. Clean-up and rehabilitation of the disturbed areas may result in the impacts lingering for only a few years. This study, however, is concerned with the 'longer-term' residual effects after the initial 5 year period when concern for reclamation is greatest. The pipeline examined here was constructed in 1975 and the spill occurred in 1978. The secondary objective of this study is to determine to what extent remotely sensed data can be utilized in the detection and quantification of these impacts and the generation of visual records of both the degradation and rehabilitation of affected areas. It is not the intention of this thesis to criticize the manner in which reclamation or compensation have been dealt with. However, it is hoped that a candid examination of the problems of pipeline impact may focus attention on the need for long-term monitoring of affected areas.

1.2 THE STUDY APPROACH

This project was carried out using a multidisciplinary approach, bringing together the concerns of the environmental planner, the agronomist and the remote sensing specialist. The main steps involved in carrying out the study can be summarized as follows:

- delineation of a study site upon which to carry out the objectives of the research.

- compilation of all available information pertaining to the physical environment and land use of the study site, including archival aerial photography.

- identification of information required to fulfill the stated objectives.

- consultation with various federal and provincial government agencies to identify related concerns, streamline objectives and procedures, and discuss technical assistance.

- generation of new information (summer 1984) by fieldwork and aerial survey.

- analysis of field samples and remotely sensed data with respect to the stated objectives.

1.3 OUTLINE OF THE THESIS

The thesis report presents the results of research examining the following:

1- are residual impacts to certain soil properties and crop yield evident on farmland affected by pipeline construction and oil spillage ?

2- to what extent is remote sensing of value in the detection, quantification and recording of construction and spillage impacts ?

The study site is on private farmland in southeastern Ontario where construction of an oil pipeline was carried out by Interprovincial Pipelines Ltd. (IPL) in 1975 and the oil spillage occurred in 1978. It is thus an examination carried out 9 growing seasons following the construction and 7 growing seasons following the spill. The soil and crop parameters that have been selected for evaluation include bulk density, organic matter content, pH, crop height (for corn) and dry matter yield. These parameters have been used in previous studies by Mackenzie et al.(1976), Culley et al.(1982) and Stewart (1983) as an estimate of relative fertility and were found to be satisfactory as indicators of soil compaction and mixing resulting from pipeline construction. The current study examines a much smaller area in more detail than has been the case in previous studies. The assessment of the remotely sensed data focuses on archival black and white and colour infrared (CIR) aerial photography, and MEIS (multi-detector electro-optical imaging scanner) imagery obtained specifically for the project in 1984. Colour and CIR aerial photographs acquired in 1984 are also examined.

The thesis report is organized into six chapters. Chapter 1 introduces the reader to the general aspects of the research, and presents an outline of the report. The literature review in Chapter 2 provides an outline of the legislative framework related to oil pipelining and previous work carried out in three areas; pipeline construction impacts, oil spillage impacts and the role of remote sensing. Each has a distinct body of scientific literature. It is hoped that the broad nature of the literature review will facilitate a better understanding of the potential side-effects of pipelining and a more knowledgeable appreciation of the problems of reclamation. A detailed examination of the study site is attempted in Chapter 3: its location, physical characteristics and land use, followed by a description of the spill occurrence and a chronology of clean-up and rehabilitative measures. Chapter 4 provides a review of the methods utilized in the collection and analyses of the soil and crop samples, followed by a presentation and discussion of the results. Similarly, Chapter 5 looks at the acquisition and analyses of the remotely sensed data. In the concluding chapter there are comments on the findings and recommendations in relation to the stated objectives of the thesis.

chapter 2

LITERATURE REVIEW

2.1 IMPACTS DUE TO PIPELINE CONSTRUCTION

Canadians east of the prairie provinces are able to benefit from that region's oil resources by means of underground pipelines. By the very nature of pipeline construction it is expected that some impact will occur to the land which is traversed. The various 'pipelining' procedures such as clearing the right-of-way (ROW), trenching, hauling, laying out and lowering the pipe and backfilling the trench, all involve the use of heavy machinery which, depending on the climatic conditions and soil characteristics, will result in some forms of soil degradation. Energy 'corridors' have traditionally traversed rural, often good quality arable land. As concern for Canada's agricultural land resource base has mounted, national and provincial governmental agencies as well as industrial management have begun to pay closer attention to the impacts of pipeline construction on the productivity of agricultural soils, especially the productive agricultural regions of Southeastern Ontario (Shields, 1980; Culley et al., 1981, 1982).

Pipeline companies are regulated by the National Energy Board (the Board) for such activities as granting authorization to build or expand, and ensuring that regulations governing pipeline design, the protection of the environment and public safety are carried out. Guidelines and regulations for the construction and operation of pipelines have been set out by the Ontario Energy Board (1984) and the National Energy Board (1983c, 1984) with the aim of minimizing the impacts of construction. Numerous acts of federal and provincial (Ontario) legislatures give further weight to the authority wielded by the regulatory agencies:

<u>Federal</u> <u>legislation</u>:

National Energy Board Act, R.S.C. 1970, N-6,
as amended by SOR/78-926, 1978.

Environmental Contaminants Act, S.C. 1974-75, c.72

<u>Provincial</u> <u>legislation</u>:

Conservation Authorities Act, R.S.O. 1980, c.85

Environmental Assessment Act, R.S.O. 1980, c.140

Environmental Protection Act, R.S.O. 1980, c.141
as amended by Bill 143, 1981

Ontario Energy Board Act, R.S.O. 1980, c.332

Topsoil Conservation Act, R.S.O. 1980, c.504

Pipeline companies have worked towards developing a 'corporate awareness of environmental matters' supported by specialized expertise. Complex systems have been developed for managing environmental problems, including construction specifications and practices for protecting/mitigating environmentally sensitive aspects of the projects (TCPL, 1979; IPL, 1984b). However, even with a conscientious adherence to the regulations, some deleterious impacts are inevitable. It is the intention of the literature review to make the reader aware of the varied nature of these impacts. Due to practical limitations, however, not all of the impacts discussed in chapters 2.1 and 2.2 were tested for in this thesis.

2.1.1 SOIL COMPACTION

Given that pipeline construction involves the repeated passage of heavy machinery over the right-of-way (the area within which the construction activities are carried out), it is not surprising that compaction problems are a focus of landowners' concerns. The effects of compaction on soil productivity have been recognized and reviewed by Cannell (1977). A reduction in porosity restricts air and water movement in the soil, limits root growth and transfer of nutrients, and detrimentally affects crop growth. The rate of water infiltration may also be reduced, increasing surface runoff and the potential for accelerated erosion. The degree of susceptibility of a soil to compaction is highly dependent upon the moisture content which is related to soil texture and organic matter content. A sufficiently high moisture content, characteristic of soils with a high clay content, can cause the clay particle configuration to weaken. Simply stated, continued heavy construction traffic during periods of rainfall can lead to a degradation of the soil structure, converting the right-of-way (ROW) into a 'mud field' or 'quagmire'. Upon drying, the soil mass may form impervious cement-like chunks which hamper cultivation and are difficult to restore to good tilth. Moncrieff et al. (1983) related reductions in crop yields and plant heights to adverse soil structure and associated hydromorphic conditions found on a pipeline ROW in Ontario. Where no rehabilitation was carried out, the evidence of yield reductions was apparent even 25 years after the construction.

Compaction was a concern during the construction of the IPL line as finely textured, poorly drained clays were common in 3 of the 7 sections between Sarnia and Montreal, including section 6 in which the study site falls. During the construction of this section (December 1975-March 1976) through Leeds, Grenville, Dundas, Stormont and Glengarry counties, the monthly precipitation expressed as percentages of 30 year normals ranged from 100 to 150% (Culley et al., 1981). This combination of fine soils, heavy precipitation and heavy traffic would suggest a significant potential for compaction. Both bulk density and cone index values obtained with a penetrometer were significantly higher on the ROW for sites with fine textured soils including clay loam, sandy clay loam and silt loam. Sandy sites upon which similar tests were carried out exhibited no significant differences, although Stewart (1983) reported higher bulk densities on 3 IPL ROW soils including sand.

Wheel slippage has a detrimental effect on soil structure and texture (Raghavan et al., 1976; Culley et al,1981). Bulk densities were found to increase by up to 0.4 g cm^{-3} in sands and sandy loams and up to 0.2 g cm^{-3} in a clay soil for slippage rates of approximately 20%. Machinery operated at high slip rates (>20%) on wet clay soils (with a water content approaching the liquid limit) caused cement-like surface consistencies and reduced water permeability. Slippage of 30% and higher generally resulted in complete structural failure and deep rutting. Linear features such as tracks and ruts increase the potential for erosion by channeling water down slopes, especially before revegetation. Raghavan et al.(1976) have suggested that machinery should not be operated at slip rates exceeding 5-8%.

In their examination of the effects of heavy machinery on clay soils planted to corn, Raghavan et al.(1978) found delayed emergence and tasselling, and reductions in both ear yield and grain yield with increases in machine pressure and number of passes. Greenhouse experiments related to the IPL line (simulating the pressure exerted by a loaded pipe-hauling truck) indicated that compaction of both surface and subsoil in clays, silt loams and loams resulted in bulk density values of 1.1 - 1.3 g cm^{-3}, a range considered non-limiting to crop growth by Russell (1973). However, corn yield reductions of up to 17% were recorded and these were significant at all moisture levels (Culley et al., 1981). Critical bulk density values will be discussed in the context of the soil analysis results, presented in Chapter 4; however, it is clear that compaction of medium to fine textured soils may result in significant reouctions in agricultural productivity. Pipeline construotion during frozen ground conditions has been recommended on soils that are highly susceptible to compaction since frost penetration provides support for machinery (Shields, 1980).

Surface or subsurface drainage systems are subject to disturbance from construction when they are cut directly, collapse due to the weight of the heavy machinery, or are clogged with soil. Crop yields may be detrimentally affected by impeded drainage if the systems are improperly restored or left unattended.

2.1.2 SOIL MIXING AND STONINESS

Organic matter present in the topsoil has an important influence on crop vigour through its effects on nutrient levels, soil structure, water-holding capacity and root growth. A decrease in the amount of topsoil hampers seedbed preparation and increases erosion potential. To prevent continued reworking by the heavy equipment, the topsoil over the trench may be stripped and piled separately from the subsoil if requested by the landowner. The hazard inherent in this practice is in keeping the topsoil and the subsoil sufficiently separated so as to avoid mixing, often not practical when using a bulldozer for backfilling. Separate placement of the soil piles, while requiring more space and effort on the part of the contractor, is a worthwhile practice. Another conservation technique is to strip and separate the topsoil from the entire ROW. This decreases the risk of mixing but can increase the risk of subsoil compaction and damage to subsurface drains. During winter construction separation is not possible because of the fact that soil and subsoil are frozen. Compaction is less of a concern in winter, but 'dilution' of the topsoil over the trench is unavoidable. Presant (1975) observed that during the construction of almost every section of the IPL line the stripping and trenching operations were carried out more than 3 days ahead of the pipeline installation. In the event of heavy rains in an area with heavy clay subsoils, accumulation and channeling of water in the stripped area and trench was inevitable and side-wall caving, erosion, rutting and compaction also occurred. Indirectly, this resulted in further topsoil contamination with subsoil as some re-excavation of the trench was required.

Shields (1980) reported that mixing of topsoil with subsoil was the main cause of yield reductions over the trench and along the ROW of the IPL line. Culley et al. (1982) reported that subsoil from the IPL trench was spread across the ROW at most study sites, and that reduced organic matter content on the ROW adversely affected nitrogen status. Stewart (1983) stated that levels of organic matter on the ROW soils at all study sites on the IPL line for 1977 and 1978 were lower than on undisturbed soil, with trench zone levels amongst the lowest, indicating significant topsoil dilution. At the 0-15 cm and 15-30 cm depths a significant negative correlation between soil organic matter and bulk density was found at all but one site. Mackenzie (1978) suggested that reductions in topsoil organic matter may have contributed to the retarded silking of corn over the IPL trench. It seems apparent that topsoil conservation is of paramount importance in offsetting the effects of other construction-related soil problems.

The addition of cobbles or stones to the topsoil and upper subsoil may occur as a result of soil mixing during the trenching operation or when blasting through bedrock. There is usually a conscientious clean-up of larger stones from the surface during site restoration. However, if stones are not cleaned out of the subsoil to the depth of winter frost penetration they will be brought to the surface by cultivation and frost heaving for many years, with adverse affects on tillage machinery. Shallow soils over bedrock are a particular problem; the trench must be blasted through the bedrock and there is a risk of contaminating the topsoil with shot-rock fragments, which are difficult to remove and may be a hazard to farm implements and grazing animals. Contamination of the topsoil with rock fragments may also result in decreased moisture-holding capacity, thus impeding revegetation.

2.1.3 SITE RESTORATION AND MITIGATIVE MEASURES

Guidelines for pipeline construction and mitigative measures have been developed to minimize all of the potential impacts of construction previously mentioned. A summary review of the more common practices is presented here. More detailed information regarding these guidelines and mitigative measures can be found in the following reports: Mackenzie et al., (1976); Shields, (1980); Culley et al., (1981); and Ontario Energy Board (1984).

The Ontario Energy Board (1984) recommends that a 'topsoil inspector' be present at all times during stripping, excavation and backfilling to exercise control over the operations and prevent soil mixing. Topsoil should not be stripped when soil moisture conditions would lead to marked increases in soil density. It is the responsibility of the pipeline company to make the landowner aware of the potential impacts from construction, to obtain from him approval for construction practices and precautionary measures applying to his land, and to consult with him regarding exact methods of repair should damage occur. Terms of construction must be formalized prior to commencement of construction. The sequence of clean-up procedures, generally carried out during the summer following construction, includes drainage system repairs, the sealing of cut drainage tiles, subsoil and topsoil replacement, stone removal, fence rebuilding and revegetation. While a prompt, thorough clean-up following pipeline construction reduces the overall impact, unforeseen and often unavoidable circumstances can prolong yield reductions. Pipeline companies are generally held responsible for restoration and compensation until crop yields are restored to the satisfaction of the landowner.

While many variables influence the rate at which a site will respond to efforts at restoration, it is generally agreed that by carrying out a program of good soil and crop management, eg. sod crops, green manure, tillage, fertilizer, etc., the detrimental effects of pipeline construction will disappear after 'a few' years. However, even with these measures, Maclean et al. (1977) recorded numerous sites on the IPL line with problems of soil compaction, impaired soil drainage, decreased fertility arising from the loss of fertile topsoil and replacement with subsoil, and increased stoniness of the surface soil layer. Culley et al. (1982) reported that after 5 years, relative yields improved although reductions still persisted at most row-cropped sites, leading him to suggest that ROWs should be seeded with legumes rather than row-cropped and that particular emphasis should be placed on topsoil conservation. Mackenzie (1980) compared 1977-1979 corn yields at 5 sites on the IPL line and found that yields on the stony glacial till soils were markedly affected indicating that some soil physical problems remained.

Post-construction monitoring practices may currently include weekly passes of low-flying aircraft and linewalks at prescribed intervals. Abnormal surface conditions, such as visible crude oil, odours of crude vapour or withering vegetation generally result in swift action (IPL, 1984b). Environmental reports are required by the National Energy Board within 6 months of the granting of leave to begin construction, and by November 1 after the first full growing season following the post-construction report. This allows the maximum benefit of a full growing season to check any damage problems before they have progressed 'too far' (Maclaren Plansearch, 1984). Should unresolved issues remain the Board may require a second 'year-after' report be submitted for approval (NEB, 1984). Periodic monitoring of soil parameters could prove useful in determining the long-term effects of construction and the extent of recovery of productivity of the disturbed soils.

2.2 IMPACTS DUE TO OIL SPILLAGE

In Canada, the history of oil spills is as old as the petroleum industry itself, dating to the 1850's. The volume and frequency of spills have increased, not unexpectedly, with the growth of the petroleum industry. In Alberta, the country's major oil-producing area, spill volumes vary between 0.01% and 0.03% of total production (McGill and Bergstrom, 1983); an average of approximately 70,000 barrels per year. While the majority of land spills are under 100 barrels in size, each year a small number of spills of over 10,000 barrels occurs. The main sources of such spills according to Brushett (1975), are pipeline failures resulting primarily from internal corrosion and secondarily from external corrosion. Other additions of oil to soil and vegetation occur because of spillage at extraction, transportation and storage facilities. The land-use impacts caused at production facilitites often overshadow the effects of oil spillage: however, a review of these impacts is outside the scope of this report.

In 1974-75, pipelines released more than 50% of the volume of oil spilled in Canada accounting for approximately 8% of the spill events. McGill and Bergstrom (1983) suggest that, since corrosion is a major causative factor of spills, 'time' is contributing to the relative importance of pipelines as spill sources. An indicator of spill volume risk has been developed using average spill volumes as a function of pipe diameter, total pipeline lengths and sizes in each region, and probability of spill as a function of length (Mackay et al., 1974). The spill volume risk per unit of pipe length is greatest in Ontario. Land-use impact indices, to indicate the relative extent of potential land-use interference or reduction in land use options created by oil spills from pipelines, have been developed by McGill and Bergstrom (1983). These indices indicate that the potential for impact of pipeline spills on land use appears to be greatest in Ontario; perhaps understandably, as Ontario is the main oil-consuming province in Canada.

2.2.1 ADVERSE EFFECTS ON SOIL PHYSICAL CHARACTERISTICS

Oil spilled on land will spread over the surface and penetrate the soil. The degree of penetration is dependent upon the nature of the surface materials and the characteristics (type and volume) of the oil. Researchers in Alberta have defined a 'light' spill as less than 2.5% oil by weight in the plow layer, 'medium' as less than 6.1%, and 'heavy' as greater than 11.1% (NEB, 1978c).

Petroleum hydrocarbons are grouped into 4 basic classes (alkenes, naphthenes, aromatics and alkanes) according to the structural arrangement of hydrogen and carbon atoms (see

Rowell, 1977, for detailed description of the classes). These classes have different physical and chemical properties and are found in varying proportions in the different petroleum types. Crude oils are complex mixtures of hydrocarbons of different molecular weight and structure, and may contain up to 300 unique compounds. All crudes contain lighter fractions as well as heavier fractions (tar or wax), and their consistency can range from a light volatile fluid to a viscous semi-solid (Fingas et al., 1979). A low viscosity oil will rapidly infiltrate into a porous, sandy soil, thus reducing its rate of surface spread. A finer textured soil will resist penetration, and the spilled oil will continue its horizontal spread over a much larger area. The more viscous oils often form a tarry mass of limited spread extent when spilled. Oil leaving a pipeline will have a relatively low viscosity and may be at a temperature of up to 150 °F (Mackay and Mohtadi, 1975). However, spilled oil will typically saturate the upper 10-20 cm of agricultural soil, irrespective of the viscosity (Fingas et al., 1979). Penetration will be deeper in dry depressions, but will be halted if the depressions contain water. In the latter case, volatile components of the oil will immediately begin to evaporate creating a fire hazard. Rowell (1977) reports that with most crude oils losses of between 30-40% occur through volatilization. Schwendinger (1968) reported a similar range (36-41%) from laboratory testing. The rate and amount of oil lost by volatilization or evaporation depends on air temperature, wind speed, topography, quantity of oil spilled, depth of penetration, etc. There seems to be little restriction to free volatilization provided that the soil is cultivated to improve aeration and prevent formation of oily crusts at the surface.

Spilled oil has a tendency to migrate along artificial fills (pipeline trenches, utility ducts) as soil mixing often results in these areas being backfilled with material more permeable than the original soil. Penetration of the oil mass into the subsoil is influenced by such factors as the soil moisture content, depth to the water table, slope, the absorptive capacity of the soil (affected by soil texture, structure and organic matter content), as well as the quantity and type of oil spilled. Kloke and Sahm (1961) suggested that soils are able to absorb oil to a maximum of one third of the water held at field capacity, an approximation found reasonable by Rowell (1975). When the spill is on a slope, the oil will tend to flow downslope with only slight lateral spreading. With small quantities of spilled oil, or where the water table is low, the oil will usually dissipate during infiltration leaving behind a trail of immobile oil. Subsequent precipitation may cause further downward movement of the water soluble components of the residual oil. Generally, the oil mass will migrate until it is completely absorbed by the soil, halted by an impermeable layer, or reaches the groundwater. While Rowell (1977) found that there was little lateral or vertical movement of oil below the surface horizons in an experimental spill on a cultivated chernozem soil in Alberta, it was reported by Duffy et al. (1975) that the water-soluble components of crude oil are very persistent and may pose long-term threats to groundwater.

As crude oil infiltrates, it has a considerable effect on the soil structure and wettability. Dispersion of soil particles and a complete structural breakdown has been reported by Plice (1948) and Odu (1972). Rowell (1977) suggests that the oil entering the soil displaces the air and water from the soil pores, with the solvent properties of the lighter oil fraction possibly enhancing dispersion by dissolving gums and waxes that tend to cement aggregates, causing a drastic reduction in water infiltration. Plice (1948) found that once heavily oiled soils wet up, they remain wet. Rowell (1977) has suggested that the macropores between the soil aggregates are filled with a hydrophobic layer preventing wetting of the aggregate centres. Production of poor soil structure, crust formation (a consequence of clean-up techniques such as burning) and waterlogging all reduce the rate of gas exchange and promote anaerobic conditions. This will be considered in greater detail when discussing the impacts of oil spillage on the microbiological processes. The thermal regime in soils is also affected by oil spills, with decreases in albedo and evapotranspiration, and increases in infrared re-radiation from the ground surface and downward soil heat movement (after McGill and Bergstrom, 1983).

2.2.2 ADVERSE EFFECTS ON SOIL MICROBIOLOGICAL AND CHEMICAL PROCESSES

It is generally accepted that the cultures capable of attacking crude oil or its fractions are ubiquitous in soil, and that microbial activity is stimulated by the addition of petroleum hydrocarbons (Baldwin, 1922; Plice, 1948; Ellis and Adams, 1961; Schwendinger, 1968; McGill, 1977; Rowell, 1977). Reported increases in microbial numbers have ranged from slight to over fifty-fold, although the number of microbial types was found to be reduced by larger applications of crude petroleum. Generally, a short lag or reduction in microbial numbers is apparent shortly after contact with oil, considered to be due to the toxic fractions in the oil killing or inhibiting certain microorganisms (Rowell, 1977). A rise in numbers follows until a maximum is reached, then a decline as the oil and nutrients are depleted.

Since the early 1900's, more than 100 species of soil bacteria, actinomycetes and fungi, representing at least 30 genera, have been described that are known to attack one or more kinds of hydrocarbons and are, with very few exceptions, aerobic organisms (Ellis and Adams, 1961). When anaerobic conditions are created by the oil displacing the soil air, Harper (1939) observed a shift from aerobes to facultative anaerobes in the microbial population. According to E.W. Russell (1973), even short periods of anaerobic conditions can result in a loss of structural pores, perhaps because these conditions may encourage bacterial degradation of polysaccharide gums into molecules unable to bond soil particles. Anaerobic organisms utilize petroleum molecules with difficulty, as they have a metabolism rate 10% that of aerobes. This is an important factor to consider during reclamation, since aerobic conditions will hasten decomposition and soil recovery. Organisms which utilize hydrocarbons as their sole energy source are uncommon, reflecting the rarity of these organic molecules in a typical soil. However, many organisms which generally utilize other organic compounds can adapt their metabolism to a hydrocarbon (Schwendinger, 1968).

Measurements of the respiration of soil containing oil show a direct relation to the microbial numbers; ie. a rapid rise and later slow decline (McGill et al., 1981). Schwendinger (1968) found that the production of carbon dioxide rose steadily as the oil content was increased to about 5.5% by weight, but dropped at a rate of about 8.5%. He attributed this to the anaerobic conditions at high oil contents. McGill et al. (1981) attributed the decline in respiration to the complete decomposition of the oil fractions, the limited availability of nitrogen and phosphorous, with hydrocarbons inhibiting nitrification and, to a lesser degree, ammonification of the soil. Murphy (1929) found that 0.4% crude oil by weight reduced nitrification by 50%, and that it was completely inhibited by 1% oil content. Baldwin (1922) reported that while the extent of this inhibition was dependent on the rate of, and time since, the application of oil, all soils eventually recover their nitrifying ability. McGill et al. (1981) could not detect nitrifying organisms in freshly oiled soils, and found that the numbers of nitrifiers only began to increase after germination, plant growth and soil wettability had returned to normal. Increases in total nitrogen during oil decomposition have been attributed to increased (di)nitrogen fixation, reported for Pseudomonas, Methanobacterium and an Azotobacter species growing on a hydrocarbon medium (after McGill et al., 1981). An interesting occurrence reported by Ellis and Adams (1961) is that of large numbers of bacteria that oxidize volatile hydrocarbons being found in the surface soil near oil fields. Their presence, in definite patterns of distribution, form the basis of the 'geomicrobiological' oil prospecting method (Zobell, 1945). However, little success has been reported in discovering new oil fields using this procedure.

The relative amounts of the various end-products of decomposition remaining in the soil will depend on the environmmental factor controlling their growth rate. One important point to consider, which contributes to the understanding that oil spillage can ultimately improve soil conditions, is the addition made to the soil organic matter content ('incorporation into soil humus'). Initially, organic solvents may serve to keep separate the added oil from the in situ soil organic materials. However, as the oil is gradually broken down and less hydrocarbon can be extracted, the residual oil is transformed into more stable soil organic matter fractions. Incorporation of these fractions into the soil through the long-term formation of humic materials can result in an improvement of soil aeration and water-holding characteristics and a reduced erodibility. Jobson et al. (1972) found the residue of oil decomposition products to be closely related in structure to soil humic acid. Large increases in total organic matter, total carbon and total nitrogen have been reported for soils affected by petroleum (Plice, 1948) and natural gas leaks (Harper, 1939; Adams and Ellis, 1960).

Investigations into the effect of oil on soil pH are inconclusive. Ellis and Adams (1961) found that products of petroleum saturation tend to buffer the soil toward more neutral pH values, while McGill et al. (1981) argued that organic acid production during hydrocarbon decomposition under conditions of reduced aeration would increase soil acidification. Reduced aeration lowers the oxygen level and decreases the reduction-oxidation (redox) potential (Plice, 1948; Ellis and Adams, 1961).

2.2.3 ADVERSE EFFECTS ON PLANT GROWTH

Oil may affect plant growth in a variety of ways. It may directly kill a plant on contact, or inhibit vegetation growth due to its toxic effects. Oil can inhibit seed germination and create nutrient deficiencies due to the immobilization of nutrients during microbial degradation. At low concentrations oil may serve to stimulate growth (Carr, 1919). However, the stimulatory effects of oil spills cannot be counted upon, since they only result from low level applications of specific organic compounds in petroleum occurring in very minor spill events (McGill, 1977).

The degree of hydrocarbon toxicity generally decreases with an increase in molecular size and increases with the degree of oxidation within each hydrocarbon class, eg. fuel oils are more toxic than unrefined oils (McGill et al., 1981). According to Toogood and McGill (1977), however, refined oils are generally less toxic because the refining process removes many potentially toxic compounds. Branched compounds are slightly less toxic than straight-chain forms, due to a lesser ability to penetrate the plant tissues. The initial impact of the oil on plant growth depends not only on the type and volume of oil, but on the ability of the plant to intercept or resist oil, a factor influenced by leaf size, angle and degree of pubescence (assuming an above-ground spray of oil), rooting system, etc. Seedlings, annuals, shallow rooting species and plants with large surface areas or without rooting systems, such as lichens and mosses, are most susceptible. The more resistant plants include those with taproots and plants with thick, waxy cuticles (xerophytes). Deciduous species are generally more at risk than conifers. Plants with higher stomatal densities absorb the greatest amounts of oil and the effects are most severe on hot, sunny days when stomata are open.

At high levels of contamination, seed germination may be inhibited by the oil soaking through the outer layer of the seed. At lower levels, germination and subsequent growth may be retarded due to interference with the seeds ability to imbibe moisture from the soil. There is a wide variation in the ability of species to germinate in the presence of oil (Murphy, 1929; Ellis and Adams, 1961; Schwendinger, 1968; Rowell, 1975; de Jong, 1980). Kloke and Leh (1963) found that oils of low viscosity delay germination to a greater extent than high viscosity oils because lighter oils are more uniformly dispersed. The variation in the effects on different plant species has permitted the use of petroleum oils in low concentrations as selective herbicides (Currier and Peoples, 1954). The herbicidal potency of oil results from damage to the cell membrane with subsequent leakage of cell contents. Photosynthesis is reduced as a result of oil blocking the stomata and intercellular spaces (Baker, 1970). Carr (1919) reported that the growth of soybeans was apparently improved when a small amount (up to 0.75%) of oil was added to a 'sandy peat', but that the plants began to die at 4%. Murphy (1929) reported less than 4% germination rate for wheat on a fine sandy loam at oil contents greater than 1.7% by weight. Schwendinger (1968) reported a somewhat higher germination rate (25%) for oats on a loamy sand at an oil content of 5.0%. Rowell (1975) found that germination was unaffected by oil contents up to and including 4% by weight, but at 8% oil content germination was completely inhibited. Rowell (1977) found that a 2% paraffinic oil had a deleterious effect on the germination of barley, flax and rapeseed. Rapeseed was found to be particularly sensitive and showed no germination at all even after 4 years. It is clear that seed germination in mineral soils will be significantly affected at oil contents as low as 2-4% by weight: higher values (up to 15%) can be tolerated in organic soils (Nyborg and McGill, 1975).

Increases in manganese and iron concentrations in soils affected by oil have been attributed to the increased solubility of these minerals in reducing conditions which may develop as a result of oil spillage. Such increases have been reported by Schollenberg (1930) and Adams and Ellis (1960). The Fe/Mn ratio for maximum plant growth should be between 1.5-2.5:1 (Somers, Gilbert and Shive, 1942). Black (1968) reported that even 4 ppm of exchangeable Mn would result in reduce yields of soybean and barley, and that corn tolerance was at 15 ppm. Morris and Pierre (1949) found that 1-10 ppm damaged legume stands. Udo and Fayemi (1975) found an Mn concentration of 99 ppm at 8.5% oil content resulting in Mn toxicity since all Fe/Mn values were below 1.

Increases in organic C and total N as a result of oil contamination were generally reported throughout the literature. Increases in N of up to 62% were found in soil with a 10.6% oil content, while the increase in organic C at the same oil content was 470% (Udo and Fayemi, 1975). The high C level, resulting from the carbon in the oil, produces very high C/N ratios (up to 53.3 at the 10.6% oil level). Odu (1972) reported C/N ratios nearing 100 for an area in Nigeria affected by an oil well blowout. Such high C/N ratios may lead to immobilization of soil nitrates and low nitrate N levels. A reduction in the extractable phosphorous at oil levels above 4.2% was noted by Udo and Fayemi (1975). This occurs because the hydrocarbon-attacking microorganisms immobilize the inorganic P in the soil.

It seems clear from the literature that the addition of oil to the soil contributes significantly to poor plant growth as a result of Mn toxicity, P and N immobilization, and reduced oxygen availability to plant roots due to the displacement of air by oil or by increased microbial activity. However, upon decomposition of the hydrocarbons, increased organic matter and atmospheric nitrogen fixation may improve soil structure and increase fertility. Reclamation techniques aimed at hastening decomposition can speed recovery of the soil and a return to the original, or potentially more productive condition.

2.2.4 RECLAMATION OF SPILL SITES

The primary effect of oil spillage on soils in an agricultural area is the reduction in productivity of the area for crops or forage. Depending on the volume of oil spilled and the reclamation efforts, the damage effect can last for up to 25 years or more (McGill and Bergstrom, 1983). The long-term effects on vegetation result from soil structural damage, reduced wettability and nutrient deficiencies. While a stress factor such as oil spillage may change the soil system in the short-term, the soil will eventually return to its original condition as long as the soil forming factors of climate, parent material, vegetation and topography remain constant. Often the landowner is not willing to wait for this length of time and so various procedures to speed recovery have been developed. There can be no cook-book approach to restoration, and each spill must be considered as site-specific with a program of reclamation efforts tailored to the particular edaphic, climatic, and spill characteristics.

The initial clean-up of standing oil following a spill may involve draining and collecting the oil, removal and replacement of the contaminated soil or dilution with uncontaminated soil. Burning is often carried out to remove any remaining free oil and many of the volatile fractions. However, burning has been found to create structural problems in the soil. A crust of tarry residue may remain which can seal the surface and reduce gas exchange and seedling root penetration (McGill, 1977). The burning of organic litter has been found to vaporize hydrocarbon fractions, which are then translocated downwards and form a water repellant layer when they condense (Debano et al., 1976). Incomplete burning may only partially destroy some petroleum products, or rearrange them into phyto-toxic compounds by pyrolysis. Burning is usually followed by discing or ploughing to break up the crust. Deeper ploughing using chisels or moles can be of advantage in reducing the bulk density of the soil, promoting volatilization of the hydrocarbons, and increasing the exposed surface area of the oiled soil for microbial activity thereby improving water and oxygen movement. On poorly drained soils, drainage (followed by tillage) may improve aeration and thus encourage gas exchange.

The addition of oil-degrading microorganisms to the soil has met with a mixed response. Schwendinger (1968) found that by adding the bacteria Cellulomonas to soils with high levels of oil contamination, decomposition of the oil was hastened. Others have reported only slight increases in decomposition rates with the addition of mixed cultures of microorganisms (Jobson et al., 1974). McGill (1977) suggested that this technique be limited to some very acidic sandy soils and some very acidic peats, since hydrocarbon-utilizing microorganisms are (practically) ubiquitous in most other soils.

In some cases, areas affected by low levels of oil contamination may be naturally revegetated without any special treatment (Odu, 1972): soil cultivation without fertilization is sufficient to reclaim mineral soils in a short period of time (Plice, 1948). However, in the case of larger spills, several studies have shown that the addition of nitrogen and phosphorous fertilizers was beneficial in that it increased numbers of bacteria, improved the decomposition of the crude oil and restored the C/N balance (Schwendinger, 1968; Jobson et al., 1974; Gudin and Syratt, 1975). It is difficult to determine the nitrogen demand for optimum decomposition rates because it is a function of such factors as the rate of decomposition and leaching of individual oil components and the rate of release of nutrients from the soil minerals and organic matter and their uptake by plants. In general, the requirement for added nutrients is reduced as the organic N content increases, and the amount of oil that can be added to the soil before deleterious effects occur is increased (McGill, 1977). In some poorly drained soils where nutrient additions increase microbial activity and hence the biological oxygen demand of the soil, anaerobic conditions and acidification (the production of toxic organic acids and sulphides) may be encouraged (Smith and Dowdell, 1974), necessitating the use of lime to maintain a neutral pH.

After the initial loss of the volatile fractions, oil toxicity has not been found to be a factor limiting vegetation regrowth. However, the continuing interference with nutrient availability and water relations can adversely affect plant growth. Therefore by supplying nutrients in sufficient quantity to promote oil degradation and encourage plant growth, and by maintaining a favorable pH and water regime, the re-establishment of vegetation can be accelerated. Plant types better suited to oil-contaminated soil were discussed earlier. Gudin and Syratt (1975) have suggested a vegetative cover of legumes to improve the rhizosphere, as they are not dependent on soil nitrogen for which microorganisms compete. In the absence of any restoration program, McGill (1977) agrees that legumes will be among the first invaders for that reason, but legumes need not necessarily be considered over other crops so long as the affected area is carefully managed.

De Jong (1980) noted the procedure for improving aeration and applying nitrogenous fertilizers may be difficult to implement when oil is present in the subsoil. As the oil is not uniformly distributed, anaerobic micro-sites may still be present to some depth. In his studies, available nitrogen in the subsoil was found to be below the optimum level for microbial degradation of the oil. It is difficult to incorporate fertilizers at these depths. To remedy this situation, de Jong suggested that the fertilizer be incorporated in the topsoil immediately following harvest, so that maximum nitrate-N would be leached downward with soil moisture recharge during autumn and early spring. Subsoil temperature may also be a factor limiting microbial activity. Gudin and Syratt (1975) recommended covering the affected areas with black polyethylene sheeting in winter to increase soil temperatures, and covering dry areas in summer with transparent polyethylene to reduce evaporation losses.

In summary, it is generally agreed that the application of oil, unless in very small amounts, will have an initial negative effect on soil structure and wettability characteristics, hindering plant growth through the formation of anaerobic and hydrophobic conditions that interfere with soil-plant-water relationships. Subsequent microbial activity, encouraging humus formation and nutrient availability, may promote an improved soil physical and chemical status. Reclamation procedures aimed at improving aeration and nutrient supply will, in many cases, hasten this process and pipeline companies are continuously updating their contingency plans to deal with oil spills (IPL, 1984a). Oil spill impacts and reclamation efforts specific to the study site will be discussed in chapter 3.4.

2.3 THE ROLE OF REMOTE SENSING

Applications of remote sensing techniques to land resource studies are extensive, both in the range of sensors utilized and the problems addressed. The review of literature presented here will focus on agricultural and environmental applications.

Radiant energy received on a plant canopy is absorbed or reflected within the internal cell structure of green plants. Variation in such plant characteristics as leaf orientation, pigmentation and physiology can alter a plant's ability to absorb or reflect energy (Bauer, 1975). Plant leaves typically have a low visible reflectance due to absorption by chlorophyll. An increase in the near infrared reflectance has been associated with plant maturity peaking with maximum foliage development (Sinclair et al., 1971). Gausman et al. (1972) related this to the greater number of IR-reflective intercellular air spaces in the mesophyll of the mature leaves, compared to the more compact structure of young leaves. As plants senesce there is a decrease in the infrared reflectance related to the decrease in chlorophyll content, and an increase in the visible reflectance (Swain and Davis, 1978; Mack et al., 1980). Each plant type can be distinguished by a characteristic spectral 'signature', although the reflectance of a canopy is influenced by shadows, background soil reflectivities and the non-uniformity of incident solar radiation (Knipling, 1970). Stress has a direct influence on a plant's physiological development and reflectance characteristics by suppressing growth or changing leaf orientation. Information about soil and subsurface conditions, drainage patterns and the impact of pollutants can be obtained through an assessment of the vegetative cover. The ability of remote sensing to be used in the collection of baseline data (inventory, yield) and to monitor change via multitemporal studies has made it a valuable tool for environmental and agricultural monitoring and impact assessment (Sayn-Wittgenstein and Aldred, 1976; Gwynne, 1983).

Colwell (1956) produced one of the earliest reports on the ability of aerial colour infrared (CIR) film to record changes in crop reflectance resulting from stress (stem rust). CIR photography is now routinely used to detect crop stress (Wallen et al., 1977; Basu et al., 1978; Toler et al., 1981). The assessment is carried out visually or by means of a densitometric analysis of film transparencies. Singhroy (1984) reported a positive correlation between optical density readings and field estimates of corn and soybean yield. He pointed out, however, that the correlation may not always be reliable since the film density can be influenced by field conditions and crop phenology which do not necessarily affect yield. Crown (1979) found that CIR photography provided the best colour and textural detail of any film type in a study of alfalfa vigour in Alberta. With respect to the assessment of agricultural land following pipeline construction, it is clear that CIR photography can be used to obtain an indication of crop stress and subsequent crop growth improvement relative to an unaffected area. Problems associated with the use of high altitude CIR film due to atmospheric scatterring, and the use of compensating filters have been reviewed by Pease and Bowden (1969) and Worsfold (1972).

Remote sensing can also make a significant contribution to the various phases of route (pipeline, electrical transmission line) selection, construction and post-construction monitoring of impacts and rehabilitation efforts. Appropriate sensor/scale combinations can be utilized to acquire land-use/cover information on a regional or site specific level. Graham (1975) reported on the utility of airborne colour and CIR photography in locating subsurface drainage systems as an aid to route selection. Dubois et al.(1981) and Klunder and Arend (1982) found that colour and CIR aerial photos at scales ranging from 1:5,000 to 1:60,000 were useful in powerline right-of-way selection and impact analysis. The use of multitemporal colour and CIR photography to record ground conditions prior to construction for reference purposes and during and following pipeline construction is strongly encouraged by Aird (1981). Remote sensing in conjunction with field studies is a useful tool in determining whether the impacts predicted in the environmental assessment actually accurred and whether the proposed mitigative measures proved to be effective. Grumstrup et al.(1982) found that aerial colour photography provided a sound data base for assessing the impact of electrical transmission structures on agricultural land in the U.S. Midwest. Morton et al.(1979) found CIR photography at the 1:5,000 scale to be the most suitable type of imagery for locating rural gas pipelines in Alberta installed before 1975. Prior to this date pipeline location plans were not required to be submitted to the Alberta Energy Resources Conservation Board.

Large scale aerial imagery (70 mm stereo photography and airborne video) offers the most practical and economical methods of pipeline monitoring during and after construction. Both types of imagery are commonly used by the pipeline companies and regulatory agencies (Singhroy, 1984). They provide general information for monitoring the progress of ground operations. CIR photography (70 mm vertical and oblique) taken before and during construction provides a record of any reduction in crop vigour along the right-of-way. Taken after the clean-up, the moisture-responsive CIR photography can provide information regarding subsurface drainage disturbance, ponding and rutting due to compaction and machinery traffic. Crop development can be monitored throughout the growing season with sequential CIR photography, which is invaluable in the detection and delineation of stress factors and yield variation.

The NASA Landsat satellite, first launched in 1972 as the Earth Resources Technology Satellite (ERTS), demonstrated the ability to carry out multispectral (MSS), multitemporal studies from space. The MSS data are available on a regular basis for single band or multiband colour composites simulating CIR photography, or on digital computer compatible tape (CCT) facilitating data manipulation and analysis. Landsat MSS bands, either singly or in combination (differences, ratios, etc.) have proven to be useful in monitoring green vegetation (Gausman et al., 1973; Richardson et al., 1975; Richardson and Wiegand, 1977; Tucker, 1979). Landsat-4 launched in 1982, and more recently Landsat-5 launched in July 1984, carried into orbit a Thematic Mapper (TM) that improved the spatial, spectral and radiometric resolution of earlier Landsat data. Prelaunch simulations concluded that the TM would produce more than ten times the data of the MSS due to the increased ground resolution (30 m as compared to 80), and band radiometric quantization levels (256 as compared to 64) (Tucker, 1978; Staenz et al., 1980). A comparison of the Landsat MSS and TM bands and their characteristics is provided in table 2-1.

table 2-1 SPECTRAL SENSITIVITY OF LANDSAT MSS AND TM BANDS AND THEIR USES

LANDSAT MSS	(μm)	THEMATIC MAPPER	(μm)
-		TM1	0.45 - 0.52
MSS 4	0.50 - 0.60	TM2	0.52 - 0.60
MSS 5	0.60 - 0.70	TM3	0.63 - 0.69
MSS 6	0.70 - 0.80	TM4	0.76 - 0.90
MSS 7	0.80 - 1.10	-	
		TM5	1.55 - 1.75

<u>band</u> <u>characteristics</u> (Brown et al., 1983; Godby, 1984):

TM1: sensitive to chlorophyl absorption; useful for water penetration and for soil/vegetation discrimination.

TM2: sensitive to chlorophyl absorption; useful for measurement of visible green reflectance peaks of vegetation for assessment of vigour.

TM3: sensitive to chlorophyl absorption; useful for vegetation, brown biomass discrimination.

TM4: useful for determining green biomass content and delineating water bodies.

TM5: useful for vegetation density, soil and leaf moisture content differentiation.

Research has shown that the Landsat MSS bands were too wide to detect important shifts in vegetation spectra resulting from senescence and stress (NRC, 1976). Senescence results in a reduction in reflectance at wavelengths less than 0.55 μm and an increase at higher wavelengths. 0.55 μm is approximately the mid-point of MSS band 4 sensitivity therefore senescence changes could pass undetected since the total return remained nearly constant: the decrease in energy at wavelengths less than 0.55 μm compensated by the increase at larger wavelengths. A narrower band with a cut-off at 0.52 μm was incorporated in the TM to improve the capability for studying vegetation. The wide MSS band 5 (0.60-0.70 μm) was modified for similar reasons. Changes in crop response produce different and opposite effects in the red and near-IR portion of the spectrum, and so the limits of the TM band 3 were set at 0.63 μm and 0.69 μm so that it was responsive only to the IR effects. MSS bands 6 (0.70-0.80 μm) and 7 (0.80-1.10 μm) were found to contribute little useful information (after NRC, 1976). A single band (TM4, 0.76-0.90 μm) was favoured for above-ground biomass estimates, eliminating wavelengths between 0.90 and 1.10 which are affected by water vapour absorption in the atmosphere. The establishment of a new IR band, TM5 (1.55-1.75 μm), was viewed positively by many researchers due to its sensitivity to leaf water content (Ahern et al., 1983).

In order to reduce the amount of data for analysis, studies have attempted to define a subset of TM bands as indices to be used in feature selection (Haas and Waltz, 1983; Perry and Lautenschlager, 1984). Staenz et al.(1980) using ground spectrometric measurement of 9 common crop types and 1 soil type found that TM bands 1 through 3 provided similar information allowing for interchange of each, while TM4 and TM5 each provided spectrally unique data sets which, in combination with any of the absorption-dominated bands, provided useful information about the soil background. Bernstein and Lotspeich (1983) found similar results using a TM image of an urban area. Kimes et al.(1981) and Markham et al.(1981) reported that, for corn, a significant relationship exists with the integrated red and IR spectral radiances (normalized difference of TM3 and TM4) and such agronomic variables as total wet and dry biomass, grain yield, plant height and percent canopy cover. Tucker (1979) found the NDVI (Normalized Difference Vegetation Index), the transformed vegetation index and the square root of the IR/red ratio to be the most significant in evaluating similar agronomic variables. Colwell (1983) found the overall quality of TM data to be excellent with improved texture and tone contrast and sharpness of feature boundaries. The improved spectral and spatial characteristics allowed for improved spectral characterization of individual features as a result of the reduction in measurement errors when the number of boundary pixels is reduced. Haas and Waltz (1983) found that the improved spatial resolution facilitated a more efficient visual interpretation of land use and vegetative status.

Landsat has been found to be a valuable tool for power companies in transmission line routing (NASA, 1982). Singhroy (1984) suggested that geometrically corrected 1:250,000 scale Landsat MSS colour composites and TM data at 1:100,000 can be used in conjunction with existing resource maps and field data for pipeline route selection. TM data could be used to study current land cover and construction-related geological structures, such as fractures, folds and outcrops. He also suggested that terrain roughness, steep gradients and shallow soils over bedrock could be recognized through the visual interpretation of SEASAT-synthetic aperture radar (SAR) data. Alfoldi and Prout (1982) examined the use of satellite data for the surveillance and monitoring of oil spills. However, their analysis is restricted solely to marine spills. The quality and impact of Landsat images can be improved by using such techniques as band ratioing and standard reflectance enhancements (Ahern, 1983).

The Canada Centre for Remote Sensing (CCRS) has recently developed an airborne sensor which can simulate the spectral characteristics of the TM sensor, among others. The multi-detector electro-optical imaging scanner (MEIS II), as described by McColl et al.(1983), is a 'pushbroom' sensor with 5 channels covering the visible and near IR regions of the spectrum with provision for 3 additional channels to extend the range. The MEIS channels correlate with the TM and MSS bands in the following manner:

MSS	TM	MEIS	band center (nm)	width (nm)	range (nm)
-	1	0	487	67.5	455.25-522.75
4	2	4	573	88	517-605
5	3	7	664	53	634.5-687.5
6	X	6	769	36	751-787
7	4	1	843	155	747.5-902.5

The 'pushbroom' concept uses a fixed linear array to image a line on the ground orthogonal to the flight path, allowing the forward motion of the aircraft to sweep out the second dimension of the image. This appears to have some advantage over the conventional scanning imagers which use a single detector and a moving mirror to provide the image line scan (McColl et al., 1983). The term 'scanner' is thus a misnomer as it suggests a sequential sampling of the pixels in an image line. MEIS carries out a virtually simultaneous sampling of all pixels on the line, within the constraints of the pulse propagation speed, using a 'fixed' array of detectors ensuring good geometric accuracy (Till et al., 1983).

CCRS has utilized its airborne MSS rotating mirror line scanner for numerous agricultural applications including crop classification and yield estimation (Ryerson et al., 1978; Brown et al., 1983). Tests results have shown that MEIS II has improved radiometric and spatial precision (Till et al., 1983). The spectral band pass of each channel is selected by interchangeable filters (more than 20 are presently available) greatly increasing its operational capability and flexibility to simulate satellite sensors. More detailed information on MEIS II will be given in Chapter 5 - analysis of remotely sensed data.

chapter 3

THE STUDY AREA

3.1 LOCATION AND RATIONALE FOR SELECTION

The area examined in this study falls within the pipeline 'corridor' which stretches from Sarnia, Ontario to Montreal. This corridor which runs parallel to highway 401 includes a pipeline constructed during the period September 1975 to March 1976 by Interprovincial Pipelines Ltd. (IPL), and two earlier pipelines running adjacent to it. The study site lies completely within section 6 of the Sarnia - Montreal line, and is situated in Glengarry County, southeastern Ontario, north of the town of Lancaster in the Ottawa-St. Lawrence Lowlands (see location map-fig. 3.1). The term 'study site' used in this report will refer to the four fields in which the field work was carried out (see fig. 3.2), while the 'study area' refers to the general area in which the study site is located.

The study site was considered to be ideally suited for the examination of the impacts resulting from pipeline construction and oil spillage: the pipe was installed in 1975-76 and spillage occurred in 1978. Its close proximity to both Montreal and Ottawa facilitated fieldwork by the researcher and acquisition of remotely sensed data by the Canada Centre for Remote Sensing (Ottawa). Access to the affected fields was granted by the landowner. As the site has been of interest to various governmental agencies since the spill incident in 1978, archival material, both documentation and aerial photography, was accessible. The frequency of reported spill events in Eastern Canada is relatively low, and the Glengarry site selected provided a unique opportunity to carry out the stated objectives of the thesis.

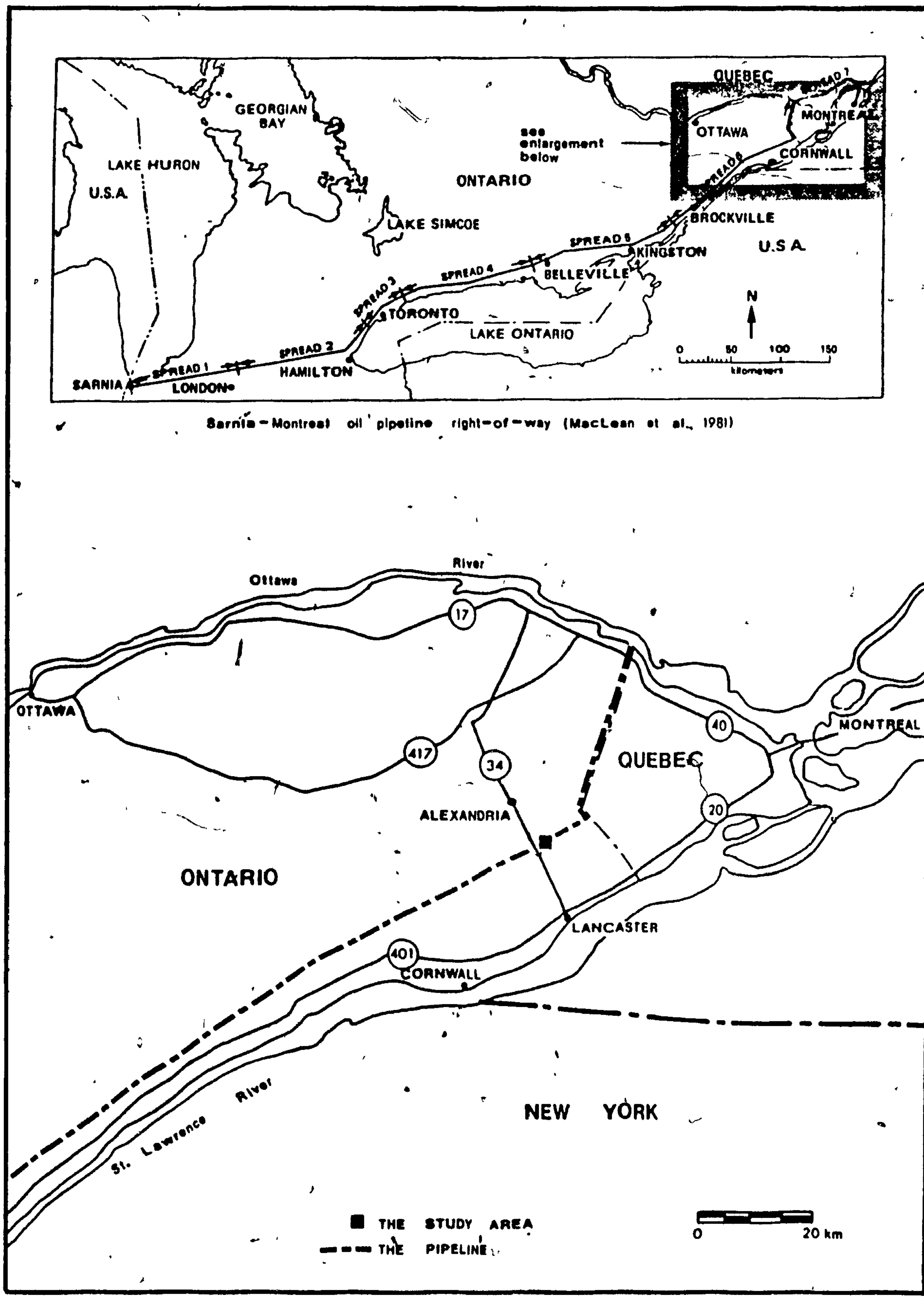
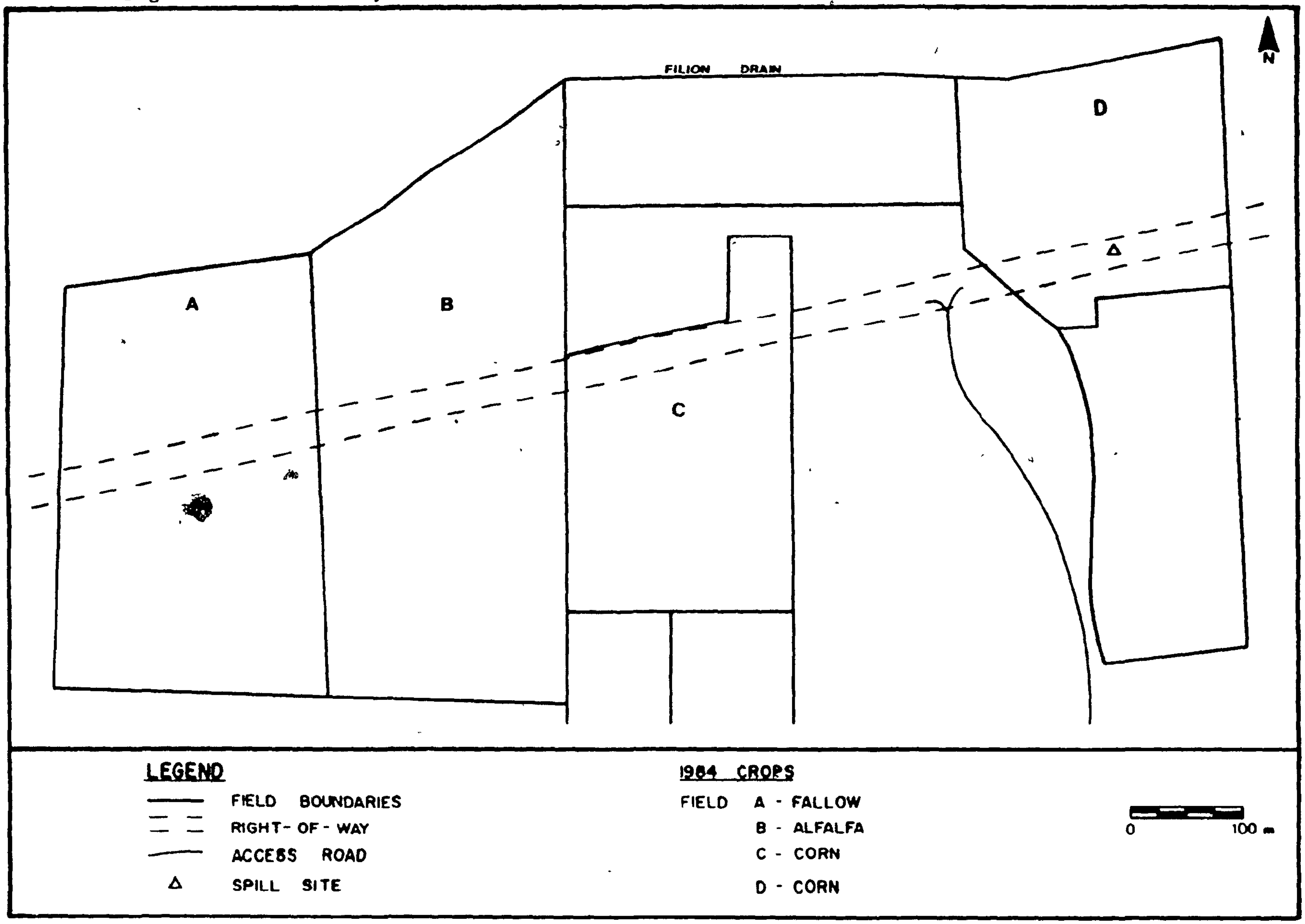


Figure 3.1 Location map of the study area

Figure 3.2 The study site



3.2 SOILS AND SURFICIAL GEOLOGY

Following retreat of the late-Wisconsin icesheet, the post-glacial marine transgression inundated much of Eastern Ontario. With isostatic readjustment there was gradual uplift and a change from deep water to shallow water and littoral sedimentation. The surficial cover resulting from this episode consists of clays, silty clays and sands.

The study area is underlain by Middle Ordovician (Chazy) limestone and a cover of glacial till, the weathering of which accounts for the calcareous nature of the fine to medium textured soils which make up over 40% of Glengarry County (Matthews et al., 1957). The soils found at the study area, first discussed by Ruhnke (1926), include the poorly drained North Gower series and the very poorly drained Belmeade series (at the spill site), belonging to the Great Grey Gleisolic Soil Group (Richards, 1961) - the Humic Gleysol of the present Canadian System of Soil Classification (Agr.Canada, 1978). The Belmeade muck at the study site exhibits a typical profile of black organic material (0-35 cm) overlying massive clay. Under cultivation, deep ploughing mixes a portion of the clay subsoil with the topsoil resulting in a very dark grey clay or clay loam topsoil layer (15-20 cm in thickness). The topography is typically depressional. In contrast, the North Gower clay loam is found in areas that are generally more level. It has a more friable texture, better structure (blocky) and a slightly better drainage than the muck. However, poor drainage in both soils can result in indistinct horizon boundaries and mottling below the Ap horizon.

Linear troughs were observed infrequently both in and adjacent to the study site. Terasmae (1965) suggested that they were inherited features formed over faults, fractures or bedding planes in the bedrock as a result of seepage of groundwater into the rock. Leighton and Brophy (1961) suggested that longitudinal crevasses in the marginal zone of the icesheet had served as channels for meltwater which cut straight shallow depressions. Notwithstanding their origins, these depressions are only a few meters wide but stretch over the width of a field and will typically have a poorer drainage than the surrounding area.

Chapman and Putnam (1966) placed the study area in the 'Lancaster flats' within the Glengarry till plain. Adjacent to the study area are found boulder beaches and gravel ridges characteristic of the plain and corresponding to the Champlain Sea shallow-water phase. The bouldery beach ridges are used for pasture and would be difficult to clear for cereal cultivation. The gravel ridges border a section of the study area and were a concern during pipeline construction since pipelining activities could possibly redistribute some of the coarse material onto previously gravel-free topsoil. While stoniness may tend to hinder agricultural activities in small patches of the study area, the primary concerns are the poor drainage and aeration, conditions more pronounced in the Belmeade muck than in the North Gower clay loam.

3.3 CLIMATE, VEGETATION AND LAND USE

The study site is located within the Eastern Ontario climatic region (designated 3H) and its climatic characteristics are typical of the Lower Great Lakes-St. Lawrence Valley area (Chapman and Brown, 1966). Thirty years of data (1951-1980) have shown that the growing season typically lasts from April 13 to October 30, with a frost free period of 140 days (ranging from 105-186 days) from May 13 to September 30 (Env. Canada, 1982). The annual precipitation is commonly 93 cm of which one half falls between May and September. Periods of excessive dry or wet weather are uncommon. Climatic region '3H' refers to the temperature zone '3' with 2171 degree-days greater than 5.0 °C and 2600 corn heat units; moisture class 'H' exhibits a 5 cm water deficit.

Prior to human occupation this region was characterized by a hardwood forest, although softwoods were not uncommon (Dore and Gillett, 1955). The better drained areas were associated with sugar maple, beech, and lesser numbers of ash, birch and elm. Poorly drained areas were dominated by elm, ash, red maple and white pine. Much of the area of Glengarry County has been cleared for permanent pasture. Dairy farming is popular. Cropland and pasture alternate on the better drained areas where till soils are found or where surface or subsurface drainage is in place.

Both alfalfa and silage corn, the two crops grown on the study site, are well adapted to the area (Chapman and Putnam, 1966) but are sensitive to problems of soil aeration resulting either from excessive soil water, impervious subsoil (compaction) or poor tilth. Both crops prefer deep, fertile, well-drained, stone-free soils (Heinrichs, 1969; Dube, 1982). The Canada Land Inventory, which considers both climatic and soil characteristics in rating the suitability of soils for agriculture, has mapped the muck soils of the study site as 'O' or 'organic soils' (CLI, 1967). These are not rated for agricultural purposes but are commonly high in natural fertility. Poor drainage is the main impediment to agricultural production. The stony beach or gravel ridge soils touching on fields B and C fall within capability class 6p, indicating a level of stoniness which can severely impede agricultural production. The clay and clay loam soils (North Gower series) are in class 3 with slightly excessive moisture, which restricts the range of crops. These soils are well suited to pasture or hay production. The productivity of the soils in the study area is especially dependent upon climate (precipitation) and sound management practices, more so for the very poorly drained Belmeade muck. The inherent fertility of the soils and the landowner's ability to reduce or contain stoniness and improve drainage suggests an area well suited to long-term, high yielding dairy production.

3.4 OIL SPILL IMPACTS AND RECLAMATION EFFORTS

In June of 1978 a drop in discharge pressure alerted IPL maintenance personnel to a break in the Sarnia-Montreal Extension. A shutdown was promptly initiated, but not before 595,000 gallons of U.S. crude oil had spilled from the 30 inch (762 mm) pipe. The rupture was attributed to mechanical damage to the exterior pipe wall combined with high operating pressures. The ensuing 55 hour interruption resulted in the deliveries of crude oil to Montreal falling behind schedule by approximately 750,000 barrels (1 barrel=160 liters).

The environmental damage from the spilled oil was confined to agricultural land and drainage ditches. Heavy rains shortly after the rupture caused the oil to flow with the natural slope into the Filion drain, filling it to a depth of 18 inches (45 cm) over 1.5 miles (2.4 km). IPL constructed earth dams and flumes to contain the movement of the oil. Vaccuum trucks were used to recover a total of 18,200 barrels. Some of the remaining 500 barrels were removed by controlled burning while the rest soaked into the soil. The affected field, then owned by a Mr. Macdonell and planted with corn, measured 5.75 acres (2.3 ha.). Following IPL recommendations to use nitrogen-rich fertilizer to stimulate microbial degradation of the oil, an initial crop loss period of 2 years (including 1978) was projected (NEB, 1978b).

IPL initiated reclamation procedures immediately after the spill clean-up. During July, August and September of 1978 eight tons of commercial fertilizer and 150 tons of manure were applied to the affected areas, a rate approximately 20 times the normal. The land was cultivated (rototilled, harrowed) ten times within this period. These measures were carried out with the aim of stimulating microbial degradation of the oil. The natural drainage of the field towards the Filion drain accounted for some variability in the concentration of oil across the field. This led to an initial qualitative distinction between heavily, moderately and lightly oiled areas of the field, with the heaviest concentration of oil (17% by weight in the 0-15 cm layer in 1978) occupying 0.5 acres (0.2 ha). The carbon-nitrogen (C:N) ratio at this site was 37 as compared to 12 for an unaffected site (NEB, 1981a). The significant effect of the oil on the carbon content of the soil was reduced to a C:N ratio of 24 by the end of the 1978 season. The 'visible' content of oil appeared to decrease significantly over the first season. This was attributed to the intensive cultivation and fertilization. Fall rye and red clover were sown in September 1978 with the intent that crop vigour would delineate zones of oil concentration.

1979

The affected area was fertilized with 4.5 tons of fertilizer (5 times the normal amount for corn production), 10 tons of manure and twice cultivated. It was felt that this treatment, combined with residual fertilizer from the 1978 application, would maximize biodegradation of the oil. Yields of red clover and fall rye were extremely poor in the affected areas, attributed to winter-kill as a result of late planting and water damage (NEB, 1981a), both factors resulting, possibly, from the effects of oil on the physical characteristics of the soil (reduced wettability, impeded drainage, etc.). Fall rye clippings from the affected area were negatively correlated with percent oil concentration in the topsoil (although not at a statistically significant level) which suggests that factors other than actual oil content may have influenced crop growth.

1980

In endeavouring to return the field to its original level of productivity, it was decided to follow the landowner's normal corn planting routine. However, since the field had not been fall-ploughed (necessary for maintaining good structure in clay soils) both ploughing and secondary tillage took place in May resulting in late planting and a rough seedbed. A corn hybrid considered appropriate for the delayed planting was selected, and two tons of fertilizer were applied. By late September the physiological development of the corn crop was incomplete. This was attributed to the poor seedbed preparation, late planting, high N fertilization and low June temperatures (NEB, 1981a). Crop yield samples for the 'lightly' oiled areas were 65% of the control, while yields from soil with moderate to heavy oil content were 29% of the control site. The C:N ratio at the heavily oiled site was still high at 23 +/-5. Based on the 1980 corn crop yields, IPL stated that a 'moderately high' yielding crop suitable for silage could be expected, except on the heavily oiled area where intensive reclamation was still required (NEB, 1981a). The estimate at this time was that full production would probably be attained on the heavily oiled soil within 2-3 years (from the 1980 growing season), earlier for the less severely affected areas; the estimation being based on a reclamation timetable from Alberta (Toogood, 1977, p.53).

1981

The reclamation procedures carried out on the affected area in 1981 included picking of the standing 1980 corn crop, broadcasting of urea fertilizer, ploughing-down of corn stover and urea, discing, planting of a hay mixture, fertilization at seeding and spraying of herbicide prior to the 3-leaf stage of alfalfa. In addition, measures to correct the drainage problems were carried out in January

1981 including cleaning of the surface drains, which had been silted in and contained sludge. While some improvement was noted, the heavily oiled area showed little progress. National Energy Board (NEB) monitoring visits of August and October 1981 reported that the rehabilitative measures indicated by IPL had not been fully carried out (NEB, 1981b, 1981d). Standing water, indicative of drainage problems, was evident in some sections of the affected area, as was oil seepage in one collector drain. Slumping was evident in three areas along the Filion drain. Crop yield remained 'visibly' reduced in certain sections and, in general, the monitoring group was not satisfied with the progress of the rehabilitation. The capability for a successful corn crop was not yet restored (the condition prior to the spill) and the high water content and ponding in the field had an adverse effect on tillage, germination, aeration and thus microbial degradation of the oiled soils.

<u>1982</u>

Reclamation activities for 1982 included improvements to surface drainage which appeared to reduce the soil water content, applications of topsoil to sites subject to ponding, and ploughing to a depth of 20-25 cm (as opposed to 10-15 cm used previously) to encourage soil aeration. Fertilizer was applied twice, and the timothy planted in early summer was ploughed-under during late October. Both the landowner and the NEB were satisfied with the progress of the rehabilitation, anticipating normal corn production in 1983 (NEB, 1982b). Sampling to determine soil hydrocarbon content was carried out in the fall of 1981 and 1982 by the Environmental Protection Service (Nagy, 1982). Their data confirm that biodegradation of the oil was proceeding. However, residual oil remained with both large and small areas of oiled soil still visible in the field.

At a meeting of IPL and NEB staff in November 1982, IPL admitted that they were inexperienced in restoration techniques, that the restoration was far from complete, and that they were basically treating the spill site as an experiment (NEB, 1983b). Heavy rains and failure of the contracted farmer to carry out assigned work were cited as reasons for failure to implement the 1981 restoration measures. IPL considered the landowner's desire to sell his farm (which he did, just prior to the 1983 growing season) as 'indifference' and did not give the work a high priority. It was felt that this had been the reason for the slow recovery of the field. It is difficult to assess this opinion due to incomplete documentation of IPL's testing program and its reluctance to release data. However, efforts at rehabilitation intensified in 1982, and some improvements were noted (NEB, 1983b).

1983

In August of 1983 a joint IPL-NEB monitoring visit was made to the affected area (NEB, 1983d). It was found that while corn 'was' growing on the affected soils, the crop height varied from 0 to 2 m, with 5 sections of the field varying from zero growth to 0.3-0.6 m. The 5 sections of poorest growth were in the lowest lying section of the field, with oiled soil evident. The new landowner attributed the poor corn growth on these sections to the high oil content within the soil while IPL attributed it to high water content, but not the oil. The NEB considers a successful corn crop as the measure for complete rehabilitation. It was apparent that in late 1983, six growing seasons after the spill occurred, this criterion had not been met.

chapter 4

FIELD OBSERVATIONS AND RESULTS OF SOIL & CROP ANALYSES

4.1 METHODS OF INVESTIGATION

4.1.1 FIELD DATA COLLECTION

The study area comprised four agricultural fields (see fig. 3.2, p.53). As they did not all belong to the same landowner and had been subjected to various cropping practices, they were studied individually. The field work for the current study was carried out in July-August 1984; the soil sampling being done during the last two weeks of July and the crop sampling between 10-24 of August. This being the ninth growing season since the construction, it was felt by both the landowner and the researcher that the continuous field preparation and harvesting activities had served to minimize any residual differences between the soils of the different sections of the right-of-way. As the study was aimed at determining if 'any' evidence of long-term impacts remained, the sampling was directed away from the trench zone which disturbed 3.0 m of the 18.3 m wide ROW, and more towards the center of the ROW which falls within the 'working side' (see figure 4.1).

Sampling was carried out following the point transect method (Wang, 1982), with transects located on and off the ROW. OFF-ROW sampling was located at even intervals to the north and south of the ROW center, depending on the field layout (modified for field D - the site of the oil spill).

The limits of the ROW were set by fence markers placed by IPL. The soils of each field were considered as homogeneous after consultation with existing soil maps and spot checks. Thus the OFF-ROW transects were intentionally located well outside the possible zone of construction activities, notwithstanding the predetermined limits of the ROW. The sampling layout for each field will be indicated (figs. 4.1, 4.3, 4.5, 4.8).

The observation interval was chosen 'arbitrarily' following the method suggested by Wang (1982). The length of each ROW-transect was divided by 5, 10, or 20 to yield the interval for that field (depending on the number of OFF-ROW transects), so that there would be the same sample size and degrees of freedom both on and off the ROW. For example, field A had 10 ROW samples and 2 OFF-ROW (control) transects with 5 samples each. This method facilitated precise locating of samples which was considered essential for correlating field data with the remotely sensed data.

In each sample location in fields A, B and C, a 30 cm pit was dug. A metal core, 8.5 cm in diameter by 7.7 cm in length was centered and inserted laterally between 0-15 cm and again between 15-30 cm to obtain undisturbed samples for measurement of bulk density. Soil from the same sample was later used for determination of organic matter content. Vegetation samples were not taken from field A as the field was fallow and had been invaded by a multitude of weed species. A qualitative assessment of field A will be given in Chapter 4. Field B was in alfalfa in 1984 and was sampled using a .25 m^2 quadrat placed randomly within a 1 m^2 area while standing over the soil sample site. All the plants within the quadrat were clipped at 1 cm above ground and collected for dry weight measurement.

Field C and D were in corn (silage) in 1984. The sampling grids were oriented with respect to management, i.e. with the crop rows. The heights of 10 corn plants, randomly selected from an area 3 m in length by 1 m wide (2 rows) and centering on the soil sample site, were measured to the tip of their tallest leaf held vertically. One randomly selected whole corn plant was collected at each site for dry weight and grain measurement. The soil and vegetation sampling for field D was more intensive so as to enable a more detailed examination of the impacts of the oil spillage.

4.1.2 LABORATORY ANALYSES

Standard laboratory techniques were carried out for the crop and soil analyses. Dry matter vegetative yield was obtained by weighing the samples after drying at 70 °C for 4 days. The cobs were threshed to obtain both grain and straw yields.

Soil from the core samples was weighed after air drying at 105 °C for 48 hours. Bulk density was calculated using the core volume and sample dry weight. The organic matter content was determined using the loss-on-ignition method (Ball, 1964), using a factor of 2% to correct for water lost from clay minerals and amorphous hydroxides (Moore, 1979). It is understood that this method provides only an approximation of organic matter content. Soil pH was determined potentiometrically using a 1:1 soil-water suspension (1:2 for those soils high in organic matter content). Data processing was carried out using the Statistical Analysis System (SAS, 1982) employing analyses described by Steele and Torrie (1980). The data were normally distributed and met the requirements of the t-test, used to test for significance between ON and OFF-ROW samples (Hammond and McCullagh, 1980).

4.2 FIELD A - FALLOW

Field A was left fallow during the 1984 growing season and had been invaded by a variety of weed species. Most prominent was the purple-flowered Bull thistle (*Cirsium vulgare (Savi) Tenore*). This weed is common in pastures throughout Ontario (Alex and Switzer, 1976). It prefers moist soils (Frankton and Mulligan, 1971) and was most abundant on the ROW suggesting some distinction between ON versus OFF-ROW soils (see fig. 4.2). The abundance and height of the weeds (commonly over 1 m) made a visual delineation and assessment of the ROW difficult. However, the data clearly suggest some disturbance to the ROW soils. Referring to table 4-I, the data indicate that bulk density, pH and organic matter content of the 0-15 cm layer show statistically significant differences ON versus OFF the ROW. An increased bulk density and pH and a decreased organic matter content are characteristic of both sampling levels on the ROW, although not to a significant degree at the 15-30 cm level. This suggests a sensitivity of the surface layer to construction activities resulting in long-term impacts to the soil.

The soils typically range from slightly alkaline subsoil to slightly acidic topsoil, the calcareous nature of the parent material contributing to the former and the acidity of the humic material to the latter. The value of pH 7.27

for ROW topsoils versus pH 6.75 for OFF-ROW topsoils may have resulted from mixing and dilution of the ROW top and subsoil during construction. Values between 6.0-7.5 are generally considered non-limiting to nutrient availability (Brady, 1974).

E.W. Russell (1973) states that roots will experience difficulty in penetrating heavy textured soils with bulk densities exceeding 1.5-1.6 g cm^{-3}. Viehmeyer and Hendrickson (1948) found no root penetration into clay soils with a density of 1.6-1.7 g cm^{-3}, with the critical density beyond which root penetration of sunflowers did not occur being 1.46 g cm^{-3}. Mean bulk density values for field A did not exceed 1.33 g cm^{-3} at either depth sampled ON or OFF the ROW, while mean pH values were within the 6.75-7.5 range. Thus, while the ROW soils do exhibit characteristics that are (statistically) significantly different from the OFF-ROW soils, they remain suitable for crop production. Correlation coefficients were calculated to determine the strength of the relationships between the parameters measured. Table 4-2 indicates a very strong inverse relationship between bulk density and organic matter ($r=-0.95$ at both depths). The strength of this relationship suggests a significant potential for heavy construction machinery to disrupt the soil organic matter content and soil tilth.

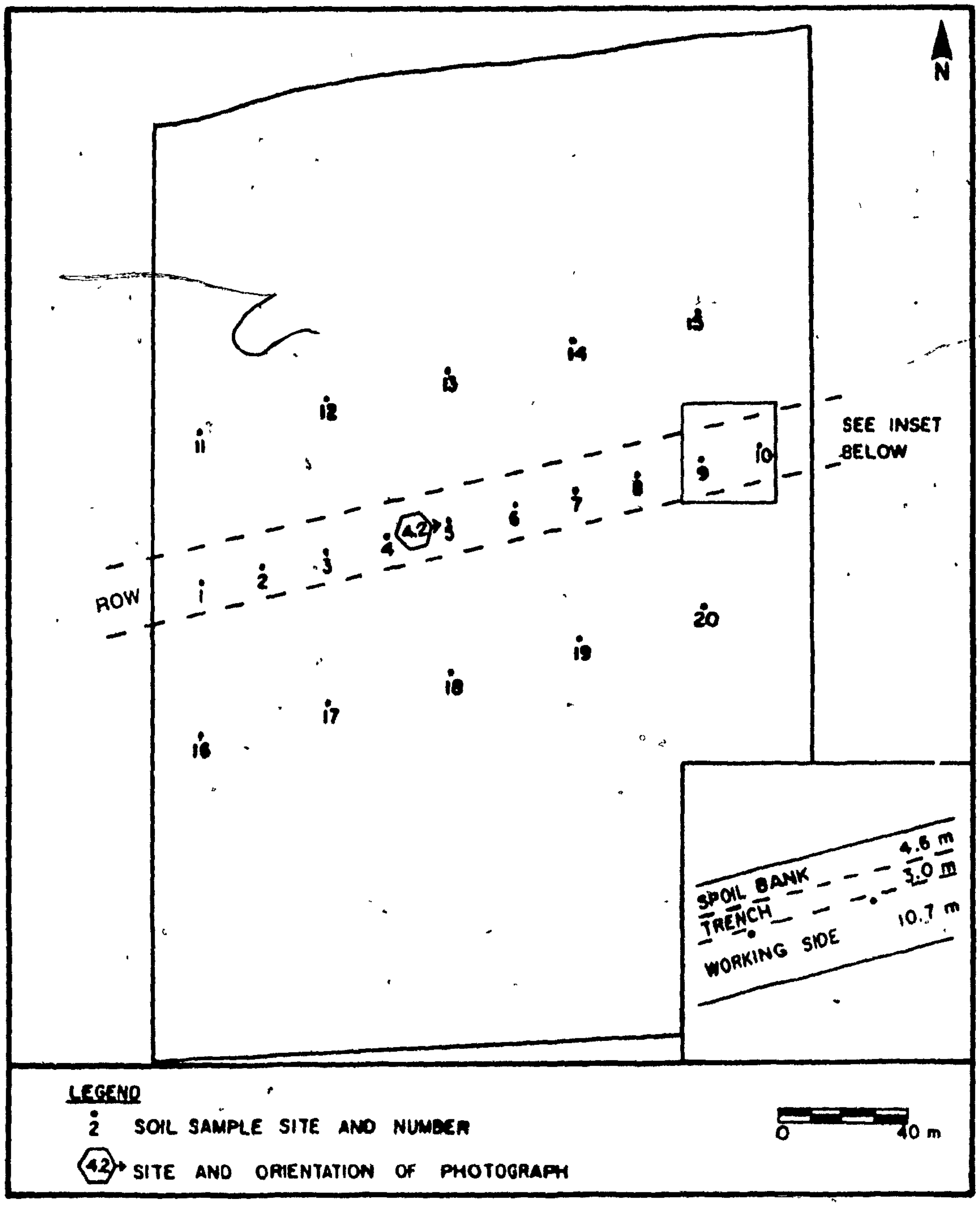


Figure 4.1 Field A - sampling layout

table 4-1 AGRONOMIC DATA - FIELD A

variable	ON-ROW n	ON-ROW mean	OFF-ROW n	OFF-ROW mean	t-value	significant at
BDA	10	0.98	10	0.68	2.636	.02
BDB	10	1.33	10	1.24	0.610	ns
PHA	10	7.27	10	6.75	5.241	.01
PHB	10	7.32	10	7.26	0.524	ns
OMA	10	30.38	10	54.03	-2.696	.02
OMB	10	12.17	10	18.91	-0.795	ns

BD - bulk density (g cm^{-3})
PH - pH
OM - organic matter content (%)
A - 0-15 cm depth
B - 15-30 cm depth

table 4-2 CORRELATION COEFFICIENTS - FIELD A n=20

	BDA	BDB	PHA	PHB	OMA	OMB
BDA	1.0000					
BDB	0.4818	1.0000				
PHA	0.6820*³	0.0527	1.0000			
PHB	0.3700	0.6266**	0.1111	1.0000		
OMA	-0.9521*⁴	-0.4548*	-0.7118*³	-0.4418	1.0000	
OMB	-0.4124	-0.9469*⁴	-0.0747	-0.5476*	0.3896	1.0000

*: P≤0.05; **: P≤0.01; *³: P≤0.001; *⁴: P≤0.0001;
otherwise not significant

Figure 4.2: Field A right-of-way, with the purple flowers of the Bull thistle visible. (28/8/84)

Note:
►◄ arrows will be used on the photographs to designate the path of the right-of-way

4.3 FIELD B - ALFALFA

Field B was seeded to purple-flowering alfalfa (Medicago sativa L.) in the 1984 growing season, and was used for pasture. While grazing must certainly have contributed to variability in the standing crop yield, sampling procedure remained as described. The ROW was clearly discernible due to its reduced crop growth, bare patches and the abundance of a variety of weed species relative to the OFF-ROW area (see fig. 4.4). These included Lamb's quarters (Chenopodium album L.), Common milk weed (Asclepias syriaca L.) and Wild oats (Avena sativa L.), all common in Southern Ontario (Alex and Switzer, 1976).

Field B sloped gently (0-2%) upward towards field C (to the east). The ROW soil became stonier towards the B-C fenceline, making sampling difficult for the last 40 m. This area may be naturally stony due to its proximity to the rock knob. Alternatively, it may have become more stony as a result of construction activities mixing-in the adjacent stony soils. This will be discussed further when looking at the archival aerial photographs in chapter 5. While no core samples could be taken, samples of the gravelly to very gravelly loam topsoil were taken for determinations of pH and organic matter content. This area would be classed as 'very stony', with sufficient stones to handicap cultivation (Canada Dept. of Agric., 1978).

The data show that to varying degrees of significance, the measured properties differed between ON-ROW and OFF-ROW situations (table 4-3). At the 'A' level (0-15 cm) the bulk density and pH values for ON-ROW samples showed increases significant at the .1 and .05 levels respectively. The organic matter content was significantly reduced (.1 level). The 'B' level samples were affected in a similar fashion, but generally to a lesser or not significant degree. Thus, as was found with field A, it appears that the significant long-term impacts from soil compaction and mixing during construction are confined to the upper 15 cm. Of ultimate importance is the reduction in yield found on the ROW, although not statistically significant.

Correlation coefficients, shown in table 4-4, indicate a significant negative correlation between bulk density and organic matter content at both depths ($r=-0.65$ and -0.86, sig. at $P \leq 0.01$ and $P \leq 0.0001$ respectively). This suggests that soil dilution as a result of construction activities contributes to the compaction. This correlation was stronger for the soils of field A which had a greater organic matter content, thus emphasizing the importance of topsoil conservation. While the bulk density at the 0-15 cm depth is the soil property most strongly (negatively) correlated with yield ($r=-0.55$), it is not sufficiently strong to suggest that it is the sole factor contributing to the yield reduction.

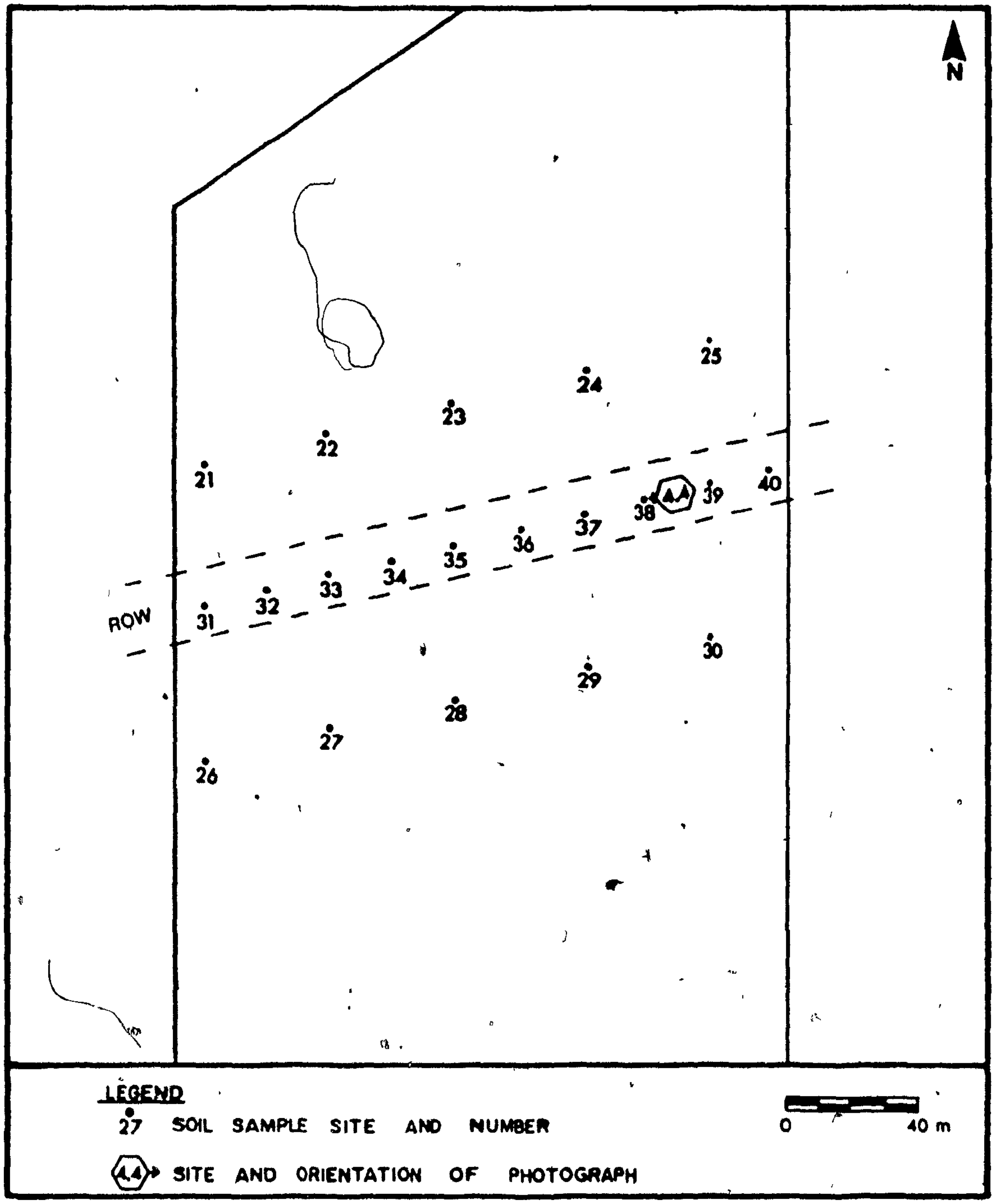


Figure 4.3 Field B - sampling layout

table 4-3	AGRONOMIC DATA - FIELD B					
	ON-ROW		OFF-ROW			
variable	n	mean	n	mean	t-value	significant at
BDA	8	1.24	10	1.09	-1.957	.1
BDB	8	1.30	10	1.23	-1.187	ns
PHA	10	7.72	10	7.54	-2.324	.05
PHB	8	7.69	10	7.56	-1.749	.1
OMA	10	14.52	10	20.22	1.929	.1
OMB	8	13.32	10	15.85	1.093	ns
YIELD	10	110.66	10	135.56	1.681	ns (.2)

BD - bulk density (g cm^{-3})
PH - pH
OM - organic matter content (%)
YIELD - alfalfa dry matter yield (g m^{-2})
A - 0-15 cm depth
B - 15-30 cm depth

table 4-4 CORRELATION COEFFICIENTS - FIELD B n=18

	BDA	BDB	PHA	PHB	OMA	OMB	YIELD
BDA	1.0000						
BDB	0.4391	1.0000					
PHA	-0.0530	-0.0913	1.0000[1]				
PHB	-0.0915	-0.0595	0.9219	1.0000			
OMA	-0.6508**	-0.5999**	-0.1419[1]	-0.2245	1.0000[1]		
OMB	-0.4877*	-0.8557*[4]	0.0523	-0.1038	0.6497**	1.0000	
YIELD	-0.5519*	-0.0525	-0.3251[1]	-0.2414	0.3589[1]	0.1543	1.0000[1]

[1] n=20
*: P≤0.05; **: P≤0.01; *[3]: P≤0.001; *[4]: P≤0.0001;
otherwise not significant

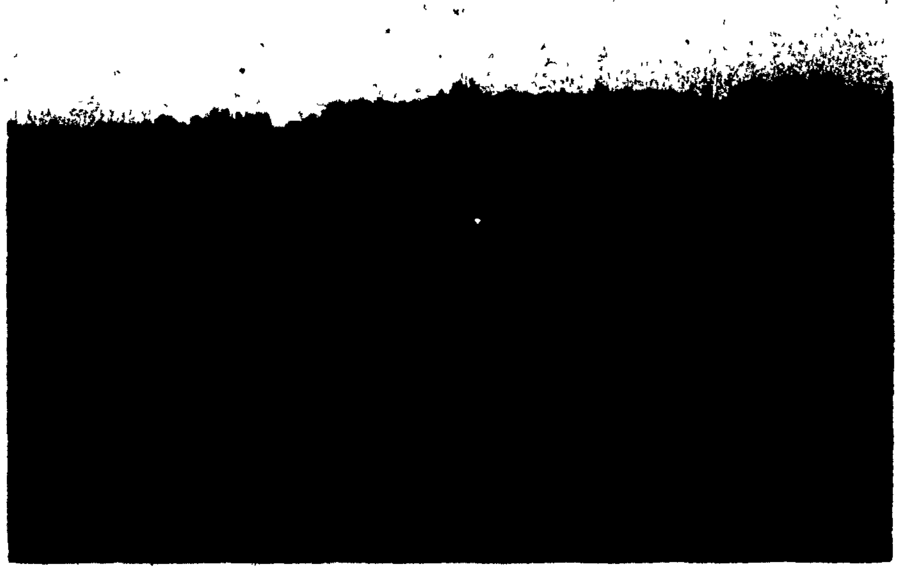


Figure 4.4: Field B, with bare patches visible on the right-of-way. (28/8/84)

4.4 FIELD C - CORN

Field C was in corn (Zea mays, L.) for silage in the 1984 growing season. Unlike fields A and B which exhibited little or no variation in relief, the northern edge of field C extended onto the stony ridge of a rock knob and displayed a gently undulating topography. The ROW is located on this ridge, and sampling of the 15-30 cm depth was not possible due to stoniness.

In 1981, 5 years after the pipeline construction, variably reduced yield was clearly visible on the ROW. Figure 4.6 shows the stony, puddled ROW after a rain in June. Compaction as a result of pipeline construction was probably responsible for inhibited germination on the low section of the ROW. Crop yields on the upper portion of the ROW were reduced, indicated by the somewhat lower crop heights on the ridge. Figure 4.7 shows the same area in August of 1984. While the yields on the ROW were generally more uniform, the abundance of weeds (Fall panicum)- visible in the foreground but prolific over all the ROW, suggest that complete germination of the corn had still not been attained. The ROW exhibited characteristics that were all significantly different from the OFF-ROW samples (table 4-5). As with the previous two fields, soil bulk density and pH were increased. Interestingly, the soil organic matter levels were also higher, possibly stemming from the decomposition of the abundant interrow weeds which were absent from the OFF-ROW site. Most significantly, the crop yield was reduced. The values were significant at the .05 level in each case, suggesting very marked differences between ON and OFF-ROW properties.

The correlation coefficients (table 4-6) indicate a strong relationship between crop height and yield (AVGHT X BIO, r=0.77), suggesting that the former be used as as 'indicator' for the latter. The importance of the organic matter content for plant growth is revealed by the strong relationship between it and the plant height (r=-0.70) and yield (r=-0.69). Bulk density appears to play less of a role in differentiating ON versus OFF-ROW soils, presumably because it is in the range considered limiting to plant growth in both ON an OFF-ROW situations. The severity of the stoniness on the ROW is probably the salient factor contributing to reduced corn yield by inhibiting seed germination and root penetration. The calcareous nature of the stones may also serve to increase soil pH. In the case of field C, it is difficult to assess the impact of construction since the ROW was placed over a naturally very stony area. The question of whether or not the construction aggravated the situation is one of speculation, although the stoniness and ponding of the lower areas off the ridge suggest that this may be so.

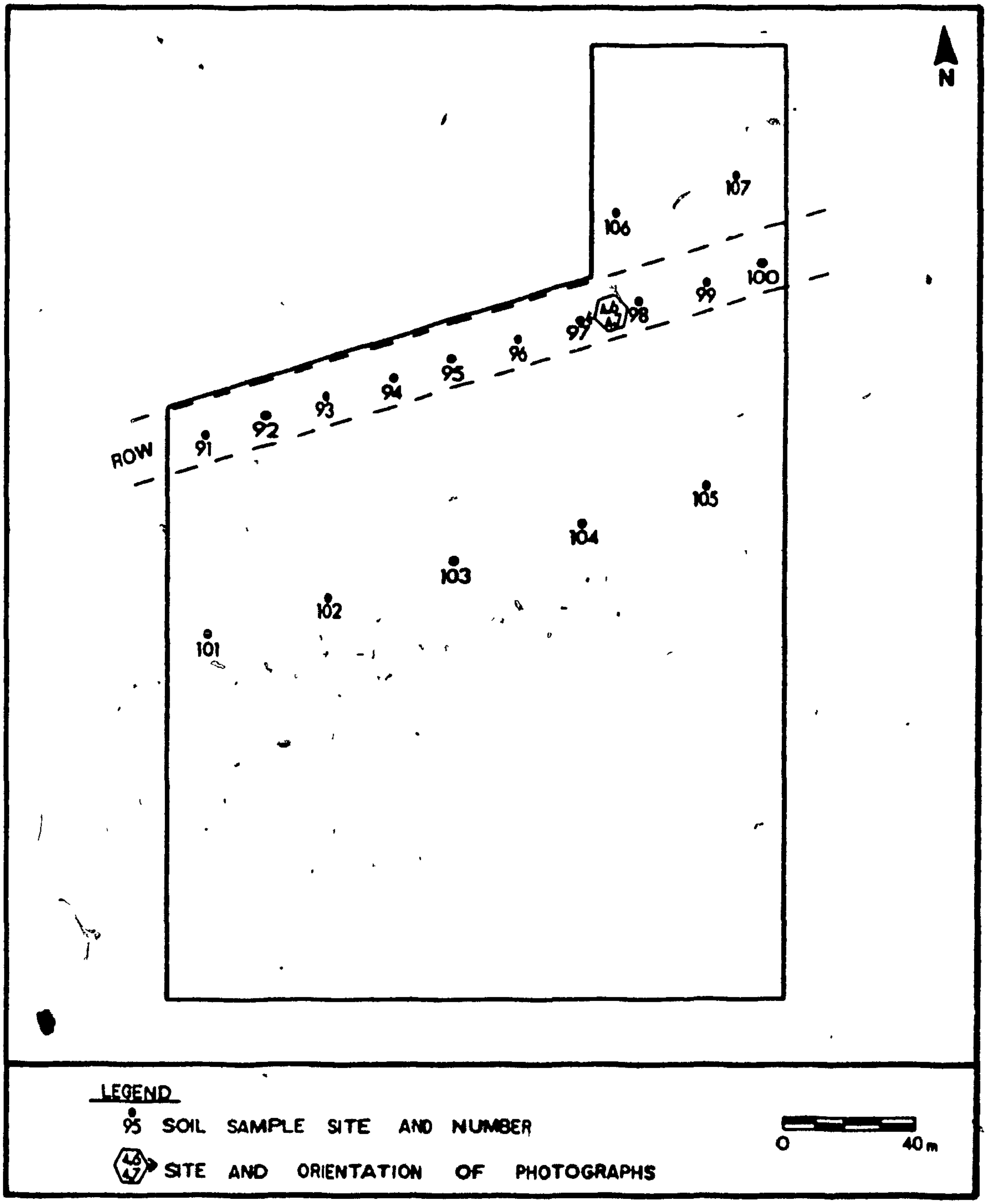


Figure 4.5 Field C - sampling layout

table 4-5 AGRONOMIC DATA - FIELD C

variable	ON-ROW n	ON-ROW mean	OFF-ROW n	OFF-ROW mean	t-value	significant at
DMWT	10	64.44	7	106.05	-2.799	.02
GRAIN	10	29.80	7	50.40	-2.421	.05
BIO	10	117.45	7	185.14	-2.843	.02
AVGHT	10	170.70	7	211.40	-4.421	.001
BDA	10	1.95	7	1.83	2.406	.05
PHA	10	7.32	7	6.67	4.794	.001
OMA	10	20.41	7	12.33	7.215	.001

DMWT - dry matter weight/plant (gm)-exc. ear
GRAIN - grain weight/plant (gm)
BIO - total dry biomass/plant (gm)
AVGHT - mean height of 10 corn plants (cm)
BDA - bulk density 0-15 cm depth (g cm^{-3})
PHA - pH 0-15 cm
OMA - organic matter content 0-15 cm (%)

table 4-6 CORRELATION COEFFICIENTS - FIELD C n=17

	DMWT	GRAIN	BIO	AVGHT	BDA	PHA	OMA
DMWT	1.0000						
GRAIN	0.5314*	1.0000					
BIO	0.9331*4	0.7777*3	1.0000				
AVGHT	0.6879**	0.7977*3	0.7715*3	1.0000			
BDA	-0.2922	-0.4360	-0.3121	-0.4473	1.0000		
PHA	-0.4598	-0.4081	-0.4971*	-0.5379*	0.2398	1.0000	
OMA	-0.6808**	-0.5319*	-0.6850**	-0.7027*	0.3661	0.7608*3	1.0000

*: $P \leq 0.05$; **: $P \leq 0.01$; *3: $P \leq 0.001$; *4: $P \leq 0.0001$; otherwise not significant

Figure 4.6: 1981 photo of field C indicating the stony, puddled right-of-way.(22/7/81)

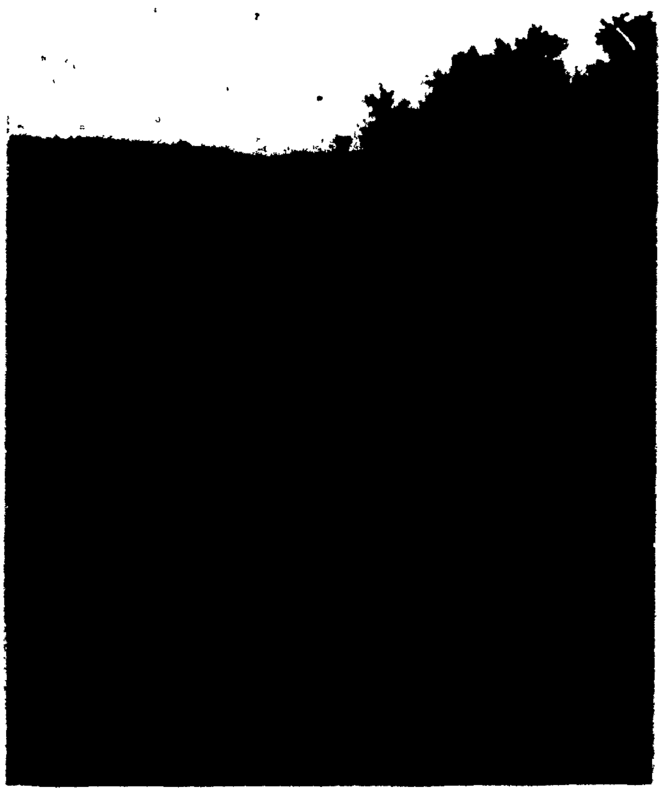


Figure 4.7:
1984 (28/8) photo of field C with weeds in the foreground and a more uniform crop coverage than in 1981. (Fig. 4.6)

4.5 FIELD D - CORN: OIL SPILL SITE

Field D, the site of the 1978 pipeline break, was in corn (*Zea mays*, *L*.) in the 1984 growing season. The field is situated in a low-lying area and there is a gentle slope towards the Filion drain. The area thus affected by the spill extended from the ROW (to the south) to the Filion drain (to the north), and was contained to sections D2 and D3 (see fig. 4.8 and also fig. 5.6). A close examination of figure 4.9 (August 1984) reveals patches of reduced growth in both D2 (western) and D3 (eastern) sections of field D. Crop height in these patches ranged from 0-50 cm and there was typically no development of tassels or ears on the corn plants. Section D2 is further characterized by an abundant interplant and interrow weed growth; D3 has little weed growth and common bare patches. Figure 4.10 provides a more detailed view of the reduction and variability in the standing crop. Note the tasselled corn to the rear and at the sides of the photo, indicative of variation in stages of development and inhibited growth. Figure 4.11 shows a tarry mass present in the drainage ditch on the east side of the field.

Initially the sampling layout considered the unaffected adjacent field to the west as the control site. Assuming the same management practices, the adjacent field would provide a reference for assessing the yield of the affected area in field D. However, the planting date for part of field D (D3) was significantly delayed due to field wetness. Sections D1, D2 and the adjoining fields were seeded on 6-7 May. However, germination of section D2 was minimal and reseeding was carried out with the seeding of section D3 on 13-15 of June. Poor crop yields were characteristic of these areas reseeded or seeded late. The comparison between the spill versus non-spill areas can thus be carried out in two stages: the first data set (table 4-7) is comprised of samples from sections D2 and D3 (affected sites) with the control being those samples numbered 1 through 5 (see fig. 4.8); the second (table 4-8) is comprised of samples from affected (D2, D3) and unaffected (D1) sections within field D. The data from table 4-7 indicates very significant differences at the .01 or .001 levels between all measured crop variables on the affected area versus the control, the control being samples taken from the field adjacent to field D and from the visibly unaffected near-border rows of field D. Of primary concern, the affected area clearly exhibits very significantly reduced crop yield as compared to what would have been attained had the seeding date not been delayed. Soil properties, however, are not affected by seeding date. Soil pH and organic matter content at the 0-15 cm depth show very significant variation from the control levels, although not to levels unsuitable for crop growth. Increased machinery traffic due to clean-up and reclamation activities following the spill may have been partially responsible for this.

The data in table 4-8 provides a comparison between spill and non-spill conditions using samples from the two westernmost rows of field D as the control. Checks with archival aerial photographs indicate that this section of the field, sloping very gently upwards from the field's center, was affected by the spill only to a minimal degree if at all. The relationships are similar to those of table 4-7, although the differences are significant to a lesser degree. The difference in average crop height was significant only at the .2 level, while total plant biomass was significantly different at the .02 level. The difference in ear weight, significant at the .01 level, and the dry matter weight (exc. ear weight) at only the .1 level suggests that the factor or factors inhibiting growth had a greater negative influence on the physiological development of the ear than the stalk.

The C:N ratio for the oil-affected area was determined using Ball's (1964) correlation of loss-on-ignition and organic matter content ($y=0.476x-1.87$, where y=organic C and x=loss-on-ignition) and a mean value of 0.5% total nitrogen taken from previous work done by IPL (NEB, 1982a) and the Ontario Ministry of the Environment (1982) at the spill site. The calculated C:N ratio of 13.5 for the affected area (table 4-8) is a satisfactory ratio, and is extremely close to the value of 13.6 calculated by IPL (NEB, 1982a) in 1981 for sections of field D excluding the heavily oiled area. Analyses carried out by Nagy (1982) on samples obtained from a heavily oiled 1/2 acre site in the field revealed a marked drop in oil content. He reported values of 17%, 1% and 0.3% oil content by weight for 1978, 1981 and 1982 respectively.

Correlation coefficients shown in table 4-9 (same raw data as for table 4-8) do not suggest strong relationships between yield (BIO) and average height or between any of the crop and soil parameters. Whether this is a result of high natural or induced variability or inadequate sampling, it is apparent that the crop growth on the area affected by the oil spill is reduced and that the soil and crop parameters have been significantly affected by the spill. The presence of a tarry substance in a drainage ditch (fig. 4.11) with no evidence of increased organic material and reported marked reductions in oil content in the upper 30 cm of the soil suggests that very little, if any, of the spilled oil remains in the upper soil layer, while it is the more viscous fraction of the oil which has remained at depth. While not tested for, the soil moisture of the affected area is clearly higher than adjacent unaffected areas as evidenced by interrow puddling. This suggests that the spilled oil is impeding the already poor soil drainage and thus contributing to the delayed seeding and reduced yield.

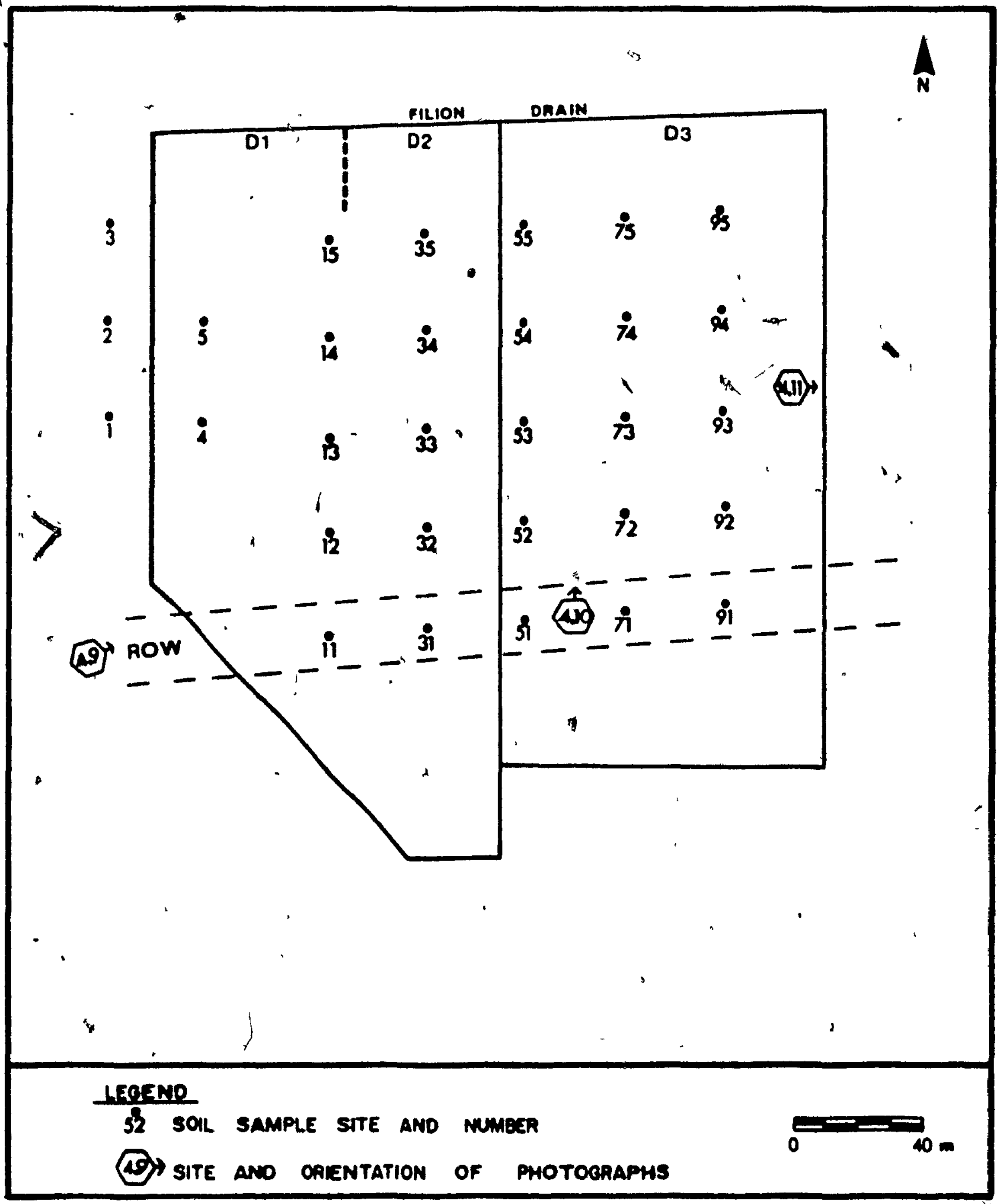


Figure 4.8 Field D - sampling layout

table 4-7 AGRONOMIC DATA - FIELD D

variable	AFFECTED n	AFFECTED mean	CONTROL n	CONTROL mean	t-value	significant at
DMWT	25	102.85	5	244.39	-5.197	.001
EAR	9*	26.19	5	167.57	-6.085	.001
GRAIN	6	7.17	5	38.42	-3.838	.01
BIO	25	129.04	5	411.96	-6.179	.001
AVGHT	25	159.87	5	224.50	-3.547	.01
PHA	25	7.08	5	6.60	2.898	.01
PHB	25	7.26	5	7.06	1.310	ns
OMA	25	18.97	5	27.98	-4.208	.001
OMB	25	14.44	5	17.72	-1.310	ns

DMWT - dry matter weight/plant (gm)-exc. ear
GRAIN - grain weight/plant (gm)
EAR - ear weight/plant (gm)-inc. grain weight
BIO - total dry biomass/plant (gm)
AVGHT - mean height of 10 corn plants (cm)
PH - pH
OM - organic matter content (%)
CN - carbon:nitrogen ratio
A - 0-15 cm depth
B - 15-30 cm depth
* - only 9 of the 25 plants sampled from the affected area had developed ears; of these only grain yields greater than 3 gm were considered.

table 4-8 AGRONOMIC DATA - FIELD D (revised)

variable	AFFECTED n	AFFECTED mean	CONTROL n	CONTROL mean	t-value	significant at
DMWT	20	104.21	7	168.43	-1.977	.1
EAR	20	18.62	7	104.66	-3.443	.01
GRAIN	3	6.86	5	27.17	-1.244	ns
BIO	20	122.83	7	273.09	-2.751	.02
AVGHT	20	157.86	7	186.58	-1.568	ns (.2)
PHA	20	7.15	7	6.69	3.051	.01
PHB	20	7.26	7	7.16	0.690	ns
OMA	20	18.14	7	20.53	-1.769	.1
OMB	20	14.77	7	13.69	0.547	ns
CNA	20	13.53	7	15.80	-1.769	.1
CNB	20	10.31	7	9.29	0.547	ns

table 4-9 CORRELATION COEFFICIENTS - FIELD D N=27

	DMWT	EAR	GRAIN[1]	BIO	AVGHT	PHA	OMA
DMWT	1.0000						
EAR	0.8237*^{4}	1.0000					
GRAIN[1]	0.9581*^{3}	0.8965**	1.0000				
BIO	0.9612*^{4}	0.9482*^{4}	0.9656*^{4}	1.0000			
AVGHT	0.5317**	0.6051*^{3}	0.4259	0.5924**	1.0000		
PHA	-0.5702**	-0.4353*	-0.5938	-0.5313**	-0.5467**	1.0000	
OMA	0.1424	0.0830	0.1978	0.1202	-0.1230	-0.3815*	1.0000

[1]n=8
*: P≤0.05; **: P≤0.01; *^{3}: P≤0.001; *^{4}: P≤0.0001;
otherwise not significant

Figure 4.9: Field D with patches of reduced growth visible. (15/8/84)

Figure 4.10: Field D with variation in crop height and development apparent (note tassels). (15/8/84)

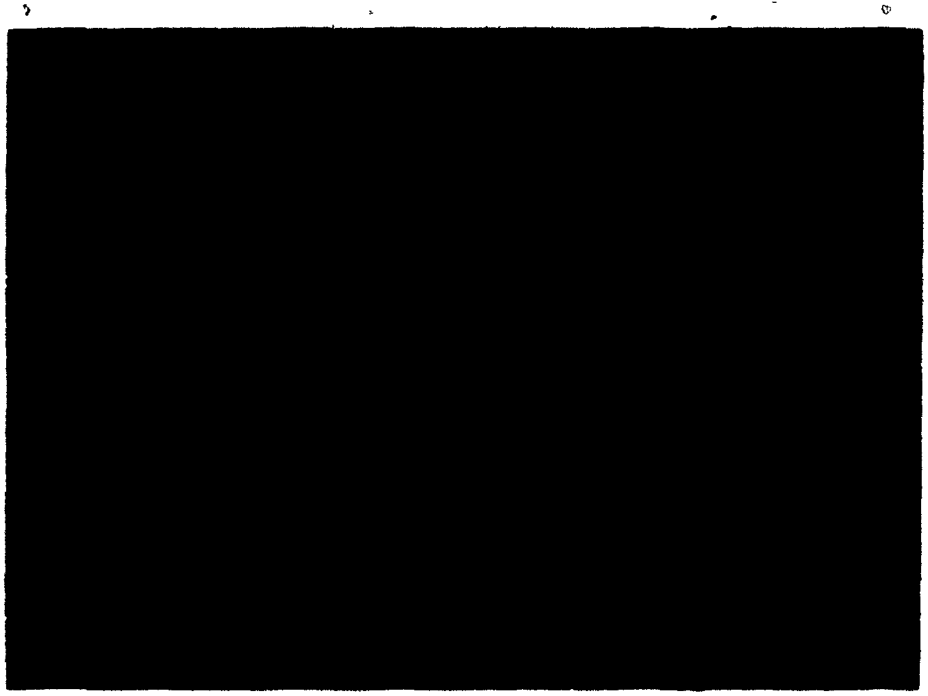


Figure 4.11: Field D with a tarry mass present in the drainage ditch on the east side of the field. (15/8/84)

4.6 SUMMARY AND CONCLUSIONS

Table 4-10 presents a summary of the soil and crop data obtained for the four fields of the study site. For each field and at both sampling depths, the ON-ROW bulk density was greater than the OFF-ROW. Similarly, except for field C and field D at the 0-15 cm level, the organic matter content was lower ON-ROW compared to OFF-ROW. Each field exhibited increased pH values at both depths in ON-ROW sites. While the differences range from not significant to very strongly significant from a statistical point of view, the data clearly shows that the properties of the soil on the pipeline right-of-way have still not returned to their original condition. The significance of this for crop production becomes evident when considering the total plant yield, which is characterized by reduced values on the affected sections in each field. No comparisons were made of yields between fields since both the seeding dates and sampling dates varied.

The area affected in each field was calculated using the measured width of the field and the right-of-way, subtracting 10% to account for variability in growth near the fencelines and unaffected growth near the ROW boundaries. The areas were verified using an HP digitizing table, but need only be considered as an approximation. For field C the number of plants affected was calculated using the mean number of plants per meter (4.8), the length of the ROW and the number of rows affected. For field D, the mean number of plants per meter (4.7) was converted to number of plants per hectare using a measured row spacing of 80 cm. This was multiplied by the area affected, as interpreted and measured using the digitizer and a 1984 CIR photograph. Sampling of field D was not sufficiently detailed to accurately characterize the highly variable crop yield found in sections D2 and D3. To obtain an indication of the income lost to the farmer as a result of the reduced crop growth, dollar values of the crops were obtained from the 1984 Agricultural Statistics for Ontario (OMAF, 1984): $178.12/m.tonne grain corn, $54.03/m.tonne hay (for alfalfa). The calculated worth of the lost yield (per field) is given at the bottom of table 4-10. The amount lost represents only the value of the crop and does not reflect the cost of the inputs and labour required to produce the crop. It is thus solely an indication that a real dollar loss is encountered by the landowner, but does not reflect the actual value of this loss.

In conclusion, the research has clearly provided an affirmative answer to the first of the questions posed in this thesis. Long-term impacts 'are' evident in certain soil properties and crop yield on farmland affected by pipeline construction and oil spillage, resulting in a real dollar loss to the producer 9 growing seasons after the pipeline construction and 7 seasons after the oil spillage.

table 4-10 SUMMARY OF SELECTED AGRONOMIC DATA AND ECONOMIC IMPACTS

variable	FIELD A ON	FIELD A OFF	FIELD B ON	FIELD B OFF	FIELD C ON	FIELD C OFF	FIELD D ON	FIELD D OFF
BDA	0.98	0.68	1.24	1.09	1.95	1.83	-	-
BDB	1.33	1.24	1.30	1.23	-	-	-	-
OMA	30.38	54.03	14.52	20.22	20.41	12.33	18.14	20.52
OMB	12.17	18.91	13.32	15.85	-	-	14.77	13.69
PHA	7.27	6.75	7.72	7.54	7.32	6.67	7.15	6.69
PHB	7.32	7.26	7.69	7.56	-	-	7.26	7.16
BIO(YIELD)	-		110.66	135.56	117.45	185.14	122.83	273.09
GRAIN	-		-		29.80	50.40	6.86	27.17
area or no. of plants affected			3240 m²		8200 plants		2.6 ac(1.06 ha)	
% yield reduction[1]			18/-		37/41		55/75	
total yield lost (kg)[2]			81		164		704	
value of lost yield ($)[3]			17.82		11.48		49.28	

ON - on the right-of-way
OFF- off the right-of-way
BD - bulk density (g cm^{-3})
OM - organic matter (%)
PH - pH
A - 0-15 cm depth
B - 15-30 cm depth
YIELD - dry matter yield (gm m^{-2})
BIO - total dry biomass/plant (gm)
GRAIN - grain weight/plant (gm)
[1] - % reduction in total vegetative yield / % reduction in grain yield on the area affected
[2] - total reduction in vegetative yield (field B-alfalfa) or grain yield (fields C & D-corn)
[3] - dollar value represented by reduced yield as a result of impact from pipeline construction and/or spillage (to nearest dollar) (see discussion, p.94)

chapter 5

ANALYSIS OF REMOTELY SENSED DATA

5.1 INTRODUCTION

This chapter, dealing with the results of the remotely sensed data analyses, looks first at the aerial photography, then considers the data obtained from the scanner imagery. It is the 'type' and 'scale' of the output which has suggested this sub-division; the photography providing an 'overview' of the study site using various film type and scale combinations and the imagery providing a detailed 'look' at each individual field using a number of narrow wavelength bands and digital analysis techniques. The object of this analysis is to determine which product would best highlight (visually) the variations in ground condition as revealed by the crop cover. It was not possible to apply all of the digital analysis techniques to each image of each field in the study area due to limited availability of the CCRS image analysis system. Nonetheless, it became clear that certain procedures provide better results than others and on this basis it is possible to suggest an optimum remote sensing system for the analysis of pipeline construction and oil spill impacts.

Note:
► ◄ arrows will be used on the photographs and plots to designate the path of the right-of-way

5.2 DATA ACQUISITION

The archival and recently acquired (1984) remotely sensed data utilized for this study are listed in table 5-1:

table 5-1 REMOTELY SENSED DATA USED FOR THIS STUDY

type of imagery	date	scale	agency
B+W photography	16 Aug 71	1:15,840	OMNR[1]
B+W "	1 July 78	1:10,000	OMNR
CIR "	23 Sept 80	1: 3,100	CCRS
CIR "	17 Aug 84	1: 9,500	CCRS
colour "	4 Sept 84	1: 1,640	IPL
MEIS imagery	17 Aug 84	-	CCRS

[1] - Ontario Ministry of Natural Resources

The 1971 photograph of the study site was used here to examine the conditions previous to any disturbance from pipeline construction. The 1978 photograph was obtained to view the conditions two years after the construction and immediately following the spill. These panchromatic photos were taken as part of the provincial aerial photography program of the Ontario Ministry of Natural Resources. In 1979-1980, CIR photos were taken for the expressed purpose of monitoring the spill site and adjacent fields. CCRS flew this area five times between April and October 1979 as part of the impact monitoring study. However, the 1980 photos were utilized here as they allow for an additional season of reclamation efforts which is significant in a study of this type concerned with the examination of long-term residual impacts. The 1984 colour photography (handheld) was obtained in order to examine the usefulness of this type of photography combination in terms of its visual impact and level of detail. The CIR photography acquired by CCRS in 1980 and 1984 was acquired specifically for the purpose of examining the spill site. Prints for both dates and transparencies for 1984 were obtained. The prints were examined using both pocket and mirror stereoscopes. The transparencies were found to provide much more detail than prints because of the higher resolution of the emulsion. These were examined using a Bausch and Lomb zoom stereoscope. The aerial photographs have been photographically enlarged or reduced from their original 9 x 9 inch (23 x 23 cm) size to conform to a 3.5 x 5 inch (8.8 x 12.6 cm) format for presentation here. This process was done commercially and the originals were used for optimum colour matching. The resulting scale of each photograph is given in its caption.

The 1984 MEIS imagery and CIR photography were flown by CCRS in response to a proposal put forward by the researcher. Both are part of a total airborne data acquisition system which includes the MEIS camera head, an RC-10 camera, an inertial navigation system, an auxilliary data acquisition system (MAID) and a high density digital tape recorder. The scale of the CIR photography was dictated by the minimum flying height of 4750 ft ASL at which MEIS imagery could be obtained. This flying height allows for the imaging of a 0.68 mile (1.09 km) swath and a pixel resolution of 1.0 m. Two factors were taken into consideration in determining the flight date: firstly, the fact that in order to detect crop stress the canopy must be sufficiently developed so that its response predominates over that of the soil background (Bauer, 1975); second, the fact that the landowner was intending to harvest and/or plough-down the crop in the oil-affected field somewhat earlier than normal due to the poor (negligible) yield. This set a limiting date on the period available for photography. Unfortunately, cloud cover was a problem during the data acquisition flight. Two passes were made, however 100% cloud-free conditions were not available. The CIR photography was taken with Aerochrome IR type 2443 film and a 525 AV 2.0X filter. In aerial photography the ratio of reflected IR to visible radiation is reduced by absorption and by increased scatterring of visible light (Pease and Bowden, 1969). However, at altitudes less than 5,000 feet this effect is not severe and so no additional filters were used. The actual film roll was tested for a stable IR colour balance.

The MEIS sensor bands used for this study (the TM simulation package) were selected because of their narrow band width and their proven value in studying vegetation stress (see chapter 2.3). The output from the 5-channel MEIS array detectors was digitized and transmitted to the data processor for radiometric correction. The data from each array were then transmitted to the image data resampler to generate output lines consisting of 1024 pixels. This resampling is designed to accomplish pixel registration to within +/- 1/8 pixel. These real time corrections eliminate geometric distortion and the effects of aircraft roll. The field of view after resampling is approximately 40°, or 80% of the initial 49°. The processed data was then written to high density digital tape (HDDT) for post-flight analysis. The MAID system records navigational data on computer compatible tape (CCT). A 'quick-look' hardcopy image was then produced from the HDDT after the flight, and the HDDT was processed to produce a CCT in standard format.

5.3 INTERPRETATION OF B&W, CIR AERIAL PHOTOGRAPHY

The black and white (b&w) aerial photographs show clear and dramatic evidence of the disturbance due to pipeline construction and oil spillage. Figure 5.1 shows the study site as it was in August 1971 before any disturbance, while figure 5.2 was taken on 1 July 1978, just 2 weeks after the spill occured and 2 growing seasons following the construction. The ROW is distinctly visible in fields A and B of the 1978 photo and exhibits a sharp tonal contrast with the OFF-ROW areas. Field C was in corn at that time, however because of the early stage of the crop's development the soil background predominates, obscuring the differences between ON versus OFF-ROW areas. In field D (also in corn) the area blackened by oil, enhanced by increased surface wetness as a result of drainage impedance, is easily discernible. The oil clearly moved more readily in a northerly direction with the natural slope of the land. The patchy tonality of other nearby corn fields, presumably results from variations in relief, surface moisture, seed germination or seeding efficiency. The tonal contrast resulting from the effects of the oil spill is significantly sharper than that visible in nearby fields.

The colour infrared (CIR) photography obtained on 23 September 1980, reveals well-marked traces of the ROW. This is a three layer film which, when used with a yellow or 'minus blue' filter eliminating the blue wavelengths, has green, red and near-infrared sensitivity. Thus, while not strictly an IR film, the dye couplings are manufactured to display 'false colours', with green reflective objects shown as blue, red as green, and IR as red. The strong reflectance of healthy vegetation in the near-infrared allows for clear recognition of areas with poor crop growth and exposed soil. In figures 5.3 and 5.4 the recovery of the ROW in field B appears to be more successful than in field A, but the ROW is readily identifiable across the whole area. A faint trace, probably the result of a slight but visually perceptible reduction in crop vigour or canopy density, is evident within the coarse textured red-magenta canopy of alfalfa. Field C exhibits variation in crop vigour due to variation in relief, but there is a also a perceptible reduction in crop vigour along the ROW: the red signature of the mature tasselled corn being somewhat reduced compared with OFF-ROW areas. This is most evident in the elongated right-hand (east) section of the field where bare patches can be seen. Field D, while clearly showing signs of rehabilitation, exhibits variation in crop development ranging from patches of zero growth to full maturity. The dark background in much of the field reflects the severe problem of surface wetness, either attributable to or influenced by the oil spill, which has hampered seeding and germination. This type of photograph could be utilized, in conjunction with field crop measurements, to delineate and measure areas within set categories of crop response or 'zones of impact'. While this is a visual and subjective method of interpretation, it would provide a visual record of the change (improvement) in crop status and could be used as a basis for compensation.

Figure 5.5, taken on 17 August 1984, shows that the efforts at rehabilitation, however conscientious and well-intended, have not succeeded in erasing the impact of the pipeline in any of the four fields examined. Linear features corresponding to reduced crop vigour, bare patches and remnant trenches are strikingly visible on sites where no such features existed before the pipeline construction, as evidenced by the textural uniformity of the fields in the 1971 photo (fig. 5.1). Field D, photographed in its seventh growing season following the spill, has clearly not been restored to a pre-impact condition. The colour photography, figure 5.6, taken when harvesting of the field's easterly section had begun, provides a more detailed look at field D. Full physiological development of the corn is indicated in the dark green areas of the field and in adjacent fields to the north and west. The light green and yellowish green patches represent areas where only 20% of the plants developed any grain at all and where patches of zero growth or extreme weediness (yellowish green) were not uncommon. (The farmer ultimatly ploughed-under sections of this field). The aerial photographs allow a fairly precise delineation and measurement of zones of crop vigour for purposes of compensation to the landowner and assessing rehabilitation efforts.

In evaluating the relative suitability of the various film types it must be emphasized that the photography was obtained at different stages of crop growth. The writer had control over the acquisition date for only one of the photographs (fig. 5.5). That date was specified with the intention of nearing the period of maximum vegetative development so that the contrast between stressed and vigorous crop growth would be emphasized. The b&w photography was not taken with this specific purpose in mind, but the crop was well enough into the growing season to provide good coverage.

The scale of the 1984 photography was predetermined by the minimum flying height of 4750 feet (1448 m) required for the primary sensor (MEIS). Bearing in mind the scale of the original products before reformatting for presentation in this report, the photos all vary in the level of detail presented. Clearly, for any 'detailed' study involving crop assessment, especially for an area as small as the study site, the larger the scale the better. Basu (1981) suggests that CIR photography with scales ranging from 1:640 to 1:4200 is best suited for crop discrimination and detection of stressed areas. However, valid interpretations can still be made and valuable information gleaned from photographs with scales up to 1:10,000. The b&w photography is least suited to this type of study, since the tonal variations are less informative than colour variations. The human eye has a much greater sensitivity to slight changes in colour than brightness. The handheld colour photograph is, however, very well suited to this study, where regular low level data acquisition can provide timely, useful information. In accord with Basu (1981) and others, low level CIR photography would seem to offer the most appropriate film type/scale combination for detailed studies examining stress in field crops.

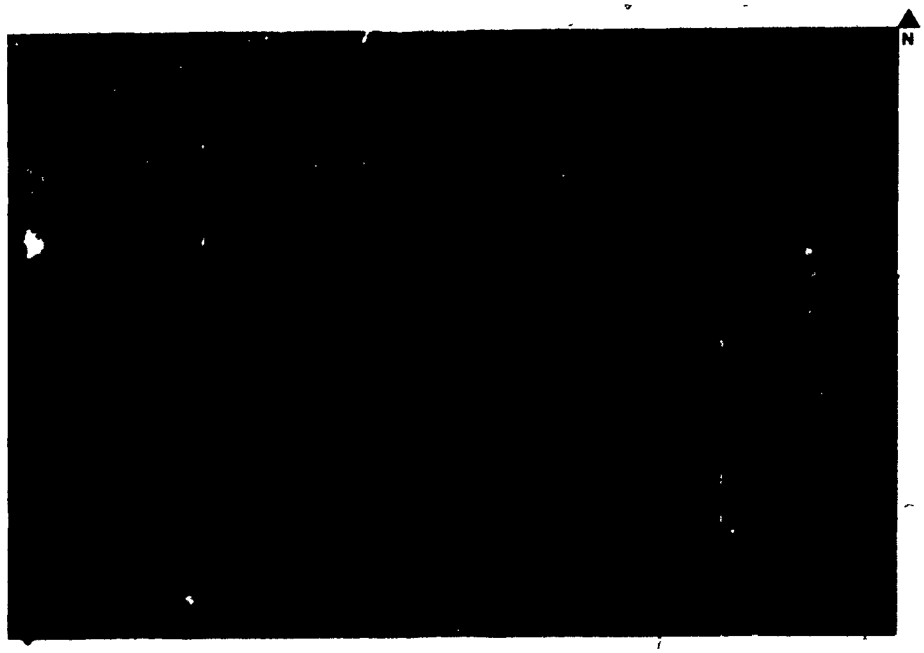
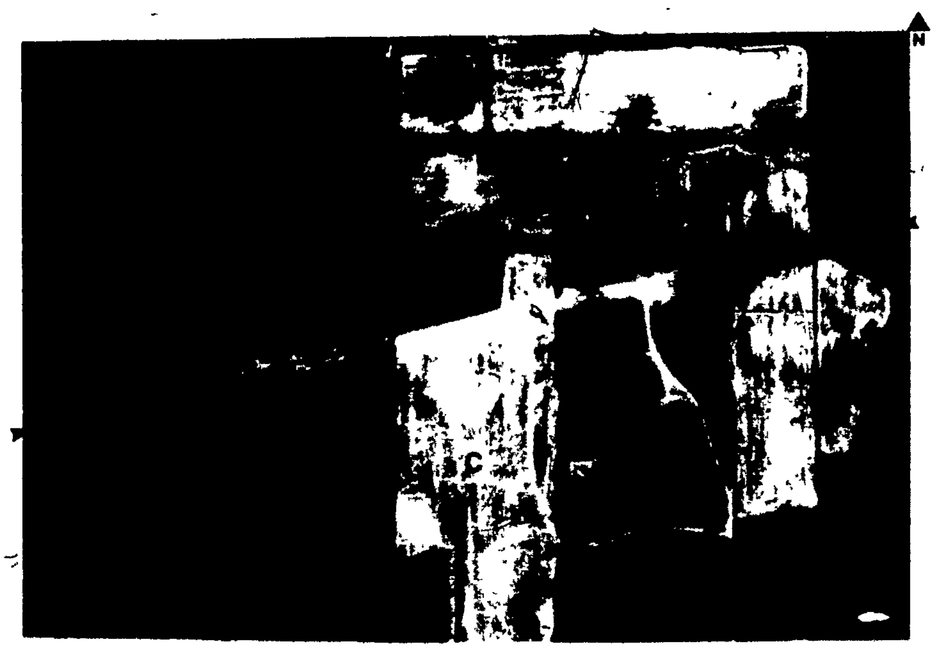


Figure 5.1: B&W airphoto of the study site, 16 Aug 1971, 1:8900.



△ SPILL SITE

Figure 5.2: B&W airphoto of the study site, 1 July 1978, 1:8900.

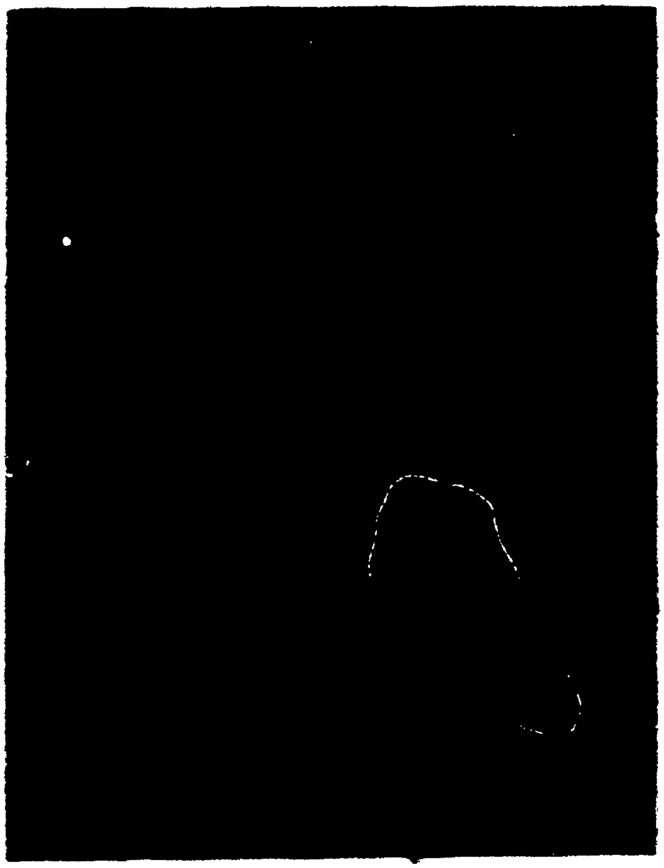
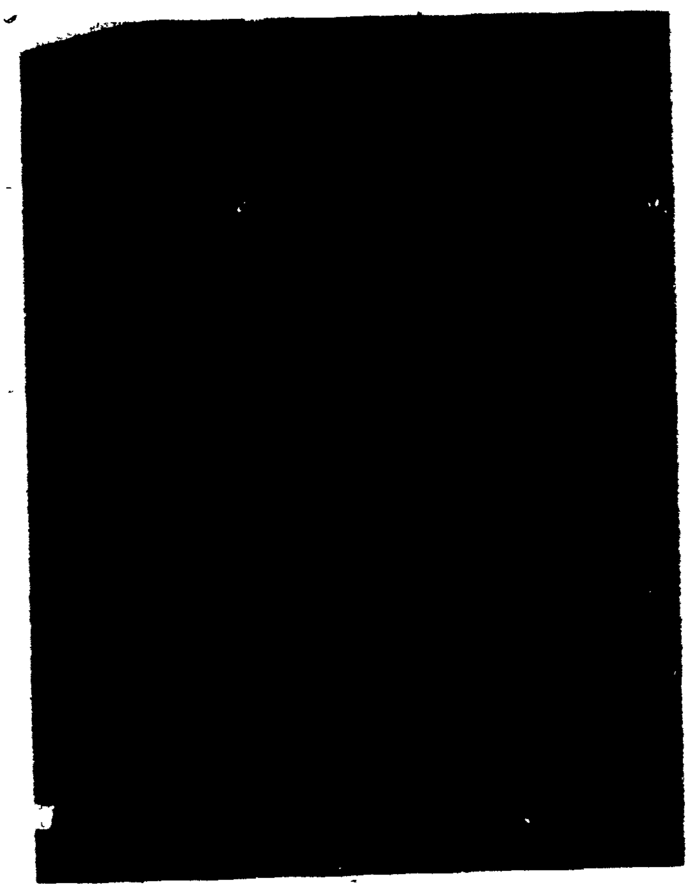


Figure 5.3:
CIR airphoto of fields A&B,
23 Sept 1980, 1:4880.



Δ SPILL SITE

Figure 5.4:
CIR airphoto of fields C&D,
23 Sept 1980, 1:6095.

Δ SPILL SITE

Figure 5.5: CIR airphoto of the study site, 17 Aug 1984, 1:7600.

Figure 5.6: Handheld colour airphoto of field D, 4 Sept 1984, 1:2740.

5.4 INTERPRETATION OF MEIS II DATA

5.4.1 COMPUTER-ASSISTED IMAGE ANALYSIS

Analysis of the data stored on the CCT was carried out on the Image-100 Analysis System (CIAS) at the Canada Centre for Remote Sensing in Ottawa. A description of this system can be found in Goodenough (1979). As the system has only 4 channels for storage of image data, TMX was excluded from the analysis. One channel is reserved for classification or 'theme' data. The four fields of the study area were examined individually, each being scaled to a 512 x 512 pixel size to fill the display screen from an original scene size of 1024 x 4311 pixels. The classification methods used have been described by Goodenough (1976).

In unsupervised classification, the system scans the digital imagery for clusters of similar spectral characteristics or radiance values. The number of classes, or themes, is selected by the interpreter. In supervised classification the interpreter defines the classes based upon his knowledge of the ground cover, and uses a number of known field sites to 'train' the computer. The system can then identify all pixels in each band of each image with radiance values between the minimum and maximum values obtained for the training site. The measured radiance values, converted from analog to digital, provides for 64 radiance or brightness values in each of the 4 bands recorded. These pixels are then designated to a particular theme and can be displayed on the CRT. This 1-dimensional (1-D) supervised classification is so-called because the upper and lower intensity limits are obtained for each channel independent of each other. In N-dimensional (N-D) supervised classification a pixel is included in a class only if the intensity values of each of the 4 bands match those of the training sites and is thus a much stricter classification. Correlation between the field data and the themes obtained through the computer analysis of the MEIS imagery was attempted only for field D: no vegetation sampling was carried out in field A, and the analyses of fields B and C were hindered by cloud.

The distribution of radiance values for each field and for each of the 4 bands are displayed in a set of histograms (figures 5.9, 5.14, 5.16, 5.20, 5.23, 5.24). For each set, histograms are numbered 1 to 4 and correspond to TM bands 1 to 4 (blue, green, red and infrared respectively). The abcissa represents radiance values from 0 to 63, while the ordinate shows the relative frequency of pixels with a given value. The hatched vertical lines show the limits of the range of radiance values found (unsupervised) or selected (supervised) by the interpreter. The 'overview and comparison file' describes the histograms as follows: # - channel number; LB, UB - lower and upper bounds of the class; DEL - the range between the upper and lower bounds; PEAK - the highest number of pixels for a single intensity. The mean and standard error are also given. The training area indicates the number of pixels in the whole image (512 x 512 pixels) used to define the class. Using figure 5.8 as an example, it can be seen that while field A is aligned diagonally across the screen (the flight line being parallel to the ROW) the training area can be a parallelogram situated at the discretion of the interpreter. The training area, shown by the white square, is the largest one possible without the risk of 'contamination' by the inclusion of pixels from adjacent fields not desired in the classification. The alarmed area is the number of pixels which have radiance values falling within the limits of the histogram. The bar graph to the right of these values represents the range of radiance values for pixels in the alarmed area in a given channel. The abscissa of this graph represents the radiance values from 0 to 63 and the position of the mean radiance value is shown by the point marked within each bar.

Tonal variation of the images could be manipulated by varying the intensity of the blue, red and green guns of the CIAS display monitor when generating the false-colour images. A linear contrast stretch was carried out on the data to highlight the tonal variation. This is done by assigning digital counts of 0 and 255 to the minimum and maximum reflectance values respectively. The enhanced contrast facilitates the identification and delineation of ground cover.

Hard copies of the band histograms and grey level theme plots were obtained from a Tektronix hard copy unit and Versatec electrostatic plotter. The grey level plots, while not presenting information different from that of the colour prints, are included here as further examples of the output obtainable from the CIAS. Colour slides (35 mm) were taken of the display screen using a Matrix Colour Graphics camera. Photographs were then produced from the slides.

5.4.2 FIELD A

The data for field A were scaled and brought up on the display of the CIAS. TM bands 1, 2 and 4 were used to generate the composite image. The training area was selected, centering on the ROW and eliminating areas outside the field. Figure 5.7 displays the annotated image with the training area shown. The ROW and its remnant trenches are clearly discernible as vertical, linear features. The vegetative cover of weeds, which was not sampled in this field, exhibits a pink to red tone. The colour variations indicate differences in density, microtopography and surface moisture. The bluish areas represent zones where surface moisture content is probably greater than adjacent sites. Figure 5.9 shows the band histograms produced from the training area. The alarmed area of 98.3% indicates that the spectral responses of nearly all the pixels within the scene fall within the bounds of the histogram, suggesting no anomalous features. The bar graphs indicate that the infrared TM4 band exhibits the widest range of radiance values.

The unsupervised classification of the image is shown in figure 5.8. Three classes were selected after visual examination of the image (fig. 5.7), in order to differentiate the flat to gently rising areas, the slightly depressional areas and a gradient zone. Left uncultivated, the vegetative growth has adapted to this distinction in relief and the areas identified by the unsupervised classification reflects these three classes. The unclassified areas result from cloud interference and are black on the image and left blank on the grey scale plot (fig. 5.10). The cluster diagram shown in figure 5.11 indicates the extent to which there is separability of themes using the 3 classes from the unsupervised classification as the truth file. It suggests that while all classes overlap in feature (band) 1 (selected as it exhibits maximum response in the visible region) there is maximum separability of themes in feature (band) 4 - the infrared band.

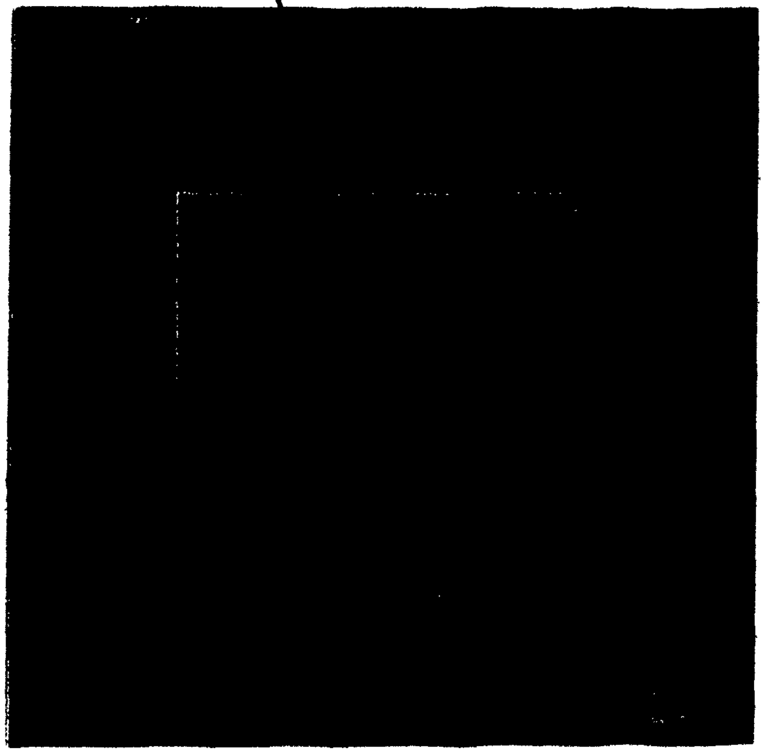


Figure 5.7: Field A - colour composite, TM bands 1 2 4, 1:2800.

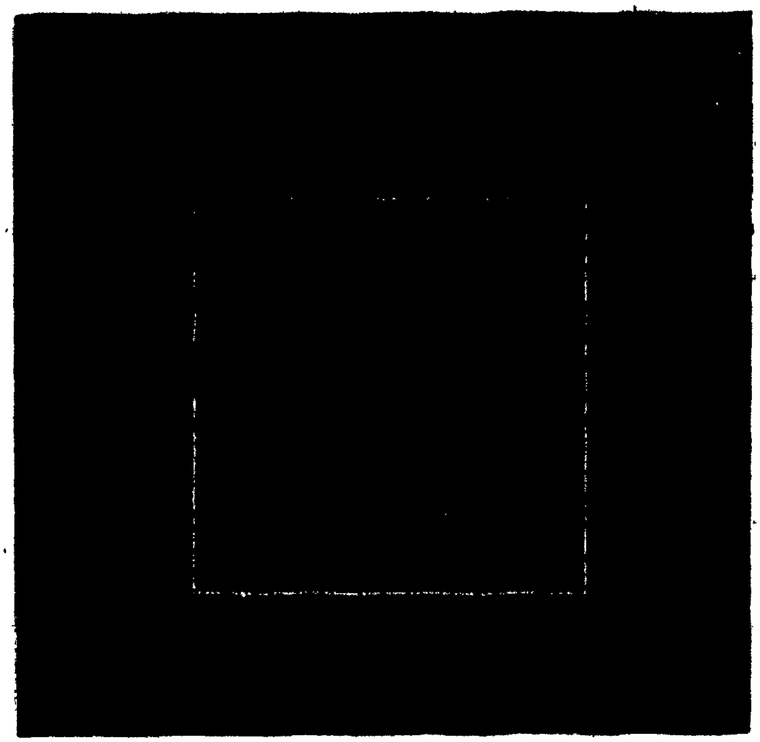
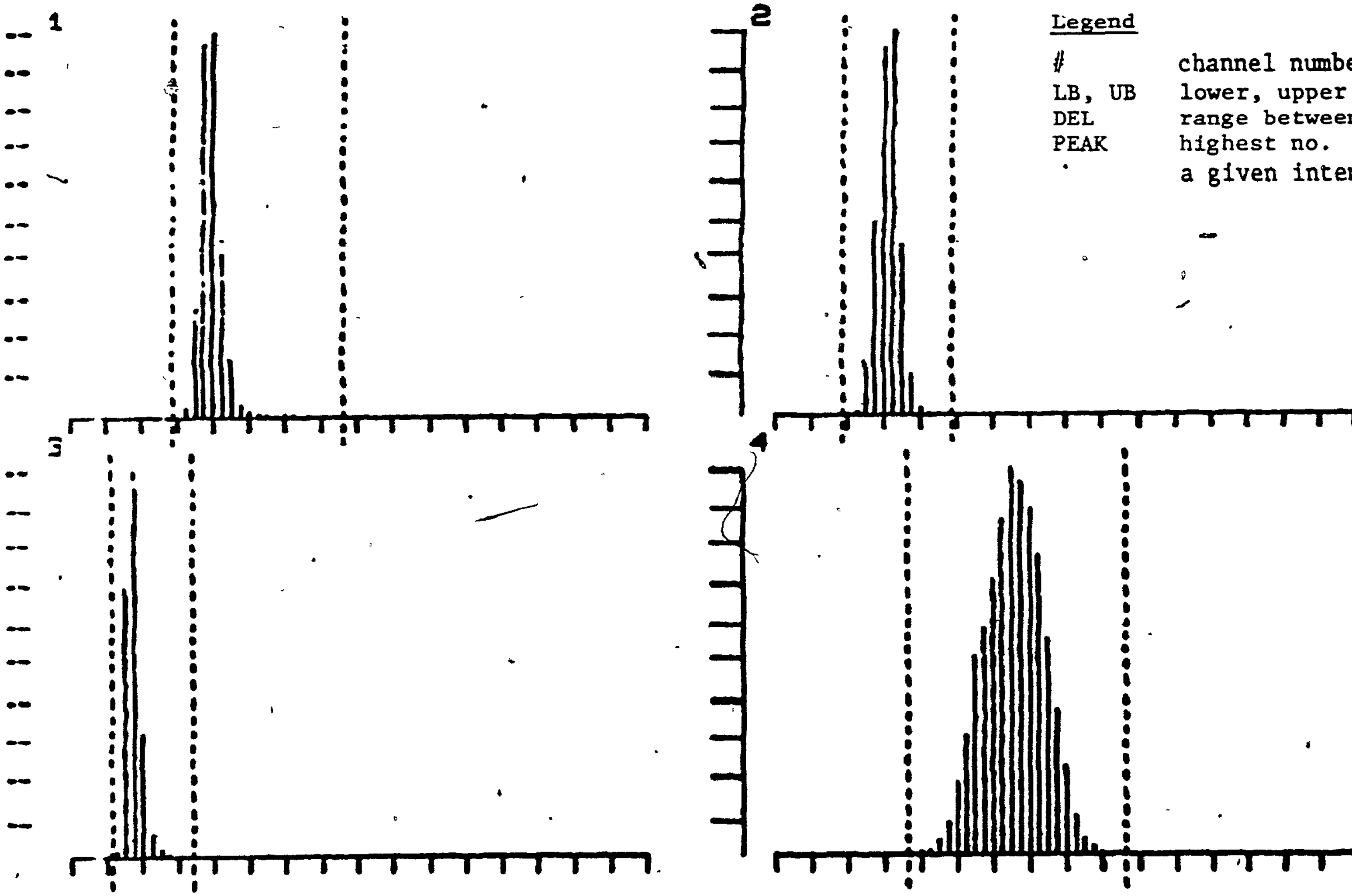


Figure 5.8: Field A - unsupervised classification (3 themes).



Legend

#	channel number
LB, UB	lower, upper class bounc
DEL	range between LB and UB
PEAK	highest no. of pixels fc a given intensity

: $ OVERVIEW $$ + COMPARISON FILE:

#	LB	UB	DEL	PEAK	MEAN	S.E.	+
1	12	30	19	21757.	15.8	1.2	+
2	8	19	12	20331.	12.5	1.2	+
3	9	13	9	30047.	6.9	0.9	+
4	15	38	24	7685.	28.3	3.3	+

TRAINING AREA= 63500. PIXELS +

ALARMED AREA=257723.PIXELS(98.3%)+

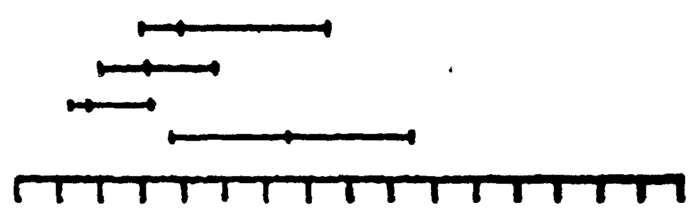


Figure 5.9 Field A - band histograms.

Figure 5.10 Field A - unsupervised classification (3 themes).

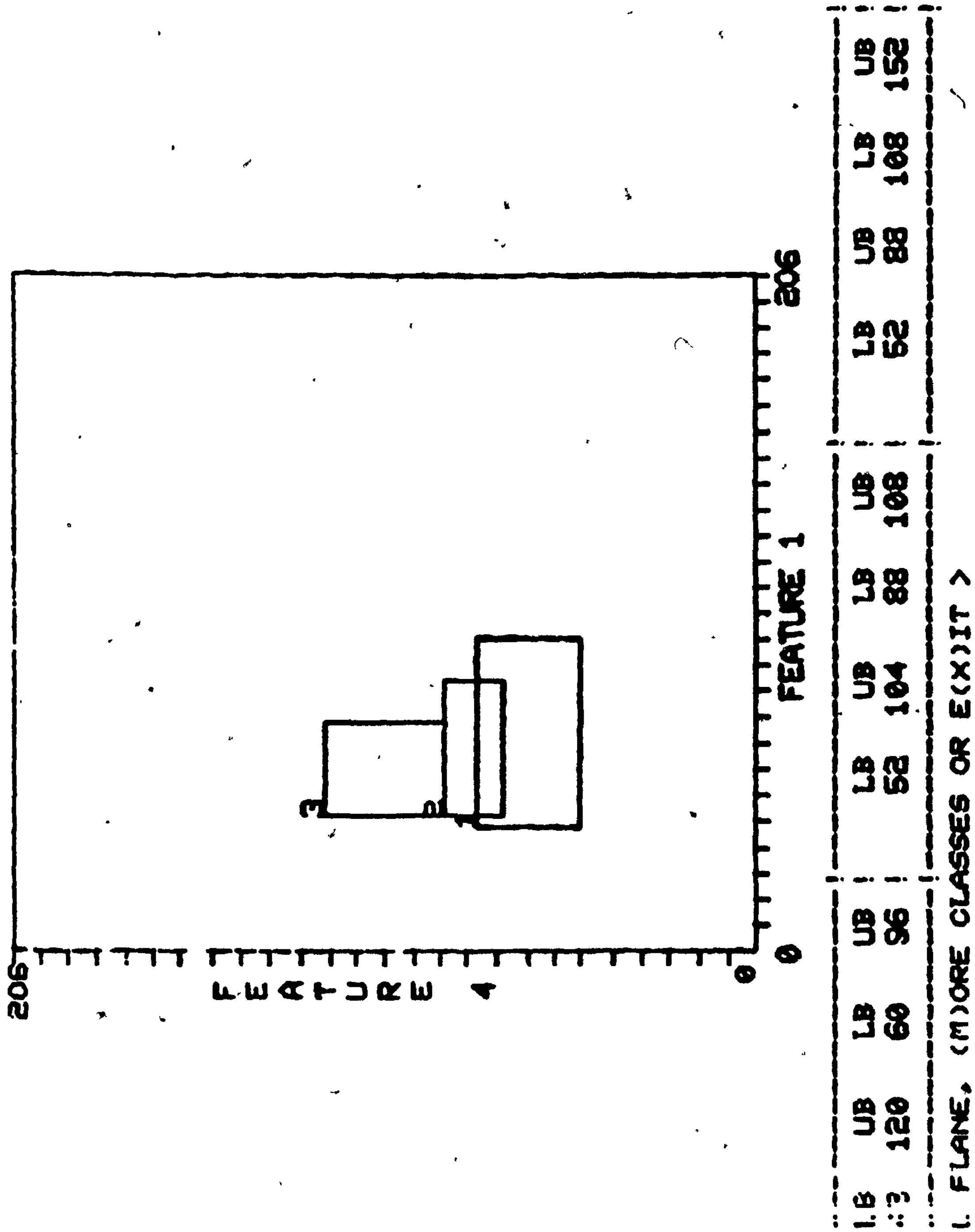


Figure 5.11 Field A - cluster diagram.

5.4.3 FIELD B

The analysis of the field B data was hampered by interference from cloud cover. The data from TM bands 1, 2 and 4 were scaled to the monitor and a training area was selected which centered on the ROW and eliminated the adjacent fields and cloud interference (fig. 5.12). While the ROW is clearly visible due to the linear patterns of bluish patches, the contrast between these areas of poor growth and the areas of more vigorous growth is weak.

The alarmed area indicated below the band histograms (fig. 5.14) reveals that only 59.2% of the pixels had radiance values between the histogram bounds, with the clouds' interference accounting for most of the anomalous response. In an unsupervised classification the CIAS would only permit 2 themes (excluding the portion of the image obscured by cloud) as shown in the grey scale plot (fig. 5.15). Figure 5.13 shows a linear contrast stretched image of TM bands 1, 2, and 4. A somewhat larger training area than the previous image was used to produce the band histograms (fig. 5.16) with the result that a greater number of pixels are within the bounds of the histogram limits (69.2% versus 59.2%). This may have been aided by a wider range of radiance values in the pre-stretched training area (histogram not shown). Cloud interference was, however, undiminished. In section 5.4.4 an attempt will be made to reduce cloud interference in field C data. A problem with band 3 was encountered at this stage. Both its lower and upper bounds on the original and stretched histograms are nearly identical. The operator considered this a hardware problem; an examination of band 3 data revealed missing scan lines indicating a memory malfunction. This raised an element of uncertainty regarding the use of band 3 in the analyses. This situation notwithstanding, the stretched image provides better differentiation between the bare and vegetated areas. The stronger blues and greens more clearly provide an impression of the actual variability than the original image.

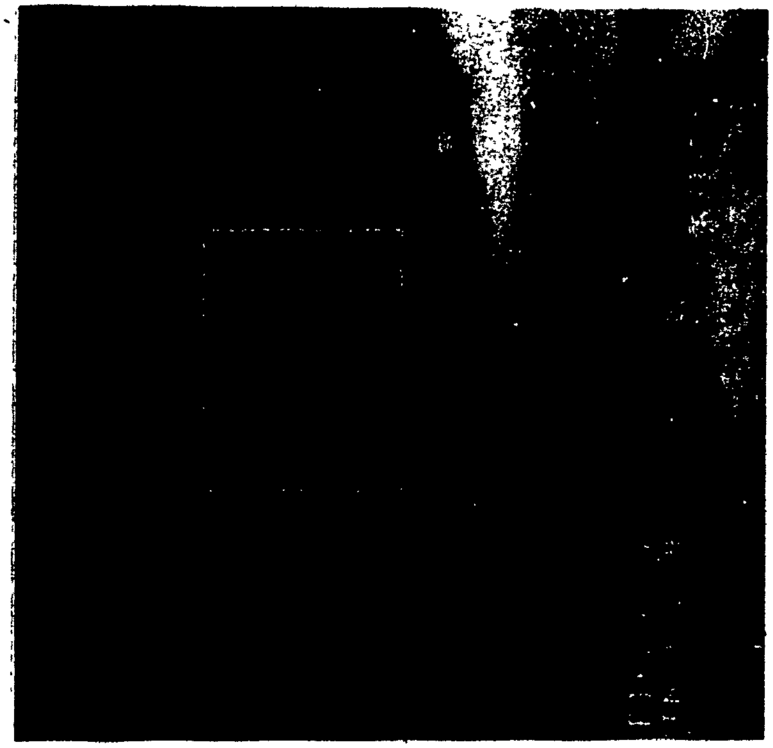
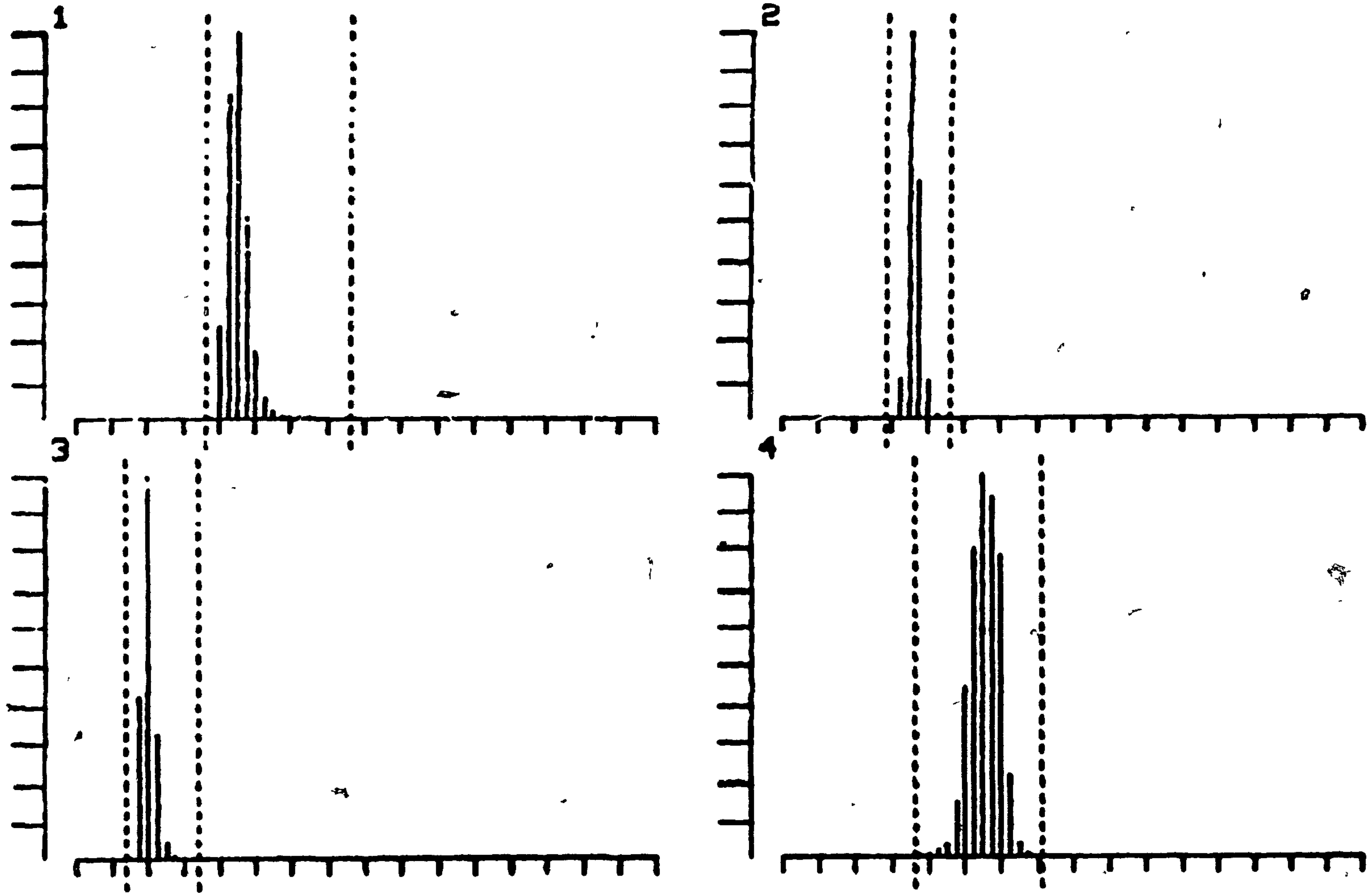


Figure 5.12: Field B - Colour composite, TM bands 1 2 4, 1:2880.

Figure 5.13: Field B - contrast stretch enhancement.



$$ OVERVIEW $$				+ COMPARISON FILE:			
#	LB	UB	DEL	PEAK	MEAN	S.E.	+
1	15	30	16	7486.	18.0	1.3	+
2	12	18	7	11662.	14.4	0.7	+
3	6	13	8	11841.	8.0	0.8	+
4	15	28	14	4826.	22.2	1.6	+

TRAINING AREA= 21420. PIXELS +
ALARMED AREA=155078.PIXELS(59.2%)+

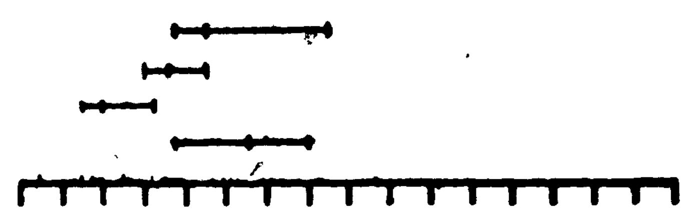


Figure 5.14 Field B - band histograms.

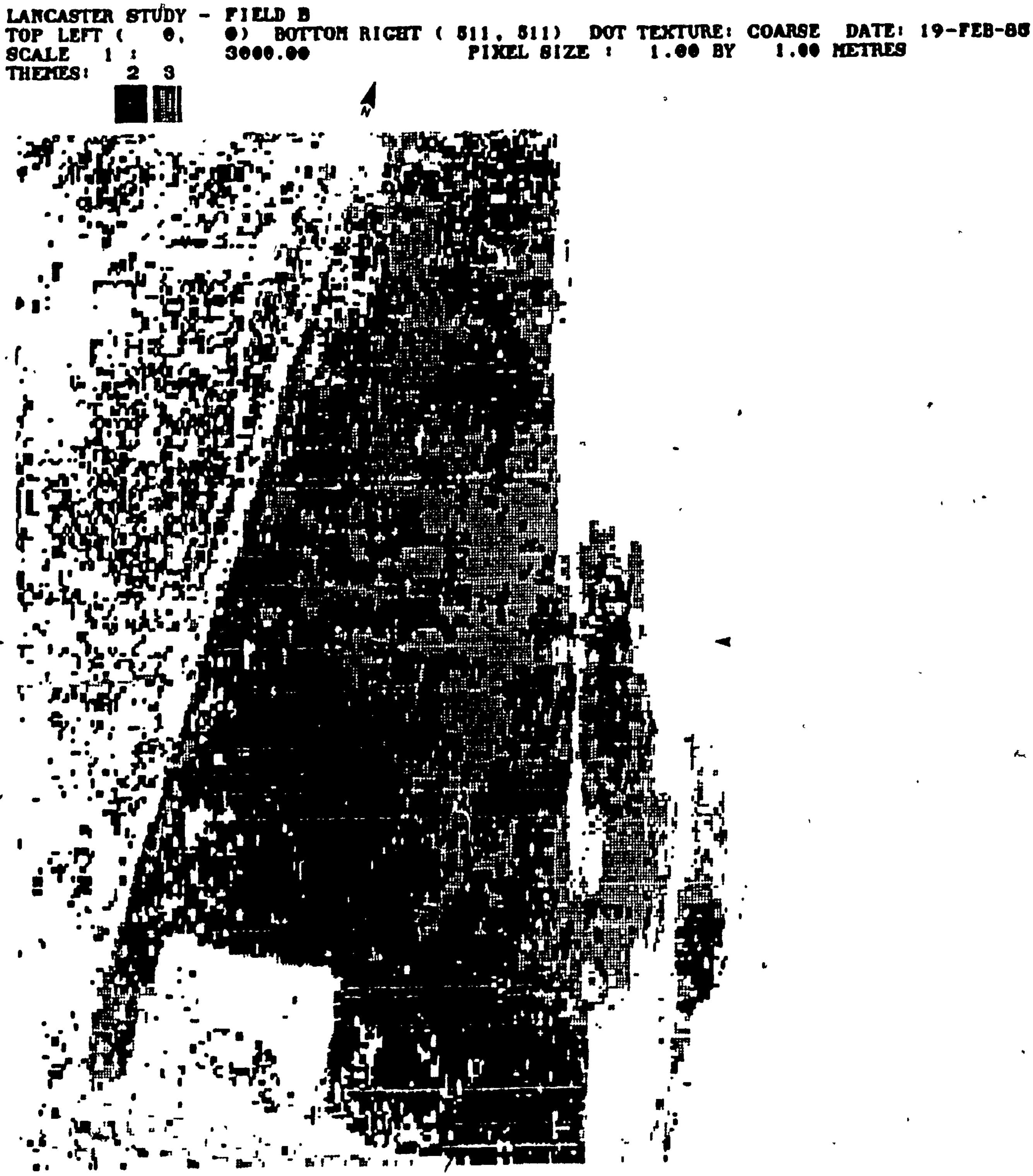
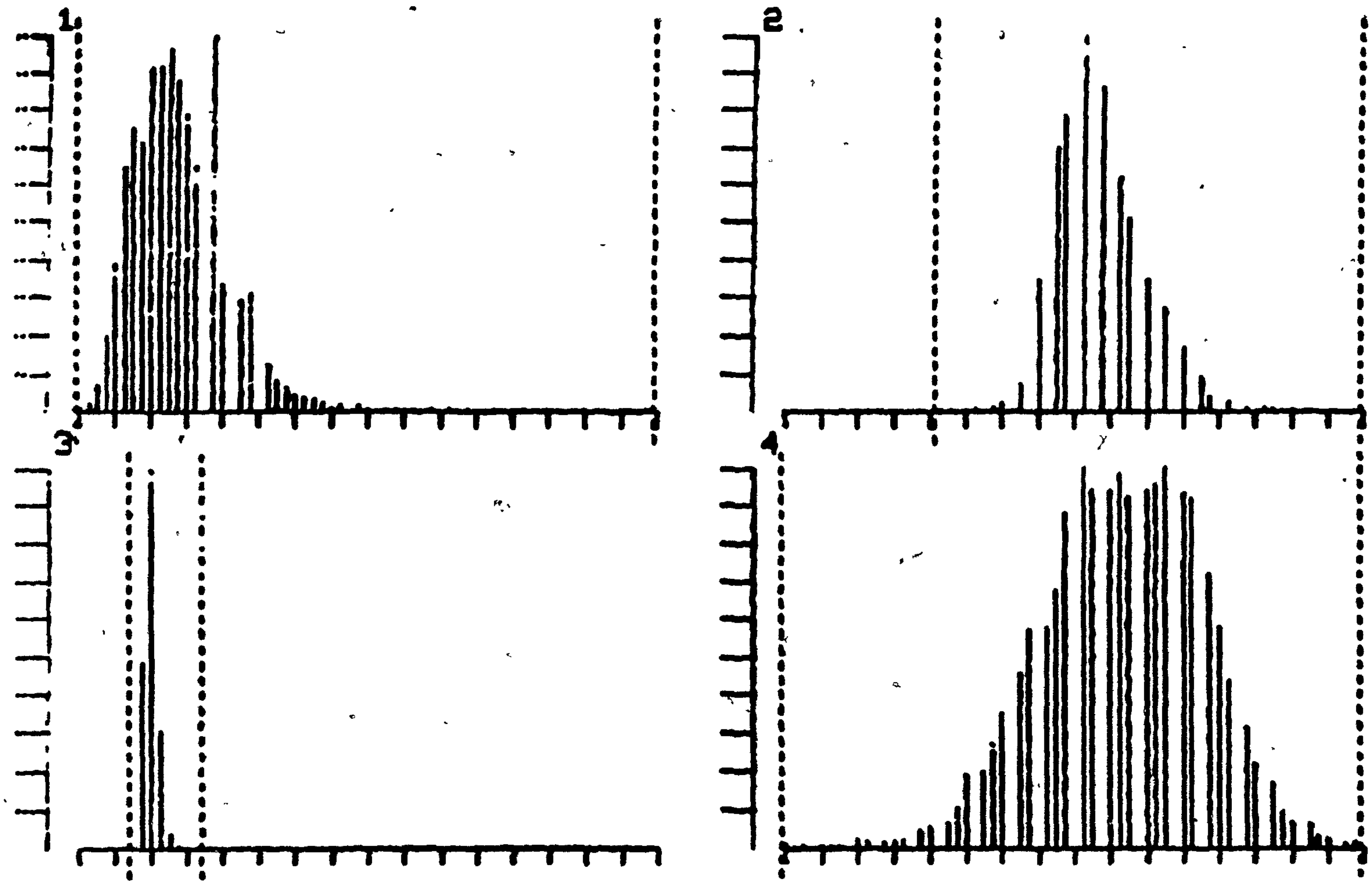


Figure 5.15 Field B - unsupervised classification (2 themes).



** OVERVIEW ** + COMPARISON FILE:

#	LB	UB	DEL	PEAK	MEAN	S.E.	+
1	0	63	64	3153.	10.8	6.1	+
2	17	63	47	5541.	34.7	4.7	+
3	6	13	8	17806.	7.9	0.7	+
4	0	63	64	1934.	37.4	8.7	+

TRAINING AREA= 32508. PIXELS +
ALARMED AREA=181480.PIXELS(69.2%)+

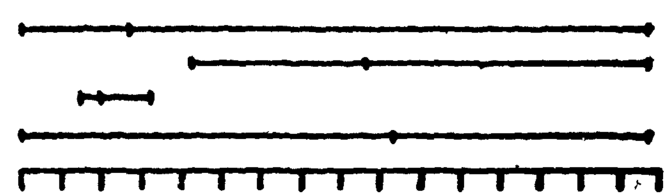


Figure 5.16 Field B - contrast stretch histograms.

5.4.4 FIELD C

The difficulty encountered with the field C data is obvious from figure 5.17. Cloud cover makes a visual examination of the field somewhat dubious, although the ROW is discernible. In contrast to the magenta of the vigorous corn, a lighter-toned trace corresponding to poor growth can be detected within the ROW. Bluish tones reveal wetter low-lying areas with poor to zero growth.

The training area (not shown) was approximately one-third of the image. As the ROW was not centered in this image, the training area necessarily included some forested land, field boundaries and, unavoidably, cloud cover. The band histograms in figure 5.20 clearly reflect the effect of the cloud cover in the visible portion of the spectrum (bands 1-3). The band 4 response is much less seriously affected. An examination of band 4 alone demonstrates the cloud penetrating capabilities of this infrared band (fig. 5.18). While not completely cloud-free and not providing the tonal variation and contrast of the original composite image, this band more readily allows for a general assessment of the ROW. The lighter toned areas correspond to areas of less vigorous growth. An attempt at an unsupervised classification was found to be of little value (fig. 5.19). Superimposing the classified theme data over the image at a 50% intensity clearly demonstrates that the themes correlate with the cloud cover and not the ground cover. No further analyses were attempted.

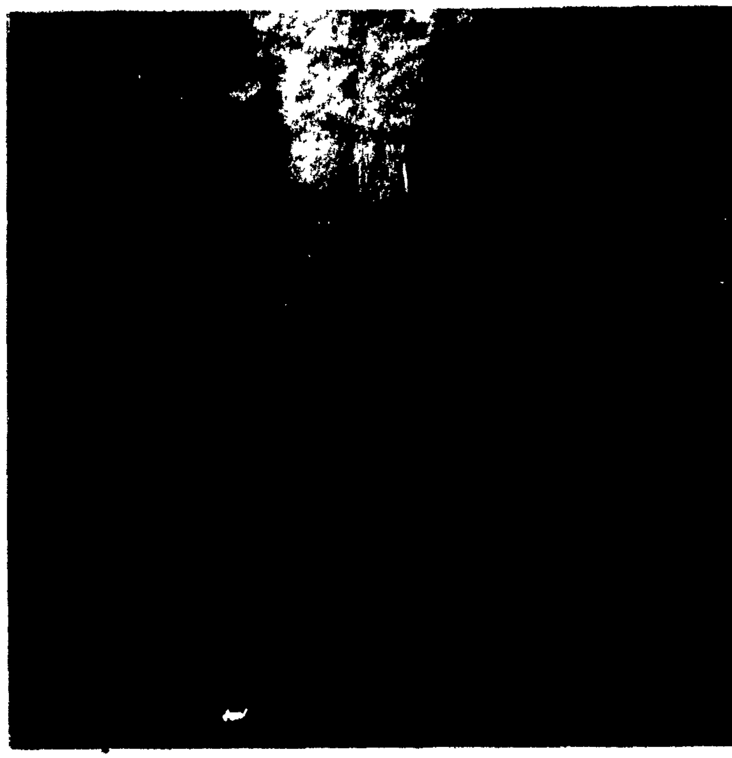


Figure 5.17: Field C - Colour composite, TM bands 1 2 4, 1:2600.

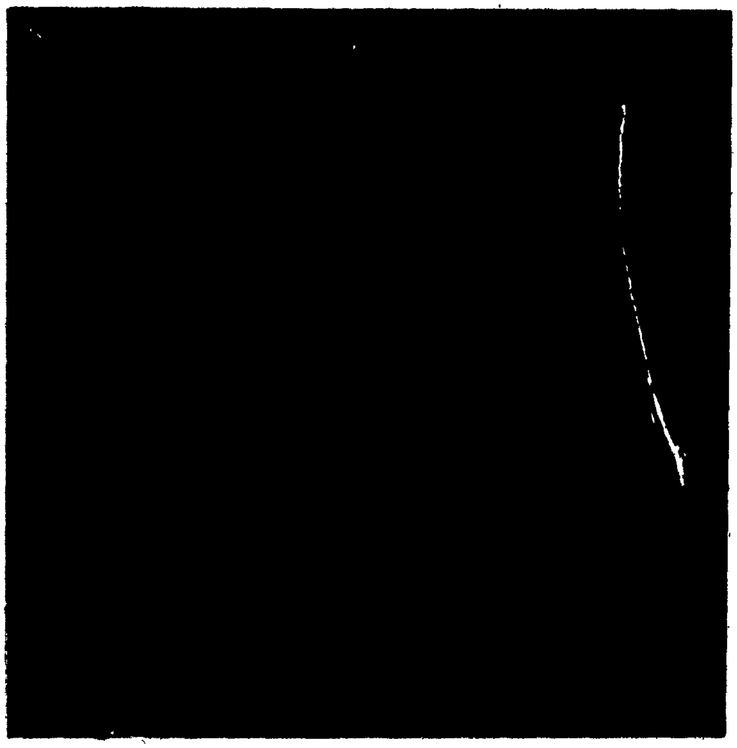


Figure 5.18: Field C - TM band 4, 1:2600.

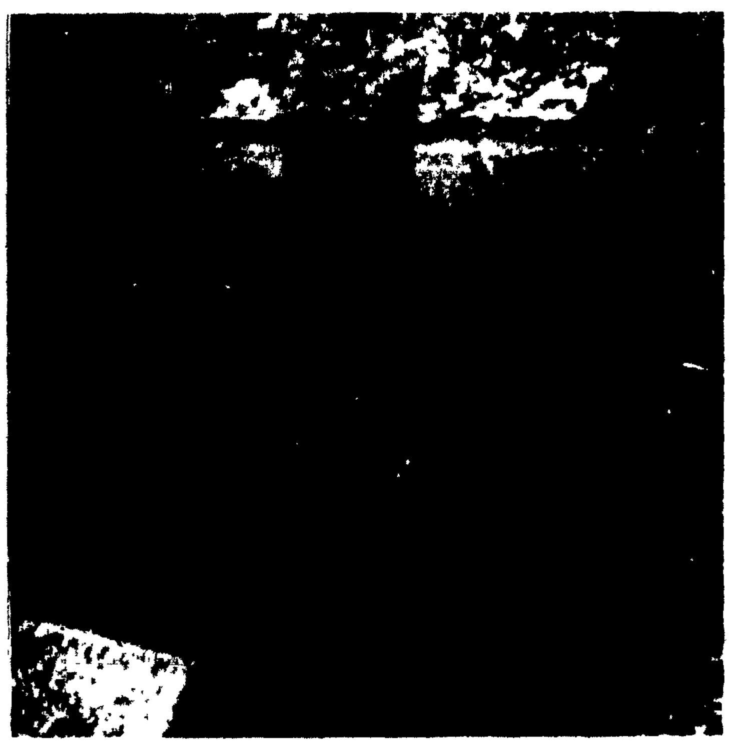


Figure 5.19: Field C - TM band 4, unsupervised classification (3 themes) at 50% intensity.

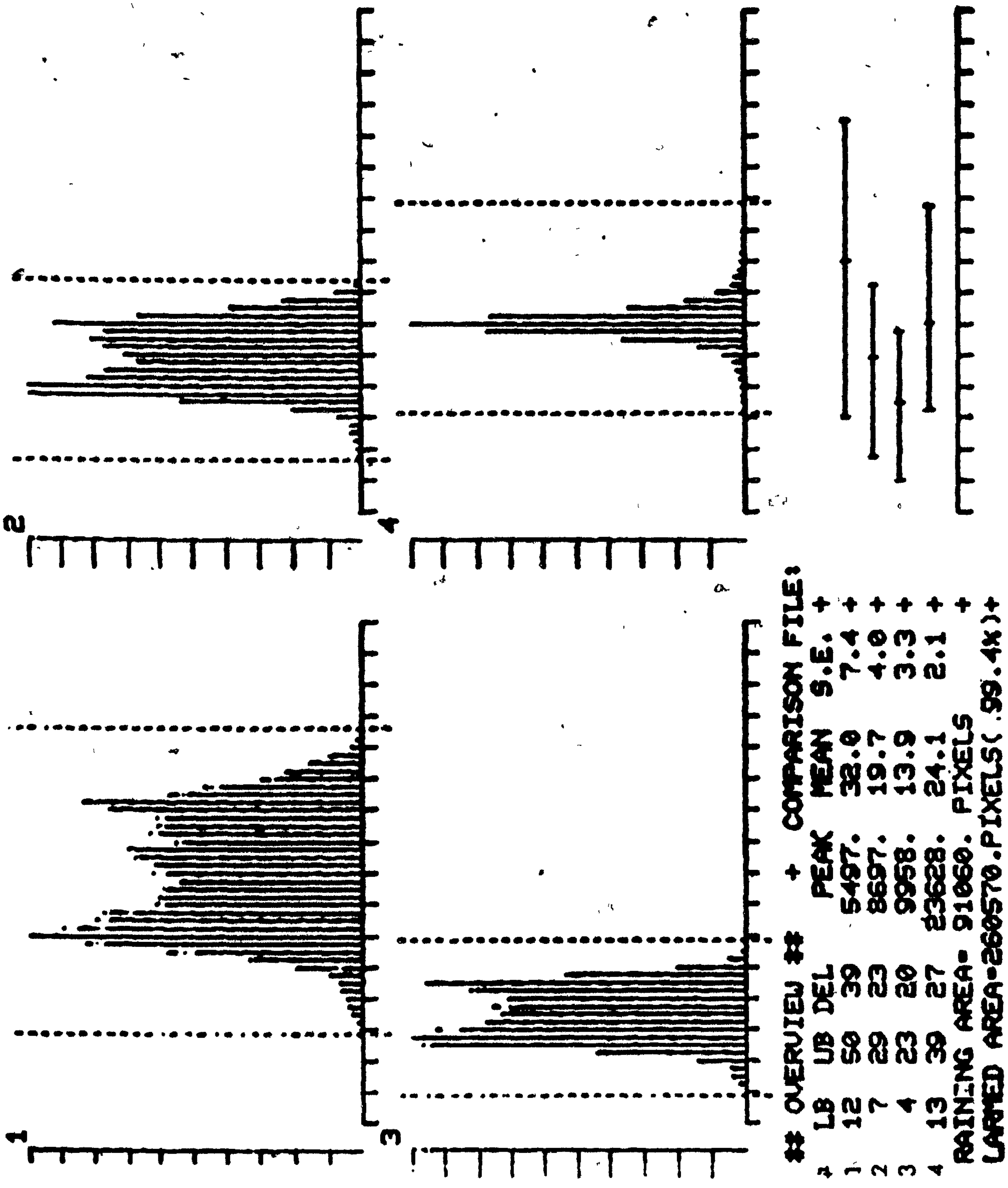


Figure 5.20 Field C - band histograms.

5.4.5 FIELD D

The data for field D were of particular interest because of the generally poor crop performance over such a large proportion of the field. Figure 5.21 is a composite image of TM bands 1, 2 and 4 and clearly shows two areas of poor growth. In comparison to the pink tones of the healthy corn crop, the yellowish area of the upper segment (D2) corresponds to an area of poor yield with a predominance of weed growth. In contrast, the blue-toned lower segment (D3) corresponds to an area where the crop growth is zero or sufficiently limited so as to allow the reflectance of the moist soil background to predominate. The band histograms, figure 5.23, reveal an alarmed area of 95.5% with the anomalous reflectance from the tree shadows accounting for the remainder. The linear contrast stretched image (fig. 5.22) and its accompanying band histograms (fig. 5.24) provide a much sharper tonal contrast between features. The stronger blues and greens permit a clearer delineation of areas with varying levels of crop performance and an assessment of variability within these areas. The band histograms for both of these images (figs. 5.23 and 5.24) indicate that it is the response in the infrared band (TM4) which predominates. An examination of the individual bands confirms this. TM 1 (fig. 5.25) demonstrates a sensitivity to soil/vegetation discrimination with bare patches identified by their white colour. The variability of the weedy area in the upper segment is not strongly shown. TM 2 (fig. 5.26) is sensitive to visible green reflectance and the white area in the upper segment of the field reflects the predominance of the weeds over the variable corn growth. The bare patches visible in the previous image are much less pronounced here. TM 3 (fig. 5.27), useful in discrimination of brown biomass, does not vividly display either of these two anomalous areas, however the poor quality of this image may relate to the earlier hardware problem associated with band 3. The infrared TM 4 band (fig. 5.28) prominently reflects the high moisture content of the soil background. The strength of this response, however, tends to mask the variable (albeit poor) vegetative growth which is apparent from previous images. Figure 5.29 presents an image produced from a ratio of bands 4/2. While displaying the variability in crop growth in both segments of the field as per their respective sensitivities, the overall quality of this image is poor. Other ratios tried were 4/3 and 4-3/4+3 but again, difficulties with band 3 resulted in poor quality output. For the purposes of this study, the original composite and contrast stretched images present the most appropriate tonal variation and contrast.

Both an unsupervised (fig. 5.30) and a supervised (fig. 5.31) classification were carried out using 4 themes. In the unsupervised version the themes correspond to ground cover as follows: theme 1, shadow and other anomalous features;

theme 2, areas of poor crop growth or uncultivated areas where the spectral response of the soil background predominates (blue on the image); theme 3, vigorous crop growth (red on the image); theme 4, healthy crop growth in fields adjacent to field D (pink on the image) and including section D2- the area of poor growth in the upper segment of the field (yellow on the image). In the supervised version, training of the CIAS was carried out using knowledge of the ground conditions. Four themes were designated, corresponding to poor, moderate and healthy vegetative growth and a wooded area. The themes from the two classifications correspond as follows:

<u>unsupervised</u> (<u>fig</u>. <u>5</u>.<u>30</u>)	<u>supervised</u> (<u>fig</u>. <u>5</u>.<u>31</u>)
theme 1: shadows, anomalies	theme 1: wooded
2: poor growth	2: poor growth
3: healthy growth (red)	3: healthy growth
4: healthy, variable (pink)	4: mod. growth

The supervised classification more accurately reflects the true ground conditions, recognizing the variability in crop growth in each section of the field. To illustrate, in the unsupervised version the entire section D3 is classed under one theme, while on the supervised version many of the pixels in that same area remain unclassified (39% of the supervised image was unclassified). This indicates that these pixels do not fit within the bounds of the classes defined by the training exercise, suggesting inadequate training to reflect the variability in crop growth. Similarly, the unsupervised version groups section D2 with the vigorous growth in the adjacent fields, while the supervised version recognizes its distinct response.

The use of an additional theme allows for an even more accurate representation of the ground conditions. In figure 5.32 the result of an unsupervised classification using 5 themes is shown. The areas of poor growth and variability in both segments of the field (D2 and D3) more clearly relate to the original composite (fig. 5.21) than do the earlier classifications. The colour coding of figures 5.33 and 5.34 (theme plots of figs. 5.30 and 5.32) facilitates the visual comparison between the unsupervised classifications with 4 and 5 themes respectively. In attempting to correlate the field data and the themes, the crop yields (rounded to the nearest gram) for field D (Appendix V) have been overlain onto figure 5.32. In general, the field data support the ability of the CIAS to delineate zones with different levels of vegetative growth. Section D2, classified as 'theme 5', is characterized by poor crop yields of less than 100 g/plant and abundant interplant and interrow weeds (discussed in section 4.5). Section D3, classified as 'theme 2', is characterized by similar, if not poorer crop yields and little weed growth. Crop yields of greater than 200 g/plant are characteristic of 'theme 4'. The analysis system permits a further assessment of the variability within these and other areas of the field. The sampling, however, was not sufficiently detailed to permit further characterization of the themes.

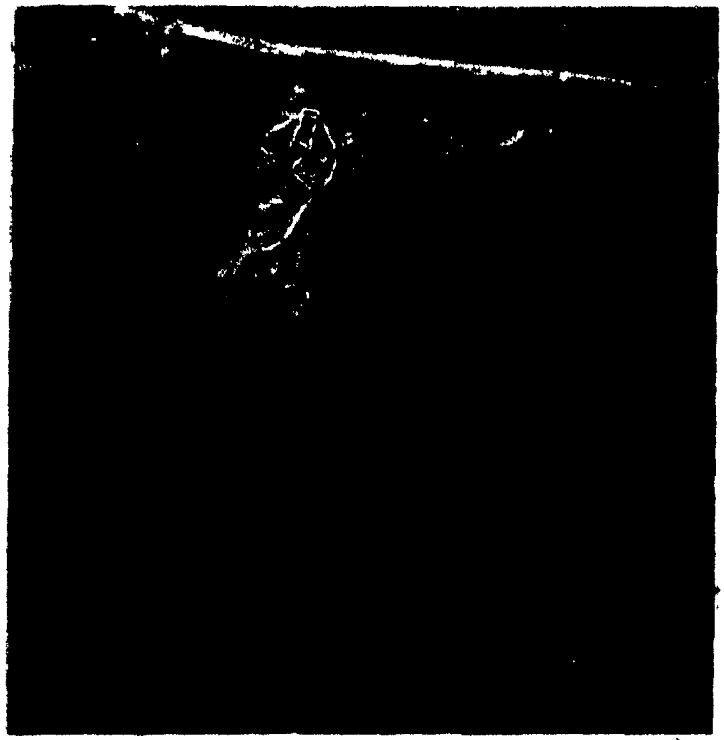


Figure 5.21: Field D - Colour composite, TM bands 1 2 4, 1:2700.

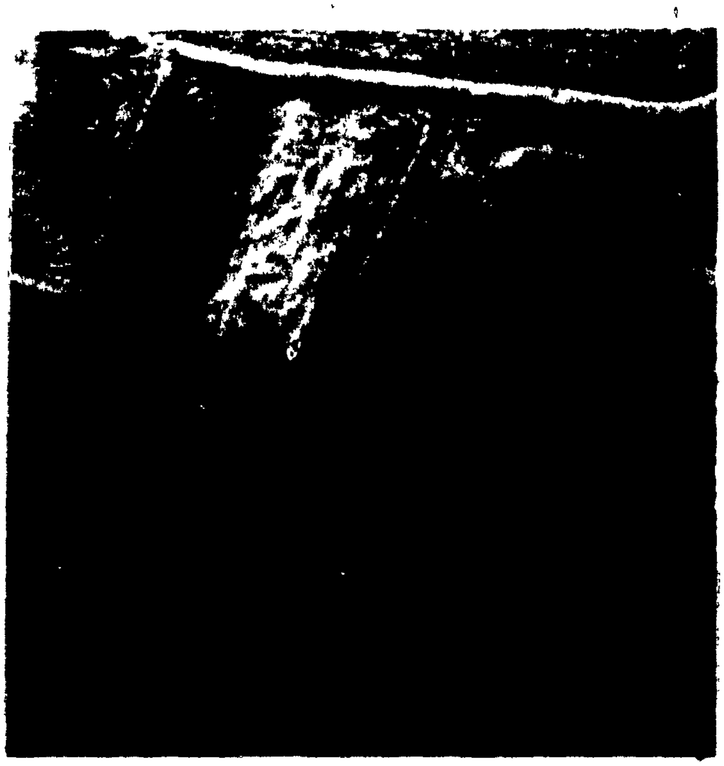


Figure 5.22: Field D - contrast stretch enhancement.

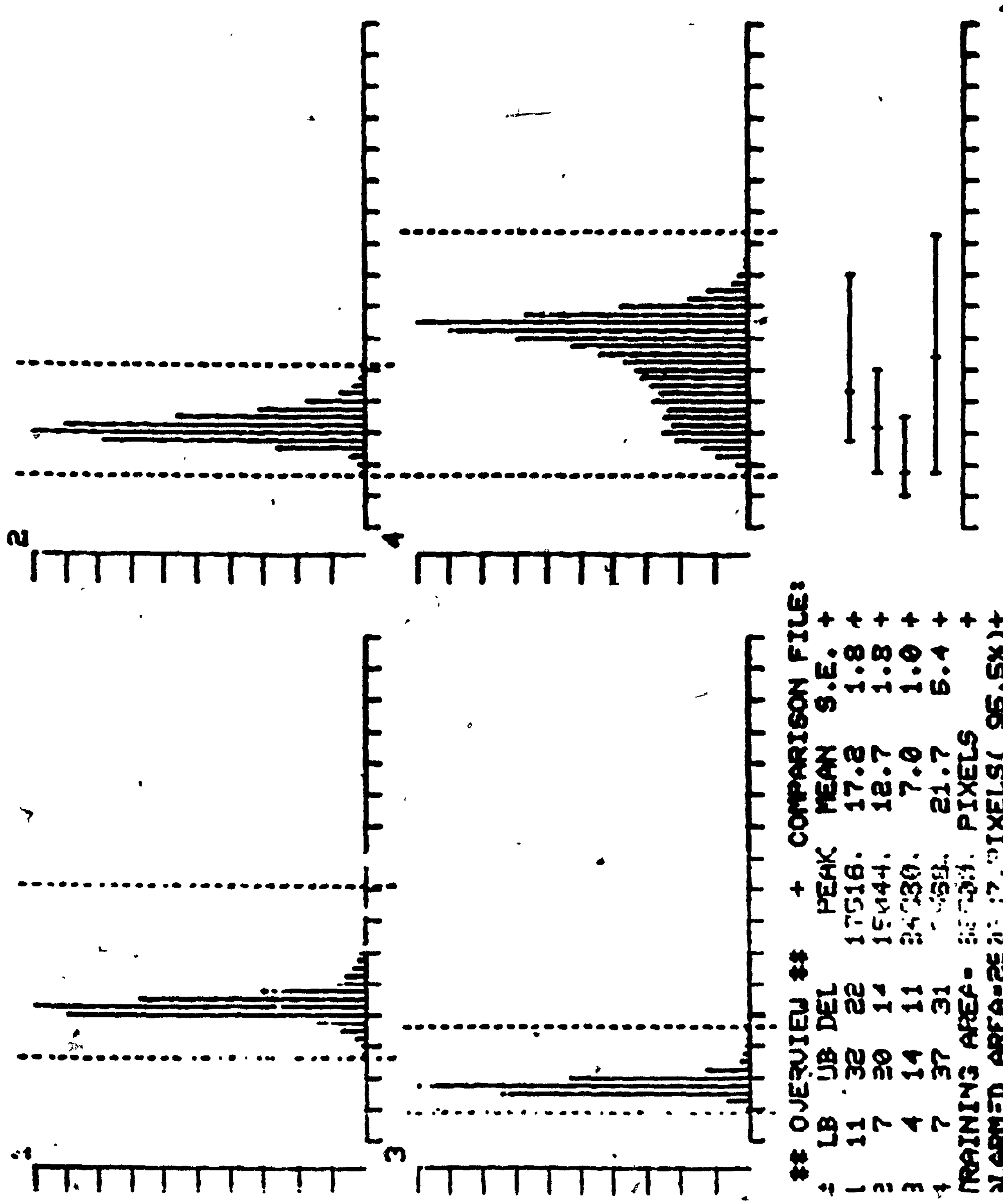


Figure 5.23 Field D - band histograms.

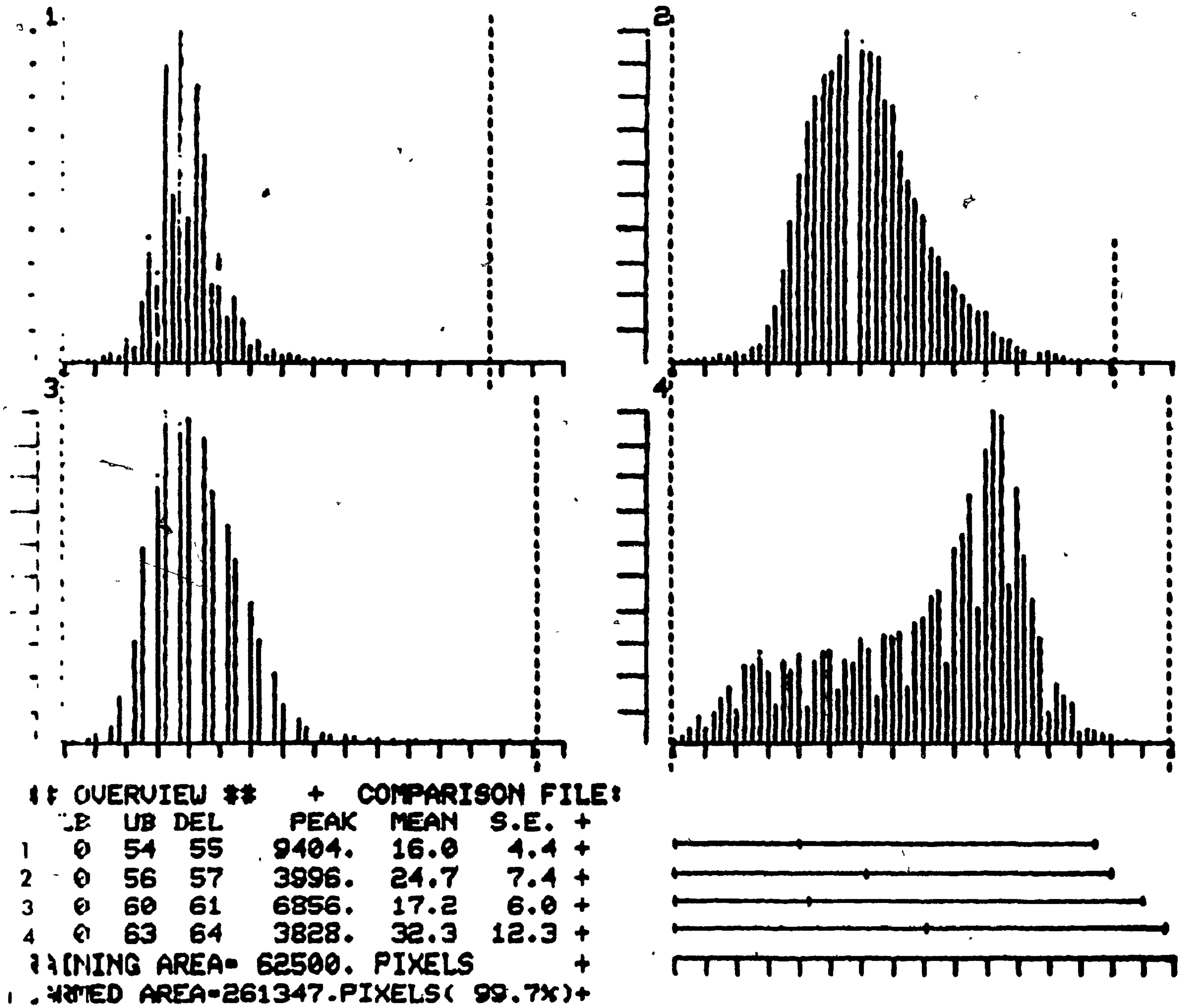


Figure 5.24 Field D - contrast stretch histograms.

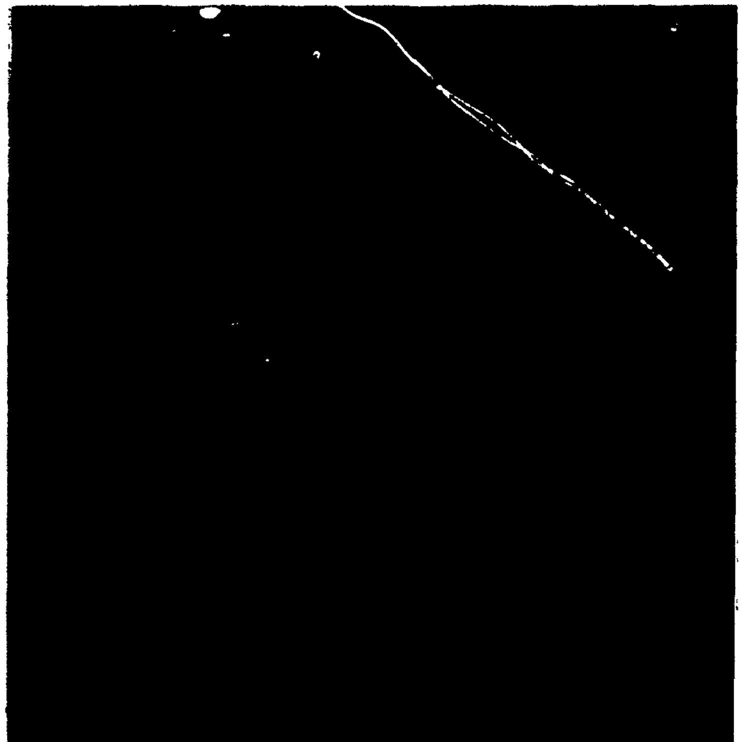


Figure 5.25: Field D - TM band 1, 1:2700.

Figure 5.26: Field D - TM band 2, 1:2700.

Figure 5.27: Field D - TM band 3, 1:2700.

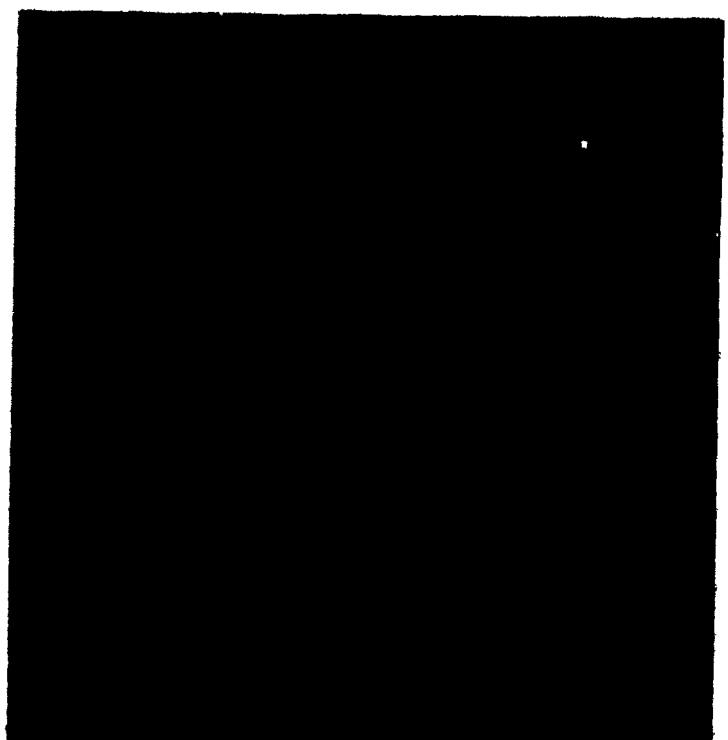


Figure 5.28: Field D - TM band 4, 1:2700.

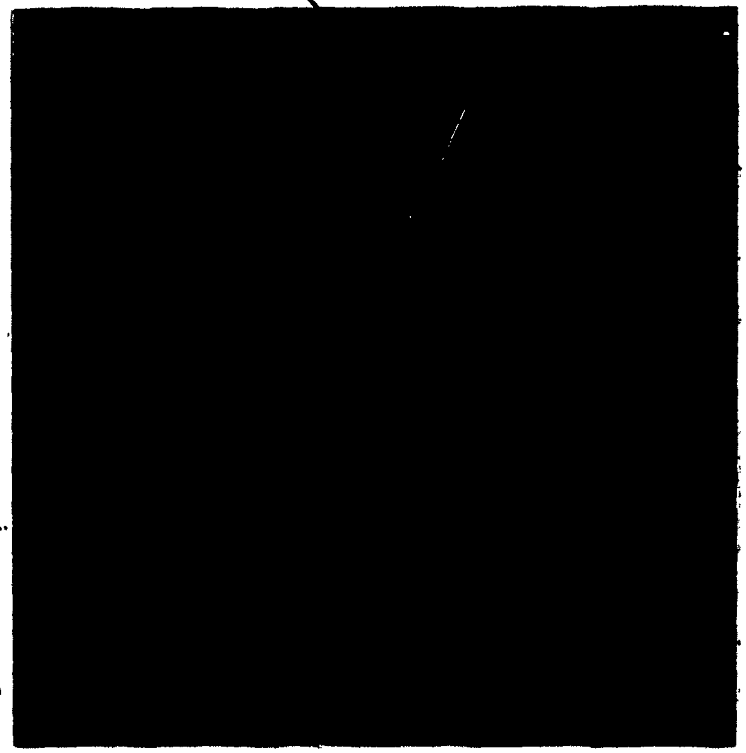


Figure 5.29: Field D - TM bands 4/2, 1:2700.

LANCASTER STUDY FIELD D
TOP LEFT (0, 0) BOTTOM RIGHT (511, 511) DOT TEXTURE: COARSE DATE: 12-MAR-85
SCALE 1 : 1500.00 PIXEL SIZE : 1.00 BY 1.00 METRES
THEMES: 1 2 3 4

Figure 5.30 Field D - unsupervised classification (4 themes).

Figure 5.31 Field D - supervised classification (4 themes).

Figure 5.32 Field D - unsupervised classification (5 themes).

OVERLAY - CROP YIELD / PLANT (gm)

• SAMPLE SITE

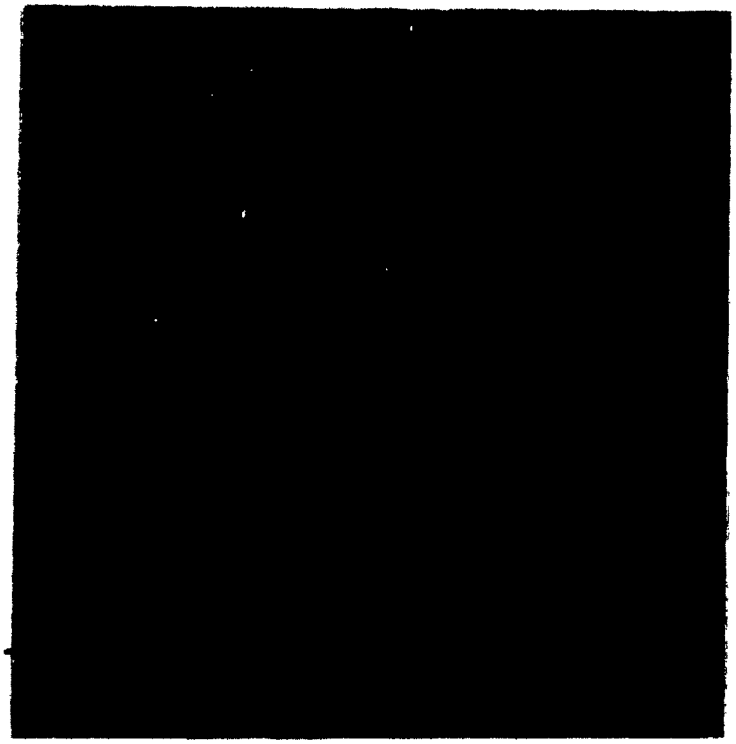


Figure 5.33: Field D - unsupervised classification (4 themes), 1:2700.

Figure 5.34: Field D - unsupervised classification (5 themes), 1:2700.

5.5 SUMMARY AND CONCLUSIONS

The analysis has clearly illustrated some value in applying remotely sensed data to the study of impacts due to pipelining. For the purposes of detecting impacts due to pipeline construction and oil spillage, and for establishing a visual record of these impacts and efforts at rehabilitation, low level aerial CIR photography appears to be the most useful sensor and scale combination. Its relative low cost, ease of acquiring, processing and interpreting, combined with its proven ability to identify stress in field crops supports its operational use in pipeline monitoring - especially when carried out in conjunction with field observations and sampling. Colour and b&w photography, while not as sensitive to the spectral responses of stressed vegetation, can be useful compliments to the CIR data. Archival CIR, colour or b&w photography can play a vital role in establishing a visual record of pre- and post-construction conditions. This can be of paramount importance in settling compensation disputes. In the present study it is shown how archival b&w and CIR photographs can be used to establish a visual 'history' of the study site, as indicators of pre- and post-construction ground conditions and relative success at rehabilitation.

The MEIS data offer a number of advantages to the aerial photography. Its ability to record spectral data in a number of narrowly defined wavelength bands for a pixel size of 1.0 m makes it a very versatile sensor capable of acquiring much detailed information. The ability to store the data on a CCT facilitates manipulation and analysis of the data in order to generate high quality images and their classification. Unsupervised image classification, and supervised classification based on sufficient ground truthing offer useful techniques for the identification and delineation of various zones of impact due to pipeline construction and oil spillage. The analysis of the MEIS data for field D, in particular the contrast stretched image and the supervised classification, permitted a delineation of areas with varying levels of crop performance and an assessment of variability 'within' these areas. While the field data was sufficiently detailed to permit a basic correlation with the MEIS data, a more exhaustive sampling of total biomass would have better characterized the ground conditions and possibly strengthened this relationship.

Direct area measurements of the classes can be carried out by the analysis system. While this method permits a greater accuracy than the digitizer used with the aerial photographs, the system carries out class (theme) area measurements for a full image scene and time did not permit the outlining of field D within the scene. The analysis clearly revealed that it is the composite image which presents the best overall 'picture' of the ground conditions. Scenes of individual bands or band ratios do not represent the true ground conditions as accurately. Cloud interference and memory problems served only to limit the capabilities of the analysis system. The IR band, however, was clearly shown to be the best able to penetrate cloud.

chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6. CONCLUSIONS AND RECOMMENDATIONS

Impacts due to pipeline construction and oil spillage:

The primary objective of this report was to determine if long-term impacts to certain soil properties and crop yield were evident on farmland affected by pipeline construction and oil spillage. Based on the research carried out at the study site, it is clear that certain impacts do indeed remain nine growing seasons following pipeline construction and seven growing seasons following the oil spill. While these impacts are not severe from an agronomic or economic point of view, neither are they negligible. The impacts from construction are predictable; they can be anticipated and prevented or minimized. Oil spillage as a result of a pipeline break is, however, unpredictable and may pose serious problems for agricultural activities. Impacts may linger for many years if rehabilitation is not carried out promptly according to a site-specific plan. The 1984 crop yields at the study site attest to this.

It has been shown that regulations concerning the construction and monitoring of pipelines have stiffened since 1980. While yield reductions may be characteristic of rights-of-way constructed pre-1980, one would now expect a more successful rehabilitation of the affected areas. Although not without exception, this clearly reflects an increased level of cooperation between engineers, right-of-way agents, construction supervisors, environmental experts, regulatory bodies and landowners. Regulatory agencies now monitor construction and post-construction practices more judiciously. The pipeline companies now conform to stricter guidelines. Generally speaking, the objective of these parties concerned with pipelining is to promptly return the land to its original state of productivity. The pipelining process is much more environmentally sound today than it was ten years ago (Hare and Watt, 1983).

As a follow-up to the 1984 study, a visit was made to the study site in August 1985. The situation did not appear to be significantly changed from 1984. The yields of corn on the areas affected by oil were poor; the farmer attributing this to residual oil at depth interfering with nutrient uptake. However, according to IPL (personal communication) the farmer did not apply the recommended nitrogen fertilizer. IPL feels that the situation will show significant improvement for the 1986 growing season since tile drainage was installed in September 1985 and the company itself will undertake to apply the fertilizer.

Recommendations concerning impacts due to pipelining can serve to emphasize the importance of monitoring. Construction and post-construction monitoring of rights-of-way must be carried out in good faith and in accordance with current guidelines. The presence of the National Energy Board environmental inspectors must be clearly visible in the field. Provincial and municipal authorities must be made aware of the potential impacts due to pipelining. It is the responsibility of these authorities to represent the interests of the landowners and to concern themselves with the impacts notwithstanding the fact that some landowners tend to 'shrug off' the entire situation. Local farm groups must make clear to their members the responsibilities of the pipeline companies with regards to rehabilitation and must make members aware of assistance available to them (eg. National Energy Board) when there is a dispute. It should be considered in the best interest of all parties concerned to minimize impacts due to pipelining and to carry out rehabilitation and compensation promptly and judiciously.

<u>The application of remotely sensed data</u>:

The application of remotely sensed data is clearly of some value in detecting, quantifying and recording pipeline construction and oil spillage impacts. In this study it was shown how archival aerial photography could be used to examine pre-construction and pre-spillage ground conditions. The CIR photographs, acquired specifically for monitoring the pipeline right-of-way, provide much more detail than the b&w photographs. The detail of the handheld colour photograph clearly demonstrates the desirability of that large a scale for an examination of variation occurring within small agricultural fields. Large scale CIR photography would seem to offer the best photographic method of acquiring information relating to stress on vegetation as a result of pipeline construction. The versatility of handheld photography with regard to such factors as scale, direction of viewing and time of day, etc., makes it an ideal tool for sequential monitoring of impact sites.

MEIS imaging presents an alternative method to aerial photography. MEIS provides a much better sensing capability (spatial, spectral and radiometric) than other multispectral scanner systems. The ability to manipulate the data with the use of a computer-assisted image analysis system greatly facilitates the display and interpretation of the imagery. However, it appears from this study that digital analysis was not sensitive enough to distinguish between very localised variations in the vegetative cover. The linear pattern of the right-of-way was clearly discernible on the images of fields A, B and C. It was because of this linearity, however, and not the spectral response of the affected vegetative growth that the right-of-way could be identified. The spectral characteristics of the vegetation on the right-of-way were similar to those found within low-yielding patches throughout the field. The ROW yields were significantly lower than the OFF-ROW yields. For field D, the classification procedures were not able to distinguish between different levels of vegetative growth within the oil-affected area to the extent that it was possible by visual interpretation. Image enhancement, or contrast stretching, appears to be more successful than classification techniques at discriminating localised sparse vegetative growth in the affected areas. These findings seem to support a statement by Colwell (1983, p. 5) referring to TM data:

> "Based on the improved spectral, spatial and radiometric quality of the TM data, we see a renewed emphasis and interest in direct visual interpretation of these image products, both for updating and improving land stratification in support of resource inventory and for enhancing the image analyst's contribution to computer-assisted analysis procedures".

Digital imagery can compliment other data sources; however, one can conclude that low-level aerial CIR photography is the most effective airborne sensor to support field sampling at this level of detail.

The integration of remotely sensed and field data should, generally speaking, be a straightforward task. It was, however, an objective of this study to determine 'to what extent' the digital and field data could be integrated in the examination of the impacts due to pipelining. The findings of this study suggest the following conclusion: beyond the acquisition of a visual record of ground conditions, the MEIS imagery does not appear to provide sufficiently good spatial resolution to use in the examination of variation within agricultural fields, where the anomalous feature (decreased yield on the right-of-way or in an oil-affected area) may only measure a few meters. It is recognized by the researcher, however, that the ground truth data for field D was inadequate. The highly variable crop growth in that field could not be adequately characterized by the field sampling carried out. A more intensive sampling of total biomass would have better characterized the affected area than did the grid sampling of plant yield. This would have reduced the possibility of innaccuracies in defining the training sites for the supervised classification and generally facilitated the integration of the remotely sensed and field data. It is possible that other image enhancement techniques would have improved the interpretability of the digital MEIS data: a- principle components transformation, which has been shown by Bryceson (1984) to be of significant value in detecting low or very low ephemeral vegetation cover on Landsat MSS digital data; b- the combination of band ratioing followed by classification techniques. While certain ratios were tried, computer memory limitations encountered during the analysis hampered the attempts at band ratioing and only one image was presented (fig. 5.29). In view of these problems no further attempts were made at examining the usefulness of various other band ratios. Bryceson (1984) reported that the end result of ratioing transformations using MSS band 7

(TM4) and MSS 5 (TM3) followed by density slicing (classification) proved to be the most visually impressive and easy to analyse of all the techniques he investigated. In order to carry out a quantitative assessment of the utility of the digital data it would be necessary to examine the reflectance characteristics of different plant species at different stages of growth (see Brown et al., 1983).

In conclusion, the study has clearly shown that impacts do remain on farmland 9 growing seasons following pipeline construction and 7 growing seasons following oil spillage. Remotely sensed data can be used as an effective tool to detect and establish a permanent record of these impacts. Multitemporal imagery can also be used for post-construction monitoring and to assess rehabilitation. Aerial CIR photography is an effective sensor used for this purpose due to its sensitivity to crop stress and other indicators of pipeline related impacts. Area measurements of zones of impact can be carried out manually using a digitizer or planimeter. The spatial resolution of the MEIS imagery would not allow for a more effective assessment of the impacts than the CIR photography. Further analysis of the MEIS data is recommended. Beyond establishing a permanent record, other analytic techniques may reveal its ability to provide a more detailed assessment of crop vigour/stress and to carry out quantitative functions.

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APPENDICES

APPENDICES:

KEY TO VARIABLE NAMES:

variable	definition
no.	sample number
BDA	bulk density 0-15 cm (g cm^{-3})
BDB	bulk density 15-30 cm (g cm^{-3})
PHA	pH 0-15 cm
PHB	pH 15-30 cm
OMA	organic matter content 0-15 cm (%)
OMB	organic matter content 15-30 cm (%)
TOCA	total organic carbon 0-15 cm (%)
TOCB	total organic carbon 15-30 cm (%)
YIELD	alfalfa dry matter yield (g m^{-2})
GRAIN	grain weight/plant (gm)
EAR	ear weight/plant (gm) - inc. grain
DMWT	dry matter weight/plant (gm) - exc. ear
BIO	total dry biomass/plant (gm)
AVGHT	mean height of 10 corn plants (cm)

APPENDIX I: FIELD A - SOIL DATA

no.	group	row	PHA	PHB	OMA	OMB	BDA	BDB
1	1	A	7.0	7.2	62.2	7.1	0.43	1.36
2	1	A	7.3	7.2	16.4	43.4	1.07	0.87
3	1	A	7.1	7.1	48.3	7.5	0.79	1.30
4	1	A	7.2	7.2	31.1	7.1	1.10	1.45
5	1	A	7.3	7.3	35.3	7.2	0.94	1.46
6	1	A	7.4	7.4	7.5	7.1	1.38	1.46
7	1	A	7.5	7.4	12.1	7.6	1.20	1.50
8	1	A	7.2	7.4	30.8	8.0	1.13	1.52
9	1	A	7.3	7.4	18.8	10.1	1.03	1.34
10	1	A	7.4	7.6	41.4	16.6	0.78	1.07
11	2	B	6.3	7.6	58.8	7.8	0.49	1.50
12	2	B	6.5	7.5	61.7	15.0	0.59	1.24
13	2	B	6.8	7.4	37.0	7.3	1.00	1.41
14	2	B	7.3	7.4	21.1	7.7	0.98	1.35
15	2	B	6.6	7.5	58.6	7.5	0.63	1.48
16	2	C	6.9	6.9	79.1	84.0	0.33	0.28
17	2	C	6.6	6.5	85.0	33.8	0.37	0.73
18	2	C	6.9	7.3	71.1	9.3	0.51	1.42
19	2	C	6.9	7.2	27.0	8.4	0.93	1.48
20	2	C	6.7	7.3	40.9	8.3	0.92	1.52

group 1 = ROW samples
group 2 = OFF-ROW samples

APPENDIX II: FIELD B - SOIL AND CROP DATA

no.	group	row	PHA	PHB	OMA	OMB	BDA	BDB	YIELD
21	1	A	7.5	7.5	40.8	23.8	0.93	0.96	165.4
22	1	A	7.6	7.6	19.1	20.3	1.28	1.14	118.5
23	1	A	7.6	7.7	18.2	7.9	1.18	1.35	185.2
24	1	A	7.7	7.8	16.7	8.7	1.11	1.36	107.8
25	1	A	7.7	7.7	13.9	15.3	1.13	1.17	89.0
26	1	B	7.6	7.6	19.4	20.5	0.93	1.08	123.8
27	1	B	7.6	7.7	16.4	14.4	0.95	1.27	143.4
28	1	B	7.7	7.6	17.0	18.9	1.15	1.21	101.8
29	1	B	7.5	7.4	28.0	18.6	0.83	1.30	188.8
30	1	B	6.9	7.0	12.7	10.1	1.40	1.42	131.8
31	2	C	7.7	7.7	13.8	15.2	1.09	1.22	163.0
32	2	C	7.7	7.6	10.3	11.3	1.44	1.30	107.4
33	2	C	7.7	7.7	12.3	9.6	1.34	1.54	116.0
34	2	C	7.8	7.7	10.2	13.3	1.31	1.31	95.1
35	2	C	7.8	7.7	16.1	20.1	1.25	1.19	132.7
36	2	C	7.7	7.7	10.5	8.3	1.32	1.39	94.1
37	2	C	7.7	7.7	13.3	11.8	1.00	1.38	151.4
38	2	C	7.6	7.7	15.6	17.0	1.17	1.10	107.8
39	2	C	7.7	.	21.3	.	.	.	60.4
40	2	C	7.8	.	21.8	.	.	.	78.6

group 1 = OFF-ROW samples
group 2 = ROW samples

APPENDIX III: FIELD C - SOIL AND CROP DATA

no.	row	BDA	PHA	OMA	EAR	GRAIN	DMWT	BIO	AVGHT
91	A	2.01	7.3	19.3	55.7	39.5	46.8	102.5	188.5
92	A	2.01	7.3	19.4	50.7	23.2	54.2	104.9	165.4
93	A	1.93	7.3	23.0	29.4	17.6	56.5	85.9	168.2
94	A	1.87	7.2	21.6	19.8	6.3	56.8	76.6	175.3
95	A	1.81	7.2	20.7	85.3	59.0	62.9	148.1	178.2
96	A	1.97	7.3	19.1	38.6	25.9	46.7	85.3	171.9
97	A	1.93	7.3	19.8	89.5	53.3	88.0	177.4	180.4
98	A	1.94	7.4	24.4	20.8	8.8	31.0	51.8	135.0
99	A	1.97	7.4	18.1	62.5	28.3	128.9	191.3	173.1
100	A	2.02	7.5	18.7	77.9	36.1	72.7	150.6	170.9
101	B	1.86	6.7	11.1	109.6	65.3	180.9	290.5	246.3
102	B	1.82	6.7	11.2	50.3	34.0	100.1	150.4	201.0
103	B	1.90	6.2	10.1	60.5	25.1	102.6	163.1	168.3
104	B	1.93	6.7	9.8	75.4	51.8	83.0	158.4	211.9
105	B	1.92	6.1	14.5	108.0	68.0	93.7	201.7	226.0
106	B	1.84	7.3	17.0	60.2	42.9	83.3	143.4	209.3
107	B	1.56	7.0	12.6	89.7	65.7	98.8	188.5	217.0

row A = ROW samples
row B = OFF-ROW samples

APPENDIX IV: FIELD D - SOIL DATA

no.	group	PHA	PHB	OMA	OMB	TOCA	TOCB
11	2	7.2	7.3	18.8	15.5	7.1	5.5
12	2	7.3	7.5	20.4	11.4	7.8	3.6
13	2	6.5	7.1	26.3	15.3	10.6	5.4
14	2	6.7	7.3	17.4	11.6	6.4	3.7
15	2	6.5	7.2	20.6	12.0	7.9	3.8
31	1	7.4	7.5	13.5	15.3	4.6	5.4
32	1	7.3	7.3	16.9	16.3	6.2	5.9
33	1	7.1	7.2	20.4	16.1	7.8	5.8
34	1	6.9	6.8	22.9	29.4	9.0	12.1
35	1	7.0	7.2	15.5	12.3	5.5	4.0
51	1	7.2	7.2	19.0	18.6	7.2	7.0
52	1	7.3	7.6	16.1	11.6	5.8	3.7
53	1	7.4	7.3	14.3	14.9	4.9	5.2
54	1	6.5	6.5	13.1	15.1	4.4	5.3
55	1	6.3	6.3	23.1	25.1	9.1	10.1
71	1	7.3	7.5	17.1	13.3	6.3	4.5
72	1	7.5	7.5	22.5	15.5	8.8	5.5
73	1	7.4	7.5	19.2	14.5	7.3	5.0
74	1	7.3	7.2	19.0	13.7	7.2	4.7
75	1	6.7	7.2	22.1	9.4	8.6	2.6
91	1	7.2	7.3	15.5	12.1	5.5	3.9
92	1	7.3	7.5	15.9	9.4	5.7	2.6
93	1	7.4	7.7	16.9	10.2	6.2	3.0
94	1	7.2	7.5	20.8	9.0	8.0	2.4
95	1	7.2	7.4	19.0	13.5	7.2	4.6
1	2	6.9	7.0	32.0	30.0	13.4	12.4
2	2	6.6	7.3	25.1	10.4	10.1	3.1
3	2	6.9	7.3	36.6	18.2	15.6	6.8
4	2	6.3	7.1	21.4	16.1	8.3	5.8
5	2	6.3	6.6	18.8	13.9	7.1	4.7

group 1 = oil-affected area
group 2 = control area

APPENDIX V: FIELD D - CROP DATA

no.	group	EAR	GRAIN	DMWT	BIO	AVGHT
11	2	75.1	6.6	116.2	191.3	167.0
12	2	89.5	7.7	128.9	218.4	178.1
13	2	30.6	.	56.2	86.8	169.9
14	2	.	.	63.2	63.2	169.5
15	2	87.0	8.0	122.5	209.5	155.2
31	1	68.3	4.1	111.8	180.0	228.0
32	1	171.0	12.6	174.0	345.0	212.3
33	1	.	.	115.4	115.4	122.7
34	1	.	.	88.0	88.0	186.2
35	1	.	.	64.2	64.2	180.4
51	1	.	.	105.7	105.7	121.2
52	1	.	.	102.6	102.6	189.2
53	1	.	.	45.7	45.7	192.4
54	1	.	.	95.9	95.9	215.3
55	1	51.5	3.9	189.6	241.2	246.9
71	1	.	.	75.8	75.8	100.4
72	1	.	.	37.1	37.1	110.2
73	1	.	.	52.6	52.6	110.7
74	1	.	.	125.7	125.7	124.9
75	1	.	.	202.4	202.4	136.7
91	1	57.4	.	156.5	213.9	146.4
92	1	.	.	65.7	65.7	126.6
93	1	.	.	127.5	127.5	140.6
94	1	.	.	49.7	49.7	135.4
95	1	24.2	.	98.2	122.4	130.9
1	2	166.4	25.9	210.9	377.3	238.5
2	2	154.5	40.9	188.4	342.9	214.4
3	2	66.6	11.8	130.7	197.3	203.2
4	2	208.8	60.9	354.0	562.8	233.5
5	2	241.6	52.5	338.0	579.6	232.9

group 1 = oil-affected area
group 2 = control area