DOCTOR OF PHILOSOPHY

Monitoring the condition of semi-natural vegetation: the application of remote sensing and geographical information systems (GIS)

Williams, Jeremy Hugh

Award date:
1992

Awarding institution:
Bangor University

Monitoring the condition of semi-natural vegetation: the application of remote sensing and geographical information systems (GIS).

VOLUME 1.

Jeremy Hugh WILLIAMS

BSc (Hons) Wales, MIAgrE, MICFor.

School of Biological Sciences

University of Wales, Bangor, UK.

November 1992.

A thesis submitted in candidature for the degree of

Philosophiae Doctor

of the University of Wales.

UNIVERSITY OF WALES

Summary of thesis

Surname: WILLIAMS
Other names: Jeremy Hugh

Candidate for the degree of: *Philosophiae Doctor*, Ph.D.

Title of thesis: Monitoring the condition of semi-natural vegetation: the application of remote sensing and geographical information systems (GIS).

Summary

The principal objective of this thesis was to investigate the use of remote sensing and Geographical Information System (GIS) technology in the survey and monitoring of semi-natural vegetation.

The effects of acidic deposition and airborne pollutants on vegetation were of particular interest during the 1980s and early 1990s. A first experiment studied the effect of simulated acid rain on the reflectance of birch seedlings. Plants exposed to acidic treatments lost the characteristic reflectance curve shape of healthy green vegetation. Spectroradiometer data were used to discriminate between plants in different rainfall treatments. A second experiment studied the effects of combinations of pollutant gases (O_3, SO_2+NO_2, and O_3+SO_2+NO_2) and acidic mists on the reflectance of white clover. Plants in the two treatments containing ozone showed marked changes in reflectance, and were statistically separable from the control. Simple and 4-waveband vegetation indices showed positive linear relationships with shoot dry weight. Plants in the treatments containing ozone showed marked decreases in shoot dry weight and vegetation index.

Airborne Thematic Mapper (ATM) data were used to study the relationships between remotely-sensed radiance and water and soil chemistry on a large flood-plain mire in south Wales. Strong relationships between radiance and chemistry were found, suggesting associations between nutrient concentrations and the health and vigour of the mire vegetation.

A study on the Glyderau mountains in Snowdonia investigated the potential for mapping upland vegetation using Landsat Thematic Mapper (TM) data. It addressed the problems involved in classifying highly variable ground cover on valley floors, steep slopes and high plateaux, and the problems involved in reconciling the need for a generalised vegetation map with the fine detail present on the ground and in TM data. Pre- and post-classification digital spatial filters were used to produce TM classmaps which agreed closely with the ground survey data. GIS was used to extract management information.

ACKNOWLEDGEMENTS

I would like to express my gratitude to all who have helped me complete this work.

Firstly, many thanks are due to Dr Barry Wyatt (1) and Ralph Oxley (2) who supervised this work. They offered many positive suggestions, maintained a keen interest and gave much of their time to check the thesis.

At an earlier date, Dr Cedric Milner (1) inspired a keen interest in remote sensing through his own enthusiasm for the subject. I am very grateful to Dr Milner and Dr John Good (1), for the valuable ITE facilities made available for this work.

I acknowledge the help given by the following people:

For statistical advice: Dr Dorian Moss (1), Chris Whitaker (2) and Dr Jeff Settle (3). For collaboration and contribution to the radiometer studies: Dr Trevor Ashenden (1). For collaboration and contribution to the ATM Crymlyn Bog study: Dr Alistair Headley (4). For help with radiometers, loggers, software and instrumentation: Ray Rafarel (1) and Gwilym Hughes (1). For help with experimental plant material: Mrs Sam Bell (1). For assistance with the clover radiometry: Mr Pat Green (2). For help with digital cartography and data transfer: Geoff Radford (1), Nigel Brown (1) and David Norris (1). For image analysis support: Roger Parsell (1), Bill Slade (1) and Jeremy Stocks (2).

The Natural Environment Research Council funded this work through a CASE award (GT4/84/TLS/61) held by ITE and UCNW. The financial support, provision of airborne and satellite data, image analysis and experimental facilities by NERC is acknowledged with thanks.

The Welsh Office funded Dr Ashenden's plant physiology and pollution work and are thanked for their interest in the radiometer studies.

BP International Ltd. funded research into the condition of Crymlyn Bog by the University of Sheffield and NERC and are thanked for their interest in the ATM study.

I thank my family for their help and patience during this work.

(1) Natural Environment Research Council (NERC), Institute of Terrestrial Ecology (ITE).

(2) University of Wales, Bangor (UCNW).

(3) Remote Sensing Applications Development Unit (RSADU), British National Space Centre (BNSC).

(4) Department of Botany, University of Sheffield.

CONTENTS

VOLUME 1

VOLUME 2

LIST OF PLATES, FIGURES AND TABLES

The plates, figures and tables follow the text of each chapter. The following table shows their order and page number.

CHAPTER 1

OBJECTIVES, AN INTRODUCTION TO THE THESIS AND TO TERRESTRIAL REMOTE SENSING

1.1 OBJECTIVE OF THE THESIS:

To investigate the use of remote sensing and Geographical Information System (GIS) technology in the survey, monitoring and evaluation of semi-natural vegetation.

Subsidiary objectives:

To utilise a range of instruments, sensors and methodologies in the application of remote sensing;

To test statistical multivariate techniques in the analysis of remotely-sensed data;

To investigate the use and combination of spatial data analysis methodologies in image analysis and classification;

To utilise GIS functionality in the application of remote sensing.

1.2 INTRODUCTION TO THE THESIS

Remote sensing in the 1990s offers a diverse and exciting range of instruments and techniques for use by environmental scientists. From ground level upwards there is a choice of radiometers, airborne scanners, earth-orbiting satellite sensors and geostationary satellite sensors for use in monitoring the reflected and emitted electromagnetic spectrum.

The Natural Environment Research Council (NERC) supported and encouraged the use and investigation of many of these instruments and methodologies from an early date. The opportunity for scientists from a wide range of disciplines to develop research programmes in the field of remote sensing was enhanced by the provision of resources through NERC. The principal equipment included radiometers, the Daedalus Airborne Thematic Mapper (ATM) scanner and image analysis systems at several sites. In addition to these resources, data from a range of sensors was acquired for use and interpretation by terrestrial and marine scientists. The principal data for terrestrial applications came from sensors mounted on Earth-orbiting satellites: the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA series, the Multispectral Scanning System (MSS) and the Thematic Mapper (TM) from the Landsat series, and the HRV sensor on the SPOT series (see sections 1.6 and 1.7).

These sensors have been exploited individually according to the appropriate selection of spatial and spectral resolution. They have also been combined where different resolutions have been appropriate for the various phases in this rapidly evolving methodology. Radiometers, for example, have been used in the field calibration of the relationships between vegetation parameters and reflectance for subsequent use with aircraft and satellite sensor data. Field radiometry has been combined with both SPOT HRV data (Girard et al., 1990) and with ATM data (Curran and Williamson, 1987).

The general background to terrestrial remote sensing is developed in Chapter 1. The text is based on a document prepared for the BBC Domesday Project; the original text appears with Landsat colour images from many UK locations on the BBC Domesday National Disc (Williams, 1986).

This thesis then investigated the use of remotely sensed data at three levels:

Chapter 2 Laboratory-based studies of basic vegetation / radiation interactions using radiometry;

Chapter 3 Field-scale observations of vegetation composition and condition using airborne scanner data (ATM);

Chapter 4 Large-scale mapping applications using satellite data (Landsat TM) and GIS.

Chapter 2 consists of two laboratory-based radiometer studies which investigated the effects of acid rain, acid mist and pollutant gases on tree seedlings and herbaceous vegetation. The experimental material was pot-grown and the radiometer had high spatial resolution (nominally 25cm at 1m height) and limited spectral resolution (4 broad wavebands in the visible and near infra-red regions). The first study was a pilot investigation of the effects of simulated acid rain on the reflectance of birch seedlings. The second study looked at the effects of combinations of acidic mists and pollutant gases on the reflectance of white clover and the relationship between shoot dry weight and remotely-sensed vegetation indices.

Chapter 3 presents the results of a study investigating the relationship between calibrated airborne scanner multispectral radiance data and field data obtained by vegetation, peat and water sampling. The study area was relatively small (253ha) and the ATM data had a relatively high spatial resolution (nominally 2m) and wide spectral range (11 wavebands from the visible to thermal infra-red regions). The vegetation of Crymlyn Bog, a large flood-plain mire, was thought to be affected by soil nutrient status and water quality. This study tested the statistical relationships between remotely-sensed and field-measured variables.

Chapter 4 presents the results of a study using satellite data to map montane vegetation in Snowdonia. The study area was extensive (1384ha) and the Landsat TM data had a moderate spatial resolution (nominally 30m) and good spectral range (7 wavebands from the visible to thermal infra-red regions). Several methodologies were tested in an attempt to classify vegetation communities in an area with rugged topography and variable ground cover. Spatial filters were used to increase the statistical correspondence and visual comparability between a vegetation map produced by conventional ground survey methods and the remotely-sensed product. GIS functionality was used to extract management information from the resulting maps.

Some of the significant points are then discussed in Chapter 5 with comments on likely future developments.

1.3 AN INTRODUCTION TO TERRESTRIAL REMOTE SENSING

The advantages of a high viewpoint have been known for many years. On land, surveyors use hills to look across the landscape when mapping; at sea the lookout climbs high up a ship's mast to the 'crows nest' for a better and further view. When hot-air balloons were first flown, their potential for observation and surveillance was noted by both civilian and military organisations.

The military saw the benefits of this high viewpoint for planning manoeuvres during battles. Civilian authorities sent surveyors and planners up in balloons to study the layout of cities. A permanent record of the scene below was required and by the late 1860s simple plate-cameras were being used to photograph from balloons. These first aerial photographs started a new technology that would revolutionise mapping, surveying and the study of the Earth's resources.

The term 'remote sensing' has been used for over thirty years since 1960 (Fischer, 1975) to refer to the observation and measurement of an object without touching it. It has included use of the human eye, conventional photography and electronic measurement techniques. Today, remote sensing includes black and white, colour and infra-red photography on the ground and from the air, airborne geophysics, digital scanning and radar surveys from aircraft, Earth-observation spacecraft and satellites.

Non-photographic remote sensing refers to the use of sensors to record information in an electronic form rather than on film. More recently, the environmental sciences have used remote sensing to refer to the use of electromagnetic energy sensors to record images of the environment which can be interpreted to yield useful information (Curran, 1985).

Many sensors record their information in digital form rather than on film. Digital data are ideal for rapid adjustment, correction and statistical analysis. It is also possible to combine sensor data with other digital data to improve the accuracy of the final information, and to make more complex analyses possible. An example of this technique is the combination of digital map data with satellite data to improve surface cover identification (Belward and Valenzuela, 1991). The direct estimation of bio-physical variables (e.g. albedo, soil moisture and surface temperature) is a major advantage of digital remote sensing.

Multitemporal data sets from one sensor at several dates have been compiled to improve land cover classification and for use in the monitoring of land use change (Fuller, et al., 1992). Multisensor datasets have also been compiled using digital data from several different sensors resampled to a common resolution for use in vegetation assessment (Paris, 1990). These datasets have often been used where the only data available for the desired dates have been obtained by different sensor / platform sources. However, future space missions, such as NASA's Earth Observing System (EOS) and the European Space Agency's Polar Orbiting Platform (POEM) are increasingly designed to carry synergistic sensors. An example is the use of sensors which measure atmospheric chemistry to correct for the effects of atmospheric attenuation on visible and infra-red imagery.

There are certain features of digital remote sensing that distinguish it from its precursors. The new sensors can record a far wider range of wavelengths than conventional photographic film. They can, in particular, detect wavelengths in the hyper-visible infra-red and microwave regions. A great deal of information about the Earth, its land cover and water, is contained in these portions of the electromagnetic spectrum. One major problem with visible and infra-red region photography and sensors is that they have no ability to obtain data through cloud cover. Microwave or radar sensors on satellites such as the European ERS-1 are now being developed to provide all-weather day or night information for regions of the Earth that are routinely obscured by cloud (Allan, 1990).

Remote sensing has already shown its potential as a formidable new tool for surveying natural resources and monitoring the environment. Weather forecasting is an obvious example of a near real-time use for remotely sensed data in the U.K. and many other parts of the world (Barrett and Martin, 1981). Meteorological satellites provide a continuing and reliable source of information, while other systems are still at an experimental stage. Remote sensing is a major contributor to applications where rapid survey and repetitive observations with wide views are required (Prince, 1990). Land and marine applications have been examined and an extensive archive of high-resolution multispectral images of the Earth has been established.

In many parts of the western world, including the U.K., existing information relating to land-use and natural resources is sufficiently comprehensive and accurate for many purposes. In the U.K., remote sensing is helping to complement this information base in two respects. The first relates to extensive and remote upland regions where information about land use and condition is sparse (Chapter 4). Remote sensing can supplement and update existing information on the location and extent of different land classes. Since land use does not alter very rapidly in these regions, the information may only need to be updated on a 5- or 10-year cycle. Plate 1.1 shows the extensive and varied upland vegetation of Snowdonia in north Wales.

The second type of information will be used and updated on a more frequent basis. It relates to our more intensively used regions: the urban, industrial and lowland agricultural areas and the fragile semi-natural habitats that are found in those areas (Chapter 3). In urban areas it is often necessary to review the extent and condition of land use on an annual basis. It is also necessary to monitor the pollution of air and water bodies and the effects of pollution on vegetation (Chapter 2). In agriculture, it may be necessary to look at the condition of large areas of crops on several occasions during the growing season (Prince, 1990).

The benefits of relatively low cost survey of extensive tracts of land are great when large and remote areas are involved. Satellite remote sensing has revolutionised this work in many of the areally extensive countries across the globe. Vast tracts of forest and rangeland can now be surveyed on a regular basis at a fraction of the cost of ground survey (Belward and Valenzuela, 1991, p261).

In Africa and other arid regions satellite sensors are being used to map soil and rock types, to estimate soil moisture and the extent and amount of green vegetation. It is in these regions, where information relating to the land surface is either out of date or missing, that remote sensing may prove to be of greatest value (Belward and Valenzuela, 1991).

1.4 PHOTOGRAPHY FROM AIRCRAFT

Following the development of aviation in the First World War some regions were being photographed systematically from the air by the late 1920s. The development of skills and equipment for the interpretation of aerial photographs led to widespread use of the technique for civilian and military applications. Many hitherto inaccessible regions of the world were studied in detail for the first time from above.

Following military use during the Second World War, increasingly skilled interpretation led to the more widespread application of aerial photography. Many of the early British surveys were undertaken by the Royal Air Force (RAF). The technique was put to good use in surveying and mapping, geography, geology, agriculture, forestry and many other disciplines with an interest in the land surface.

Aerial photographs provide one of the most detailed and comprehensive historic records of the British landscape. The Ordnance Survey undertook a major map revision using aerial photography in the early 1970s, and the RAF covered most of the U.K. at a 1:50,000 scale in 1980/81. Future photographic surveys may be done on a more piecemeal basis, with satellite images providing the basis of regular countrywide coverage. In a relatively small nation such as Britain the most popular scale for aerial photography is 1:10,000; Plate 1.2 shows part of a 1:10,000 scale monochrome aerial photograph of greater London. For the larger nations, in Africa for example, a 1:20,000 scale is used more routinely. Plate 1.3 shows part of a 1:25,000 scale aerial photograph of the Northern Oman Mountains.

One of the advantages of aerial photography has always been the ease with which surveys can be undertaken. Photographs taken with a small hand-held camera can provide valuable and detailed information about the land below. Foresters frequently use this simple form of aerial photography to locate windblown trees after severe storms. For them it provides a fast and inexpensive form of field survey.

Highly sophisticated camera and interpretation technology has also been available for many years for the surveying and mapping industry where high precision is of vital importance. Experience, skill and the appropriate instrumentation are needed to extract accurate and detailed information.

1.5 PHOTOGRAPHY FROM SPACE

The first successful pictures of the Earth were taken from the U.S. Mercury IV satellite in 1961. Many thousands more were taken on subsequent space missions using relatively small format cameras (70mm). In 1983 and 1984 two photographic missions were flown on the Space Shuttle - the European Metric Camera and the U.S. Large Format Camera. The launch of Spacelab was delayed until November 1983 when lighting conditions were unfavourable over much of Europe and the U.S.A. However, excellent photographs are available for North Africa, the Middle-East and West China. These are being used to test the potential for mapping using stereo photography from space.

1.6 PLATFORMS FOR EARTH OBSERVATION

Platforms are the structures that hold and often transport cameras and sensors to their viewpoint above the Earth. Platforms used in remote sensing have included scaffolding towers, aircraft, rockets, satellites and the space-shuttle. The distances involved in Earth-observation range from a few metres above the ground, using cameras and portable sensors, to the orbit of some weather satellites at almost 36,000 kilometres.

Near ground level, cameras and sensors can be hand-held or mounted on tripods to photograph the ground cover in detail. In order to raise the camera or sensor higher, above small trees for example, mobile hydraulic platforms ('cherry pickers') and scaffold towers have been used. Small balloons and radio-controlled aircraft have been used, and light aircraft are employed on a regular basis for survey work. At a much greater height, sounding rockets and spacecraft record pictures of the Earth.

The busiest orbits are those at 700-1000 kilometres where the polar-orbiting satellites are to be found. These satellites include the American NOAA (National Oceanic and Atmospheric Administration) series of weather and ocean-monitoring satellites, the Landsat and SPOT land-observation satellites, ERS-1 and, later in the 1990s, the Polar Orbiting platforms to be launched by NASA (National Aeronautics and Space Administration) and ESA (European Space Agency).

The orbit of geostationary satellites is dictated by the laws of physics. For our Earth, geostationary equatorial satellites are in an orbit of 35,900 kilometres. In this orbit, satellites maintain a fixed position relative to the surface of the Earth. The geostationary characteristic is a particularly important property for applications in meteorology, where continuous monitoring of cloud cover and atmospheric moisture is needed, and in telecommunications.

Meteosat, operated by the European Space Agency (ESA), is located on the Greenwich Meridian above West Africa. It provides valuable weather information for the U.K. and Europe. Its pictures showing cloud patterns and developing storms are received every 30 minutes day and night: they are a main input into the worldwide weather forecasting services.

Two satellites operated by NOAA provide weather information for the western Americas and the Pacific (GOES-West), and the eastern Americas and the Atlantic (GOES-East). Other products based on satellite data include sea-surface temperature, sea-ice forecasts and, in combination with ground station radar data, the monitoring and forecasting of regional precipitation in near-real time.

1.7 DIGITAL SENSORS

A variety of instruments are used to obtain images of the ground, atmosphere and sea surface, making use of visible light, infra-red and microwave radiation. The United States pioneered the collection of digital data for environmental studies with their Earth Resources Technology Satellites. The first satellite, ERTS-1 launched in 1972, was renamed Landsat-1 and was followed in 1975 and 1978 by the similar Landsats-2 and-3. All three satellites were equipped with Multi-spectral Scanning Systems (MSS) and Return Beam Vidicon (RBV) cameras. The MSS recorded digitally: the RBV cameras recorded analogue data.

In July 1982 the series continued with the launch of Landsat-4. The RBV cameras were replaced by the Thematic Mapper (TM) sensor; see Chapter 4. The currently operational Landsat-5 was launched on 1st March 1984. France's SPOT (Système Probatoire d'Observation de la Terre) satellite was launched on February 21st, 1986 and is providing high resolution data from its HRV (High Resolution Visible) sensors. Plate 1.4 is a monochrome 'quick-look' from the SPOT-1 HRV sensor showing a 60km x 60km area of Brazil in 1986.

Airborne scanners have been used when fine resolution has been required and for experimental work when ground data collection must coincide with the overpass. One such scanner used in the U.K. is known as the Daedalus or Airborne Thematic Mapper (ATM); see Chapter 3. The MSS, TM, Daedalus and SPOT sensors all utilise optical systems to detect reflected and emitted radiation from the Earth's surface.

The NOAA series of weather satellites carry instruments for atmospheric and oceanic monitoring. Their AVHRR (Advanced Very High Resolution Radiometer) sensor has also been used for a number of terrestrial applications (Malingreau and Tucker, 1990).

1.8 BASIC PRINCIPLES

All remote sensing systems record electromagnetic energy entering the camera or sensor. Visible light is the form of electromagnetic energy most familiar to us. The full spectrum of this energy, however, ranges from short-wavelength X-rays, through visible light, to the longer radio wavelengths. At its simplest, remote sensing detects sunlight that has been reflected back from the Earth's surface.

On its journey from the sun to the camera light first interacts with the Earth's atmosphere and certain wavelengths are absorbed or scattered. At the ground surface, light is reflected, absorbed and scattered to an extent which depends on the nature of the object that it strikes. Green plants, for example, absorb red wavelengths for use in photosynthesis but reflect green and near infra-red wavelengths; see, for example, Guyot (1990).

Remote sensing can also detect wavelengths that are emitted from the ground. An example of these is heat. Thermal infra-red wavelengths are emitted from warm objects on the ground and can be detected by thermal infra-red sensors. Photographic films are used to record visible and near infra-red wavelengths, and electronic sensors are used to detect these and other reflected and emitted wavelengths.

Photographic films are only sensitive to the visible and near infra-red wavelengths. Electronic sensors can utilise detector and filter combinations to record wavebands of particular interest across the light spectrum from the ultra-violet, through visible, to short radio wavelengths. Sensors record the intensity of the radiation they detect as an analogue value or as a 'digital number' - a value on an arbitrary scale which may be calibrated to measure actual radiance.

In any one spectral waveband, the signal detected from similar ground surfaces in different locations will be similar, but usually not identical. Variation in incident illumination can have a major effect on the detected signal (see section 4.4). When translated into digital numbers, that signal will have a range of values which is to some extent characteristic of the ground surface. When two wavebands are considered, the data from surfaces tend to form clusters or clouds of points rather than single points. This phenomenon is characteristic of remotely sensed data, and results from the inherent randomness of nature, atmospheric interactions and background 'noise' from the sensor. The data continue to cluster when all the wavebands are considered, and it is possible to associate localised regions in multi-dimensional feature space with specific ground cover types (Curran, 1985, p211). If there is no mixing of data points the cover types are said to be separable. If some degree of overlap exists, there is likely to be some confusion of the cover types when computer-based classification of the digital imagery is attempted.

Whereas photographs record a complete scene with each opening of the shutter, electronic sensors build up each strip of image from small units called picture elements or 'pixels'.

Spatial resolution describes the ability of a sensor to detect objects of a certain size. In general, objects smaller than the spatial resolution will not be visible on an image. Linear features and relatively bright features may, however, be visible even if they are smaller than the spatial resolution.

Spectral resolution is the term used to describe the sensitivity of films and sensors to the wavelengths of visible light and other electromagnetic radiation.

Visible and infra-red instruments are affected by the weather. Cloud cover, haze and dust will obscure the sensor's view. Radar systems are not affected to the same extent by these conditions and can be used in most weather conditions by day or by night. Consequently, radar has considerable potential particularly for the study of the U.K., other cloudy areas, and humid tropical regions.

There have been several important and encouraging radar missions which included the U.S. Seasat which was primarily intended to study sea conditions. There have also been two Shuttle Imaging Radar missions (SIR-A and SIR-B) and a number of airborne radar campaigns (SAR-580, AGRISAR, MAESTRO-1). The U.K. is maintaining a strong position in microwave systems by developing instruments for the European Space Agency ERS-1 satellite which was launched on 17 July 1991.

Data from sensors may be recorded directly onto magnetic tape (aircraft) or transmitted from satellites by radio (telemetry) to a ground receiving station where it is recorded on tape. A certain amount of correction and reformatting of the data occurs before it is ready to be sent out to the users. For Landsat, there are three ground receiving stations serving Europe: Fucino in Italy, Kiruna in Sweden and Maspalomas in the Canary Islands. In Europe, the distribution of Landsat data is coordinated by the Earthnet organisation.

1.9 PROCESSING AND INTERPRETATION

Digital data from infrared and visible sensors have to be processed by computer to yield images and useful information. The first step in this process is to display the data on a monitor screen to check their quality and ground location. Single wavebands can be used to generate a monochrome image. Image analysis computers can also generate colour images by displaying three wavebands to the red, green and blue inputs of a colour monitor. The appearance of the resultant image will depend on the chosen wavebands and the colour inputs to which they are assigned. For example, if the red, green and blue wavebands from the TM sensor are assigned to red, green and blue inputs respectively, a natural colour image results.

The great advantage of the image analysis computer is that wavebands that cannot be captured on film and which are otherwise invisible to our eyes can be used in classifications and can be displayed in full colour for interpretation. These other wavebands (infrared, microwave) contain a great deal of useful information about the weather, land cover and water quality.

There are systematic errors in the data received from the satellite, for example because of known changes in its orbit and altitude or because of seasonal differences in illumination as a result of changes in the elevation of the sun. Computer programs can correct the images for these differences.

For many purposes it is desirable to improve the raw image by a process known as 'scaling' or contrast enhancement. The original data often occupy only a small range within the full brightness scale of the scanner and image processor. Scaling spreads the intensity values for each waveband over a greater portion of the full range to make image brightness and contrast more visually acceptable.

Aircraft and satellite data can be adjusted to overlay maps by changing both scale and projection, a process known as geometric correction. In Britain, the Ordnance Survey British National Grid (BNG) usually forms the base for this correction. Corresponding points are found on the map and on the displayed image. Junctions on linear features (roads, hedges, railways) are often suitable. When an adequate number have been identified, their paired coordinates are used to realign the whole image to the map base. The image may have to be moved to differing degrees in its various sections giving rise to the alternative term of 'rubber sheeting'. This process can also be used to register two or more images.

An important application for digital remotely sensed data is in the study of vegetation. Vegetation indices can be computed to produce information on the type, extent and amount of plant life. In a characteristic manner, green plants reflect near infrared light strongly and absorb red light for use in photosynthesis. This is known as the vegetation 'red edge' effect. High values in the resulting index generally represent healthy, actively growing green vegetation.

Image classification is the process of reducing the total amount of information contained in multispectral data by identifying areas with similar spectral characteristics. This simplifies the task of interpreting such images. Classifications can be performed either by human interpreters or computer. In a classification, an analysis of the data relating to known sample sites is made. This is followed by the application of fixed rules to govern the grouping of unknown data points into classes.

Two forms of computer classification are in common use. They are supervised and unsupervised classifiers. Supervised classifiers are frequently used to extend detailed knowledge of small but representative areas to a larger area (Chapter 4). When mapping woodland, for example, the location and extent of several small blocks may be known in detail. It may be necessary to estimate the quantity and location of woodland over a much larger area. The known woodland is marked out on the image analysis computer to provide a training set. A statistical analysis is made of this relatively small training dataset to determine the numerical decision rules for the classification of each pixel in the image. Classifiers can usually cope with many classes at one time.

Unsupervised classifiers examine the dataset for patterns or clusters of pixels which can be used to create a number of classes. These classifiers are objective, remove human bias and require little or no prior knowledge of the area.

Image analysis computers have spatial filtering routines to enhance or smooth features in an image. Fault lines, for example, that generally lie in one particular direction can be emphasised by a filter that seeks and emphasises trends in that direction. There are other filters to remove small variations in otherwise large and even areas of the image. These are frequently used to simplify classified images; see Chapter 4. The filter might, for example, remove isolated woodland pixels in large areas of grass.

1.10 APPLICATIONS

Although remote sensing depends on advanced space technology to obtain its data the ultimate use of the results is often very practical. There are commercial and non-commercial users of the final data. For commercial users, the information is likely to have some direct application and financial justification. The most ready market for remote sensing is in weather forecasting, using the Meteosat and NOAA satellites for national and global meteorological observations (Barrett and Martin, 1981).

With a global perspective, Drury (1990) presented an applications-led approach to the use of remote sensing. Applications of remote sensing in agriculture have been well documented in a review by Steven and Clark (1990). A comprehensive review of applications in forestry was presented by Howard (1991). Other applications in the field of natural resources have been reviewed by Heit and Shortreid (1991). Satellite images and geographical information systems have been particularly useful in developing countries where map information may be missing or out-of-date. Applications in these regions have been reviewed by Gastellu-Etchegorry (1990) and by Belward and Valenzuela (1991). A number of UK applications, with particular emphasis on Scotland were presented by Bibby and Thomas (1990).

Non-commercial users include the military and environmental agencies. There are many specialised and high-performance military systems using advanced remote sensing technology. The spatial resolution of these systems is extremely fine, and tailored to specific surveillance requirements.

1.11 CONCLUSION TO CHAPTER 1

In contrast to the previous shortage of up-to-date information about our environment, the quantities of data now available are enormous. Indeed, the problem is now how to select from these data in order to produce useful and accurate information about the landscape and the environment.

The initiatives taken by the U.S. and their cooperation in making the satellite data so widely available around the world have been invaluable. This began on a national basis and expanded to fill the needs of users internationally. In meteorology, this has resulted in cooperation involving both the Eastern and Western alliances in the exchange of data to help in the understanding of world weather systems. All concerned hope that the continuity of data supply can be maintained. Landsat has become a working tool for terrestrial applications of remote sensing throughout the world; NOAA AVHRR similarly so for both terrestrial and marine applications. With the operational use of the French SPOT satellite since 1986 and the reception of the first radar images from the ERS-1 satellite in 1991, Europe has added new sources of Earth observation data.

Third Party Material excluded from digitised copy.
Please refer to original text to see this material.

CHAPTER 2

RADIOMETER STUDIES OF SEMI-NATURAL VEGETATION EXPOSED TO SIMULATED AIRBORNE POLLUTION

2.1 GENERAL INTRODUCTION

Wide-area surveys of natural and semi-natural vegetation using remote sensing techniques record a mixed signal response from vegetation, soil background, exposed rocks and a miscellany of other components. A valuable precursor to extensive studies such as this can be the examination of the spectra of individual plant canopies and even leaf sections when necessary. Radiometers with an appropriate field of view provide the opportunity to examine the reflectance spectra of plant canopies and plant components. The effects of acidic deposition in rain and mist and airborne pollutants on vegetation in Europe was of particular interest during the 1980s and early 1990s. The topic merited further examination through the application of remote sensing techniques.

Two experiments were undertaken to study the effects of acidic deposition and airborne pollution on plant material:

In the first experiment, a pilot study examined the effect of simulated acid rain on the reflectance of birch seedling canopies using plants grown on two soil types.

In the second experiment, the effects of combinations of pollutant gases and acidic mists on the reflectance of white clover were studied in detail. The relationships between shoot dry weight and remotely-sensed vegetation indices were also examined.

EXPERIMENT ONE

DIFFERENCES IN THE SPECTRAL CHARACTERISTICS OF BIRCH CANOPIES EXPOSED TO SIMULATED ACID RAIN

2.2 SUMMARY OF EXPERIMENT ONE

Seedlings of silver birch in a polythene tunnel were exposed to simulated acid rain at pH's of 2.5, 3.5, 4.5 and 5.6 while growing in pots of either John Innes No. 2 potting compost or an Arfon series soil. Measurements of visible and near infra-red radiance were taken from the canopies of groups of plants exposed to each of the rainfall treatments - firstly after 34 weeks for plants grown in John Innes compost, and secondly after 75 weeks for plants grown in both soils. Plots of reflectance against wavelength revealed that only plants exposed to the control pH 5.6 treatment retained the characteristic curve shape of healthy green vegetation. Discriminant analysis showed that the radiometer data could be used to distinguish between birch canopies which had been exposed to the different rainfall treatments after both 34 and 75 weeks (Ashenden and Williams, 1988).

The potential of radiometry is discussed in relation to identifying plants growing under conditions of acid rainfall in both controlled environments and in the field. It was apparent that further research using the more sensitive scanners now available would be required in order to improve the accuracy of this survey technique.

2.3 BACKGROUND TO EXPERIMENT ONE

Sulphur dioxide (SO_2) and nitrogen oxides (NO_X) were the main pollutant gases responsible for increasing the acidity of rainfall. Most combustion processes result in the release of both gases and they were widespread pollutants in Britain. Following release into the atmosphere, SO_2 and NO_X may combine with atmospheric moisture to form sulphuric and nitric acids. In these forms, the pollutants may become incorporated into clouds and can be carried long distances before being deposited in rain, hail or snow. Even without the addition of pollutants rainwater would be slightly acidic because water in equilibrium with atmospheric concentrations of carbon dioxide has a pH of 5.6. In Britain, the presence of pollutants substantially increases the acidity of rainfall and most rural sites have annual mean acidities within the range pH 4.1 - 4.7. Monthly mean values as low as pH 3.4 have been reported (see Barrett et al., 1983). Individual events have deposited rain with a pH of

2.4 in Scotland and rainfall acidities were considered to be generally much higher than 25 years ago - up to a ten-fold increase in acidity (Pearce, 1982).

The effects of wet acid deposition on vegetation were not well defined. Several authors have reported that simulated rain at high levels of acidity (lower pH than 3.0) reduced the growth of plants (Harcourt and Farrar, 1980; Amthor, 1984). At lower levels of rainfall acidity (higher pH) most investigators have found little effect on plant productivity. In a review of the subject, Irving (1983) concluded that the effects of ambient levels of rainfall acidity on crops were likely to be minimal. However, Evans et al. (1982, 1983) found that the application of simulated acid rain of pH 4.0 - pH 4.1 caused yield reductions in field-grown crops. More recent laboratory work has demonstrated 9-17% yield reductions in winter barley grown on a range of British soils in response to the critical pH 3.5 - pH 4.5 rainfall range (Ashenden and Bell, 1987). Subsequently, it was reported that exposure to a pH 2.5 rainfall treatment caused an increase in birch seedling height, when less acid treatments did not (Ashenden and Bell, 1988). In the same paper, the effect of pH 5.6, 4.5, 3.5 and 2.5 rainfall treatments on Sitka spruce seedlings grown on eight British soils was described. Height was unaffected by treatment on six of the soils, it was greatest at pH 2.5 on one soil, and greatest at pH 5.6 on the remaining soil. These results indicated that soil factors could influence the sensitivity of plants to acidified rain.

Visible foliar injury on a range of plant species resulting from exposure to highly acidic rainfall treatments (less than pH 3.4) has been reported by several authors (Wood and Bormann, 1975; Ferenbaugh, 1976; Evans, Gmur and Da Costa 1977, 1978). However, significant yield reductions may occur in some species without the presence of visible leaf lesions following exposure to less acid rainfall treatments (see, for example, Ashenden and Bell, 1987). Similar 'invisible injury' was a well known phenomenon in plants exposed to low levels of acidic gases (see, for example, Bell, 1982; Law and Mansfield, 1982). Investigations have shown that ambient levels of acid pollutants can cause changes, which were not visible to the eye, in the surfaces and internal structures of leaves (Black and Black, 1979; Soikkeli and Tuovinen, 1979; Cape and Fowler, 1981). Such 'invisible' changes in leaf structure may not have a direct effect on plant growth but may make plants more susceptible to other stresses. These stresses in combination with even very low levels of pollutants (similar to those found in rural environments) were considered to have the potential to cause severe injury to plants (Mansfield et al., 1988).

The early detection of pollution injury to plants has always been regarded as of major importance. Infrared photography has been used to estimate rates of mortality and to identify areas of vegetation under pollution stress (see, for example, Ciesla, 1989). Non-photographic spectroradiometry would appear to have considerable potential for detecting pollution stress in plants because of the extended sensitivity into the non-photographic infra-red of the instruments now available. The effects of sulphur dioxide on reflectance have been recorded for field grown winter wheat (Ferns and McLeod, 1984). The objective of Experiment One was to assess the potential for discriminating between canopies of birch seedlings subjected to different acidities of simulated rain.

2.4 MATERIALS AND METHODS FOR EXPERIMENT ONE

Seeds of Betula pendula Roth. (silver birch) collected from a local tree were germinated in trays of John Innes potting compost. Approximately 12 weeks after sowing, the seedlings were transplanted into 7.5cm diameter pots containing either John Innes No.2 potting compost or an Arfon Series soil. The Arfon soil was a brown earth collected from beneath an old pasture at Tregarth, near Bangor (GR. SH608686) and was more fully documented elsewhere (Rudeforth et al., 1984). The seedlings were then transferred to a polythene tunnel exposure system which was divided internally into four treatment bays which contained no supplementary lighting or heating. Each bay was fitted with three 'Eintal' spray nozzles which were positioned to give an even distribution of droplets over the exposure area (see Ashenden and Bell, 1987). The plants were left to acclimatise to conditions in the polythene tunnel for four weeks before the start of experimental treatments.

Simulated acid rain at pH 2.5, 3.5, 4.5 and 5.6 was made up by adding sulphuric and nitric acids in the ratio of 7:3 by volume to tap water. This rain was applied at the rate of 3cm per week with one 5-minute episode per day Monday-Thursday, and one 7-minute episode on each Friday. The rainfall treatments were continued over a period of 2 years including the winter months when the seedlings were without leaves. During this time the plants were potted on into 12.5cm diameter pots but no additional fertilizer applications were made.

Measurements of radiance were taken on two occasions. The first measurements were made 34 weeks after the start of the experimental treatments; the second series were taken after 75 weeks of exposure to the treatments. On the first occasion, a pilot study, only plants grown in John Innes compost were used, while on the second occasion plants grown in both the Arfon soil and John Innes compost were used. For the radiometry, plants were arranged in groups to form small canopies of leaves on a greenhouse bench covered with matt black paper. Additional pieces of matt black paper were placed around the bases of the stems of each plant to conceal the pots and soil from view from above. These precautions were taken to minimise the radiance of extraneous surfaces and to ensure, as far as possible, that readings of radiance were from the birch canopies only.

A radiometer and a 35mm camera were fixed in position about one metre above the bench. The radiometer was a Milton model 102 (see Milton, 1980) which measured radiance in four wavebands: green, 0.5-0.6μm; red, 0.6-0.7μm; near infra-red, 0.76-1.1μm; and near-middle infra-red, 1.35-1.75μm. The camera was used to take a black and white photograph of each canopy for estimating comparative canopy areas. Illumination was provided by direct sunlight and, to allow correction for variations in the level of illumination, radiometer readings were taken from a Kodak 18% grey card (control radiance) prior to measuring the radiance of each canopy.

For the measurement of canopy radiance, groups of plants were selected at random from each soil x rainwater treatment. After 34 weeks, the radiances of six canopies were measured, each made up of five plants grown in John Innes compost, for each rainwater treatment. After 75 weeks, the birch plants were larger and fewer were needed to make-up adequate canopies. The radiances of ten canopies, each made up of three plants, were measured for each soil x rainwater treatment.

It was necessary to estimate the apparent area occupied by each canopy in the field of view of the radiometer to standardise the radiance measurements. This was achieved by estimating the relative canopy areas on the black and white photographs taken by the camera mounted alongside the radiometer. Each radiance measurement was divided by the relative area of the canopy to give an estimate of radiance per unit of leaf area. These values were then divided by the control radiance (grey card readings) to give BRF per unit area for each birch canopy. The Bidirectional Reflectance Factor (BRF) is a ratio between the radiance of vegetation and that of a diffuse reflector within the scene (Silva, 1978; Curran, 1985). The BRF reflectance data were then used to look for differences between the conditions of the canopies rather than differences due to background illumination or areas of canopy visible to the radiometer.

An important aspect of this radiometric study was that it attempted to distinguish between the vegetation canopies by examining their spectral characteristics in all four wavebands. Multivariate classification procedures can optimise the use of all the reflectance data collected. The statistical method adopted for this procedure was Discriminant Analysis. It is similar in nature to Principal Component Analysis, except that the separation between classes, rather than individual observations, is maximised in multidimensional feature-space. The SAS Statistics package (Anon., 1985) was used to process the data using discriminant analysis.

2.5 RESULTS OF EXPERIMENT ONE

The reflectances of the birch seedlings in each rainwater treatment were measured after 34 weeks and BRF was plotted against wavelength as shown in

Figure 2.1. It can be seen that there was little difference in graph shape between the different treatments but there were generally higher BRF values for the least acid (pH 5.6) treatment. At the end of 75 weeks of exposure, however, a plot of BRF against wavelength for the different rainwater treatments (averaged over both soil types) showed a distinct change in the graph shape for the more acid treatments (see Figure 2.2). The characteristic dip in the graph between green and red wavelengths (at about 0.65μm) was missing from all but the pH 5.6 treatment; this difference in graph shape was tested using a t-test (Table 2.1). In separate plots of BRF against wavelength for plants grown in both John Innes and Arfon soils (Figures 2.3 and 2.4), it was confirmed that only plants exposed to the pH 5.6 treatment retained the marked dip between green and red wavelengths. It was this change in graph shape after the application of simulated acid rain that was of particular interest, rather than the magnitude of the BRF values.

The decrease in reflectance between green and red wavelengths corresponds to one of the chlorophyll absorbtion bands and is a characteristic feature of healthy green vegetation. Leaf pigment damage would certainly reduce the ability of the pigments to reflect green light and, more importantly, to absorb red light. The characteristic dip in reflectance between green and red wavelengths would, therefore, be flattened by pigment damage. The normal decrease in reflectance produced a negative value when green BRF was subtracted from red BRF; the more negative the result the more pronounced was the dip in reflectance. A one-tailed t-test was used to test the significance of the flattened response curves corresponding to the more acid treatments (Table 2.1).

For plants exposed to the treatments for 75 weeks in the John Innes compost, the t-test demonstrated that there had been a significant ($P<0.05$) flattening of the graphed response corresponding to the more acid treatments when compared with the pH 5.6 treatment for plants grown on John Innes compost (Table 2.1). On the Arfon soil the differences were significant ($P<0.05$) for the pH 2.5 and pH 3.5 treatments, but not for the pH 4.5 treatment. It was noted that there were no obvious differences in the visual appearance of leaves on plants exposed to the different treatments when these measurements were made.

Using the discriminant analysis procedure, mathematical functions were used to characterise and maximise the separation between the different rainfall treatments. A classification assigned the individual observations to one of the four distinct classes (treatments). The classification tables obtained indicated how typical each observation was of its treatment. Table 2.2 shows the classification obtained for plants exposed to the four rainfall treatments for both 34 and 75 weeks. It can be seen that, for plants exposed for 34 weeks, all but one of the canopies measured (96%) were correctly characterised using this technique; the only canopy mis-classified was one from the pH 3.5

treatment which gave a multispectral response more comparable with canopies which had been exposed to the pH 4.5 treatment.

There was visibly more variation in size and canopy structure in the plants exposed for 75 weeks. This made the canopies more difficult to characterise with a correspondingly lower classification figure - 73% for plants grown in John Innes compost and 85% for plants grown in the Arfon soil. Some of the plants exposed to the pH 3.5 treatment on John Innes soil appeared to have similar spectral characteristics to those in the adjacent pH 2.4 and pH 4.5 treatments. Most of the misclassifications were between adjacent treatments. When the variability of canopy size and structure was considered, however, their characterisation was generally good.

2.6 DISCUSSION AND CONCLUSION TO EXPERIMENT ONE

It was apparent from the results obtained that radiometer data could be used to discriminate between the canopies of birch seedlings exposed to different acid precipitation treatments with a relatively high degree of accuracy. The differences between the canopies were a measure of subtle changes in multispectral reflectance which had been induced by the different rainfall treatments. Thus, while visible observation and growth measurements may be unable to detect different rates of total wet acid deposition on plants, radiometry has much potential for assessing the degree of exposure to which plants have been subjected.

Milton et al. (1989) reported changes in the shapes and inflection points of spectral response curves of soybean plants affected by arsenic and selenium compounds. A comparison of the spectral response graphs (BRF plotted against wavelength) after 34 weeks and 75 weeks of exposure to the different rainfall treatments revealed a change in the response of the birch canopies to light. After 75 weeks, the birch plants subjected to all but the least acid (control pH 5.6) treatment had lost the dip in reflectance between green and red wavelengths which is characteristic of healthy green vegetation (Hoffer, 1978). This difference in graph shape for the pH 5.6 treatment was found to be significant in all comparisons except one, the pH 4.5 treatment on the Arfon soil. The presence of the dip in reflectance curves of normal green vegetation (centred at about $0.65\mu m$) corresponds to one of the chlorophyll absorption bands. Chlorophyll present in the leaf absorbs most of the incident energy and little is reflected at these wavelengths. A relative lack of absorption at these wavelengths is indicative of a lower chlorophyll content in the leaves - a common response of plants growing under stress (see Hoffer, 1978).

The use of discriminant analysis classification techniques to characterise the spectral response of plant canopies subjected to the various treatments generally proved successful. For plants exposed to the treatments for 34 weeks, there was 96% correct classification. After 75 weeks of exposure to the treatments, there was more variation between canopies but still 73% and 85% of the classifications were correct for plants grown on John Innes and Arfon soils respectively. Furthermore, where misclassifications occurred, they were generally in adjacent treatment classes - only 2 cases (5%) were outside this range for the John Innes soil with 3 cases (7.5%) outside this range for the Arfon soil.

The use of this technique for characterising vegetation canopies that have been subjected to stress-inducing treatments has good potential. The methodology used in this study for distinguishing birch seedling canopies exposed to different rainfall acidities was successful for this controlled environment study.

EXPERIMENT TWO

DIFFERENCES IN THE SPECTRAL CHARACTERISTICS OF WHITE CLOVER EXPOSED TO GASEOUS POLLUTANTS AND ACID MIST

2.7 SUMMARY OF EXPERIMENT TWO

White clover plants (Trifolium repens L. cv. 'Grasslands Huia') were exposed to combinations of gaseous pollutants and acid mists similar to those found in many parts of upland Britain. The gaseous pollutant treatments were (a) charcoal-filtered air (control), (b) SO_2+NO_2, (c) O_3 and (d) $O_3+SO_2+NO_2$. The acid mist treatments were 6mm per week of solutions at pHs of 2.5, 3.5, 4.5 and 5.6. After 12 weeks, canopy reflectance was measured at green, red, near infrared and middle infrared wavelengths using a portable radiometer. Distinct changes in the characteristic spectral reflectance of the clover canopies were noted. The effect of the gaseous pollutants was significant when examined by analysis of variance. The two treatments containing ozone showed particularly marked changes and were statistically separable from the control in a pairwise comparison; the sulphur and nitrogen dioxide treatment was not statistically separable from the control. The acid mists had no significant effect on canopy reflectance. Simple and 4-waveband vegetation indices showed positive linear relationships with shoot dry weight. The $O_3+SO_2+NO_2$, in particular, and O_3 treatments produced marked decreases in shoot dry weight and vegetation index. The green and near infrared wavebands were the best discriminators of change in canopy reflectance (Williams and Ashenden, 1992).

2.8 BACKGROUND TO EXPERIMENT TWO

Assessments of the potential toxicity of pollutants to vegetation have changed substantially in recent years. The emphasis has moved from studies using high concentrations of the major pollutant gases sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3), which result in acute injury to plants, to investigations of the more subtle effects of long-term, low-level exposure. Furthermore, it has now been recognised that wet deposition is a major route for the influx of potentially damaging levels of sulphur, nitrogen and hydrogen ions into ecosystems. This route is of particular importance in upland areas, where highly acidic mist may cloak vegetation for prolonged periods and there are high levels of rainfall (Dollard et al., 1983). Studies of the combined effects of pollutant gases and acidic mists on plants would seem to be essential for realistic assessments of the potential threat that these conditions pose to vegetation.

The early detection of pollution injury and other forms of stress in plants has always been regarded as of major importance because the growth of plants can be affected before visible foliar damage is noticed. This phenomenon has been termed 'pre-visual' or 'invisible injury' because it is not apparent to the human eye with its sensitivity restricted to a relatively small portion of the electromagnetic (EM) spectrum. It has been known for some time that colour infrared film with its slightly extended sensitivity can help in the monitoring of vegetation by allowing us to see features on the critical 'red edge' of the vegetation spectrum (Ciesla, 1989).

There is clearly an emerging methodology for assessing the effects of airborne pollutants on vegetation. The physiological effects of pollutant gases on plant ultrastructure have been reported since the early 1960s. Observations of the disruption of chloroplasts and reduced amounts of chlorophyll have been reported as a common response to pollutant exposure (Hill et al., 1961; Sabaratnam, Gupta and Mulchi, 1988). Damage to plant cellular structure was another well known effect of pollutants (Huttunen and Soikkeli, 1984). A number of reports have shown how the physiological damage was manifested in an altered reflectance spectrum as detected by photography, radiometers, and airborne and satellite scanners.

Forest damage and decline in particular have been studied using airborne and satellite sensor data. A 'blue-shift' has been characterised in the spectral response of forest canopies in Vermont and Germany where damage due to air pollution was suspected. This blue shift is a 5nm shift towards blue of the inflection point of the vegetation red edge associated with a decrease in needle chlorophylls (Rock et al., 1988). Damage has been assessed and mapped in spruce-fir forests in Vermont and New Hampshire where Landsat Thematic

Mapper data were compared with field data to estimate foliar loss (Rock et al., 1986; Vogelmann and Rock, 1988).

Under experimental control, reflectance changes have been noted in plants exposed to pollutant gases. Runeckles and Resh (1975) examined bean (Phaseolus vulgaris L.) plants after exposure to low levels of ozone at wavelengths between .45μm and .75μm using a spectrophotometer. They found reflectance data more reliable than extracted chlorophyll levels in quantifying chronic plant injury. Gausman et al. (1978) reported the pre-visual detection of ozone injury on cantaloupe (Cucumis melo L.) plants using infrared photography. Schutt et al. (1984) related a reflectance index to reduced yields in pollutant-injured tomato (Lycopersicon esculentum Mill.) plants. In an earlier experiment (Ashenden and Williams, 1988) reflectance was used to discriminate birch seedling canopies treated with simulated acid rain for 75 weeks.

The objective of Experiment Two was to assess the potential for discriminating between canopies of white clover which had been subjected to combinations of acidic mist and pollutant gases. If reflectance could be used to characterise the clover canopies, this would provide a further indication that remote sensing using airborne or satellite sensors could be used for monitoring the condition of vegetation subjected to pollutant gases and acidic mist conditions.

2.9 MATERIALS AND METHODS FOR EXPERIMENT TWO

Seedlings of Trifolium repens L. cv. 'Grasslands Huia' (white clover) were raised in an unheated glasshouse, potted on into 7.5cm-diameter pots containing John Innes No.2 potting compost, and allowed to become established. Six weeks after sowing, 60 plants were selected at random and placed in each of four 'Solardome' fumigation glasshouses at the Institute of Terrestrial Ecology (ITE) research station in Bangor. The atmospheres within the glasshouses were controlled to provide the following gaseous treatments:

a) charcoal-filtered air (control)
b) SO_2 and NO_2
c) O_3
d) O_3, SO_2 and NO_2.

The concentrations of SO_2 and NO_2 were maintained at 40 ppb (v/v) continuously. The O_3 treatment was maintained at 40 ppb, except for two peaks per week on Thursdays (3 hours at 80 ppb) and on Tuesdays (3 hours at 80 ppb immediately followed by 1 hour at 110 ppb). Atmospheres within the Solardome glasshouses were monitored using a Meloy SA285 SO_2 analyser and Monitor Labs instruments model 8840 for NO_x and model 8810 for O_3 to ensure that the pollutant concentrations remained at ±2 ppb of the desired levels.

The 60 plants of each species within each gaseous fumigation treatment were separated randomly into three groups of 20 plants, each group being designated an experimental block. Five plants within each experimental block were then chosen at random to be subjected to one of the four acidic mist treatments. For the misting treatments the trays were taken from the Solardome glasshouses into a polythene tunnel misting system. The mist treatments were three x four-hour exposures per week on Mondays, Wednesdays and Fridays. The acid mist treatments were set up to provide a relatively small total wet deposition of 6mm per week at pH 2.5, pH 3.5, pH 4.5 or pH 5.6 respectively in the four misting bays. The mist solutions were made from deionised water by adding equimolar quantities of ammonium nitrate and sulphuric acid. The length of misting and ionic balance of the mist solution was chosen to re-create conditions similar, in these respects, to those reported for Great Dun Fell (Dollard et al., 1983). Supplementary watering of the plants was provided at the rate of 24mm per week using simulated acid rain solution of pH 4.5 (made from sulphuric and nitric acids in the ratio of 7:3 by volume). Hence the total quantity of rain and mist applied was 30mm per week. The treatments were maintained for 12 weeks.

A radiometer was fixed in position between lighting units and 60cm above the plant canopies. The radiometer was a Milton model 102 (see Milton, 1980) which measured radiance in four wavebands: green, 0.5-0.6μm; red, 0.6-0.7μm; near infrared, 0.76-1.1μm; and near-middle infrared, 1.35-1.75μm. The radiometer had a 15^0 field-of-view. The radiometer was aligned vertically using spirit levels and the centre of this field-of-view on the bench was located with a plumb-line. The radiometer output was stored in an Epson HX20 laptop computer.

The laboratory bench was covered with matt black cloth to minimise extraneous and background radiance. Simulated daylight illumination was provided by a pair of light boxes each containing one Thorn-EMI Kolorarc MBIF/BUH 250W grow lamp 60cm above the plant canopies. Control radiance was taken from a Kodak 18% grey card prior to measuring the radiance of each clover canopy. Each clover plant in turn was placed under the radiometer. Two measurements of radiance in each waveband were taken from each plant; the mean of these two readings was taken to be the plant radiance in each waveband for use in further analysis. Readings were taken from a total of 240 plants. Reflectance is the ratio of vegetation radiance to control radiance, and is usually referred to as the Bidirectional Reflectance Factor (BRF). Each clover plant radiance was divided by the control radiance (grey card readings) to estimate vegetation reflectance.

Analysis of variance was used to test the effects of the experimental treatments. Multivariate classification procedures can optimise the use of all the reflectance data collected. Discriminant analysis is similar in nature to Principal Component Analysis, except that the separation between classes, rather than individual observations, is maximised in multi-dimensional feature-space. In this experiment, reflectance was measured in four wavebands so the clustering of the groups was considered in four-dimensional feature-space. Using the discriminant analysis procedure, linear mathematical functions were used to characterise and maximise the separation between the different treatments. A classification assigned the individual observations to one of the distinct classes (treatments). The classification tables obtained indicated how typical each observation was of its treatment. Discriminant analysis provided an important test because it is similar to the multivariate classification procedures used in the image processing of operational airborne and satellite data.

2.10 RESULTS OF EXPERIMENT TWO

The data were tabulated by treatment reflectance means and standard deviations in four wavebands for the sixteen gas by acid mist combinations (Table 2.3). The most immediate and striking detail was a marked reduction in near infrared reflectance (BRF) from the canopies of plants subjected to the ozone treatments (O_3, and $O_3+SO_2+NO_2$). The effect was consistent at all four levels of acid mist. It should also be noted that near infrared reflectance reduced progressively from the control treatment, through the non-ozone pollutant treatment (SO_2+NO_2), to the two ozone treatments (O_3, and $O_3+SO_2+NO_2$). The statistical significance of these differences was tested using analysis of variance. The multivariate and univariate analysis of variance (MANOVA and ANOVA) and discriminant analysis routines in the SPSSX statistical package were used to process the data.

2.10.1 Analysis of variance

It is often not possible to find significant differences between treatments using single waveband data; in many experiments, all wavebands were needed to detect the subtle differences in the plant spectra. Very significant differences ($P<0.001$) were found between the reflectances of the clover canopies subjected to the different gaseous pollutant treatments (Gas, Table 2.4). Further tests were required to establish which wavebands were providing the discrimination between these treatments, and to determine which gaseous pollutant treatments had a significant effect on canopy reflectance.

Univariate analysis of variance tests indicated that the green and the near infrared wavebands could individually detect very significant differences ($P<0.001$) between the canopies subjected to the different gaseous pollutants (Gas, Table 2.4). The reflectance data from these two wavebands were used in a Bonferroni multiple pairwise comparison between the control treatment and the three pollutant gas treatments; 95% confidence intervals were used. Using the green and near infrared wavebands individually, this test found significant differences between the control treatment and the two ozone treatments (O_3, and $O_3+SO_2+NO_2$). There were no significant differences between the control treatment and the SO_2+NO_2 treatment using either waveband (Table 2.5). No significant interactions between the gaseous treatments and the acidic mist treatments were indicated by the multivariate analysis of variance results (Gas X Acid, Table 2.4), and there were no significant differences between the acidic mist treatments (Acid, Table 2.4).

2.10.2 Discriminant analysis

The percentage of plants correctly characterised by their reflectance spectra ranged from 13% to 80% (Table 2.6). The gas treatments (Gas, Table 2.6) were considered at each level of acidity and the percentages of correct characterisation ranged from 27% to 80%; the average percentages lay between 57% and 68%. The analysis of variance indicated that these results were significant ($P<0.001$, Table 2.4). Lower percentage characterisations were found in the acidic mist dataset (Acid, Table 2.6). When the acidic mist treatments were considered in each gaseous environment the percentages of correct characterisation ranged from 13% to 67%; the average percentages lay between 38% and 48%. The analysis of variance indicated that these results were not significant (Table 2.4).

2.10.3 Regression analysis

A simple vegetation index was calculated by dividing the near infrared waveband by the red waveband (NIR/R). A plot of shoot dry weight against this simple index (Fig. 2.5) showed a weak positive linear relationship between the two variables. The correlation coefficient R provided a measure of the linear association between these two variables: $R = 0.504$. The 16 treatment means for the simple vegetation index were compared with the respective shoot dry weight treatment means (Fig. 2.6). A clear and progressive linear relationship between the simple vegetation index and shoot dry weight was seen. The $O_3+SO_2+NO_2$, in particular, and O_3 treatments produced marked decreases in shoot dry weight and vegetation index. The SO_2+NO_2 treatment overlapped with the control, but the control had a higher vegetation index at each pH level and the control shoot dry weights were clustered towards the top of the range. A 4-waveband vegetation index was obtained by regression analysis. The relationship was weak but distinctly positive and linear. The coefficient of determination R^2 for this line was 0.527. The index took the form:

Shoot dry weight (g) = -0.237 + 3.96 G - 3.05 R + 3.78 NIR - 4.20 MIR.

Waveband codes: G, green; R, red;
NIR, near infrared; MIR, middle infrared.

The predicted values of shoot dry weight using this index were calculated and plotted against the actual weights (Fig. 2.7). The correlation coefficient R provided a measure of the linear association between shoot dry weight and the predicted values using this index: R = 0.732.

2.11 DISCUSSION AND CONCLUSION TO EXPERIMENT TWO

When the spectra of plant leaves or plant canopies are examined it is obvious that there is great scope for investigating condition or plant 'health'. There are major differences between the spectra of different species of plants and minor but distinct within-species differences. There are also variations that result from water balance, nutrient status, insect and fungal attack and, of particular current interest, pollution damage. Some of these differences are obvious in the field and can be adequately described; the potential of spectroradiometry lies in detecting subtle and previsual changes in plant condition.

The results of this experiment concurred with other research. The wavebands that discriminated the effect of the ozone treatments in this experiment were green (0.5-0.6μm) and near infrared (0.76-1.1μm). Schutt et al. (1984) found that reflectance at 0.55μm (green) and 0.725μm (near infrared) were most responsive to pollutant damage on the leaves of tomato plants. However, the experiments by Runeckles and Resh (1975) and Schutt et al. (1984) measured reflectance at close range from individual leaf sections; 25mm diameter and 9mm x 20mm respectively. In our experiment, complete clover canopies were measured with the result that differences in leaf area index and soil background were able to influence reflectance. Runeckles and Resh (1975) reported an increase in reflectance from the pollutant affected plants over the range of wavelengths used (0.45μm to 0.75μm), with a particularly marked increase between 0.55μm and 0.7μm. In this experiment, the thinning of the clover canopies grown in the ozone treatments resulted in a marked decrease in near infrared reflectance.

Schutt et al. (1984) related a wavelength difference index from pollutant damaged tomato plants to reduced fruit yields when compared with a control. In our experiment, a simple 2-waveband vegetation index and a more sensitive

4-waveband vegetation index showed positive linear relationships with clover plant shoot dry weight.

No significant differences were reported between the acidic mist treatments. From a total quantity of simulated acid rain and mist of 30mm per week, 24mm per week were applied as simulated rain at pH 4.5 to all plants. Only 20% (6mm per week) of the total was applied in the form of mist at the different levels of acidity. This may have accounted for the difficulty found in discriminating between these acid mist treatments.

The radiometer detected distinct and relatively consistent changes in plant reflectance. Significant differences were established between the reflectance of plant canopies exposed to the gaseous pollutant treatments at each level of mist acidity. The changes were most apparent for the triple pollutant treatment, less so for the ozone treatment and for the sulphur and nitrogen dioxide treatment. This could be seen as a ranking of the growth reduction potential of each gaseous pollutant.

2.12 CONCLUSION TO CHAPTER 2

The application of these laboratory techniques in a field situation would be fraught with complications. An extensive range of factors were known to increase variability in the spectral characteristics of vegetation canopies. These include within-species variation, age, fungal and insect infestation, foliage and canopy structure, mixed species canopies, understorey vegetation and soil background. Even so, some success has been found when comparing the canopy conditions of large single-species stands. Koch and Kritikos (1984), for example, found differences in radiance from pollution-damaged spruce when compared with healthy stands of spruce using an airborne scanner. The more sensitive scanners now available may enable foliar damage to be more accurately characterised and possibly allow the identification of causal agents.

Radiometers with better spectral and spatial resolution may be able to quantify more accurately the very subtle changes in plant spectra resulting from pollution damage. Airborne and satellite scanners with increasingly precise spectral and spatial resolution are proving to be effective instruments in the monitoring of vegetation condition in regions with airborne pollution problems. Remote sensing research must now focus on developing precise and standardised methodologies for the operational monitoring of pollution damaged vegetation.

CHAPTER TWO

FIGURES

AND

TABLES

FIGURE 2.1
Mean BRF plotted against wavelength
for birch seedlings grown on John Innes soil
and exposed to simulated acid rain for 34 weeks

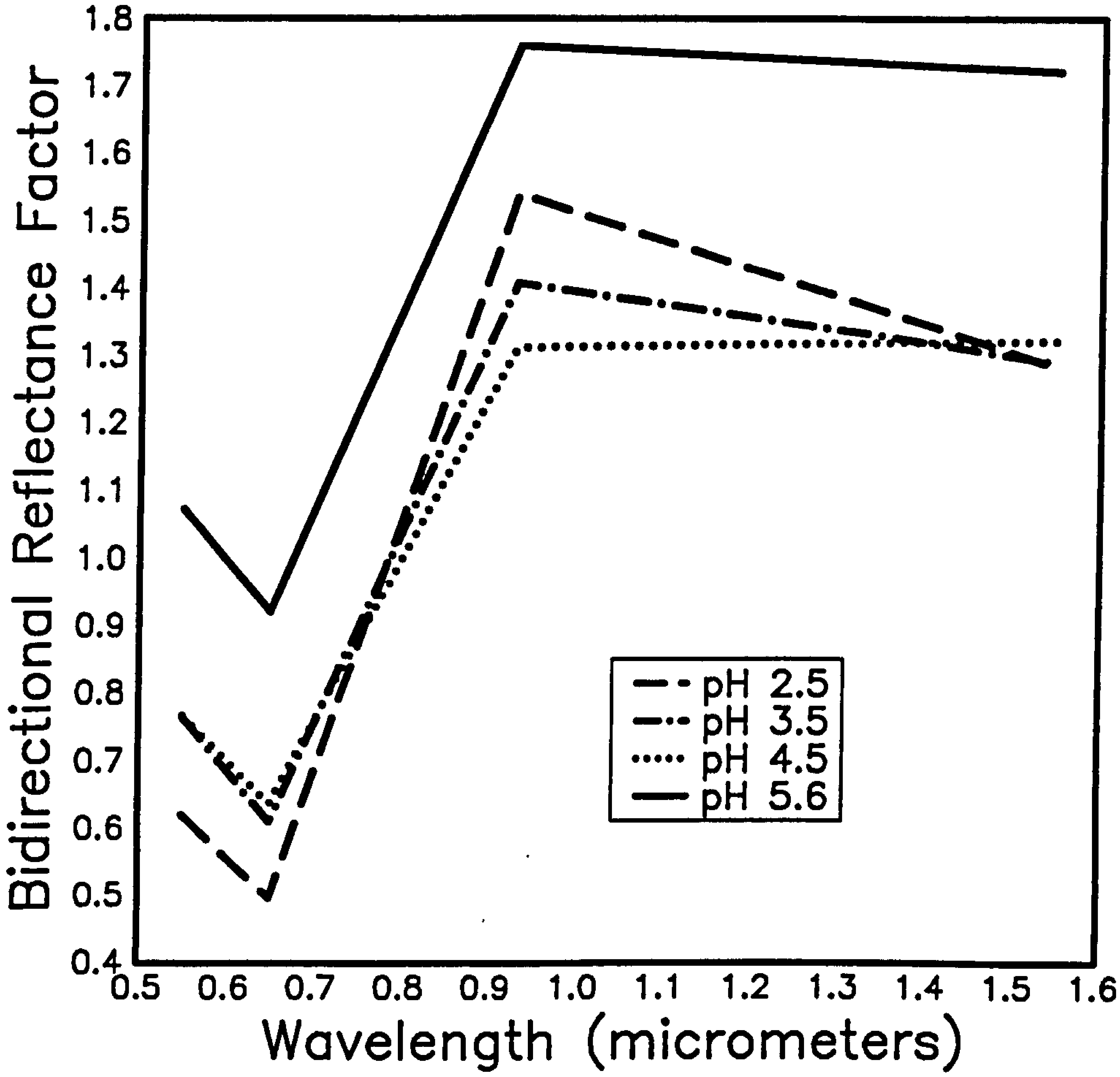


FIGURE 2.2
Mean BRF plotted against wavelength for birch seedlings exposed to simulated acid rain for 75 weeks (combined data for seedlings grown on both soil types)

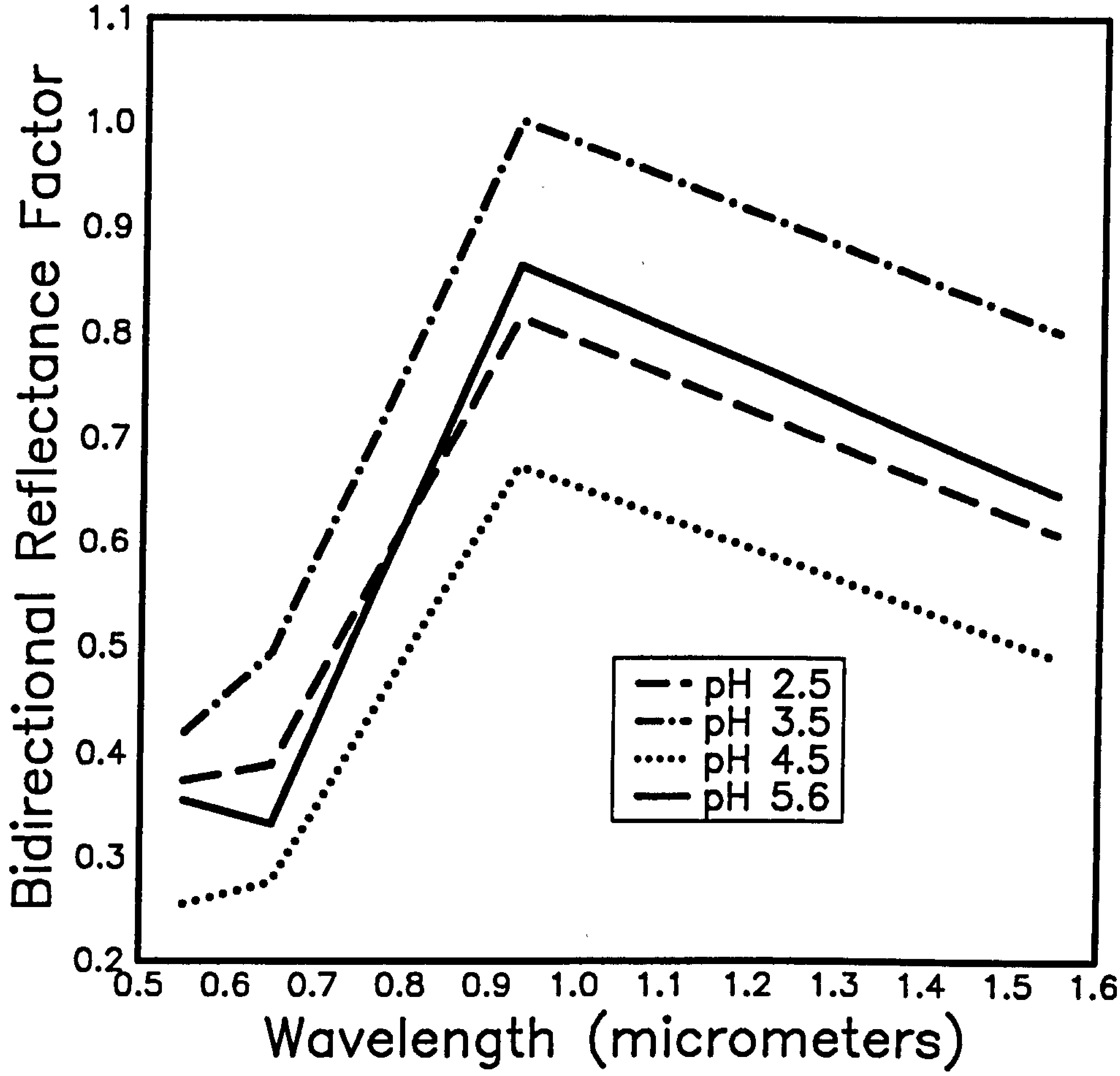


FIGURE 2.3
Mean BRF plotted against wavelength
for birch seedlings grown on John Innes soil
and exposed to simulated acid rain for 75 weeks

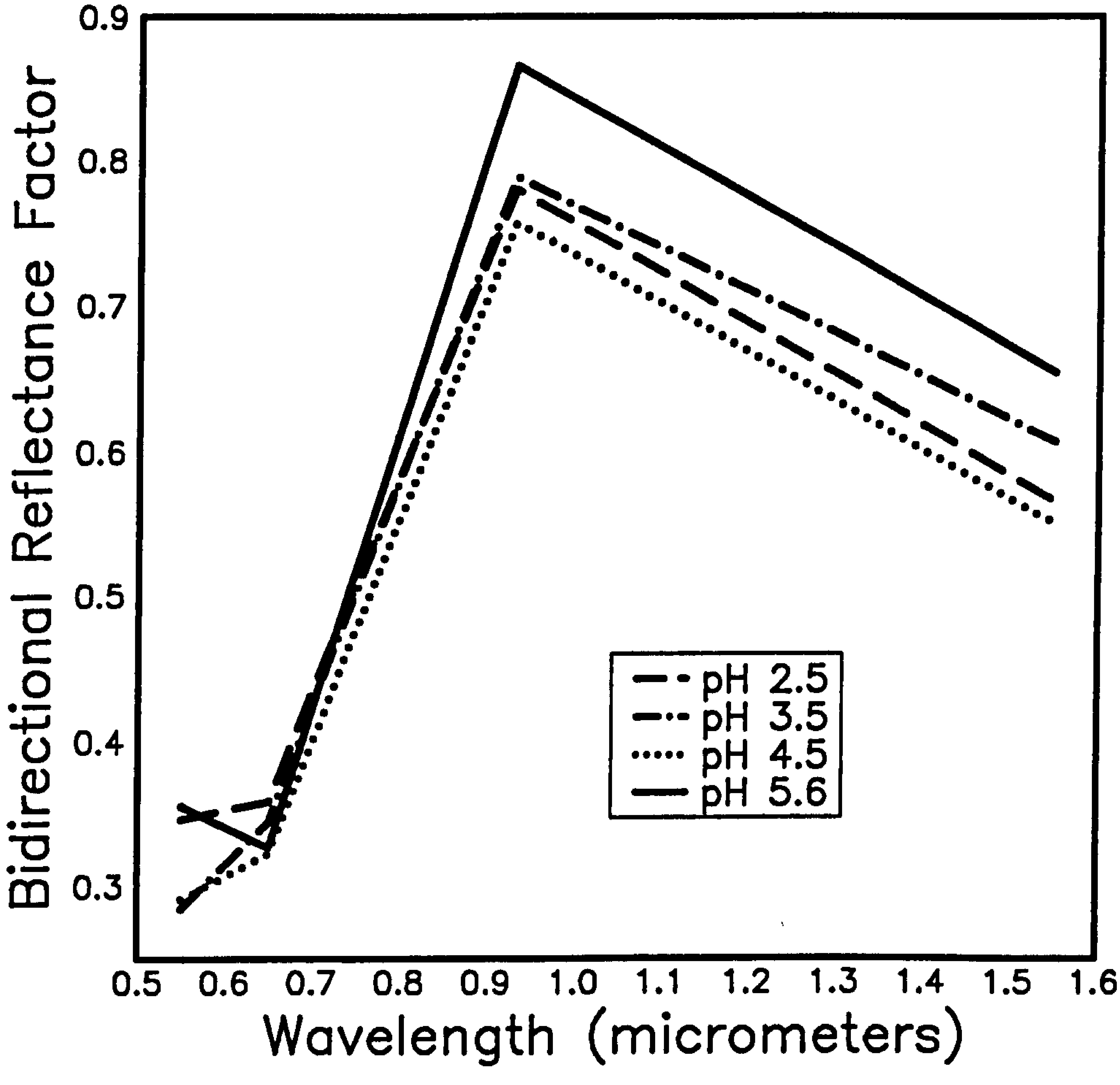


FIGURE 2.4
Mean BRF plotted against wavelength
for birch seedlings grown on the Arvon soil
and exposed to simulated acid rain for 75 weeks

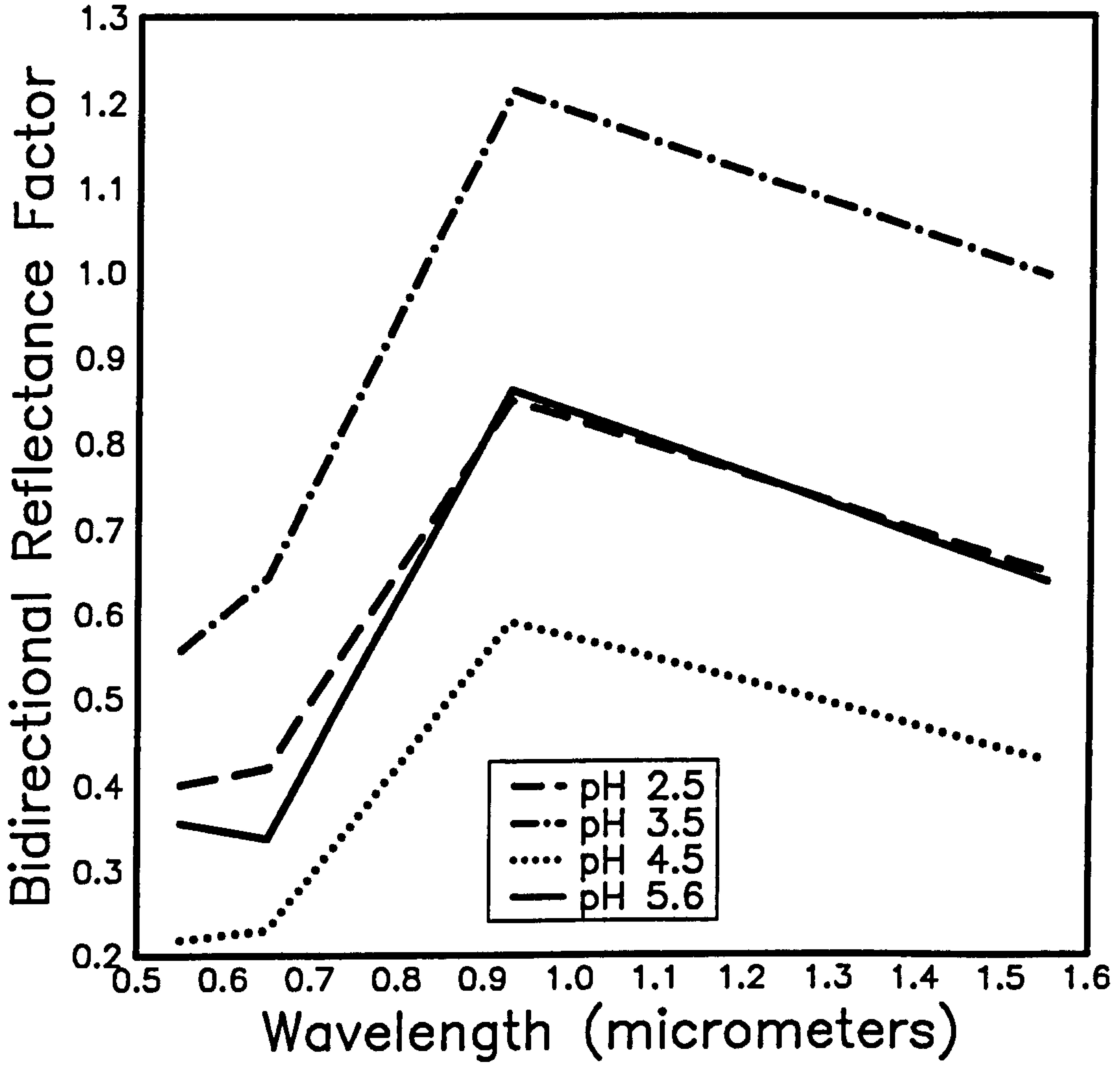


FIGURE 2.5
The relationship (weak but distinctly positive and linear) between dry weight of white clover shoots and a simple vegetation index (NIR/R)
Correlation coefficient R = 0.504

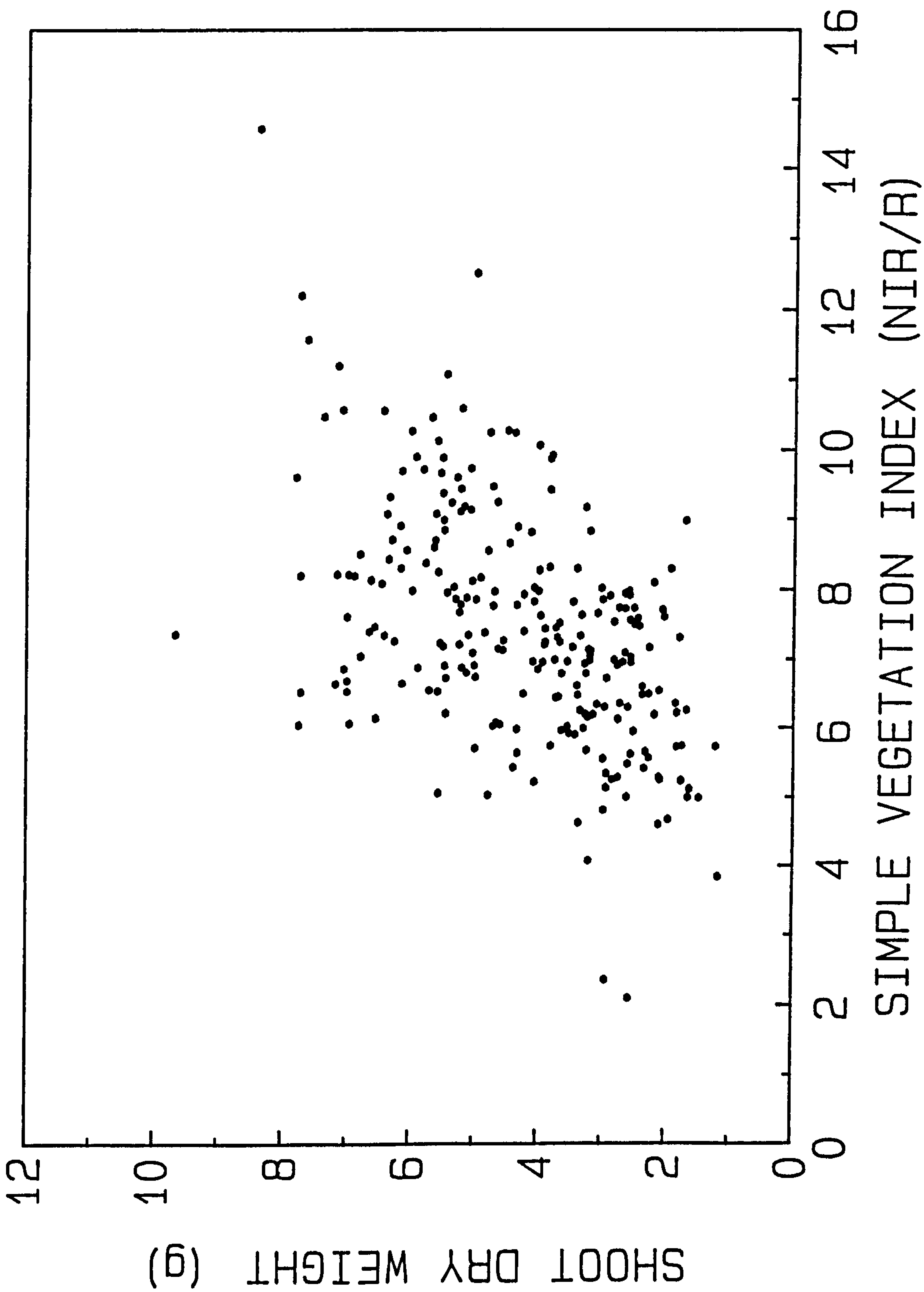


FIGURE 2.6
A plot of dry weight of white clover shoots against the simple vegetation index to illustrate the clustering of the gas x acid treatment means.

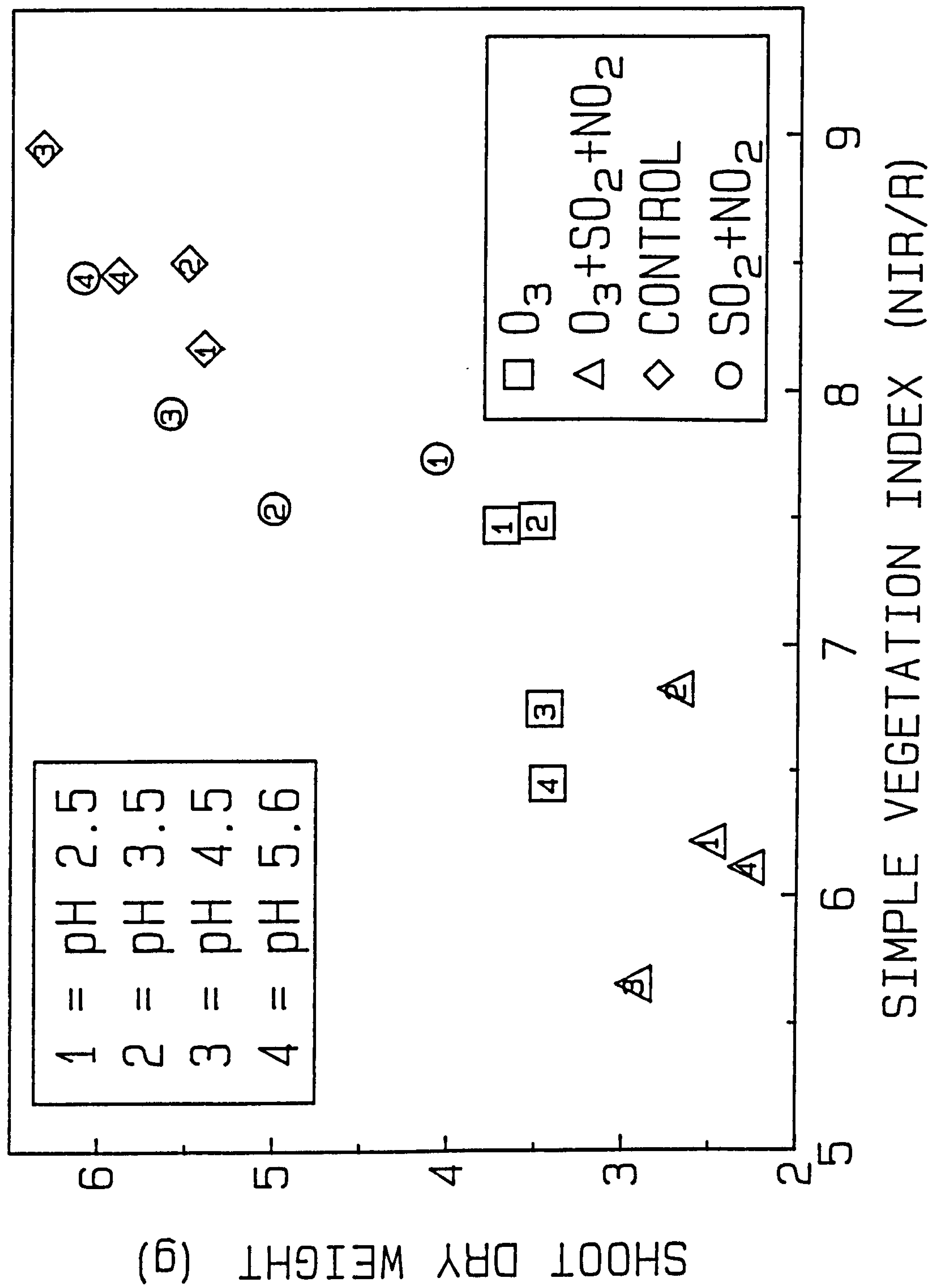


FIGURE 2.7
The relationship (distinctly positive and linear)
between dry weight of white clover shoots
and a 4-waveband vegetation index
Correlation coefficient R = 0.732

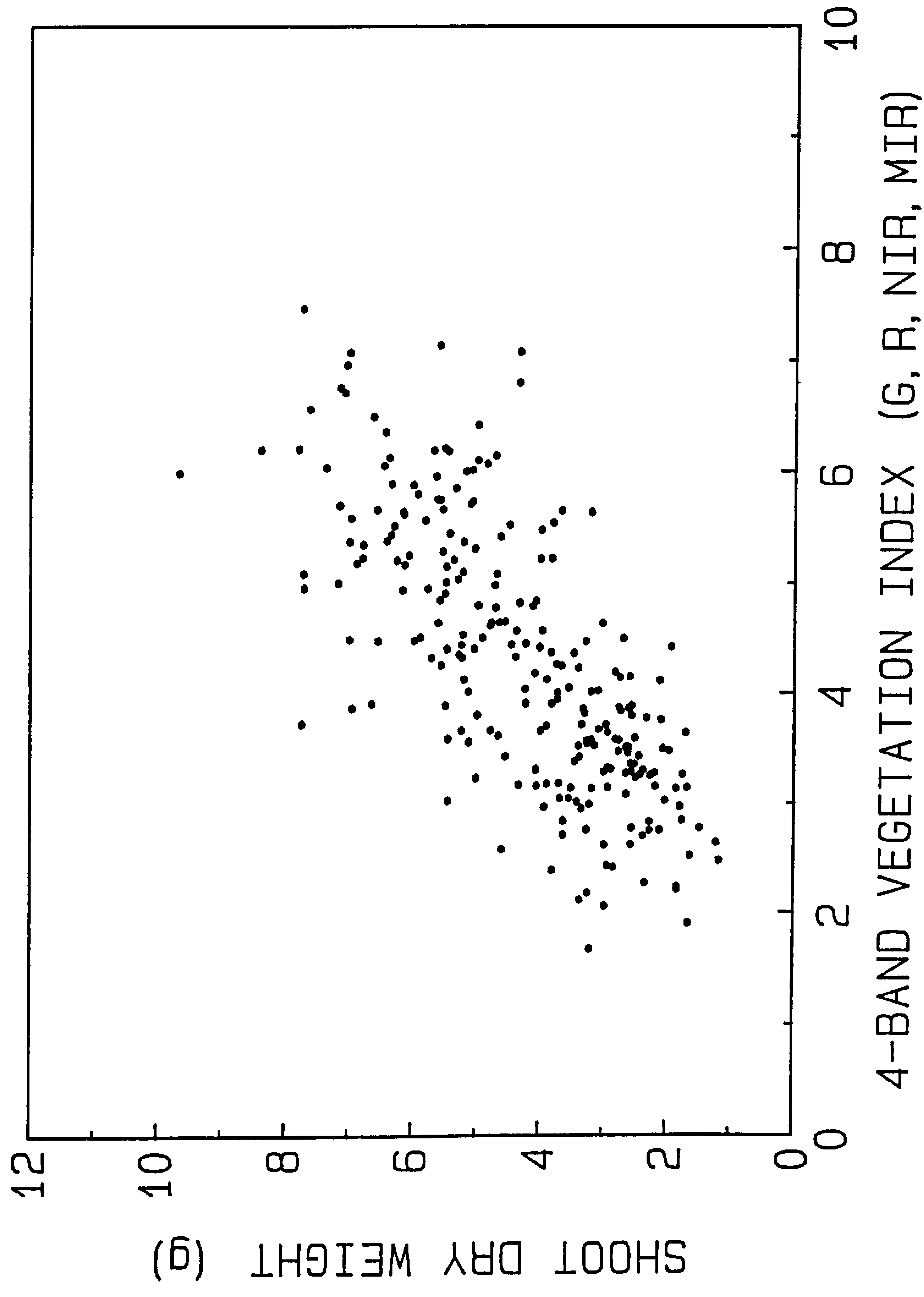


TABLE 2.1

Results of a one-tailed t test to establish whether there was a significantly greater decrease from green to red reflectance for the pH 5·6 treatment than for the other treatments after 75 weeks

Treatment	John Innes d	Arfon soil d	
pH 5·6	−0·029	−0·018	BRF decreases from green to red
pH 4·5	0·032	0·010	BRF increases from green to red
pH 3·5	0·061	0·087	BRF increases from green to red
pH 2·5	0·012	0·019	BRF increases from green to red

$d = \mu_1 - \mu_2$, where μ_1 = red reflectance, treatment mean; μ_2 = green reflectance, treatment mean.

Comparison	$n_1 + n_2$	$d_2 - d_1$	t	Result
John Innes				
pH 5·6 *vs.* pH 4·5	20	0·0606	2·73	**
pH 5·6 *vs.* pH 3·5	20	0·0899	4·04	**
pH 5·6 *vs.* pH 2·5	20	0·0407	1·83	*
Arfon soil				
pH 5·6 *vs.* pH 4·5	20	0·0288	1·42	n.s.
pH 5·6 *vs.* pH 3·5	20	0·1052	5·17	**
pH 5·6 *vs.* pH 2·5	20	0·0373	1·83	*

Probability level: ** $P < 0{\cdot}01$; * $P < 0{\cdot}05$; n.s. = not significant.
$d_1 = \mu_1 - \mu_2$ for the first treatment in the comparison.
$d_2 = \mu_1 - \mu_2$ for the second treatment in the comparison.
n_1 = number in first treatment.
n_2 = number in second treatment.

TABLE 2.2

Discriminant analysis classification of radiometric data obtained from canopies of birch seedlings after exposure to simulated acid rain at pH 2·5, 3·5, 4·5, 5·6

Actual class		n	Predicted class 1	2	3	4
John Innes, after 34 weeks of exposure to treatments (cases correctly classified, 96 %)						
pH 2·5	1	6	6	—	—	—
pH 3·5	2	6	—	5	1	—
pH 4·5	3	5	—	—	5	—
pH 5·6	4	6	—	—	—	6
John Innes, after 75 weeks of exposure to treatments (cases correctly classified, 73 %)						
pH 2·5	1	10	8	1	—	1
pH 3·5	2	10	3	4	3	—
pH 4·5	3	10	—	2	8	—
pH 5·6	4	10	—	1	—	9
Arfon soil, after 75 weeks of exposure to treatments (cases correctly classified, 85 %)						
pH 2·5	1	10	7	2	1	—
pH 3·5	2	10	—	10	—	—
pH 4·5	3	10	1	—	8	1
pH 5·6	4	10	—	1	—	9

TABLE 2.3

Reflectances of white clover plants for the acid mist × gaseous pollutant treatments after exposure for 12 weeks. Figures are treatment means and standard deviations (n = 15)

	Waveband								
	Green		Red		Near infra-red		Middle infra-red		
Mist	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Gas
pH 2·5	0·3753	0·045	0·2353	0·020	1·7450	0·178	0·8003	0·025	O_3
	0·3873	0·040	0·2650	0·038	1·6040	0·115	0·7533	0·077	$O_3+SO_2+NO_2$
	0·4620	0·048	0·2450	0·032	1·9607	0·174	0·7810	0·047	Control
	0·4520	0·054	0·2527	0·027	1·9213	0·197	0·8027	0·072	SO_2+NO_2
pH 3·5	0·3813	0·034	0·2237	0·016	1·6473	0·096	0·7780	0·044	O_3
	0·3603	0·053	0·2347	0·028	1·5743	0·140	0·7527	0·039	$O_3+SO_2+NO_2$
	0·4360	0·035	0·2363	0·017	1·9933	0·146	0·8017	0·064	Control
	0·4620	0·081	0·2640	0·024	1·9290	0·187	0·7457	0·067	SO_2+NO_2
pH 4·5	0·3857	0·073	0·2640	0·078	1·6407	0·115	0·7763	0·073	O_3
	0·4023	0·071	0·3103	0·086	1·5800	0·094	0·7820	0·061	$O_3+SO_2+NO_2$
	0·4460	0·053	0·2433	0·045	2·0840	0·196	0·8160	0·074	Control
	0·4950	0·040	0·2633	0·022	2·0533	0·136	0·7407	0·059	SO_2+NO_2
pH 5·6	0·3567	0·049	0·2397	0·014	1·5403	0·135	0·7260	0·068	O_3
	0·4027	0·049	0·2763	0·031	1·6587	0·126	0·8373	0·033	$O_3+SO_2+NO_2$
	0·4807	0·033	0·2520	0·037	2·0757	0·207	0·7737	0·038	Control
	0·4973	0·055	0·2500	0·036	2·0663	0·179	0·7653	0·051	SO_2+NO_2

TABLE 2.4

Multivariate and univariate analysis of variance tests for significant differences in mean reflectance from white clover plants exposed to acid mist × gaseous pollutant treatments for 12 weeks. This table shows the significance of the test statistic, F. The gas effect was significant and the univariate test identified the green and near infrared wavebands as significant discriminators

Effect		Gas × Acid	Gas	Acid
Multivariate	(Manova)	0·608	***	0·607
Univariate	(Anova)			
	d.f.	9,32	3,32	3,32
	Green	0·166	***	0·066
	Red	0·813	0·150	0·214
	Near infrared	0·450	***	0·697
	Mid infrared	0·661	0·736	0·960

Probability level: $P < 0{\cdot}001$ = ***.

TABLE 2.5

Bonferroni multiple pairwise comparison. The test identified clover canopies from the four gas treatments which were differentiated by their reflectance in a particular waveband. A significant F level was qualified by upper and lower confidence intervals which did not include 0. The comparisons between the following gases were significant for green and near infrared wavebands: O_3 vs *Control and $O_3+SO_2+NO_2$* vs *Control*

Green waveband

Tests of Significance for GREEN

	F	Significance of F	
Gas	50·16	0·000	***
Acid	2·65	0·066	
Gas by acid	1·57	0·166	

Estimates for GREEN using 95% confidence intervals

Comparison		Lower	95% CL Upper	
Gases				
O_3	*vs* Control	−0·10499	−0·05794	*
$O_3+SO_2+NO_2$	*vs* Control	−0·09156	−0·04451	*
SO_2+NO_2	*vs* Control	−0·00299	0·04406	

Near infrared waveband

Tests of Significance for NEAR INFRARED

	F	Significance of F	
Gas	38·74	0·000	***
Acid	0·48	0·697	
Gas by acid	1·01	0·450	

Estimates for NEAR INFRARED using 95% confidence intervals

Comparison		Lower	95% CL Upper	
Gases				
O_3	*vs* Control	−0·50501	−0·26527	*
$O_3+SO_2+NO_2$	*vs* Control	−0·54395	−0·30421	*
SO_2+NO_2	*vs* Control	−0·15564	0·08410	

***, $P < 0·001$; *, $P < 0·05$.

TABLE 2.6

*Discriminant analysis to characterize the reflectance of the clover canopies by experimental treatment. The table shows the percentage of plants correctly characterized. *** indicates results that were significant* ($P < 0{\cdot}001$) *in the analysis of variance test*

		Plants correctly characterized (%)	
		Mean	Range
By gas treatment			
At pH 2·5	***	56·7	27–73
At pH 3·5	***	65·0	53–73
At pH 4·5	***	68·3	53–80
At pH 5·6	***	65·0	47–80
By acid mist treatment			
In O_3		48·3	13–67
In $O_3+SO_2+NO_2$		38·3	13–60
In Control		41·7	33–47
In SO_2+NO_2		38·3	27–53

CHAPTER 3

MONITORING THE CONDITION OF A LARGE FLOOD-PLAIN MIRE USING AIRBORNE THEMATIC MAPPER DATA

3.1 SUMMARY OF CHAPTER 3

An aircraft survey of Crymlyn Bog, West Glamorgan, was included in the Natural Environment Research Council (NERC) multispectral flying programme for 1987 in order to investigate the possible use of multispectral remote sensing as a means of:

a) surveying and monitoring natural wetlands and
b) detecting and assessing the influence of environmental factors (principally soil chemistry and hydrological status) on wetland vegetation.

11-channel digital imagery was successfully acquired and the data were analyzed and interpreted at the NERC Institute of Terrestrial Ecology (ITE) in Bangor, using ground reference data provided by the Department of Botany at Sheffield University (Headley, 1986). The results of this analysis are presented here. Plate 3.1 shows an overview of the CRYM386 flightline using ATM bands 9, 7, 5 to red, green, blue respectively.

Correlation analysis and regression analysis were employed to investigate the relationships between remotely-sensed radiance at visible and infrared wavelengths and soil chemistry. Strong correlations were demonstrated in many cases, suggesting positive associations between concentrations of nutrients and the health and vigour of the vegetation. There were some anomalies and the study was not able to demonstrate unambiguous associations between remotely-sensed measures and environmental conditions. This would mean that the methodology could not, without refinement, be used operationally. In particular, the spatial variability of vegetation patterns appeared to conceal some of the underlying trends.

Suggestions are put forward which could resolve some of these difficulties in similar research in the future.

3.2 BACKGROUND TO THE STUDY OF CRYMLYN BOG

Crymlyn Bog, West Glamorgan, U.K. is a large flood-plain mire covering 253 hectares with a water table close to that of sea level. It is located in part of the coastal plain between the Tawe and Neath estuaries (Grid ref. SS695950).

Figure 3.1 is a 1:50,000 location map showing Crymlyn Bog to the east of Swansea; the Llandarcy oil refinery was to the east of the study area. It was notified as a Site of Special Scientific Interest (SSSI) in 1975 and part of the bog was declared a National Nature Reserve in 1987 by virtue of its floristic, faunal and geomorphological properties and because it represents the largest example of this type of habitat in Wales.

The bog was in close proximity to several industrial sites including a land-fill site and a refinery operated by BP Oil. Given the close proximity of the bog to these areas of intensive urban and industrial development, the characteristic bog vegetation was vulnerable to the influence of factors such as changes in water table, nutrient enrichment and other forms of pollution.

The type, distribution and condition of vegetation and other environmental parameters can be monitored by traditional survey techniques. This can, however, be costly, time-consuming and is usually based on a limited number of samples. The objective of this study was to assess the accuracy with which multispectral remotely-sensed data could be used to monitor a range of environmental parameters in order to assess its utility as a tool for monitoring the condition of wetland vegetation.

3.3 PREVIOUS WORK ON CRYMLYN BOG

This study was stimulated by previous research on Crymlyn Bog by Wyatt et al. (1986) to evaluate the potential of remote sensing for mapping vegetation and other ground cover and for monitoring land cover changes. Airborne Thematic Mapper (ATM) data from 18th June 1984 and Landsat-5 Thematic Mapper (TM) data from 22nd July 1984 were used in that research. Image enhancement techniques, band ratioing and principal component analysis were used to demonstrate the potential for discriminating ground cover. A supervised maximum likelihood classification using six bands of the ATM data produced a classmap showing sixteen vegetation communities on the bog. That study recommended that future research might examine the use of remotely-sensed data for identifying and diagnosing botanical variations within the bog resulting from changes in water quality.

Landsat Thematic Mapper data have been used in other studies of large peat basins. In north America, Glaser (1989) used TM data to map the vegetation patterns over extensive tracts of inaccessible peat basin. The discharge of alkaline groundwater into these basins was cited as a primary influence on the development of vegetation communities. TM data proved effective for mapping these areas.

Reports by Headley (1987a, 1987b) made data relating to water quality and vegetation cover available. This study attempted to relate this analysis of water quality to ATM data.

3.4 OBJECTIVES

The study was intended to continue the earlier research and, in particular, to explore quantitatively the relationships between physical environmental conditions, plant communities and remotely-sensed radiance. Specific objectives were as follows:

3.4.1 To carry out an airborne survey of Crymlyn Bog, using an 11-channel multispectral scanner;

3.4.2 To assess the utility of remotely-sensed data for detecting hydrological and substrate factors likely to affect vegetation condition and distribution.

This study was able to make good use of reference data describing vegetation composition, hydrology and water quality, collected on the bog (Headley, 1986, 1987a, 1987b).

3.5 ACQUISITION AND TREATMENT OF ATM SCANNER DATA

The acquisition of Airborne Thematic Mapper data by the Natural Environment Research Council (NERC) has been described in detail by Williams (1984).

Crymlyn Bog was included in the NERC Flying Programme for 1987 with the site reference 87/48CR. The NERC aircraft visited the site on several occasions during the autumn of 1987. Initially, cloud cover prevented the acquisition of suitable data. However, on the 15th and 18th September moderately good weather conditions coincided with visits by the NERC aircraft allowing ATM data and black and white aerial photographs to be obtained from the site. The pre-processed ATM data were delivered to ITE Bangor on the 27th November 1987.

3.5.1 Overflight 15th September 1987

The site was flown twice, using four parallel overlapping runs at 800 metres. The first flight covered the site in four south-north runs at 1125, 1130, 1134 and 1138 hours GMT using the scanner only. The second flight covered the site in four runs alternating south-north, north-south at 1144, 1148, 1150 and example, for the visible bands over 90% of the pixels were found within 45 of the 256 available digital counts (Table 3.9). It was noted that the proportion of the total range occupied for the reflected near and middle infra-red bands (ATM-6 to ATM-10) was much wider. Plate 3.3 shows the histograms for the source data. The image is a sub-sampled overview using ATM 7, 5, 3 to red, green, blue respectively. The red histogram shows the relatively wide distribution of near infra-red (ATM-7); the green and blue histograms show the relatively narrow distribution of digital numbers (DN) in the red (ATM-5) and green (ATM-3) wavebands respectively. Similar results were obtained for the central portion of the image covering the bog. However, because there was a smaller range of cover types on the bog, the digital range was narrower. This was a common characteristic of multispectral data in which the scanner must normally be adjusted to respond to a dynamic range much wider than that encountered in a single overpass.

3.6.2 Interrelationships between ATM bands

The relationships between the bands were examined visually and by carrying out a correlation analysis (Table 3.3). Visual examination of the imagery revealed the similarity of the reflective bands. This was confirmed by the correlation matrix, where values in excess of 0.9 were found for all intercorrelations amongst these bands. Whilst there was a high degree of redundancy between the visible bands, they were only weakly, and negatively, correlated with the near infra-red. Of the remaining intercorrelations only those between the near infra-red bands (ATM-6, -7 and -8) were strong, and ATM-9 was found to have a moderate correlation with ATM-10.

3.7 PHYSICAL FACTORS INFLUENCING SPECIES DISTRIBUTION

The species present in any given place are fundamentally determined by their physical environment, but influenced also by biotic factors such as competition and herbivory. Without disturbance, wetland vegetation usually undergoes spontaneous change - partly through the natural dynamics of plant communities (the hydrosere), and partly as a result of the accumulation of plant remains (peat) and mineral sediment. Management of semi-natural vegetation usually has the effect of modifying the normal successional sequence - as, for example, when burning prevents the accumulation of organic matter, or drainage hastens the drying process.

With the present knowledge of species preferences, it was rarely possible to account for the occurrence of species in a given stand purely in environmental terms, and it was not within the scope of this project to make a detailed ecological explanation of the vegetation of Crymlyn Bog. The following notes on the habitat preferences of a few Crymlyn species (Evans, 1988) provided some indication of the factors influencing the growth and distribution of the vegetation.

3.7.1 Phragmites australis

This species requires intermittent or permanent standing water with a depth up to 1 metre above the soil. Insensitivity to depth was thought to be a reason for its ability to supplant species that cannot tolerate prolonged flooding (Haslam, 1972). Sudden changes of water level may, however, be damaging (Haslam, 1970). Phragmites can tolerate a pH in the range 3.6 to 8.6, but grows well in the range 5.5 to 7.5 (Gorham and Pearsall, 1956).

Grazing animals will tackle only low Phragmites - either young plants or weak plants, and usually on relatively dry ground. They may therefore accelerate the natural consequences of a lowered water table (Spence, 1964); this may be partly due to rhizomes being damaged by trampling (Haslam, 1969). Local extinction of P. australis may then follow.

3.7.2 Cladium mariscus

Cladium mariscus needs to have its roots below the water table (about 40cm below the soil surface), but will not grow in more than about 40cm of water (Conway, 1942). pH must be in the range 6.1 to 8.5 (slightly higher than the pH preferred by Phragmites australis). C. mariscus is intolerant of shade, and will gradually die out in the presence of seral encroachment by shrub species. It was never grazed (Conway, 1942).

3.7.3 Eriophorum angustifolium

The occurrence of E. angustifolium at Crymlyn was surprising given the base-rich conditions but, although it was a species usually associated with acid peat, it has also been recorded, for example, at Great Close Mire near Malham Tarn where the soil had a calcium carbonate content of 68% (Phillips, 1954).

3.8 RELATIONSHIPS BETWEEN GROUND VARIABLES AND ATM DATA

The Sheffield University field sampling points (Headley, 1987a) were identified on a 1:10,000 scale Nature Conservancy Council map (Fig. 3.2). It was also possible to identify many of these points on the aircraft imagery. Plate 3.4 shows a 512x512 pixel sub-sampled overview of the flightline using ATM 7, 5 and 3. Plates 3.5 and 3.6 show 512x512 full resolution sections of the mire next to the refinery boundary. The 'spur' where contamination has been found in the past was visible on Plate 3.5. The Glan-y-Wern canal was distinct running down the centre of Plate 3.6; the boundaries of abandoned fields can be seen to the right of the canal. In total, 61 field sampling points (37 quadrat sites and 24 transect sites) were reliably identified on the contrast-enhanced image.

3.8.1 Obtaining field site radiance

The locations of these field sampling points were recorded using image pixel coordinates. It was then necessary to extract pixel digital numbers (DN) in each waveband in the vicinity of each field sampling point. A region covered by a 2x2 block of image pixels centered on each sample point was chosen to be representative of the field conditions in the neighbourhood. The DN for each pixel in the 2x2 block in each waveband was reported to a datafile. There were 11 wavebands in the ATM data, resulting in 44 (4x11) DNs for each field sampling point. With 61 sites a total of 244 (61x4) samples were extracted from each of 11 wavebands resulting in a total of 2684 (61x4x11) DNs (Table 3.4, Appendix 1).

3.8.2 Calibration of ATM data

The ATM DN extracts were calibrated using the method described by Wilson (1986). Gain and base values (Table 3.5) were calculated from the Global Daedalus 1268 scanner calibration of 8th September 1987 (Table 3.6).

Radiometric calibration of the ATM data was then implemented using the equation shown below, for the data in each waveband:

$$\text{Radiance} = \text{Gain}_G \times (\text{DN} - \text{Base}_G)$$

where $_G$ denotes the Gain-setting (.5, 1, 2, 4 or 8).

This procedure computed values of radiance in each of the 11 spectral bands for the 4-pixel extract in the vicinity of each of the 61 sample points (2684 observations in all, Table 3.7, Appendix 1). The mean radiance of each 2x2 pixel block was calculated in each of the 11 wavebands. This produced 61 site means for the radiometrically calibrated data in each waveband (Table 3.8, Appendix 1), a total of 671 (61x11) values. These values represented the mean calibrated radiance from each 2x2 pixel block corresponding to each field sampling site.

Three vegetation indices were computed from the ATM data:

Simple division	$\frac{IR}{R}$
Simple subtraction	IR-R
Simple multiratio or Normalised Difference Vegetation Index (NDVI).	$\frac{IR-R}{IR+R}$

R denotes red radiance derived from the mean of ATM wavebands 4 and 5.

IR denotes near infra-red radiance derived from the mean of ATM wavebands 6 and 7.

Summary statistics for the uncalibrated and calibrated ATM samples, and for the calibrated ATM site means are shown in Table 3.9. The radiometrically calibrated ATM data and vegetation indices were then used in statistical comparisons with the field survey chemical analysis data (Table 3.10) obtained from Sheffield University (Headley, 1987a).

The following chemical analyses were available for the transects and quadrats:

	pH	NH_4	NO_3	PO_4	K	Ca	Cond.	Cl	F	Br	SO_4	Na	Mg
Transects	*	*	*		*	*	*	*	*	*	*	*	*
Quadrats	*	*	*	*	*	*							

Details of the units of measurement and procedures for the chemical analyses can be found in Headley (1986, 1987a).

3.8.3 Statistical methodology

The chemical data and the radiance and vegetation index data were combined in a workfile for the purposes of statistical comparison. Each of the chemical parameters were correlated and regressed against the radiometrically calibrated ATM data and against the three vegetation indices; both standard (Pearson) and Spearman Rank correlations were calculated. The Spearman Rank correlation was particularly relevant because the ATM multispectral data were categorical as opposed to continuous variables. Multiple linear regressions between each chemical parameter and the 11 wavebands and 3 vegetation indices (14 predictive variables) were also calculated. The statistical significance of the Spearman Rank correlations and the regressions were measured using Student's t- and F-tables respectively.

Scatter plots were produced for all the simple linear regression models. Regression and analysis of variance parameters were calculated for both simple linear and multiple linear regressions (Appendices 2 to 7).

The significance of the Spearman Rank correlations was measured using the following standard technique. The Spearman Rank correlation coefficient r_s was used to estimate t:

$$t = r_s \sqrt{\frac{n-2}{1-r_s^2}}$$

Significant results were reported where the estimated value of t as shown above exceeded tabled values of $t_{.01}$ or $t_{.05}$ with df = n-2 in a two-tailed test.

The significance of each regression was measured using the F ratio. F was calculated from the analysis of variance parameters in Appendices 2 to 7, where F = RegressionMS/ErrorMS. Significant results were reported where the estimated value of F as shown above exceeded tabled values of $F_{.01}$ (μ_1, μ_2) or $F_{.05}$ (μ_1, μ_2); μ_1 = Regression df, μ_2 = Error df.

The correlations and regressions were calculated for data arranged in the following groups:

Transects only,	n=24;
Quadrats only,	n=37;
Transects and quadrats combined,	n=61.

3.9 RESULTS

The results of the statistical analyses have been presented in two sections. The summary results for the Spearman Rank correlations are presented in Tables 3.11, 3.12 and 3.13. The summary results for the simple linear and multiple linear regressions are shown in Tables 3.14 and 3.15. Scatterplots, correlations, regressions and Spearman Rank correlations for all significant relationships are presented in Appendices 2 to 7.

3.9.1 Spearman Rank Correlation

This statistical measure was calculated for the three groups outlined below.

3.9.1.1 Quadrats

Correlations between pH and radiance and the vegetation indices were strongly positive with many significant at $P<0.01$ (Table 3.11). Figure 3.3 shows the positive relationship between quadrat pH and ATM waveband 7, for example. Correlations between ammonium and radiance were strong but negative (Fig. 3.4; Table 3.11). For both these elements the vegetation indices showed no advantage over the individual ATM bands. Other relationships were positive and linear: phosphate and ATM waveband 6 (Fig. 3.5), calcium and ATM waveband 1 (Fig. 3.6), for example. The correlations remained positive but became progressively weaker for calcium, potassium and nitrate. The vegetation indices did produce more significant correlations than the ATM wavebands for ammonium (Fig. 3.4; Table 3.11). Nitrate showed no significant relationships with the individual ATM wavebands or the vegetation indices. In general, for all elements, the polarity of the correlation was reversed for the thermal waveband ATM-11 when compared with the other ATM bands.

3.9.1.2 Transects

The correlations between the field survey transect data and the radiance (Table 3.12) were less significant than those for the quadrats. Ammonium, sulphate and sodium were highly correlated with several of the wavebands and indices. Figure 3.7 shows the positive relationship between ammonium and the IR/R index; Figure 3.8 shows the relationship (negative, in contrast, as found with the quadrat results) between calcium and the thermal waveband ATM-11; Figure 3.9 shows the positive curvilinear relationship between fluoride and the NDVI index; Figure 3.10 shows the negative relationship between sodium and the thermal waveband ATM-11. Potassium, calcium, conductivity, fluoride and magnesium all correlated at $P<0.01$ with at least one waveband or vegetation index. The pH, nitrate, chloride and bromide all correlated at $P<0.05$ with at least one waveband and the indices showed no significant correlation. In general the correlations were negative for the visible and middle infra-red wavebands and positive for the near infra-red wavebands.

3.9.1.3 All field sites

The combined quadrat and transect dataset showed strong correlations between pH, ammonium and the radiance (Table 3.13). There were strong positive correlations between pH and all wavebands and indices except bands 4, 9 and 10; all the correlations, except bands 5 and 8, were at $P<0.01$. Ammonium showed no significant correlation with the indices but strong negative correlations with bands 1, 2 and 3 and weaker negative correlations with bands

5, 6 and 11. Nitrate showed a strong positive correlation with band 11 at $P<0.01$. Potassium and calcium were not significantly correlated with any of the wavebands or indices.

3.9.2 Simple Linear Regression

The simple linear regression model took the form $Y = aX + b$ where Y represented the chemical parameter and X represented one of the ATM wavebands or indices; a and b represented the slope and intercept regression parameters respectively.

3.9.2.1 Quadrats

The results of the simple linear regressions from the quadrat data (Table 3.14) were similar to those for the Spearman Rank correlations but in many cases the relationships were more significant. The regressions were significant at $P<0.01$ for phosphate, pH, potassium, calcium and ammonium with many of the wavebands and indices. Vegetation indices showed no advantage over the individual wavebands. There were no significant regressions between nitrate and either radiance or vegetation indices.

3.9.2.2 Transects

In general the regressions between the field survey transect data and radiance (Table 3.14) were less significant than those for the quadrats. There were regressions significant at $P<0.01$ for pH, ammonium, nitrate, calcium, conductivity, fluoride, sodium and magnesium. There were regressions significant at $P<0.05$ for potassium, bromide and sulphate, but no significant regressions for chloride. Only with fluoride did an index show some merit over the individual wavebands.

3.9.2.3 All field sites

The results of the simple linear regressions were similar to those for the Spearman Rank correlations; once again in many cases the relationships were more significant. The combined quadrat and transect dataset showed strong regressions between pH, ammonium and the radiance (Table 3.15). There were significant regressions between pH and all wavebands and indices except bands 9 and 10; all the regressions, except bands 4 and 5, were significant at $P<0.01$. There were significant regressions between ammonium and all wavebands and indices except bands 4 and 10; all the regressions, except bands 5, 8, 9 and 11, were significant at $P<0.01$. Nitrate showed a significant regression at $P<0.01$ with band 11 and potassium had regressions significant at $P<0.05$ with several wavebands and indices. Calcium produced no significant regressions with any of the wavebands or indices.

3.9.3 Multiple Linear Regression

There were significant multiple linear regressions between the full ATM dataset and calcium ($P<0.01$), pH and potassium ($P<0.05$) for the quadrat sites (Table 3.14). There were significant multiple linear regressions for pH and sodium ($P<0.05$) for the transect sites (Table 3.14). Regressions were significant for pH and ammonium ($P<0.01$) and for potassium ($P<0.05$) for the quadrats and transect data combined (Table 3.15).

3.10 DISCUSSION

It was very probable that the statistically significant correlations and regressions that have been noted were due, at least in part, to chemical factors expressing themselves through their effect on the vegetation. The attribute likely to have the most direct influence on radiance was the species mix, and this will certainly be influenced by soil and water chemistry (see section 3.7). The pH was probably the most important factor, and it was very likely that there was a sequence of species corresponding to a pH gradient. Unfortunately, there was no particular reason why such a sequence should follow a radiometric trend. The reflecting properties of different species are determined mainly by morphological and physiognomic differences, and it would be surprising if these phenotypic characteristics showed a direct correlation with chemicals in the environment.

The chemical environment does, however, influence radiance in another way which was not directly species dependent, although it must inevitably be entangled with the species response. This was through the chemical control of plant vigour through the influence of the general fertility of the substratum, and hence the quantity of green biomass present at the time of the flight. Macro-nutrients such as nitrogen, potassium, and phosphate are usually the most important in this respect, although trace elements can also be limiting. A healthy plant will normally be rich in chlorophyll, and therefore show the characteristic radiometric response for chlorophyll more clearly than vegetation that is growing less well. There was a possibility therefore that the correlations and regressions referred to in this report were, to some extent, expressions of the health of the plant communities. A healthy plant will, in general, have relatively low reflectance in the red region of the spectrum (ATM band 5), and high reflectance in the green (ATM band 2) and near infra-red (ATM band 7). Vegetation indices such as the NDVI should be correspondingly high.

Interpretations of this kind could apply to any factor that can promote or retard plant growth, although among the chemicals considered here, it seemed that positive responses (growth stimulation) were more common than negative ones. The quadrat data seemed to show more significant correlations and regressions than the transects. This was surprising, but could have arisen for a number of reasons:

i) because of the transects being located in a relatively disturbed region of the bog (around the spur), where some seepage of oil and other chemicals has been known to occur. The vegetation in this area may be influenced more by pollution incidents than in response to the conditions at the time of sampling;

ii) because the vegetation response to environmental factors was modified by the presence of oil;

iii) because the radiometric response was directly affected by oil residues in the water, or;

iv) because some of the relatively subtle responses to chemical gradients were being masked by the gross radiometric variation associated with the very marked zonation around the spur.

3.10.1 Specific chemical/radiometric relationships

3.10.1.1 pH

The quadrat data show a significant positive correlation with pH for all bands except 4, 5 and 10, and for the vegetation indices. This was consistent with growth stimulation in response to an increase in pH and, within limits, it was in line with what one would expect for fen species. The lack of a significant correlation in band 5 (red) was surprising. Radiation at this wavelength is absorbed by chlorophyll, and radiance should fall as the amount of green material (and hence photosynthetic activity) increases. This was an anomaly, and further work would be needed to determine the reason for it.

The vegetation index correlations (essentially band 7/band 5) merely follow the band 7 result. The correlation in band 9 (in the mid-IR) may relate to the absorbtion of these wavelengths by water in the plant material. The quadrat regressions confirm the correlation results. The coefficients were positive in all bands except band 11 (thermal-IR). The band 5 regression was significant but has a coefficient with an unexpected polarity. It behaves as though the ground-cover comprised dead vegetation only, but in an amount related to the productivity of the site. Given that these results have been derived from an image captured in September when the green biomass of wetland vegetation should be near its maximum, such results were difficult to explain. Once again, there was scope for further study.

3.10.1.2 Ammonium (NH_4)

Significant correlations at the 1% level occurred only in the regressions, and applied to bands 1, 6, 7 and 9, and to the vegetation indices. The polarities of the regression coefficients were all negative, however, indicating that ammonium, rather than acting in its normal role as a fertilizer, was linked to a loss of production.

3.10.1.3 Nitrate (NO_3)

Given that plants generally show a clear response to nitrate in almost any quantity, and that nitrate concentrations on the bog were sometimes quite high, the lack of significant correlations and regressions was puzzling. It was possible that the normal nitrate response was being inhibited by deficiencies in other nutrients - possibly phosphate.

3.10.1.4 Phosphate (PO_4)

Several of the correlations and regressions were significant, but the regressions were particularly significant. Bands 1 to 9 were all significant at the 1% level. The vegetation indices were also significant, and this time with the expected polarity (positive). There seemed to be a real possibility that growth, in some species at least, was being limited by phosphate (or at least available phosphate), and this could be a factor masking the response to other plant nutrients (see the discussion under nitrate, 3.10.1.3).

3.10.1.5 Potassium (K)

There were several significant correlations and significant regressions for all bands except band 11 (thermal infra-red), and for the IR-R vegetation index. Band 5 had a positive coefficient, and if the interpretation suggested for phosphate was correct, we might suppose that potassium could also be limiting in some situations or for some species. It was certainly the case that, except in the tip area, potassium levels on the bog were generally very low.

3.10.1.6 Calcium (Ca)

Concentrations of Calcium, in the form of calcium carbonate, are causally linked to pH, and one might therefore expect the correlations and regressions for calcium to repeat the pH pattern. In fact, there was little correspondence. The statistics were significant in all bands except 8, 9 and 10, with band 5 showing an anomalous positive relationship to concentration.

3.11 CONCLUSION TO CHAPTER 3

3.11.1 Airborne multispectral survey
(Objective 3.4.1)

An airborne survey of Crymlyn Bog was successfully completed in September, 1987, and the results have been used to explore the application of such data for investigating wetland ecological units and in detecting the effects of chemical variation in soil conditions.

3.11.2 Detection of environmental variables by remote sensing
(Objective 3.4.2)

Statistically significant associations have been demonstrated, using Spearman rank correlation and regression analysis, between remotely-sensed radiance and concentrations of a number of botanically-significant elements. Similar correlations have been shown to exist between remotely-sensed vegetation index (essentially an indicator of photosynthetic activity) and soil chemistry.

The physical explanation for many of these associations was by no means clear. To some extent they may correspond to differences in species composition as a response to differing soil conditions. However, while differences in the composition of a vegetation canopy will undoubtedly influence its spectral response, the relationships between soil chemistry, species composition and radiance are unlikely to be simple. Therefore, the observed systematic variations of radiance with soil chemistry may rather be indicative of gross ecosystem properties and processes which are, to some extent, species-independent (for example, rate of photosynthesis, canopy moisture levels, standing biomass). These processes would be influenced by soil chemistry.

Canopy radiance in the wavebands recorded by the Daedalus scanner was indicative of many of these physiological processes and conditions. For example, band 5 (red) recorded photosynthetically active radiation; absorption in this channel was therefore quantitatively related to levels of photosynthetic activity. Similarly, the near-infrared channels (6, 7, 8) recorded radiation that was strongly reflected at inter-cellular boundaries in healthy green foliage; radiance at these wavelengths correlates with agronomic indicators such as leaf-area index, and reduced radiance is often indicative of plant stress.

It was hoped that vegetation indices could be used to remove some of the variability due to differences in species composition and thus give a more direct measure of the underlying biochemical states and processes. In the event, vegetation indices proved to be little more informative than the basic radiance data.

Although the strength of the statistical associations between radiance and ground conditions was encouraging, it was clear from these results that remote sensing has a long way to go before it could be considered as a means of diagnosing field conditions such as soil chemistry or hydrology in natural vegetation.

There were a number of anomalies in the results presented. In particular, the positive regression between pH and photosynthetically-active radiation (ATM band 5, red), the negative regression between ammonium and near-infrared radiance and the lack of significant correlations between nitrate levels and radiance still require satisfactory explanations.

In retrospect, it was apparent that we were dealing with a highly multivariate situation, involving 12 experimental parameters (chemical determinants) and 11 observed variables (spectral bands). The spatial variability of the vegetation cover further complicated the situation and was probably a major factor in obscuring any underlying trends. Hydrological differences across the site were another potential complication; it was unfortunate that reliable information on the state of the water table was not available for the time of the overpass.

A full understanding of the many processes involved demands a more sophisticated experimental design, with much greater control over the variables than was possible, given the limited resources of this project.

3.12 FUTURE POSSIBILITIES

The spatial variability in the species composition of the vegetation canopy was perhaps the most important factor in obscuring the underlying relationships. In a field experiment, this was best overcome by stratification of the site in terms of the main vegetation communities and then ensuring representative sampling within each stratum. This procedure requires a detailed vegetation map of the site - not available at the time of this study. Alternatively, the imagery itself might be used to delineate major vegetation boundaries without the expense of field survey, using an unsupervised classification technique, such as cluster analysis.

However, given our present level of understanding, any future field experiments should be supplemented by a series of laboratory studies using radiometers, in which much greater control over experimental variables would be possible.

Third Party Material excluded from digitised copy. Please refer to original text to see this material.

FIGURE 3.3
Scatterplot showing the relationship between
Quadrat pH and ATM waveband 7.

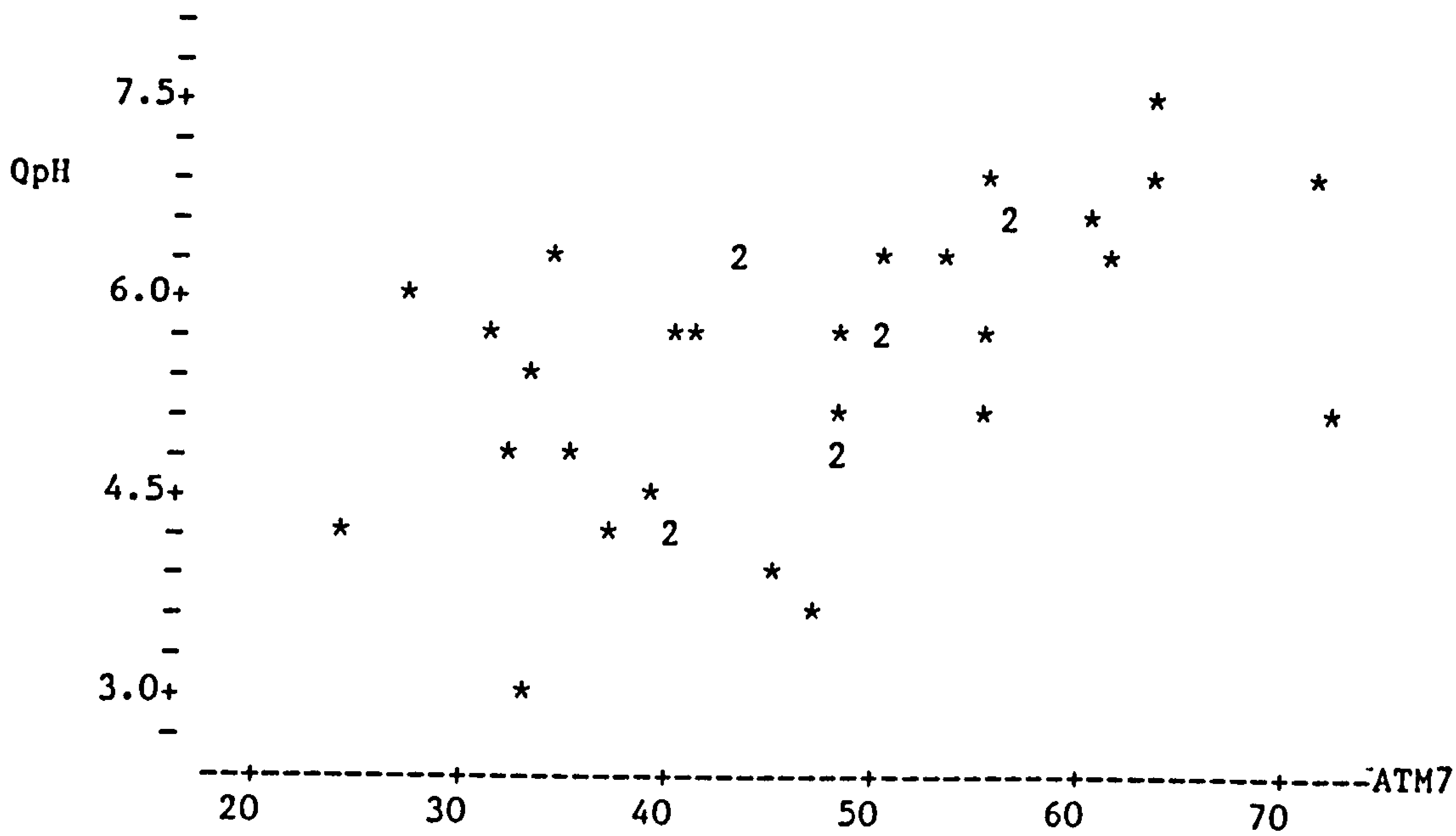


FIGURE 3.4
Scatterplot showing the relationship between
Quadrat NH_4 and ATM NDVI index.

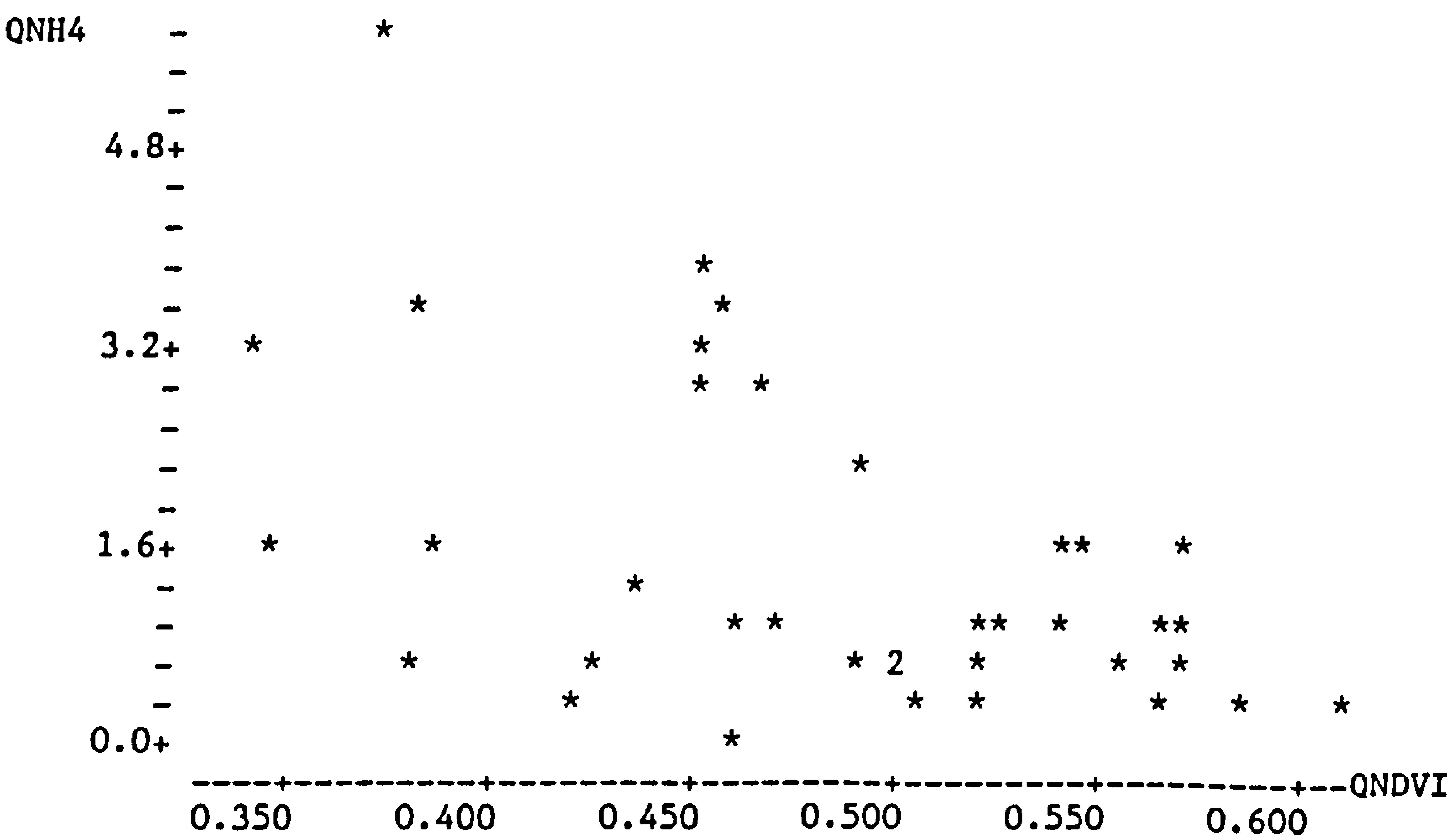


FIGURE 3.5
Scatterplot showing the relationship between
Quadrat PO_4 and ATM waveband 6.

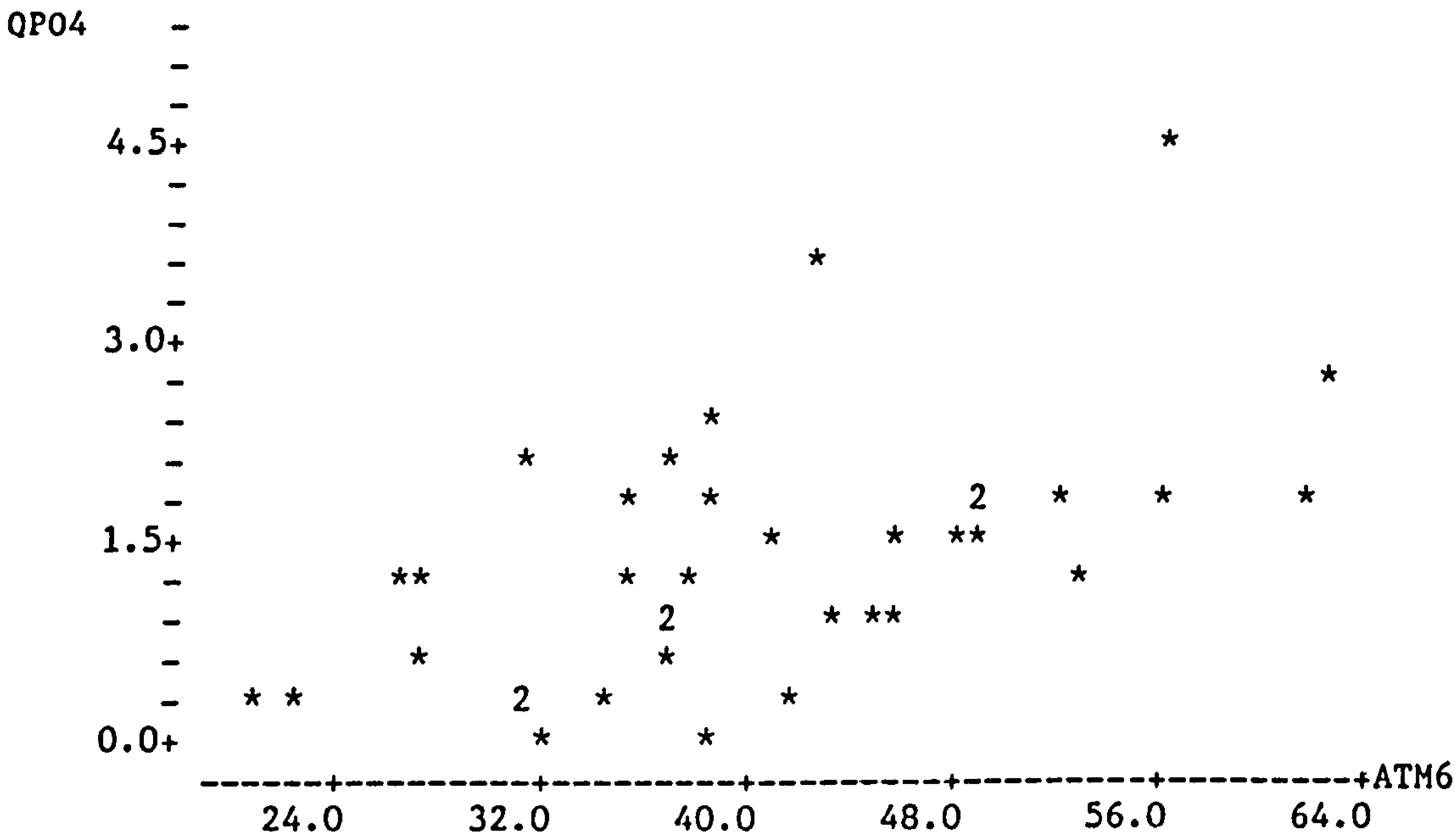


FIGURE 3.6
Scatterplot showing the relationship between
Quadrat Ca and ATM waveband 1.

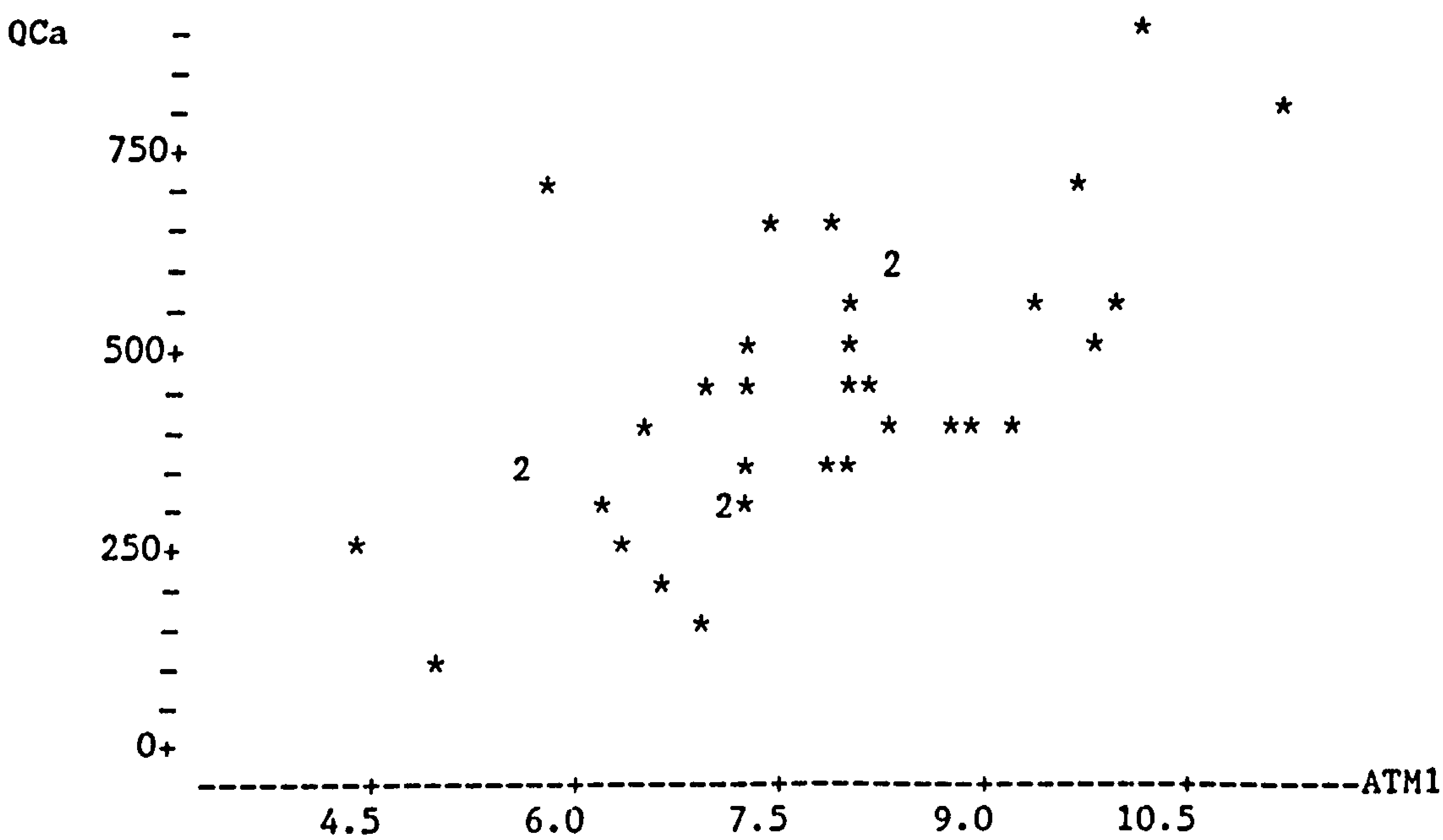


FIGURE 3.7
Scatterplot showing the relationship between
Transect sample NH_4 and ATM IR/R index.

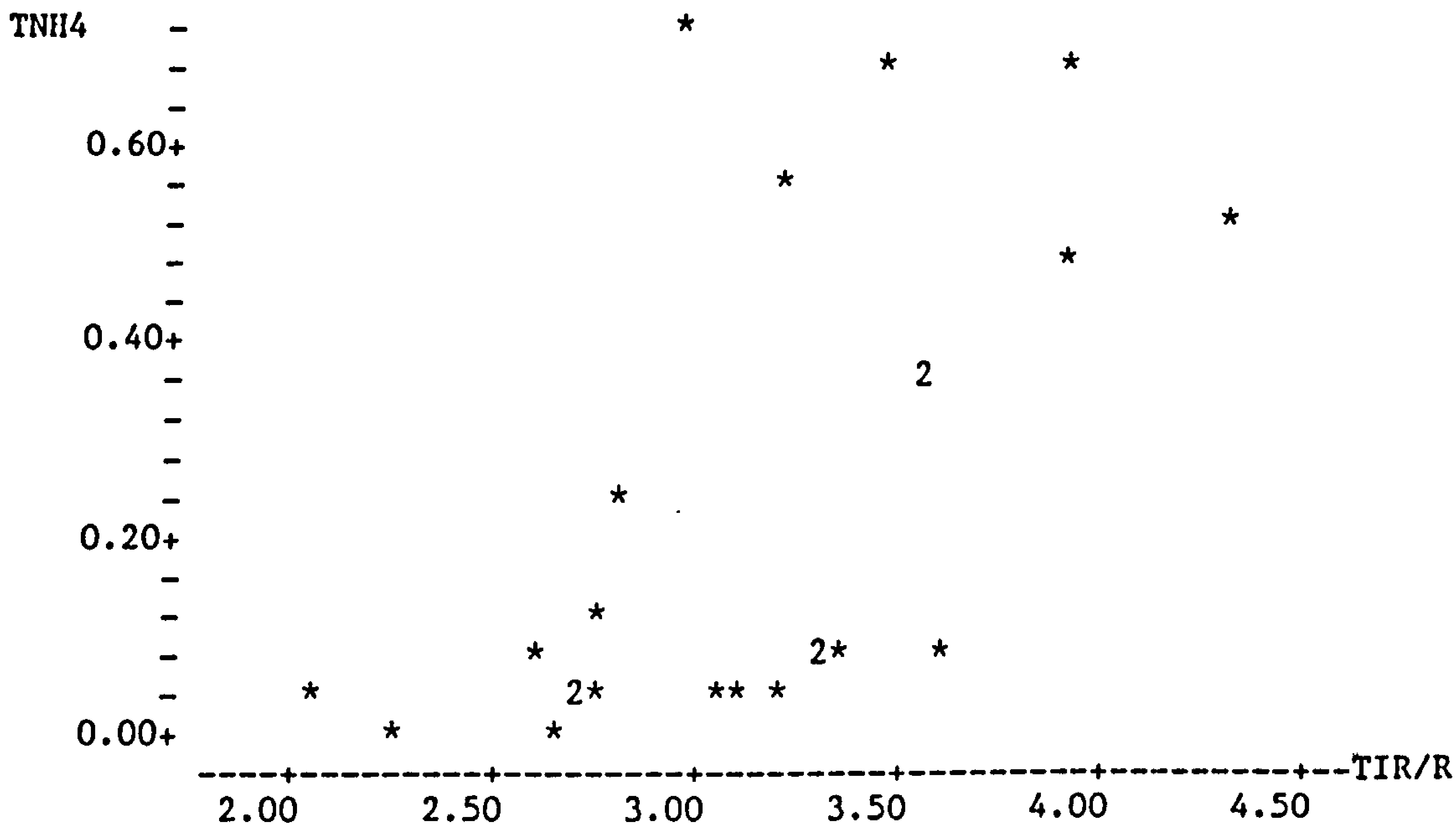


FIGURE 3.8
Scatterplot showing the relationship between
Transect sample Ca and ATM waveband 11.

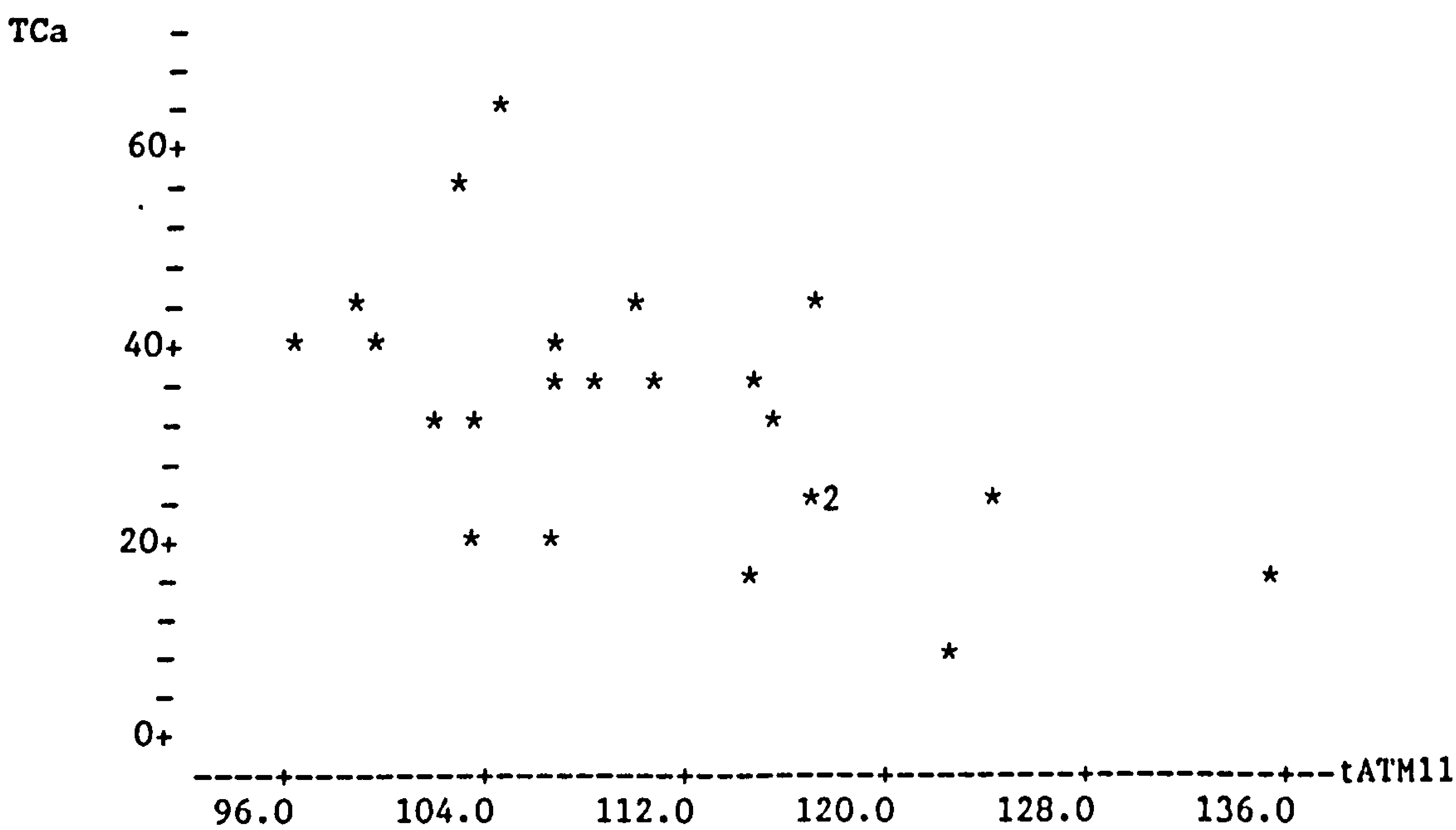


FIGURE 3.9
Scatterplot showing the relationship between
Transect sample F and ATM NDVI index.

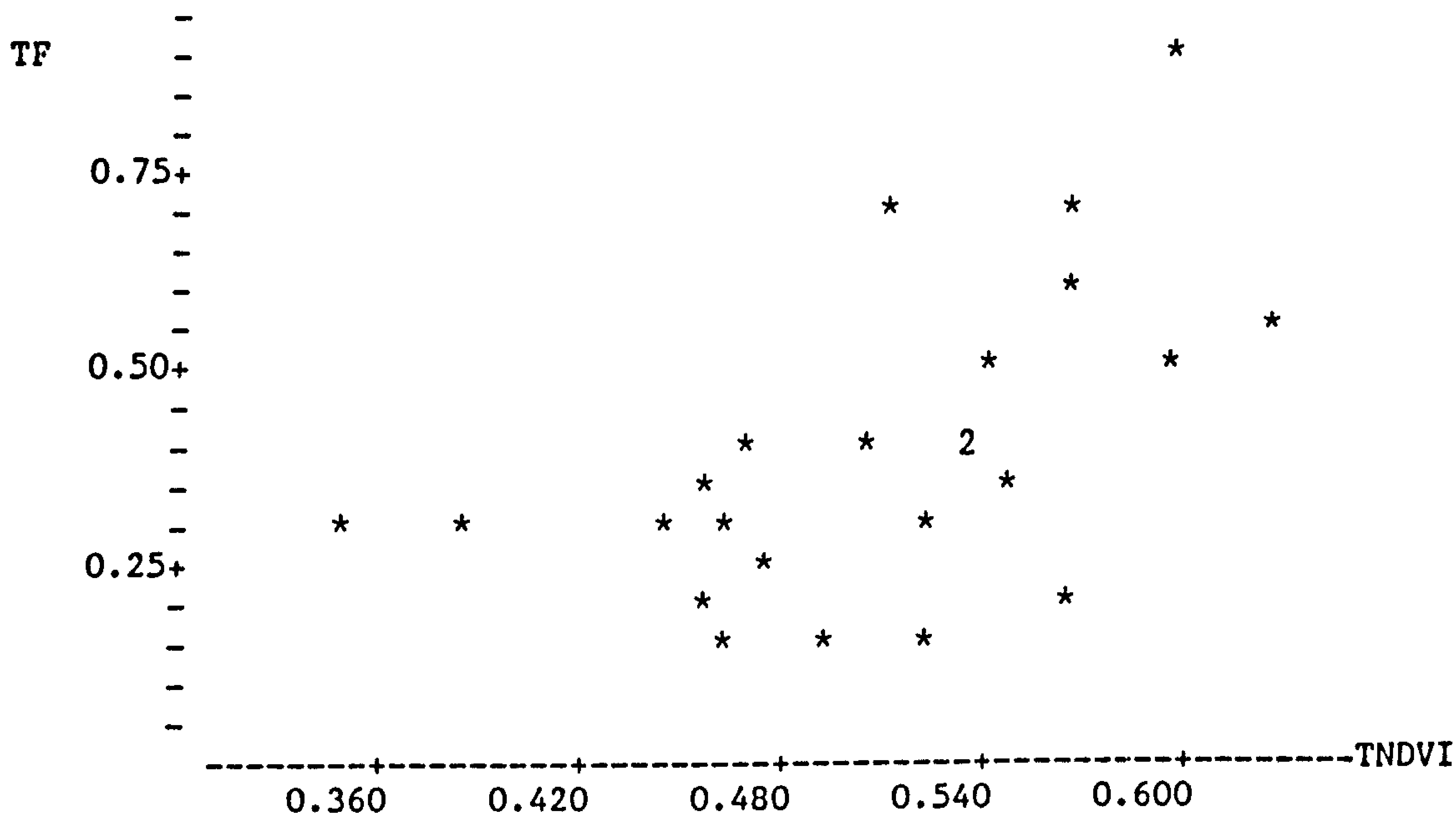


FIGURE 3.10
Scatterplot showing the relationship between
Transect sample Na and ATM waveband 11.

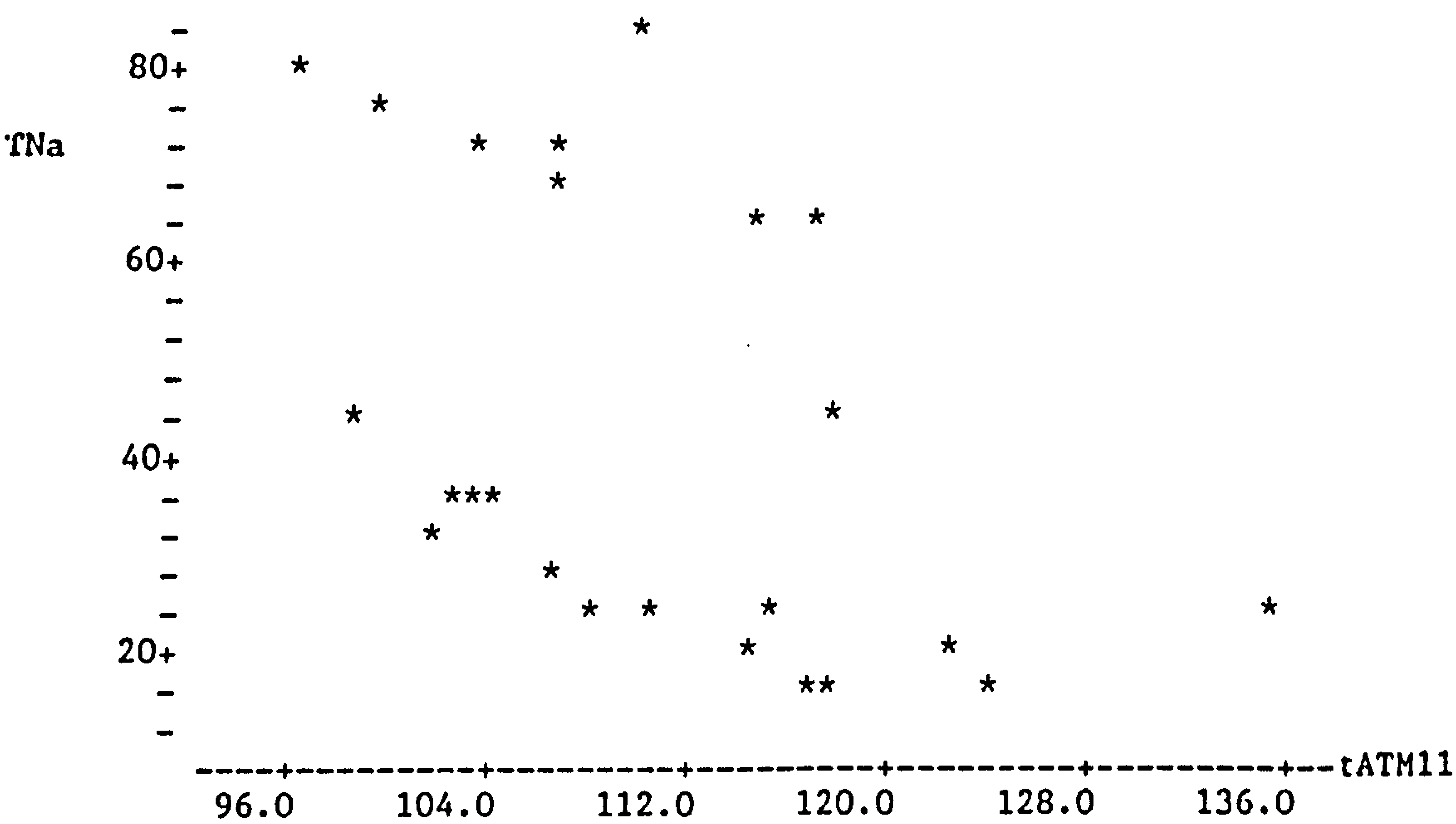


TABLE 3.1

The AADS 1268 Airborne Thematic Mapper (ATM).
Wavelengths (micrometres) of the 11 ATM bands.
Bands 1-6 are visible, 7-10 are near and
middle infra-red, 11 is thermal infra-red.

AADS 1268 SPECTRAL BAND	WAVELENGTH μm
1	0.42 - 0.45
2	0.45 - 0.52
3	0.52 - 0.60
4	0.605 - 0.625
5	0.63 - 0.69
6	0.695 - 0.75
7	0.76 - 0.90
8	0.91 - 1.05
9	1.55 - 1.75
10	2.08 - 2.35
11	8.50 - 13.00

TABLE 3.2

Tape header information for NERC ATM tape CRYM386

**** TAPE CRYM386 ****

```
Number of lines   : 2220
Number of samples : 716
Number of bands   : 12
```

```
HUNTING GEOLOGY AND GEOPHYSICS AAD1268
NERC 1987 - AUTUMN PHASE
TAPE 21
FLIGHT DATE 15-SEP-87
FLIGHT   9
BANDS 1-2-3-4-5-6-7-8-9-10-11-12
SITE - CRYMLYN BOG 87/48CR/2
SCAN/FRAME COUNT - START 36734
SCAN/FRAME COUNT - FINISH 38953
GROUND CLEARANCE  800 METRES
GROUND SPEED  160 KNOTS
PIXEL  1 METRES WIDE
PIXEL  1 METRES LONG
750 FRAME BYTES
RECORD SIZE  9000 BYTES
BAND FRAME INTERLEAVED
VIDEO START BYTE 24
VIDEO END BYTE 739
BB1 BYTE 23
BB2 BYTE 740
2.50 MILLIRADIAN RESOLUTION
SOURCE HDDT 216
SCAN SPEED  50.0 SCANS/SECOND
S-BEND SETTING ' IN'
CHANNEL NO.   1   2   3   4   5   6   7   8   9  10  11  12
GAIN SETTING 8.0 4.0 4.0 8.0 4.0 2.0 1.0 2.0 4.0 4.0 1.0 .5
LOW BLACKBODY=  19  LOW TEMP REF=  10.00 DEGREES CELSIUS
HIGH BLACKBODY= 183 HIGH TEMP REF= 26.04 DEGREES CELSIUS
```

TABLE 3.3

Correlation matrix for the ATM image
CRYM386 used in this study.
There was high correlation between some bands:
visible bands 1-6, also infra-red bands 6-8.

1	1.000									
2	.935	1.000								
3	.926	.971	1.000							
4	.900	.972	.981	1.000						
5	.903	.946	.980	.979	1.000					
6	.202	.081	.232	.119	.266	1.000				
7	-.042	-.156	.003	-.108	.015	.936	1.000			
8	-.106	-.184	-.028	-.116	-.027	.815	.953	1.000		
9	.355	.351	.475	.451	.537	.654	.592	.620	1.000	
10	.643	.718	.749	.782	.800	.218	.050	.069	.757	1.000
Band	1	2	3	4	5	6	7	8	9	10

TABLE 3.5

GAIN AND BASE VALUES USED FOR CALIBRATING DAEDALUS ATM DATA FROM CRYMLYN BOG.

GAIN VALUES:

ATM band	Gain settings .5	1	2	4	8
1	3.75000	1.98529	1.02273	0.52461	**0.27664**
2	2.64341	1.32170	0.67003	**0.33736**	0.16912
3	3.26451	1.64696	0.83476	**0.41929**	0.20941
4	6.11328	3.05664	1.56250	0.78881	**0.39409**
5	3.14128	1.55045	0.78024	**0.39215**	0.19833
6	3.29781	1.63385	**0.82540**	0.41152	0.20423
7	1.85979	**0.91472**	0.46188	0.23228	0.11434
8	2.76558	1.36750	**0.68810**	0.34542	0.17094
9	0.72993	0.36134	0.17945	**0.09034**	0.04517
10	0.17515	0.08744	0.04372	**0.02186**	0.01093

BASE VALUES:

ATM band	Gain settings .5	1	2	4	8
1	0.832	1.856	3.840	8.000	**17.152**
2	1.664	3.712	7.744	**15.744**	31.680
3	2.496	4.992	9.856	**19.584**	39.168
4	1.664	3.840	8.128	16.512	**33.536**
5	1.856	4.352	9.280	**18.944**	38.336
6	2.624	5.056	**9.792**	19.136	38.080
7	2.368	**5.056**	10.176	20.544	41.152
8	2.048	4.480	**9.280**	18.816	38.016
9	2.048	4.032	7.744	**15.296**	30.336
10	2.624	5.120	10.048	**19.840**	39.424

BOLD figures indicate the gain and base values used for calibrating the ATM data.

TABLE 3.6

GLOBAL DAEDALUS 1268 SCANNER CALIBRATION, 08-09-87

CHANNEL	CALIBRATION SOURCE	SENSOR MEASUREMENTS									
	N^1	GAIN 0.5 $Vcal^2$	GAIN 0.5 $V0^3$	GAIN 1 $Vcal^2$	GAIN 1 $V0^3$	GAIN 2 $Vcal^2$	GAIN 2 $V0^3$	GAIN 4 $Vcal^2$	GAIN 4 $V0^3$	GAIN 8 $Vcal^2$	GAIN 8 $V0^3$
1	6.48	40	13	80	29	159	60	318	125	634	268
2	12.35	99	26	204	58	409	121	818	246	1636	495
3	23.40	151	39	300	78	592	154	1178	306	2358	612
4	31.30	106	26	220	60	440	127	878	258	1765	524
5	38.60	221	29	457	68	918	145	1834	296	3640	599
6	45.80	258	41	517	79	1020	153	2038	299		(595)
7	53.80	489	37	998	79	1979	159	3940	321		(643)
8	55.40	345	32	703	70	1403	145	2800	294		(594)
9	25.60	580	32	1170	63	2350	121		(239)		(474)
10	10.75	1000	41	2001	80		(157)		(310)		(616)

1 AVG Panel Radiance in W x $10^{-7}.cm^{-2}$, nm^{-1} $.sr^{-1}$
2 Sensor voltage fm calibration source in mV.DC
3 Sensor voltage fm zero input source in mV. DC
* Calibration Source model AB532A S/N 01 with lamps 5 & 6 and barium sulphate reflectance panel

TABLE 3.9

Summary statistics for the uncalibrated and calibrated ATM samples, and for the calibrated ATM site means

SUMMARY STATISTICS - UNCALIBRATED AIRCRAFT DATA - SAMPLES

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN	MIN	MAX	Q1	Q3
DN1	244	45.709	45.000	45.745	6.374	0.408	29.000	64.000	41.000	50.000
DN2	244	48.348	48.000	48.173	4.639	0.297	39.000	63.000	45.000	51.000
DN3	244	57.049	56.500	56.886	5.860	0.375	43.000	75.000	53.000	61.000
DN4	244	68.459	68.000	68.295	4.718	0.302	58.000	83.000	65.000	71.000
DN5	244	59.775	60.000	59.573	6.443	0.412	46.000	80.000	55.000	63.000
DN6	244	60.365	61.000	60.332	11.465	0.734	30.000	88.000	53.000	68.750
DN7	244	57.627	58.000	57.555	12.101	0.775	26.000	87.000	49.000	66.000
DN8	244	57.865	59.000	57.909	10.972	0.702	31.000	82.000	49.000	66.000
DN9	244	71.906	73.000	72.236	8.559	0.548	40.000	89.000	66.000	77.000
DN10	244	52.877	53.000	53.036	4.960	0.318	35.000	64.000	50.000	56.000
DN11	244	114.55	115.00	114.44	9.37	0.60	92.00	137.00	107.00	122.00

SUMMARY STATISTICS - CALIBRATED AIRCRAFT DATA - SAMPLES

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN	MIN	MAX	Q1	Q3
CAL1	244	7.900	7.704	7.910	1.763	0.113	3.278	12.960	6.597	9.087
CAL2	244	10.999	10.882	10.940	1.565	0.100	7.846	15.942	9.870	11.894
CAL3	244	15.709	15.479	15.641	2.457	0.157	9.818	23.235	14.011	17.365
CAL4	244	13.763	13.582	13.698	1.859	0.119	9.641	19.493	12.400	14.764
CAL5	244	16.012	16.100	15.933	2.527	0.162	10.610	23.943	14.139	17.277
CAL6	244	41.743	42.267	41.716	9.463	0.606	16.680	64.553	35.664	48.664
CAL7	244	48.088	48.429	48.021	11.069	0.709	19.158	74.956	40.196	55.747
CAL8	244	33.431	34.212	33.462	7.550	0.483	14.946	50.039	27.331	39.029
CAL9	244	5.1141	5.2130	5.1440	0.7732	0.0495	2.2318	6.6584	4.5806	5.5743
CAL10	244	0.72219	0.72488	0.72567	0.10843	0.00694	0.33140	0.96534	0.65930	0.79046
UNCAL11	244	114.55	115.00	114.44	9.37	0.60	92.00	137.00	107.00	122.00

SUMMARY STATISTICS - CALIBRATED AIRCRAFT DATA - SITE MEANS

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN	MIN	MAX	Q1	Q3
MR1	61	7.900	7.842	7.898	1.464	0.187	4.384	11.093	7.012	8.776
MR2	61	10.999	10.629	10.937	1.513	0.194	8.352	15.605	10.081	12.020
MR3	61	15.709	15.583	15.635	2.373	0.304	10.866	22.711	14.116	17.418
MR4	61	13.763	13.680	13.680	1.739	0.223	10.626	19.296	12.498	14.813
MR5	61	16.012	16.002	15.917	2.428	0.311	11.296	23.355	14.090	17.424
MR6	61	41.74	41.65	41.71	9.27	1.19	20.81	62.70	35.04	48.66
MR7	61	48.09	48.20	47.99	10.81	1.38	23.73	71.75	39.97	55.17
MR8	61	33.431	34.040	33.465	7.356	0.942	17.698	46.770	27.331	38.943
MR9	61	5.1141	5.1678	5.1477	0.7174	0.0919	2.6157	6.3422	4.7161	5.5969
MR10	61	0.7222	0.7303	0.7247	0.0983	0.0126	0.3970	0.9161	0.6593	0.7768
MDN11	61	114.55	115.00	114.45	9.13	1.17	96.00	135.25	107.38	122.50

Third Party Material excluded from digitised copy.
Please refer to original text to see this material.

CHAPTER 4

CLASSIFICATION OF MONTANE VEGETATION USING LANDSAT THEMATIC MAPPER DATA; MAP RECONCILIATION AND G.I.S.

This chapter consists of two sections. Section One presents the results of classifying and filtering Landsat Thematic Mapper data in an attempt to reproduce a vegetation map derived from aerial photograph interpretation and field survey. Section Two examines the use of G.I.S. functionality in extracting management information from the two types of vegetation map.

SECTION ONE

4.1 SUMMARY OF CHAPTER 4, SECTION ONE

This study on the Glyderau mountains in north Wales, U.K. investigated the potential for mapping upland vegetation using Landsat Thematic Mapper data. In particular, it addressed the problems involved in classifying highly variable ground cover on valley floors, steep slopes and high plateaux. Here, the interaction between the sun's illumination and major terrain features produces considerable differences in spectral response for similar vegetation in sunny and shaded situations. It addressed the problems involved in reconciling the need for a fairly simple and generalised vegetation map with the fine detail present on the ground and in Thematic Mapper data. During the summer of 1984, the Nature Conservancy Council mapped the vegetation of the Glyderau mountains in Snowdonia to produce a map at the scale of 1:10,000. The Nature Conservancy Council (NCC) and the Countryside Commission in Wales have now merged to form the Countryside Council for Wales (CCW). Landsat-5 Thematic Mapper data were taken from scene 204/23 of 22 July 1984. These two datasets were spatially registered in raster format for comparison. Vegetation classes were divided into terrain-related sub-classes to reduce the effects of uneven illumination due to the mountainous relief. The sub-classes were characterised using training data, classified using a maximum likelihood classifier, and reconstituted into their original classes. Pre- and post-classification smoothing filters (median and majority-mode, respectively) were used to produce Thematic Mapper classmaps for comparison with the ground survey data. The efficacy of these techniques for improving the correspondence between the conventionally-produced map and the Landsat data classmap are discussed.

4.2 GENERAL INTRODUCTION TO CHAPTER 4

The British uplands are extensive, relatively inaccessible and provide many valuable resources. They are important in the provision of water, minerals and building materials, the products of upland agriculture, timber and, in some areas, peat. The survival of some plant and animal species relies on certain upland environments and for many people the uplands are important for recreation. The resources are difficult to quantify because of the nature of the uplands and the expense involved in surveying them.

As the use of these uplands intensifies it is becoming increasingly important to maintain information on their condition. Many organisations with a role in upland land management undertake ground and aerial surveys, but these tend to be infrequent; ten or fifteen years between surveys is not unusual for many parts of the UK.

Certain management organisations now have a mandatory responsibility for producing maps of the vegetation of these upland areas. Changes in the nature and distribution of upland vegetation resulting from pasture improvement, afforestation and bracken encroachment, for example, have increased the need for monitoring these areas. The CCW uses upland vegetation maps when considering the designation of new protected areas, and during the preparation of management agreements. Furthermore, county planning authorities now have a statutory responsibility for the maintenance of up-to-date maps of moor and heath areas within the National Parks as a result of legislation laid down in the Wildlife and Countryside Act (H.M.S.O., 1981, 1985).

A developing application for multispectral satellite data in the UK lies in mapping the vegetation of the uplands. Moving from relatively flat lowland terrain to the more rugged and variable upland regions introduces two major difficulties. The first results from a dramatic change in topography; the second is caused by a change in the structural nature of the vegetation. A third, and perhaps more subtle, difficulty results from the need to reconcile traditional vegetation survey methods with the objective classifiers used in remote sensing; this problem is true of many regions, but is compounded by a lack of clear boundaries and the heterogeneity of mountain vegetation. Traditional field survey methods and satellite survey techniques use quite different criteria for classifying upland terrain. While there are difficulties in maintaining consistent performance between two field surveyors, there are even greater difficulties in trying to obtain comparable classifications using two quite different methodologies (McMorrow and Hume, 1986).

For most of the applications involving upland vegetation maps, there is a requirement for the identification of plant communities rather than individual plant species. The Ratcliffe and Birks (1980) classification used by the Nature Conservancy Council is based on vegetation type, physiognomy and dominance, factors which have been shown to relate to spectral response (Justice and Townshend, 1982). If methodologies for processing and analysing satellite data can be refined to provide an acceptable model of vegetation cover, they may gain acceptance by those with an interest in the uplands.

Vegetation mapping methods using aerial photographs and field survey (Fuller, 1981) have traditionally provided the basis for monitoring the uplands (Budd, 1987). Aerial photograph interpretation has the advantages of being relatively simple, rapid, reasonably accurate, and cheap (Hume, McMorrow and Southey, 1986). However, these surveys are only undertaken at 10- to 15-year intervals and they are usually based on sampling methods. The opportunity therefore arises for satellite sensor data to provide more complete coverage both spatially and temporally because they can provide a repeatable complete census. Indeed, the Institute of Terrestrial Ecology (ITE) Countryside Survey 1990 has included an ambitious project to classify the complete land surface of Great Britain using Landsat Thematic Mapper data (Fuller et al., 1992).

4.3 CONTEMPORARY RESEARCH

Digital scanner data have been used in many studies of complex semi-natural vegetation in the U.K. Heather moorland is structurally and spatially complex but has been found to have some spectrally-distinct vegetation classes (Weaver, 1987b). Wardley, Milton and Hill (1987), however, noted the considerable internal spectral variability of heathland classes at high spatial resolution (1m) and that coarser data (5m) averaged out much of this spectral variability. This spatial variability of image tone has since been referred to as 'texture'. In these situations, the calculation and use of texture has generally improved classification accuracies (Pedley and Curran, 1991). The concept of distinct end-points with a continuum of vegetation composition and spectral variation in between has been tested by Foody (1992). This probabilistic mapping may be more appropriate for use in the modelling of semi-natural vegetation continua such as those found in heathland.

Undulating topography complicates the classification of semi-natural vegetation, but several studies have been undertaken in the UK uplands (Booth and Oldfield, 1989; Jones, Settle and Wyatt, 1988; Thomson and Milner, 1989; Weaver, 1987a; Williams, Brown and Norris, 1987), in the UK lowlands (Belward et al., 1990) in France (Megier, Hill and Kohl, 1991) and in Sweden (Hall-Konyves, 1987).

The addition of geomorphometry as a descriptor of parameters such as elevation, slope, incidence, curvature and relief or roughness (DEM texture) derived from a digital elevation model again improved classification accuracy (Franklin and Peddle, 1989).

Contextual (rather than per-pixel) classifiers incorporating prior knowledge about an area (Settle, 1987) are increasing classification accuracies. Knowledge-based image segmentation (Cross and Mason, 1985) enables information sources external to the image such as Ordnance Survey map data, digital terrain models or the results of previous classifications to be used to stratify the image into regions prior to classification. A split and merge process has been used by Cross, Mason and Dury (1988) to segment images into regions of homogeneous tone and texture. These regions were classified on a per-region basis and isolated pixels were classified on a per-pixel basis producing improved classification accuracies for arable and forest land in lowland Britain.

Per-field classification incorporating prior probabilities has been used to good effect in lowland situations (Pedley and Curran, 1991). The field was adopted as the standard spatial unit of land cover. The data were filtered with a 3x3 mean filter prior to classification, and texture was incorporated as a measure of the spatial variability of image tones in the classification. Per-field classification increased map agreement for the more variable land covers; texture assisted the agreement for spectrally similar classes, and prior probabilities increased agreement for the spatially more extensive classes. The methodology is initially hampered by the need and cost of defining the field boundaries. This last point indicates a major difficulty for the use of this technique in upland areas where boundaries are relatively indistinct and semi-permanent.

The improved spatial resolution of sensors such as the Landsat Thematic Mapper (TM) and the SPOT HRV has in some studies reduced classification accuracies (see, for example, Irons et al., 1985). The effects of increasing spatial resolution are dependent on the land cover being classified. For land cover classes composed of a heterogeneous mixture of component cover types, within-class variance in radiance will almost certainly increase. If this variance is high relative to the differences between classes, the resulting spectral confusion may produce classification difficulties. Conversely, there will be a smaller proportion of mixed boundary pixels which may reduce misclassification. Data processing techniques which reduce within-class variance without increasing the proportion of mixed pixels should, in many cases, improve the classification of land cover.

Image filtration prior to classification has been shown to improve lowland ground-cover classification by reducing within-class variability (Atkinson et al., 1985; Cushnie, 1987). In order to satisfy the above requirement for minimising both the within-class variance and the proportion of mixed (boundary) pixels, the type of filter needs to be chosen carefully. The optimum filter will vary according to the nature (in particular, the size and spatial context) of different cover classes. The effects of these parameters were studied in detail in this study.

The results of many of these studies have been encouraging, but most workers have found that the upland environment is extremely spatially complex, demanding a correspondingly sophisticated methodology.

4.4 TOPOGRAPHY

There are two major factors which must be considered when classifying upland vegetation using satellite data. The first is the nature of the terrain; the second is the relatively early U.K. overpass time (09.30) of Landsat satellites. The Snowdonian mountains are typical of severely glaciated regions in their physiography. Steep, shaded northern cwms contrast with sunny south-facing slopes. The valleys are deep and only those with a south-east/north-west orientation are relatively free from shadow at overpass time; in the winter months with characteristic low sun elevation, shadow is found in all valleys.

Another factor to be considered in mountainous terrain is light reflected from adjacent slopes. This source may be insignificant on well-lit areas, but can account for nearly 50% of the irradiance of shadowed areas in deep valleys (Proy et al., 1989). In the case of areas under terrain shadow, there may be insufficient information in the satellite data for any correction or accurate classification to be achieved.

A study of Landsat data for gently undulating terrain in Sweden (Hall-Konyves, 1987) indicated that the radiance of pasture land was affected by terrain to a greater extent than that of arable land or forest. Many per-pixel classifiers are strongly influenced by class statistics which describe differences in brightness. In consequence, variations in illumination interfere with the task of classifying vegetation in the uplands.

An elegant solution to this problem would perhaps involve the use of a digital elevation model (DEM) of the area to add extra dimensions to the dataset, or to produce a correction for the non-uniform illumination of the landscape. This methodology was tested using SPOT HRV data for Snowdonia by Baker et al. (1991). Anisotropic adjustment of radiance in combination with contextual information improved classmap agreement. Even with a DEM, it would still be necessary to model the detailed interactions between each ground cover type with incident illumination to produce a wholly effective correction.

Thomson and Jones (1990) examined the effects of topography on the radiance of upland vegetation in Snowdonia. Their findings indicated that the aspect-related effect on radiance was strongly related to vegetation type and structure. Agrostis grassland, for example, showed a coordinated (and perhaps predictable) response in relation to aspect; Nardus grassland, however, displayed an uncoordinated (probably far less predictable) response, and the radiance of Calluna heath was almost unaffected by aspect. This last point was interesting because while the radiance of Calluna was relatively consistent with respect to aspect, the variation in irradiance with aspect was presumably compensated for by changes in the type, structure and amount of Calluna heath on the various sites investigated.

A simple but nevertheless successful intermediate measure has produced improved classification results for remote sensing projects in areas with undulating or mountainous topography. It involved the division of vegetation classes into aspect, or spectral, sub-classes distinguished by different conditions of irradiance. The sub-classes were determined by the orientation of major relief features relative to the south-easterly sun at Landsat overpass time. In this study they corresponded to south-east slopes, north-west slopes, plateaux and other level ground.

Training areas were defined for each aspect sub-class (Level I, Table 4.1), they were classified quite separately, and then recombined into their original classes (Level II, Table 4.1) to produce the classification. This technique produced a spectral characterisation of the classes which was influenced to a lesser extent by variations in the intensity and angle of illumination.

4.5 VEGETATION STRUCTURE & TERRAIN COVER

High spatial complexity is a feature of semi-natural vegetation; this is particularly true for mountainous terrain. In the Welsh uplands there are extensive high plateaux with scattered vegetation, rocks and boulders. In places the ground is well-drained, but there are large areas of peat with impeded drainage. Steep crags hold vegetation on narrow ledges and in small clefts in the rock. The gentler slopes and valley floors consist of a detailed matrix of vegetation, boulders and scree material with few areas holding uninterrupted vegetation cover. Boundaries are less frequent and altogether less distinct than those found in the enclosed lowlands. Those that do exist frequently result from a change in substrate or drainage; others result from differential grazing intensities on land separated by streams, fences or walls. Some boundaries result from natural fires and others from burning as a management practice.

The need to identify plant communities, rather than individual plant species affects the choice of spatial resolution and the methods used in image classification. Landsat Thematic Mapper data with a spatial resolution of 30 x 30 metres have been chosen to map the land cover of Great Britain (Fuller and Parsell, 1990; Fuller et al., 1992) and were thought to be suitable for mapping the extensive vegetation communities in the Welsh uplands. The image filtration methods used in this study further reduced the influence of the individual spectral components in the study area data to obtain a 'community spectral response' rather than a 'species spectral response'.

It is difficult to know where to find the most realistic model of the vegetation cover for an area. Upland vegetation is fairly stable but its appearance and composition can alter. Grazing, the use of fire for pasture management, drought and erosion can alter the uplands from year to year. Field surveys usually record the vegetation at a limited number of sample sites, and then only at given points in time. A point of reference, however, has to be chosen and a field survey conducted close to the date of acquiring satellite data can provide a good reference for a comparison study.

4.6 RECONCILING GROUND AND SATELLITE SURVEY

The difficulties found when attempting to classify upland vegetation become clear when the interpreters' view is considered. Trained botanists or ecologists will tend to be extremely selective in their perception of the terrain. The emphasis on vegetation is strong; substrate background, surface moisture and aspect are altogether less interesting factors in the botanists' perception of the terrain. This is by no means unjustified when the purpose of field survey is to produce a vegetation map of the area. It has been stated, for example, that it may be inappropriate to try to match ecological divisions directly with classifications of satellite data (Williams, 1988; Belward et al., 1990).

This emphasis on vegetation is, however, usually restricted to the generalisations required by botanical classifications; namely, the presence or absence of species. Seasonal changes in plant phenology (vegetative growth, flowering etc.) have little place in most botanical classifications. Bracken, on a vegetation map, is bracken whether it is green or brown or, as is often the case in early summer, green with brown patches. There can be areas of grassland consisting of plants displaying the full glory of unrestricted growth, and others in the same category that are made up of mere stumps due to heavy grazing. In heavily grazed swards, the grass species are frequently identified from the appearance of their roots. More detailed ecological work concerned with, for example, grazing conditions may find important information in this variability.

While remote sensing techniques are being refined, the traditionally-produced vegetation map will often be used to identify training areas for the production of a remote sensing classmap, and to verify its accuracy. The plethora of detail which could be used to describe in the most precise terms the condition of the vegetation at the time of mapping would swamp a remote sensing analyst. And yet, every item in the wealth of fine detail which could be used to describe the vegetation, quite apart from the terrain as a whole, has its effect on the remotely-sensed signal. Satellite sensor data are influenced by a wide range of physical and environmental variables (Curran, 1985) not necessarily considered by botanical field survey methods. The result of this is that the products of satellite surveys of upland terrain usually show a greater degree of variability than do vegetation maps derived from field survey. The end product required from the remote sensing project, however, may well be a classmap as general in its detail as one produced by more traditional methods.

Statistical management information can be extracted from digital vegetation maps without aesthetic consideration of their appearance. But for some purposes it will be necessary to produce a vegetation map suitable for visual interpretation. A guideline for the appearance of such a map might be the type of map in current use. If the map produced from satellite survey is similar, in general terms, to the maps in current use then it may make acceptance and interpretation simpler.

The problem in many cases is therefore one of generalisation. To reconcile the different classification schemes requires a balanced generalisation of the terrain, the vegetation and the resulting classmaps. A method for simplifying the satellite survey products is needed to make the two types of map more comparable. This often has the additional benefit of making the satellite survey products easier to interpret.

A widely available technique for smoothing, or generalising, rasterised images is spatial image filtering. The technique can be applied to multispectral imagery or, subsequently, to the classification product, the classmap. Image filtering techniques have been used for simplifying satellite survey products, but there are several different filter types and each one can be applied with a range of 'strengths' or kernel sizes. The problem that remains is to find an optimum technique for simplifying the satellite survey products while minimising any adverse effects on the accuracy of mapping each of the vegetation types.

4.7 STUDY AREA

The Glyderau (alternative spelling- Glydeiriau) study area in north Wales (Fig. 4.1) covers 1384 hectares from Llyn Ogwen and Tryfan to Capel Curig, with the A5 road forming the northern boundary (Plate 4.1). To the south, the study area boundary is the A4086 Capel Curig to Llanberis road. The ground rises from 260 metres on the Afon Llugwy near Capel Curig to 994 metres on the summit of Glyder Fach. Plate 4.2 shows an overview of the Glyderau study area and surrounding mountains using Landsat TM bands 4 5 3 by convention represented in red, green and blue colours; image width is 30km. Blocks of conifer in Gwydyr Forest are distinct in dark brown, bare rock on the mountain summits is clear in blue and the shadows of the shaded northern cwms are visible.

In the Glyderau study area nine major classes from the Ratcliffe and Birks (1980) upland vegetation classification were found. Briefly, the classes were as follows:

Nardus-Juncus (mat grass-rush) grassland: a widespread species-poor type usually covering extensive areas on podsolised soils and shallow blanket peat.

Agrostis-Festuca (bent fescue) grassland: widespread sheep-grazed upland pastures found on mineral soils.

Vaccinium heath: heath dominated by Vaccinium myrtillus (bilberry) on well-drained sites, sometimes on rocky slopes or stabilised scree. This community is often derived from the burning of Calluna heath when grazing is heavy.

Rhacomitrium heath: summit heath dominated by Rhacomitrium lanuginosum (woolly hair moss) which may be interspersed with bare soil and stones.

Soligenous flushes: occur mainly along stream channels, in hollows and on poorly-drained slopes. Dominated by Myrica gale (bog myrtle), Molinia caerulea (purple moor grass), Juncus (rushes) and mosses.

Blanket bog: tends to be found on peat, often on sloping ground. The main types are Molinia-Calluna mires and Molinia-Erica-Sphagnum mires. (Calluna vulgaris, heather; Erica tetralix, cross-leaved heath; Sphagnum, moss). The composition of these mires is readily modified by burning and grazing.

Calluna heath: this dry heath is floristically uniform and dominated by Calluna vulgaris (heather). It is found on podsols or shallow peat. Various stages associated with recovery after burning can be identified. Vaccinium may be temporarily dominant after burning.

Molinia grassland: a species-poor community dominated by Molinia caerulea (purple moor grass). It is widespread on peaty podsols or deep peat, where it is often derived from Molinia-Calluna blanket bog as a result of grazing or burning. The vegetation becomes tussocky in the absence of grazing.

Bracken: Pteridium acquilinum (bracken) is found on well-drained lower slopes on mineral soil.

The other source of considerable interest in the Glyderau is the arctic-alpine flora. A true alpine flora is found in Snowdonia on the rock ledges of the precipitous cwms, especially those which face north away from the drying effects of sunshine (see, for example, Richards, 1973; Woodhead, 1933).

4.8 DATA SOURCES

4.8.1 Landsat Data

A Landsat-5 Thematic Mapper (TM) image of scene 204/23 from 22nd July 1984 was obtained in Earthnet system-corrected format. The data were not calibrated or radiometrically adjusted since classification was the main objective of the study. All values are shown as the digital number (DN) from the source tape. The distributions of DN values in the 7 bands of the TM for a 512 x 512 pixel image centred on the study area are shown in Figures 4.2a to 4.2g. In terms of whole-earth albedo, most of these figures show that the albedo of north Wales is towards the lower end of the range. The good spread of data in the near infra-red, band 4 (Fig. 4.2d), indicated that the area was relatively highly vegetated.

Using a cloud-free sub-scene of the study area, the image was geometrically corrected to the British National Grid and resampled to a 15x15 metre pixel size to match the scale of the map data using the nearest-neighbour method. Plate 4.3 shows this geometrically-corrected sub-scene; image width is 7.7km.

4.8.2 Ground Survey Data

During the same season as the TM overpass (summer 1984), the Nature Conservancy Council compiled a vegetation map using panchromatic aerial photographs and field survey. A portion of the original map is shown in Figure 4.3. This 1:10,000 scale map (Nature Conservancy Council, 1986) was vector digitised and re-plotted in a simplified form (Fig. 4.4), the codes are those used in the Ratcliffe and Birks (1980) classification; C2a, for example, is Nardus grassland. The vector map was converted to raster format and transferred to an I^{2}S Model 75 image processing system. Vegetation boundaries (Fig. 4.5) were used as an overlay for visual comparison with the TM image (Plate 4.4). Solid polygon masks representing each of the vegetation classes were intensity encoded and combined to form a single-band raster classmap; colours were assigned to each class to help visual map comparison (Plate 4.5); class codes refer to Table 4.1, level II. This single-band raster classmap enabled pixel-by-pixel comparisons to be made between the NCC and TM classifications.

4.9 IMAGE FILTERING

Filters are used for processing raster images in many ways. The process usually involves a consideration of pixel values within a 'window' or 'kernel'. The value of the central pixel may then be altered according to a predetermined function or set of decision rules. Two filtration methods commonly used to reduce variability in digital images are spatial smoothing and logical smoothing.

The first of these methods is a technique whereby the value of a pixel is replaced by the mean or median value of pixels within the window. This method is appropriate for the pre-classification smoothing of quantised images.

Mean filters have been used for the pre-processing of remotely-sensed data (Townshend and Justice, 1981; Dutra and Mascarenhas, 1984), but there is an increasing preference for median filtration (Cushnie, 1984; Atkinson et al., 1985) because of its boundary-preserving properties (Pratt, 1978; Cushnie and Atkinson, 1985), and because it is influenced, by definition, to a smaller extent by extreme values. Median filters are used to pre-process satellite data in an attempt to reduce within-class variability, decrease spectral overlap and improve classification performance.

In this study a median filter was used to pre-process the Thematic Mapper data before classification. When a sensor such as the TM records data, the continuous scale of global ground cover radiance (albedo) is divided into discrete quanta (256 quanta with 8-bit TM data, although only a small range was present in this scene, Figures 4.2a to 4.2g). Quantised data can be resampled using mean or median filters to smooth or generalise the digital numbers in the image. Plate 4.6 shows the unfiltered image of the study area. Plate 4.7 shows the effect of a median filter using a 9x9 pixel kernel; much of the fine spatial variability has been removed while preserving the broad spectral integrity of the major land units.

TM classifications of upland vegetation often show a high degree of spatial variability, the 'pepper and salt' appearance. This variability may be a true indication of the nature of the terrain; it may equally be due to misclassifications. Whatever the cause, this variability certainly makes visual interpretation of the vegetation map difficult. Plate 4.8 shows an unfiltered example of the TM classification of the study area and the high degree of spatial variability is clear.

Mean or median filtering is not appropriate for classified images because the values of pixels in these images are arbitrary and intended merely to differentiate the feature classes. Mean or median filtering may produce pixels with values not previously present in an image, and therefore not representative of the defined classes. The second method, logical, or modal, smoothing does not suffer from these shortcomings. The pixels within a window are examined and a decision rule determines whether the central pixel is to retain its original value or is to be changed to that of some of its neighbours within the window. The majority rule, when the central pixel's value is changed only if a majority of the pixels within the window are of a like class, is the limit to which the mode filter can be relaxed without introducing additional decision rules. As an example, in a 3x3 window at least five of the nine pixels must belong to one class before the central pixel's value is altered to that class. Logical smoothing has been discussed in detail by Townsend (1986), and has been used to improve the accuracy of classifications by removing variability from classified images (Ioka and Koda, 1986). Post-classification image filtration has been used to reduce misclassifications arising from scene noise effects (Gurney and Townshend, 1983; Schowengerdt, 1983); it is also routinely used to simplify the appearance of classmaps.

Plate 4.9 shows the effect of a powerful majority-mode filter on the classified image. Within the large regions where one class dominates, much of the variability due to the presence of other classes has been removed. In regions where there was no clear dominance of one cover type, the spatial variability remains.

Plate 4.10 shows the result of the third of the four extremes of treatment, a 7x7 pre-classification median filter but no post-classification filter. The median filter has reduced much of the initial spatial variability in the TM data. After classification, the regions of each class have become reasonably homogeneous. Only medium-sized blocks and threads of other classes remain. This map, however, still possessed considerably more spatial variation than the NCC map (Plate 4.12).

The final example of filter combinations is shown in Plate 4.11. This image is the result of the powerful 7x7 median pre-classification filter followed by the 7x7 post-classification majority-mode filter. It is clear that the combination of these two filter types, one before and one after classification, has produced an image which is closer in its general nature to the NCC map shown in Plate 4.12 than any of the other extremes of combination. Plate 4.13 shows the western part of the study area with the NCC field survey and TM classmap in the same view; Plate 4.14 shows the same comparison for the eastern part of the study area.

The visual appearance of these maps allows the observer to make a qualitative judgement of their appearance and utility. It was, however, essential to examine the consequences of the filtration on individual cover types. This study continued by making a detailed statistical analysis of the effects of all combinations of filters on each cover type.

The use of a maximum-likelihood classifier followed by post-classification filtering may not be justified if processing time is at a premium. Booth and Oldfield (1989) using Landsat TM data for the Peak District found that a minimum-distance classifier followed by a mode filter produced similar classification accuracies in half the CPU processing time on a VAX computer.

Alternative approaches to map simplification include the per-field methodology for lowland situations previously referred to (Pedley and Curran, 1991), and the RAG technique used by Nichol (1990). Region Adjacency Graph (RAG) techniques would be more suitable for upland vegetation situations than per-field because the regions can be produced by a classification routine, rather than being pre-defined as in the use of fields. RAG allows considerable control over the size-limit of regions to be merged, and the process that controls how they should be merged.

In this study an examination of the effects of combinations of pre-classification median filtering and post-classification majority-mode filtering on classification performance was made.

4.10 CLASSIFICATION AND SPATIAL FILTRATION METHODOLOGY

A high-speed maximum-likelihood classifier was employed (Briggs and Settle, 1985). This software ran in the pipeline processor of the image analysis system. Hardware restrictions limited the number of bands that could be processed by the classifier to six. TM band 2 was omitted because of its high correlation (.937) with TM3. Four six-band source images were prepared for classification: unaltered TM bands; TM bands after a 3x3 kernel median filtration; TM bands after a 5x5 median filtration and TM bands after a 7x7 median filtration.

Training areas for each of the spectral sub-classes (Level I, Table 4.1) were defined using the NCC vegetation map. Small training areas were delineated in the central zones of the vegetation classes in the NCC map. This objective process placed an implicit trust in the ground survey and avoided the influence of variations in colour visible on a TM waveband composite. An average of 1263 pixels per class were used (range 161-7499) to compute vegetation class statistics.

The classes were characterised by calculating statistics for each of the four pre-filtered six-band TM images. Divergence analysis was used to obtain a statistical measure of separability for the training classes. A fast maximum-likelihood classifier was used to classify the TM images, resulting in four single-band classmaps. The spectral sub-classes were recombined into their original vegetation classes. The final step involved subjecting each classmap to four post-classification treatments; these were no filtration and 3x3, 5x5 and 7x7 majority-mode filtrations. A graphics mask was used to 'cut' the study area out of the 512x512 pixel classmaps.

On the image analysis system two classmaps can be compared on a pixel-by-pixel basis to produce a correspondence matrix. This indicates the agreement between the two images and the errors of omission and commission. All sixteen classmaps were compared on a pixel-by-pixel basis with the NCC ground survey classmap. Early reviews of methods for summarising thematic map correspondence matrices were described by Rosenfield (1986) and Rosenfield and Fitzpatrick-Lins (1986).

Congalton (1991) reviewed methods of assessing and reporting the accuracy of remotely sensed classmaps. Correspondence or confusion matrices were reported as being very effective for interpreting and reporting map agreement or accuracy. The overall accuracy of agreement between a classified image and a reference map is reported as the sum of the leading (or major diagonal) of the correspondence matrix divided by the matrix total. This measure excludes omission (exclusion) and commission (inclusion) errors in the remainder of the matrix, which can be significant and important.

A discrete multivariate technique for accuracy assessment is normalised overall accuracy. When the matrix is normalised, an iterative proportional fitting procedure forces the elements in each row and column to sum to one. During the normalising process, each cell value has been balanced by the other values in its corresponding row and column. Off-diagonal elements (omission and commission errors) are therefore directly included in any accuracy estimate using the major diagonal. Cell values can be directly compared even though class totals in absolute pixel units may be different. Another discrete multivariate technique is called KAPPA. The KHAT statistic indirectly incorporates off-diagonal elements as a product of the row and column marginals. KAPPA is useful when a single statistic is required for comparing matrices, and for indicating whether the results are significantly better than a random result.

Normalised matrices expressed in percent were used in this study because it was necessary to be able to compare class cell values directly for classes with different total areas (pixels).

4.11 RESULTS

4.11.1 Histograms and Class Statistics

Histograms of the geometrically corrected data in the study area sub-scene (Plate 4.4) were produced (Figs 4.6a-g). This initial inspection of the data provided an indication of the range of DN values present in each waveband.

The spread of data values across the available 8-bit quantisation range of 0-255 is markedly different for some of the TM wavebands. TM1, TM2 and TM3 have their data restricted to about 30 of the 256 DN values. TM6 and TM7 have a wider spread of 40-50 DN values, TM5 has a spread of about 75, and TM4 has by far the widest spread of about 100 DN values.

The distribution of data values on these histograms can be related to the vegetation aspect sub-classes (Level I, Table 4.1) class statistics from the training areas shown in Figures 4.7a-g showing class means and standard deviations. The narrow range of data values seen in the histogram (Fig. 4.6a) for TM band 1 (60-80) is also seen on the graph of class statistics (Fig. 4.7a). Conversely, the wide range (40-120) of data values seen in TM band 4 (Fig. 4.6d) also appear in the corresponding class statistics (Fig. 4.7d).

In the case of Nardus-Juncus grassland, for example, the mean pixel values (DN) decreased as expected from 90 to 80 to 70 for the south-east (2), top (3) and north-west (4) aspects respectively. The standard deviation of the top sub-class at 40 DN was much larger than that of the south-east (20 DN) and north-west (15 DN). For Vaccinium heath (sub-classes 7, 8 and 9) the mean pixel values also decreased from south-east to north-west. However, for this class the standard deviations of the south-east and north-west aspects were greater than for the top, or level, terrain.

Blanket bog (sub-classes 13, 14 and 15) was found on level rather than sloping ground and showed very little change in either mean or standard deviation. Bracken (sub-classes 20 and 21) showed an extremely large change in both mean and standard deviation from the south-east to the north-west aspects. The classes of key interest were those with two or three aspect sub-classes. Vaccinium heath, classes 7-9, exhibits what might be described as the 'expected' response. In most wavebands there is a higher, and more variable, response for areas of Vaccinium heath lying on sunny south-east-facing slopes and this trend holds for all the TM wavebands. Bracken, classes 20-21, shows this same consistent decrease in response from south-east to north-west aspects for all wavebands.

Calluna heath, classes 16-17, has the same trend for all wavebands except TM4 where there is a higher DN response for the north-west aspects than for the south-east aspects. The summer of 1984 produced drought conditions in the shallow upland soils. The wetter, deeper pockets of soil holding Calluna on north-west slopes could have sustained a lusher growth, with a relatively high response in the near infra-red (TM4).

With some of the other vegetation classes, there are opposite trends in response for adjacent wavebands. Nardus grassland, classes 2-4, for example, has a higher response for the plateau sub-class (3) than for the others in TM3. In TM4, this situation is reversed, with the plateau sub-class showing a lower response than the south-east and north-west sub-classes. The Nardus plateau sub-class lies on some of the highest and shallowest soils in the area. During the drought, these areas took on a very scorched appearance due to the presence of large amounts of dead material which would increase the response in TM3 and decrease it in TM4.

Blanket bog, classes 13-15, had a variable response across the TM spectrum. The responses of the aspect sub-classes were linear in TM1 and TM2, then there was an upward trend from south-east to north-west in TM3, followed by a downward trend in TM4. In TM5, the response returned to linear. This wide variation in sub-class statistics confirmed the need for a strategy to reduce the effects of uneven illumination on classification.

The spectral variability of the terrain was indicated in the maximum and minimum values in the class statistics shown in Figures 4.8a-g. Water or shadows might have accounted for the low minimum values for classes 7, 15 and 21 in TM1 (Fig. 4.8a). A major stream, deeply cut with shadow, ran through the area of Vaccinium heath SE (class 7), and open pools of water were characteristic of blanket bog (class 15) for example. Some of the notable maximum class values for classes 15 and 21 in TM3 (Fig. 4.8c) could have been produced by specular reflection from the many pools and smooth boulders scattered across the study area.

The responses of vegetation aspect sub-classes in the TM wavebands outlined above emphasise the difficulties encountered in the classification of ground cover in the uplands. Firstly, the sub-class statistics show how different the response of a vegetation class can be depending on its position relative to the illumination source. It also highlights the difficulty of predicting the 'expected' response of vegetation. The study by Thomson and Jones (1990) previously referred to also found examples of coordinated and uncoordinated spectral responses in aspect sub-classes.

In this drought summer of 1984, vegetation types varied from 'normal appearance' according to the depth to which they were rooted and how well they were able to survive the water shortage. Vaccinium, for example, remained green and lush when adjacent grasses were wilted and dead.

Interestingly, it appeared that trends in the response of aspect sub-classes were not consistent across the TM spectrum. This is particularly important if some of the more simplistic measures for reducing the effect of aspect and slope are used. One such method, the division of adjacent wavebands, would be unlikely to produce a robust correction when trends in the response of aspect sub-classes can be reversed for adjacent wavebands.

The recommendations for improving the classification of upland vegetation, therefore, include the following. For a simple approach, divide the vegetation classes into a number of slope/aspect sub-classes, characterise and classify these sub-classes independently and recombine them post-classification. Current developments in classification software and the use of digital terrain models will provide more sophisticated strategies for reducing the effects of terrain and illumination. If a digital terrain model is available, it will be likely that an entire range of more sophisticated methodologies that are not considered here might be implemented.

4.11.2 Class Separability

Divergence analysis can indicate the separability of two cover types by measuring the overlap of their probability density distributions (Swain, 1978; Singh, 1984). The statistical separability of all possible pairs of classes can be computed. In this study, divergence analysis provided a measure of the change in separability of class pairs resulting from median filtering the TM data.

Transformed divergence scores were calculated to measure the separability of all pairs of classes using the unfiltered TM data (Table 4.5); a transformed divergence score of 100 indicates perfect statistical separability, scores of below 100 indicate some overlap of class feature space in the multivariate data set. This was repeated for the 3x3, 5x5 and 7x7 median-filtered TM data (Tables 4.6, 4.7, 4.8 respectively). Classes with wide variability in one or more TM wavebands had very low divergence scores; classes 7 and 15 for example. The matrix holding the scores for the unfiltered TM data was then subtracted from the three other matrices to calculate the change in score for each pair of classes after applying the median filters. Table 4.9 shows the change and percentage change in highest separability divergence scores for each class resulting from applying the pre-classification median filters.

Several points of interest are worthy of note. While there were some reductions in separability of individual pairs of vegetation classes, the general trend was of increasing separability. With the larger kernel filters (5x5 and 7x7) the general improvement in separability was greater than any reductions in separability. Improvements of up to 74% in transformed divergence score were found for several classes using the 7x7 median filter. The maximum changes in separability are shown in Table 4.10.

4.11.3 Comparing the Vegetation Maps

The last analysis of the effects of pre- and post-classification filtering involved comparing each of the sixteen TM classifications with the digitised NCC vegetation map. This was done on a pixel-by-pixel basis to produce a correspondence matrix for each comparison. Tables 4.11a to 4.11p (Appendix 8) show the normalised correspondence measure discussed by Congalton

(1991). The leading (or major) diagonals were extracted from each matrix to provide a measure of correspondence (Table 4.12). As discussed earlier, the off-diagonal elements (omission and commission errors) are directly included in any accuracy estimate using the major diagonal. Table 4.12 shows these measures of correspondence for the sixteen comparisons. There were improvements in correspondence of between 1% and 169% (mean 36%) when using the filtered rather than the unfiltered TM data. Some of the filtered data produced worse correspondence than the unfiltered TM data; the improvement in correspondence from the worst combination of filtrations to the best was between 16% and 278% with a mean improvement of 52%.

Table 4.13 separates the effects on correspondence for the different filter types. It identifies the change in correspondence resulting from the application of each filter type. Table 4.14 summarises these results; + indicates that the cover type had generally improved correspondence after the application of that filter type, - indicates a general decrease and = indicates no substantial effect. Half of the cover types generally showed increased correspondence after pre-filtering; half showed a decrease. Most of the cover types showed a general increase in correspondence after post-filtering. One cover type, Bracken, showed a general decrease in correspondence after either filter type.

The effects of pre- and post-classification filtration are more easily interpreted by looking at graphical representations of the changes in correspondence when using unfiltered and filtered data. Figures 4.9a to 4.9d show the changes (%) in correspondence resulting from an increase in pre-classification median filtration for each level of post-classification filtration. These graphs show that for all but one class (3, Agrostis-Festuca), the 3x3 median filter produced a decrease in correspondence between TM and NCC mapping. The 5x5 median filter produced increases in correspondence for some classes, and decreases for others. In most cases, the 7x7 median filter increased correspondence between the TM and NCC maps.

There were large increases in correspondence for some classes resulting from the median filtration: Agrostis-Festuca up to +60%, Soligenous flushes up to +20%, Calluna heath up to +15%. But also some notable decreases: Molinia grassland down to -30%, and many other classes down by -10% or -15% for some of the filter combinations. Almost any combination of filters reduced correspondence for some classes, notably Bracken, Blanket Bog and Rhacomitrium heath.

Figures 4.10a to 4.10d shows the changes resulting from an increase in post-classification majority-mode filtration for each level of pre-classification filtration. The major feature noted from these plots was that almost without exception post-classification filtering increased correspondence. This increase was in general between 5% and 15% with a progressive increase in correspondence resulting from the increasing kernel size (3x3 to 5x5 to 7x7).

There was a reduction in correspondence for only one class (3, Agrostis-Festuca), and then by only about 2%. The other feature of note was that as the pre-classification filter increased in size from none to 7x7, the effect of the post-classification filter was reduced and became less erratic.

The effect of filtration on correspondence for each vegetation class is also more easily examined on a graph. Figures 4.11a to 4.11k show the effects of each combination of filtration on each vegetation class. For Nardus-Juncus grassland and Calluna heath there were small decreases in correspondence after a 3x3 median filtration; the larger 5x5 and 7x7 pre-classification median filtrations, however, produced progressive increases in correspondence. All the post-classification filtrations increased correspondence, but the increase was smaller when there had already been some pre-classification filtration.

There were markedly different trends for other classes. Molinia grassland showed a dramatic decrease in correspondence after 3x3 and 5x5 median filtrations; it did, however, benefit from post-classification filtration at all stages. Vaccinium heath and blanket bog showed a similar response with some small increases in correspondence after 7x7 median filtration, but larger increases after all of the post-classification filtrations.

There were strikingly-different responses from Agrostis-Festuca grassland and Soligenous flushes. Both of these classes showed large increases in correspondence after pre-classification filtration, but with little to choose between the 3x3 and 5x5 filters; post-classification filtration increased correspondence more when there had been some pre-classification filtration. Bracken showed responses that were quite unlike any other class. Pre-classification filtration progressively decreased correspondence; there was a small increase in correspondence after post-classification filtration at all stages, but the 7x7 kernel produced no more increase than the 5x5.

The classes with a minimal amount of vegetation cover, crags which were in heavy shadow on the Glyderau and scree which received full sun, were the only classes to show two reverses in trend. The reverses in trend occurred after the 3x3 and 5x5 median filters, but in opposite directions for each class.

4.12 DISCUSSION AND CONCLUSION TO SECTION ONE

For seven out of eleven vegetation classes the highest correspondence was achieved with the maximum level of both pre- and post-classification filtration, using a 7x7 kernel in each operation. However, the intermediate effects on correspondence were not consistent; there was a relatively consistent trend for only two classes (Agrostis-Festuca grassland and Soligenous flushes). For many of the classes, some of the intermediate treatments produced decreases in correspondence. There were no reductions in correspondence for any classes resulting from the post-classification majority-mode filtrations.

The extensive nature of the Glyderau study area, the complex topography and vegetation communities and the large patches of scree and boulder material contrast with the terrain of lowland areas. These and other factors must certainly be implicated in the response of the TM data to median filtration. Features under the control of the fieldworker also appeared to need consideration. There may be some link between the distribution and nature of the vegetation on the ground, the way in which it is mapped by the fieldworker, and the subsequent correspondence between the vegetation maps. Bracken, for example, was often found in small but dense stands on the Glyderau, and because of the interest in this invasive species it was mapped in great detail. Other vegetation types such as Nardus grassland dominate extensive swathes and were mapped accordingly. Small patches of Nardus in other classes, however, were not mapped in such detail as bracken; and, conversely, small patches of vegetation other than bracken in the extensive Nardus swathes were also not mapped in as much detail.

Amongst some of the large areas of homogeneous vegetation were many small rocks, boulders, patches of exposed soil and other non-vegetative debris. Pre-classification filtering helped to reduce the effect that these small objects had on the spectral characterization of the classes; this, in turn, produced a classification which was closer to the field survey, increasing correspondence. Field surveys tend to concentrate on the botanical nature of the terrain; median filtration will help to reduce the influence of minor non-vegetative components in the terrain, 'concentrating' the attention of the machine classifier on the vegetation.

The effect of the pre-classification median filter on TM data from the upland site in this study was not expected. On the Glyderau, the effects of the 3x3 and 5x5 median filters were both class- and waveband-specific. The divergence analysis supported these findings by indicating a reduction in separability of class pairs following the application of the 3x3 and, in some cases, the 5x5 median filter. The 7x7 median filter produced the only consistent increases in separability.

Post-classification image processing with a majority-logic filter increased correspondence between the two survey products in all cases. This type of filter produced a 'smoothing' or generalization of the image with the 7x7 kernel producing a more marked effect than the 3x3 or 5x5 filters. Some heterogeneous vegetation classes had components that were spectrally similar to other classes, or components in other classes. This produced some isolated pixels which were classified, rightly or wrongly, as being different from the majority of their neighbours, this filter removed them. An increase in correspondence always resulted because the classifications were being compared with a simplified field survey map.

The improvements in correspondence produced by the post-classification filtering were not always as large as some of those resulting from the median filters, but they were far more consistent in their effect. The majority-mode filter produced a classmap with a similar appearance to the type of vegetation map derived from field survey and increased the correspondence between the TM and NCC maps. It was reassuring to find that the common practice of smoothing classmaps need not detract from their quantitative agreement with ground survey.

In conclusion, it appeared from this study that the adoption of relatively large kernel sizes (7x7 rather than 3x3 or 5x5) for both pre- and post-classification filtering suited the variable terrain on the Glyderau uplands. While the spatial resolution of TM data is useful for locating boundaries and training areas on the ground, one conclusion that might be drawn from the success of the 7x7 filtrations is that Landsat MSS data could be quite adequate for the mapping of general upland vegetation types.

There were, however, some vegetation types (notably Bracken) which suffered severely-reduced correspondences when filtered to any extent. Bracken showed responses that were quite unlike any other class; pre-classification filtration progressively decreased correspondence, there was a small increase in correspondence after post-classification filtration at all stages, but the 7x7 kernel produced no more increase than the 5x5. The smoothing effect of the median filters may have diluted the distinct appearance of the small patches of bracken and increased the confusion, or spectral overlap, with other classes resulting in lower correspondence. The post-classification filtration had only a small effect on correspondence because there was little variability in the areas classified as Bracken.

There do not appear to be any obvious reasons for the responses to filtration of the other classes. It should be possible to establish the consistency of the response of the vegetation types from repeated studies in other areas. If the characteristics determining the response to filtration of vegetation and terrain can be established, it may be possible to predict the ideal combination of filtration for other vegetation types.

Image filtering provides a technique for simplifying raster-format vegetation maps. In general, a fairly 'strong' or large kernel size filter increased the correspondence between the vegetation map derived from ground survey and those produced by satellite survey. However, correspondence was reduced for at least one important vegetation type.

A hybrid approach using the combination of filters most suitable for each vegetation type might help to maximise classification agreements between ground and satellite surveys. Each class would be classified using the appropriate filter combinations, resulting in several classmaps; a composite classmap would then be constructed by taking the appropriate classes from these. As experience in the use of filtration is gained, it may be possible to draw up decision rules for predicting the optimum combination of filters according to sensor, vegetation and terrain.

While the spatial resolution of TM data was useful for locating boundaries and training areas on the ground, one conclusion that might be drawn from the success of the 7x7 median filtrations is that Landsat MSS data could be quite adequate for the mapping of general upland vegetation types.

It should be noted that in the temperate upland grasslands of Snowdonia, vegetation dominates ground cover at all but the highest altitudes. In more arid regions, vegetation is frequently a minor element of ground cover; in that situation, this methodology could be useful in reducing the effect of vegetation when, for example, classifying soil types. In vegetation studies of arid regions, pre-classification spatial filtering may be distinctly unwise. A pilot study has to be strongly recommended if this technique is to be implemented in other regions.

SECTION TWO

G.I.S. APPLICATION FOR UPLAND MANAGEMENT INFORMATION

4.13 SUMMARY OF CHAPTER 4, SECTION TWO

A small experimental Geographic Information System (GIS) was set up for part of the Glyderau mountain range in Snowdonia. The objective was to be able to provide management information relating to this important upland area. An NCC vegetation map from 1984 and land ownership boundaries were vector digitised and transferred to a raster image analysis system. Landsat Thematic Mapper (TM) data from July 1984 were registered to the map base, and classified. The system was interrogated to produce areal estimates of vegetation type by ownership category from both the NCC and TM classifications.

When the mapping of upland vegetation from satellite data becomes sufficiently accurate, there will be a real possibility for the updating of management information more frequently than the 10- to 15-year intervals between ground surveys. The addition of other datasets (soils, geology, hydrology) to systems like this will increase the utility of the information system.

4.14 INTRODUCTION TO SECTION TWO

In the early days of digital mapping most work concentrated on developing software and hardware in order to reproduce in a digital form the traditional paper map. However, it was soon apparent that much of the potential of these digital techniques lay in their ability to process map and map-related information in many more flexible ways in response to individual information needs. As a result, the manufacturers of digital mapping systems have become increasingly geared towards the 'information systems' idea.

There are a number of British manufacturers (and many in the U.S.A.) who can supply 'off-the-shelf' mapping systems that are able to interrogate digital cartographic data, and link it with non-mapped information and text. Large organisations such as the Central Electricity Generating Board (CEGB) use digital mapping techniques to produce large-scale diagrams of local electricity networks. The British Geological Survey (BGS) use similar systems to address the problems of geological mapping in three dimensions. Rural resource management is another area where such techniques can be usefully applied.

The objective of this study was to produce management information relating to upland vegetation for part of the Glyderau mountain range in Snowdonia. Organisations such as the Countryside Council for Wales (CCW) require estimates of the areas of certain vegetation types lying within the various ownership boundaries in the mountains. This information can assist their monitoring of rare and important vegetation types lying within protected and unprotected ownerships.

An important technique currently being implemented by many digital mapping organisations is 'polygon overlay'. Given an area 'A' and an area 'B' which overlap, a new third area 'C' is formed which is a combination of 'A' and 'B'. The formation of such areas/polygons is straightforward on most systems, but the automatic re-classification of the new polygon (area 'C' in this example) is a more complex task.

On most systems cartographic data are stored in vector format. Polygon overlay with automatic reclassification of new areas is more readily achieved with raster format data. Some digital cartography systems already have this facility. Another route to achieve the same end-product involves the use of a vector-based cartographic system and a raster-based image analysis system. This approach was used for the Glyderau study. The map information was vector digitised on a Sysscan Mapping System (SMS), converted to raster format and transferred to an International Imaging Systems (I^2S) raster image analysis system. The polygon overlay was carried out in raster format on the I^2S system.

The Sysscan system can access non-mapped data stored on more conventional database packages such as 'Datatrieve' or 'Oracle'. Several organisations hold information relating to topographic and physical environmental variables as well as flora and fauna species distribution data in various formats. The interrogation of these data can be improved by registering each dataset to a common base which for most purposes in the UK is the British National Grid (BNG).

For example, the Glyderau dataset can be interrogated to discover the vegetation types lying within each ownership. However, with the addition of an information file, on Datatrieve, it is also possible to call-up other non-mapped information such as a history of events or management activities relating to that area.

4.15 DIGITISING THE MAP DATA

For the purposes of this pilot study it was necessary to digitise two maps of the study area. The first was an NCC vegetation map produced from ground survey in the study area during the summer of 1984 (Fig. 4.3). This was a fairly complex 1:10,000 map consisting of lines representing vegetation boundaries, and text describing the nature of the vegetation. The boundaries were converted to solid polygons for use on the I^2S system and the text enabled each polygon to be classified into one of twelve major vegetation types.

The second map (Fig. 4.12) represented ownership boundaries for the same area at a scale of 1:25,000. This map was digitised and registered to the vegetation map. Trial plots were made of each map, and software routines checked the linework to make sure that all the polygons were 'closed'.

These maps were transferred to the I^2S in two formats. Firstly as linework (Fig. 4.13) to be used for visual interpretation of the remotely-sensed data, and secondly as solid polygons for polygon overlay in raster format. The solid polygons were created by defining a line width and spacing for plotting that would appear as a solid area on the I^2S; current GIS systems would use a vector-to-polygon, ploygon-to-raster conversion routine. The polygons for each vegetation class were transferred separately to the I^2S and then combined in the form of an intensity-encoded composite image (Plate 4.12).

4.16 POLYGON OVERLAY

With the map data in raster format on the I²S it was a relatively simple step to overlay the ownership boundaries on the vegetation map and produce a tabular output showing the area of each vegetation type within each ownership. Each ownership area was fed into a graphics plane and this was used to 'cut through' the vegetation map. The product of this process was a new image showing only that ownership area and the vegetation classes within it. It was then necessary to run a function on the I²S which counts the number of pixels in each intensity level of the image. With a known pixel size (15x15 metres) and with each intensity level representing a vegetation class the output of this function was a table of vegetation class by area. Figure 4.14 shows a plotted representation of this 'cut' for Owner 13, an area of National Trust land. The various hatching patterns represent the intensity-encoded vegetation classes. Table 4.15 shows the area (hectares) of each vegetation type derived from the NCC field survey for this ownership. This procedure was repeated for the other ownerships in the study area to produce a summary table for the whole area (Table 4.16).

4.17 CLASSIFICATION OF LANDSAT TM DATA

The Glyderau study area was classified using Thematic Mapper data and a maximum likelihood classifier on the I²S as described earlier. The result of this classification was an intensity-encoded classmap in raster format similar to the digitised NCC vegetation map. Pre- and post-classification spatial filters were used to improve the correspondence between the NCC vegetation map and the TM classification. Full details of this methodology were presented in section 4.10. It was then a simple step to repeat the process of polygon overlay and produce estimates of the areas of each vegetation type in each ownership from the remotely-sensed data.

The estimates from ground survey and from the remotely-sensed data differed. For Owner 13 (Fig. 4.14) National Trust, Table 4.16 shows the areal estimates from both the NCC survey (OWNER13) and from the classified TM data (IISML13). Some of the areal estimates for particular vegetation types were comparable (Nardus-Juncus), others were very different (Blanket bog). This was to be expected because it is extremely difficult to classify mountain vegetation from satellite data. There are problems arising from the interaction between terrain and illumination, and from the heterogeneity of the ground cover. It is also difficult to reconcile the objective classification of multispectral data with the more subjective botanical classification of plant species.

4.18 CONCLUSION TO SECTION TWO

Geographic Information Systems offer a real opportunity for the incorporation of data from different sources. For example, an increasingly-popular addition to the dataset for upland applications is terrain data. Information relating to the physical structure of the area or its previous condition can be used to stratify training areas prior to classification; it can also be incorporated in the classification to provide another dimension of detail. The classification of TM data in the Countryside Survey 1990 (Fuller et al., 1992), for example, includes reference to the use of prior knowledge from previous field surveys in validating the TM classifications. It is beneficial to have spatially registered data which can be used to evaluate and verify new data sources. In this study, for example, pixel-by-pixel comparisons were made between the NCC field survey data and the classified Landsat TM data to determine the most suitable classification methodology. As the techniques for classifying ground cover from satellite data improve there will be realistic opportunities for updating vegetation maps of the uplands using satellite or aircraft remotely-sensed data.

CHAPTER FOUR

PLATES
FIGURES
AND
TABLES

PLATE 4.1
The Glyderau Study area in Snowdonia
Image width is 7.7km; top of page is North
Local features are visible: Llyn Ogwen, Tryfan mountain,
Llynau Mymbyr lakes at Capel Curig

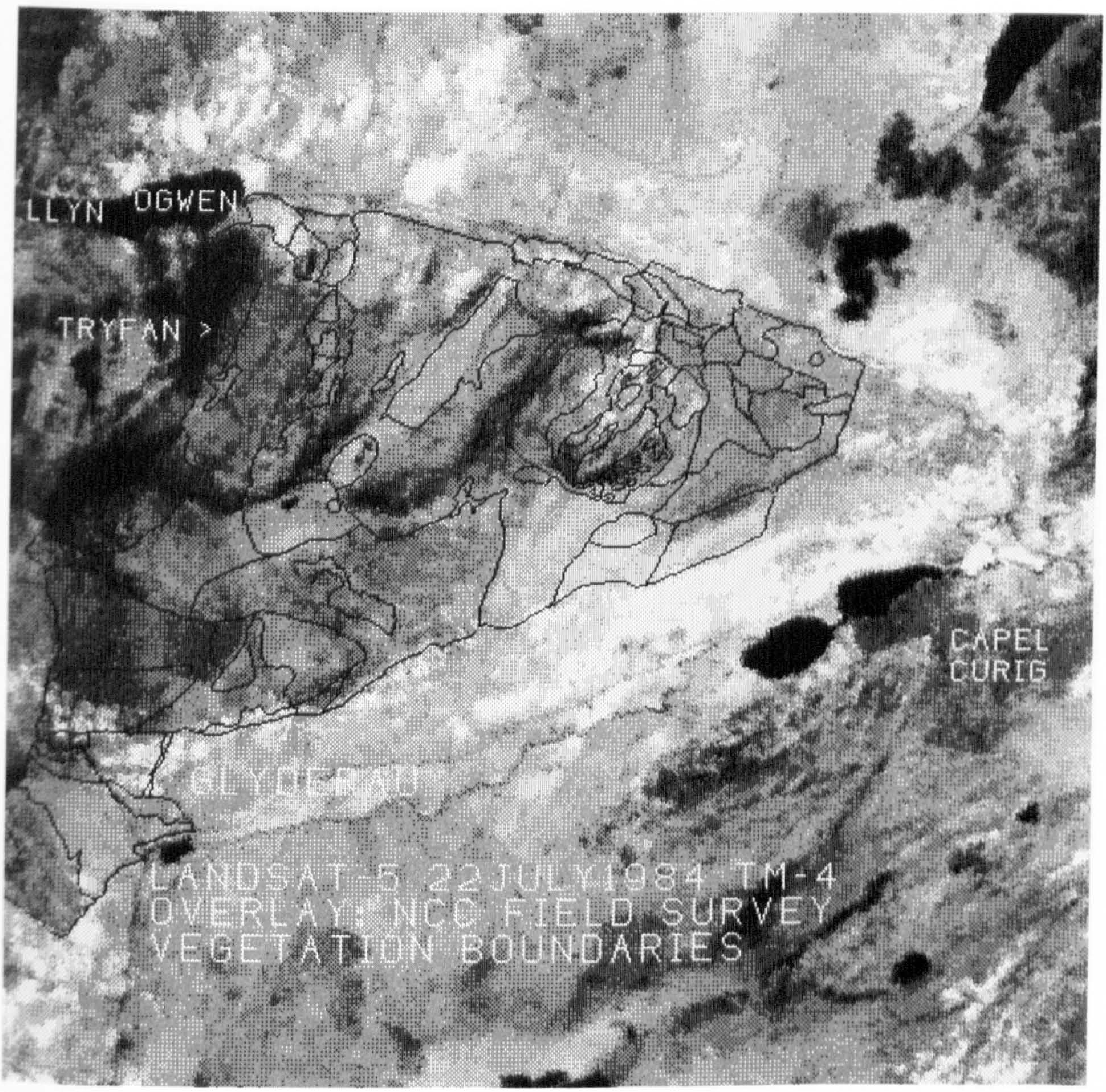


PLATE 4.2
Snowdonian mountain massifs: Glyderau
Snowdon, Carneddau and the Nantlle Ridge
Image width is 30km; top of page is North
Cloud cover on the north-western Carneddau

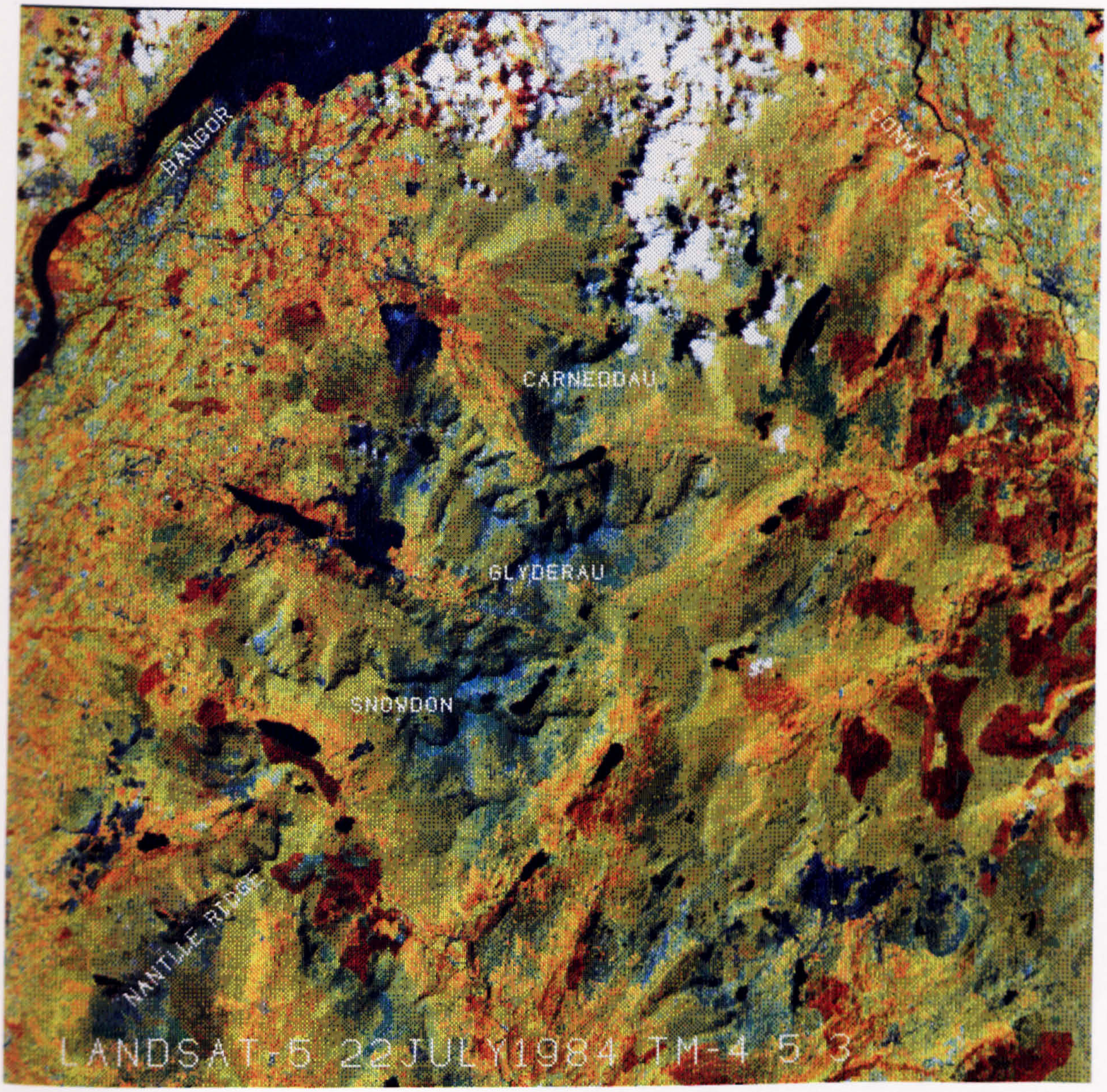


PLATE 4.3
Landsat Thematic Mapper data
Geometrically-corrected study area
Image width is 7.7km; top of page is North
Field survey vector boundaries shown

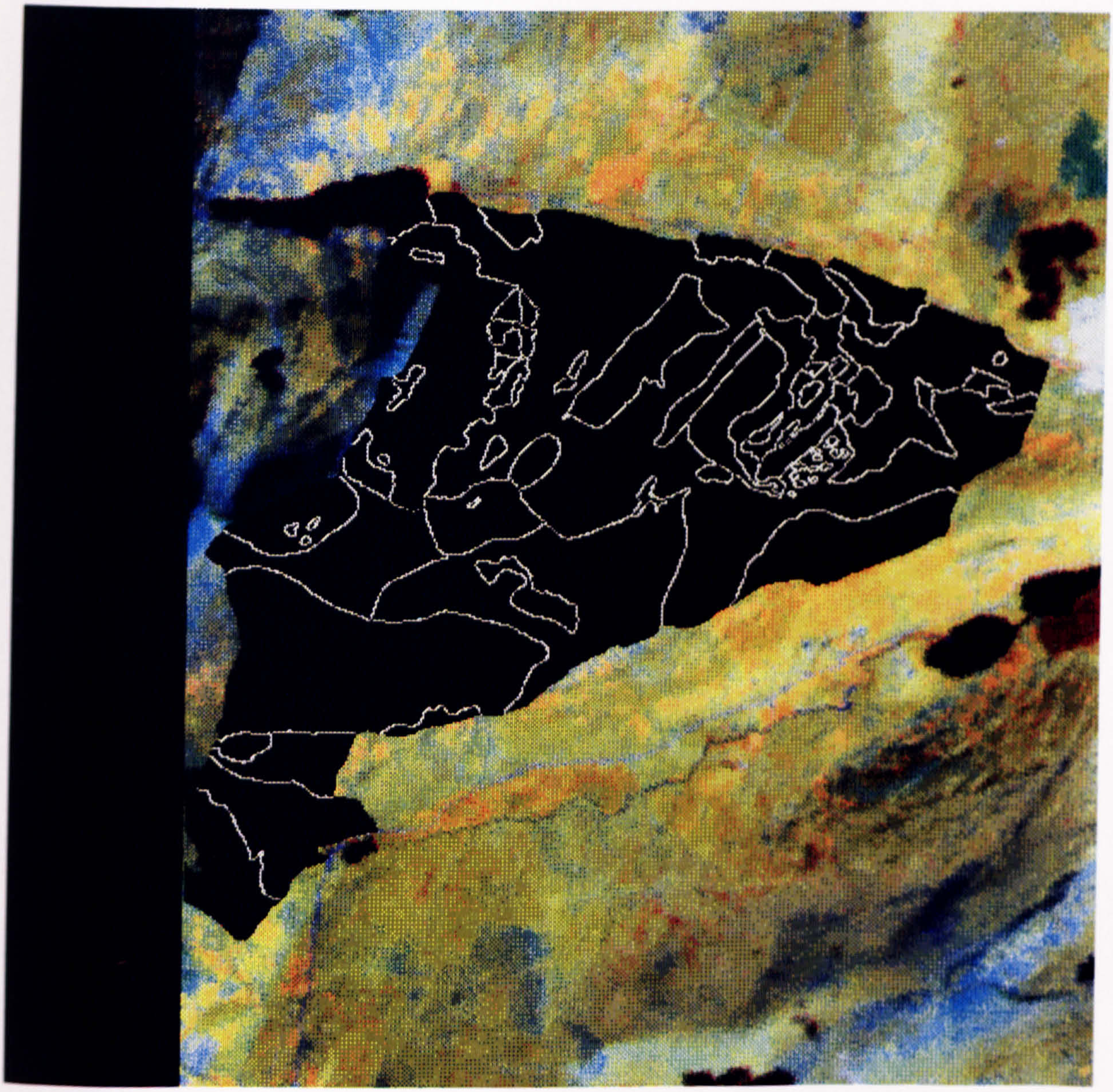


PLATE 4.4
Field survey vegetation boundaries
shown on study area Thematic Mapper composite
Image tones show some correspondence with boundaries
Image width is 7.7km; top of page is North

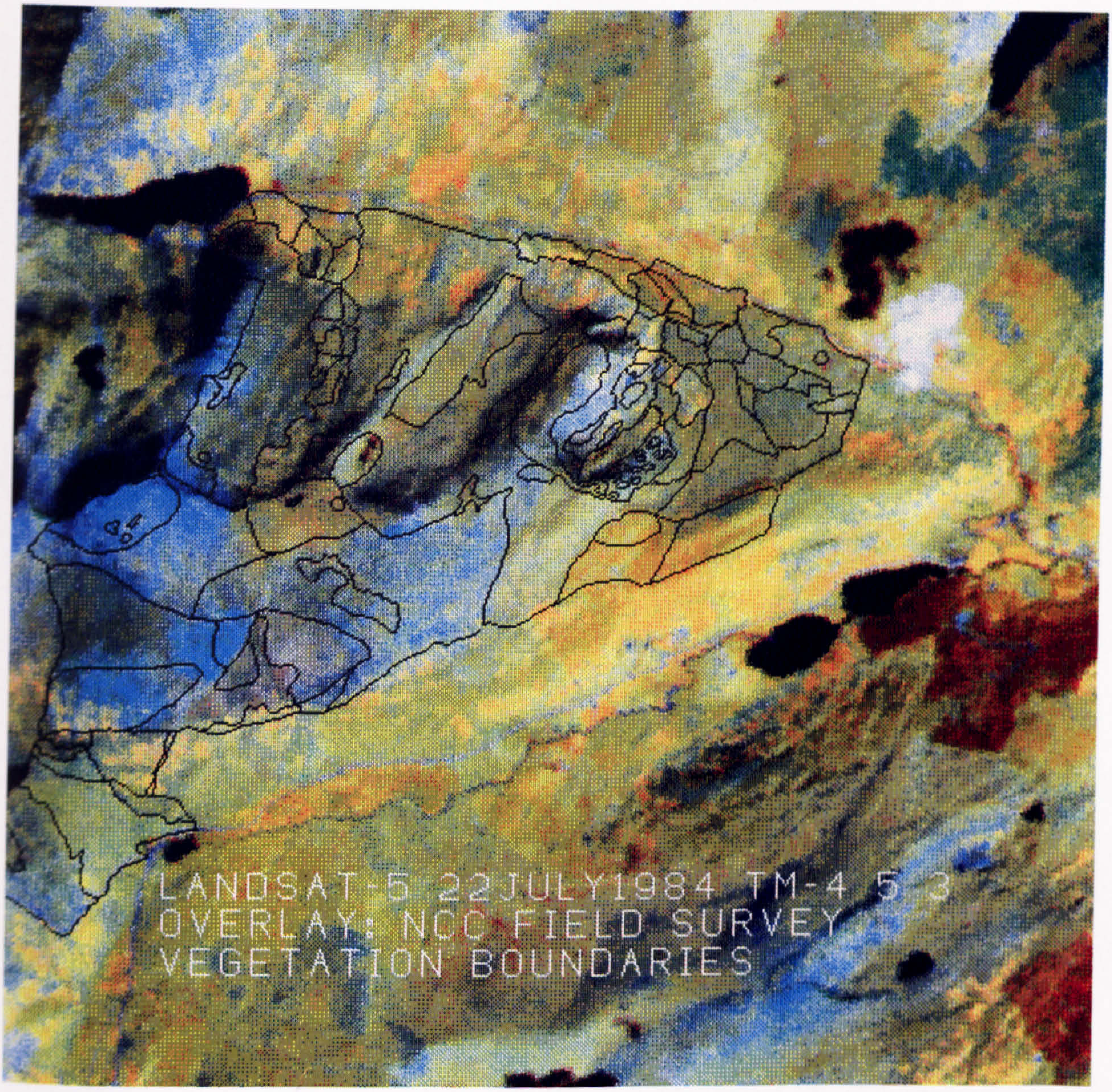


PLATE 4.5
NCC Field survey vegetation classes
Vector boundaries converted to raster masks
Class codes refer to Level II, Table 4.1
Image width is 7.7km; top of page is North

PLATE 4.6
Unfiltered Thematic Mapper data
High degree of variability in land cover units
TM bands 4, 5, 3 to Red, Green, Blue
Image width is 7.7km; top of page is North

PLATE 4.7
Median-filtered Thematic Mapper data
Kernel size: 9 x 9 pixels
Variability reduced in land cover units
Image width is 7.7km; top of page is North

PLATE 4.8
Thematic Mapper classmap of study area
Maximum-likelihood classifier used
High spatial variability present in image
No spatial filters applied to initial classmap

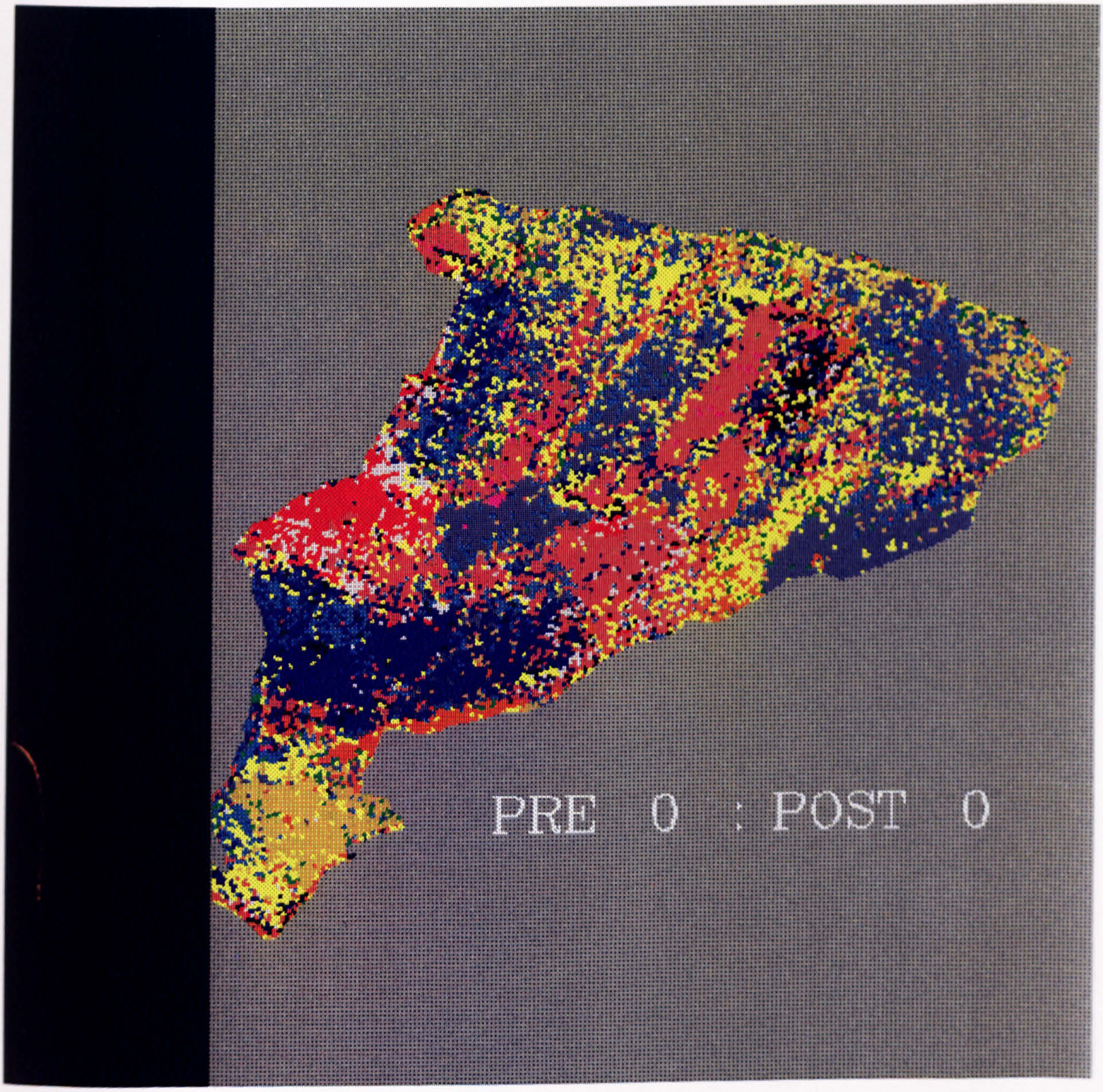


PLATE 4.9
Post-classification majority-mode filter
applied to initial Thematic Mapper classmap
Many isolated pixels re-classified
Variability remains in heterogeneous regions

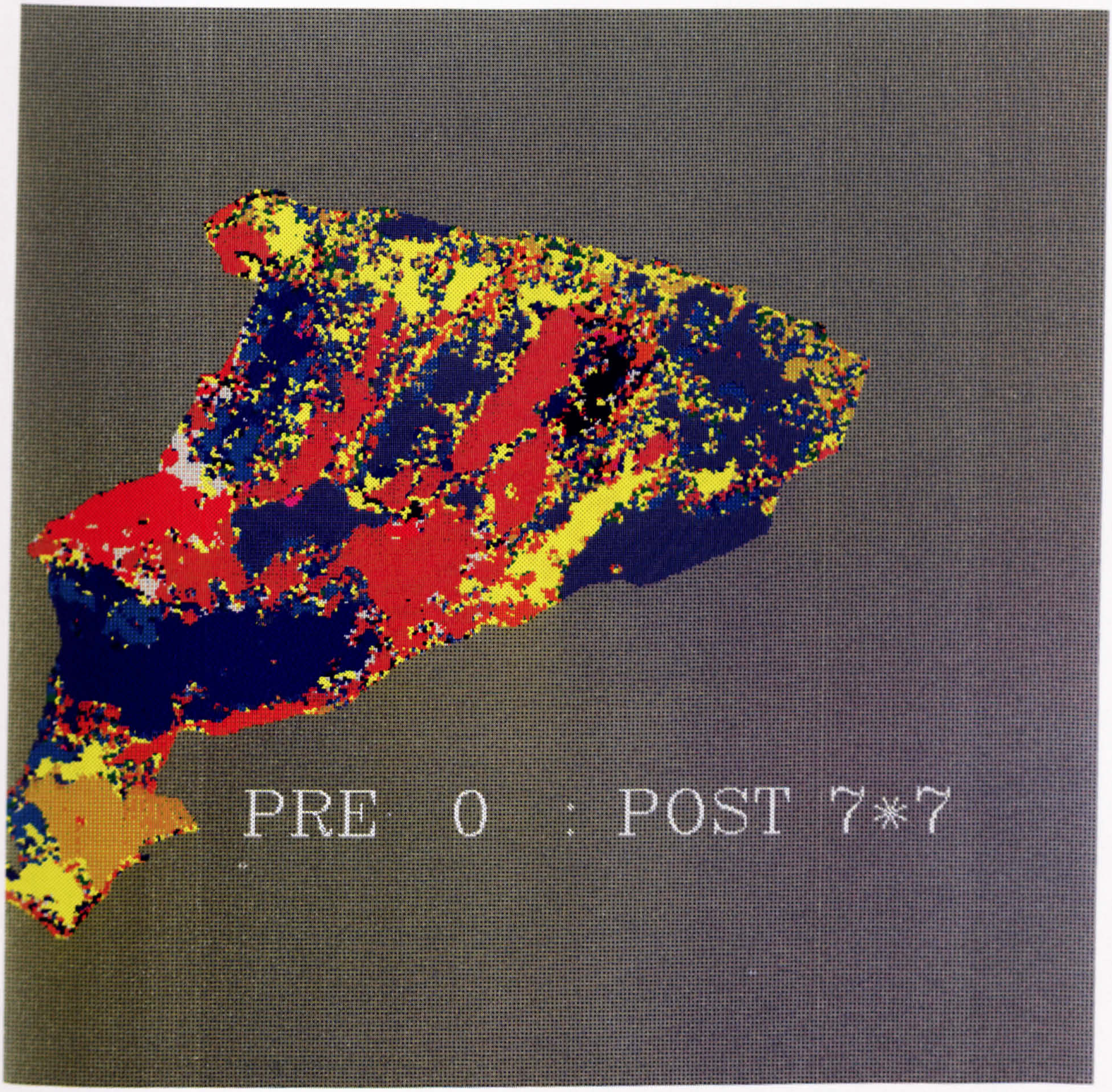


PLATE 4.10
Pre-classification median filter
applied to Thematic Mapper data
Regions classified with lower variability
Isolated pixels remain in many boundary zones

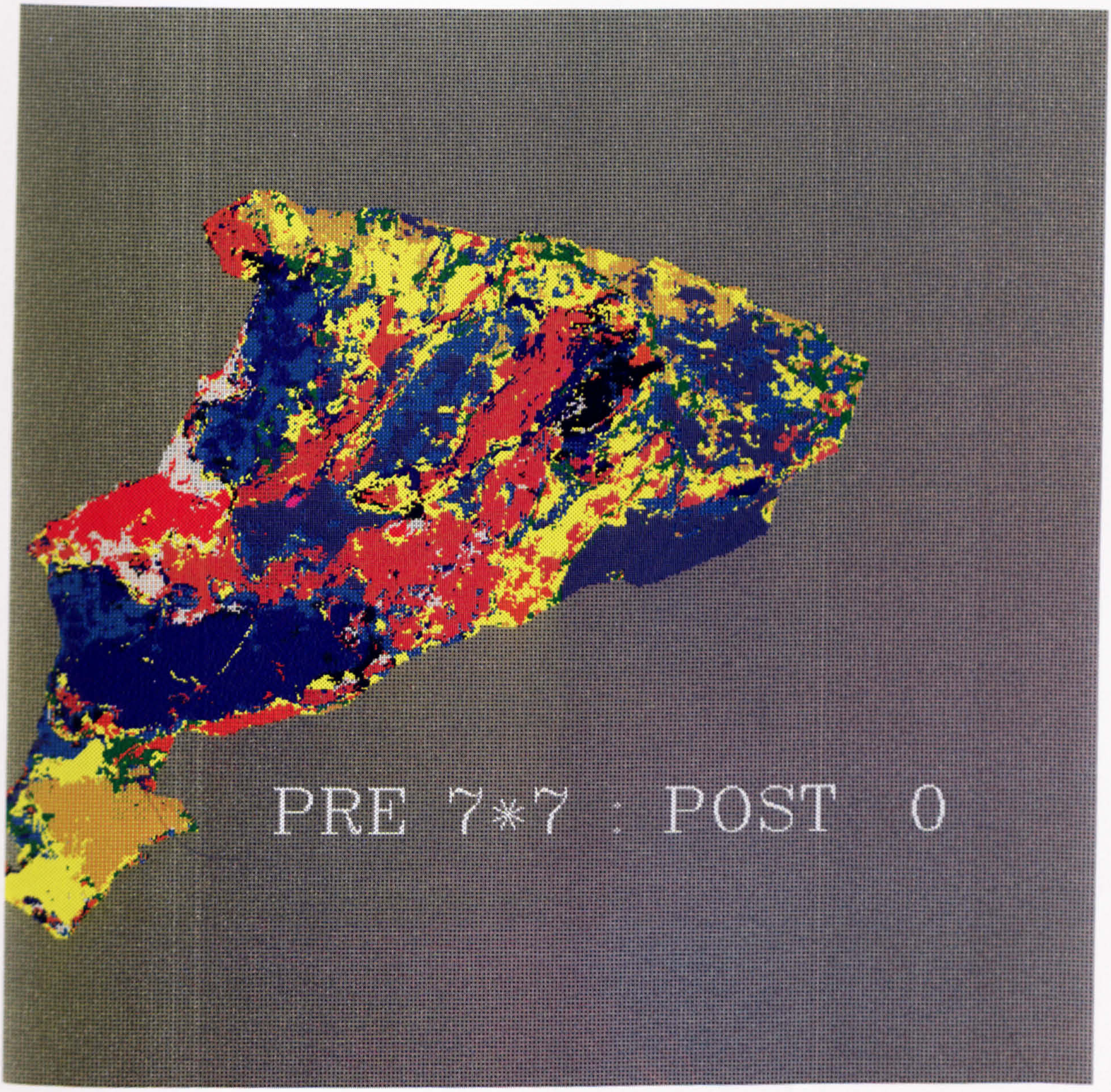


PLATE 4.11
Pre- and Post-classification filters applied
Regions classified with lower variability
Many isolated pixels re-classified
Image is more comparable with NCC survey

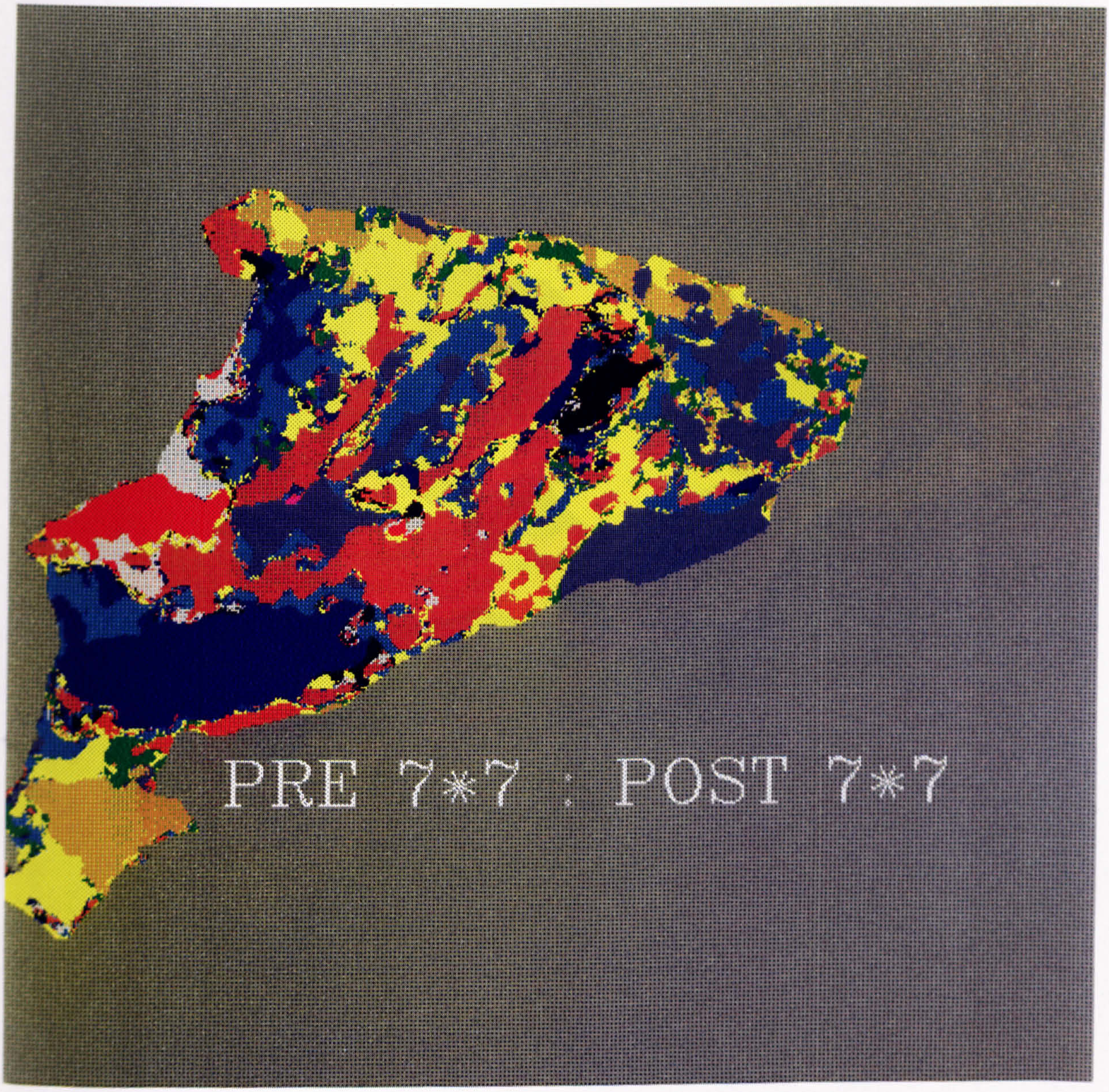


PLATE 4.12
NCC Field survey vegetation classes
Very generalised vegetation regions
Simulation from remote sensing
may need to be visually comparable

PLATE 4.13
Western part of study area
NCC Field survey on left
and TM classmap on right
together for comparison

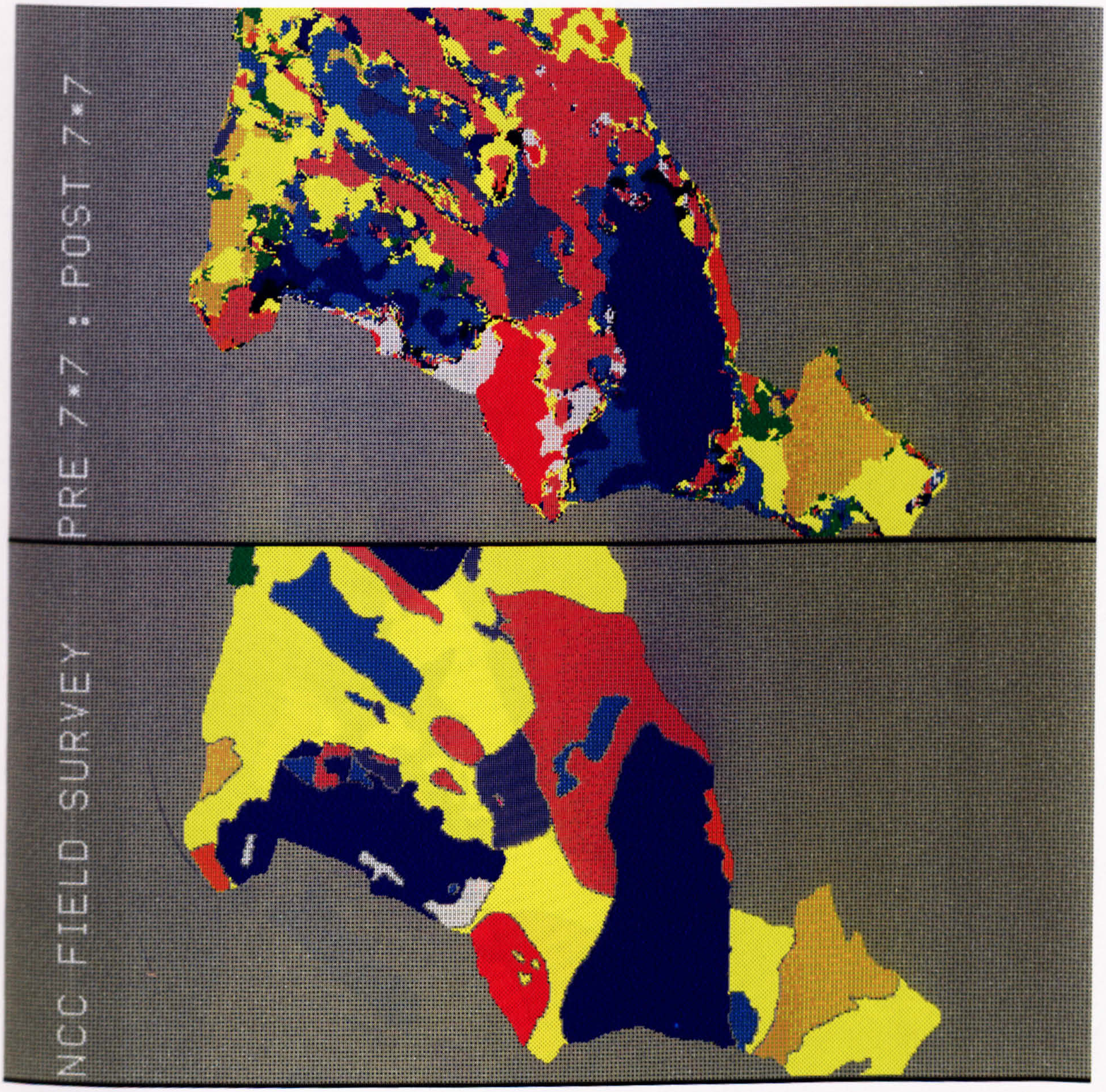


PLATE 4.14
Eastern part of study area
NCC Field survey on left
and TM classmap on right
together for comparison

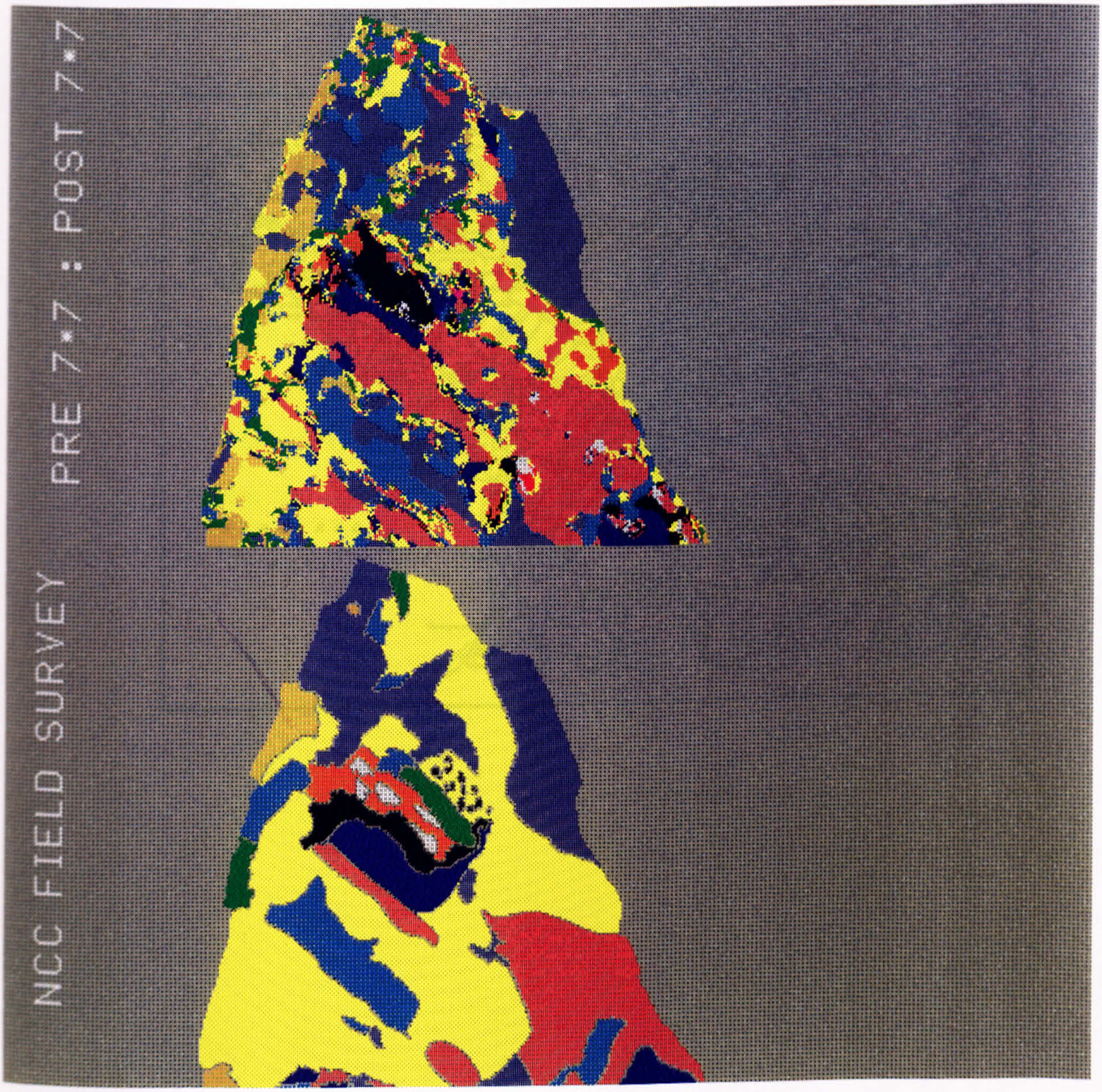
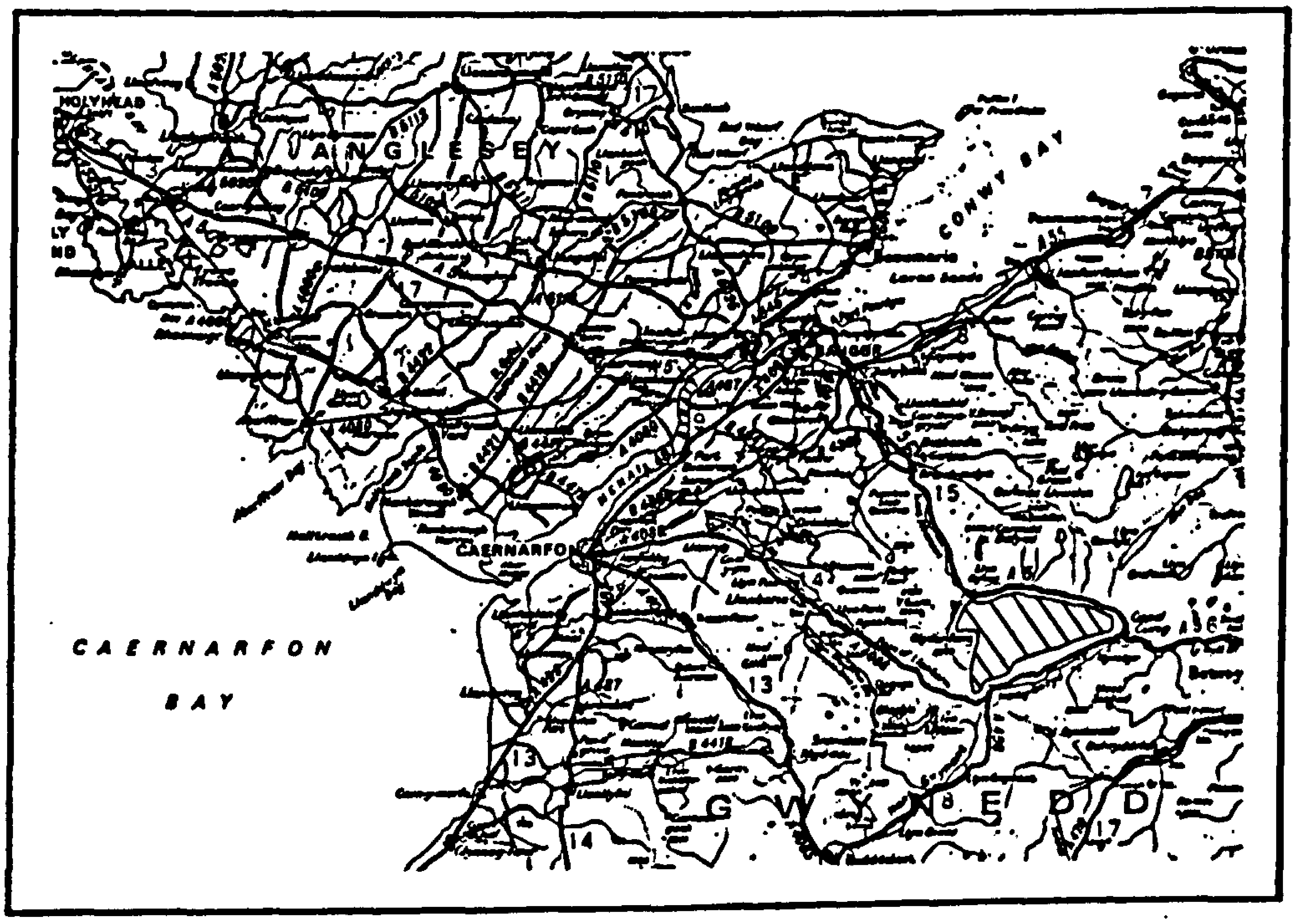


FIGURE 4.1

Map width is 60km.
Location map showing the Study Area (hatched)
on the Glyderau mountains in Snowdonia, north Wales.



FIGURES 4.2 a to g

The following seven histograms display the frequency distribution of digital numbers (DN) from the Earthnet system-corrected source image.

The data were extracted from a sub-scene of the 204/23 Thematic Mapper image from the 22nd July 1984; a 512 x 512 pixel image centred on the Glyderau study area.

Thematic Mapper waveband 1	Figure 4.2 a
Thematic Mapper waveband 2	Figure 4.2 b
Thematic Mapper waveband 3	Figure 4.2 c
Thematic Mapper waveband 4	Figure 4.2 d
Thematic Mapper waveband 5	Figure 4.2 e
Thematic Mapper waveband 6	Figure 4.2 f
Thematic Mapper waveband 7	Figure 4.2 g

Figure 4.2 a
The histogram shows the frequency
distribution of digital numbers (DN)
from the Landsat Thematic Mapper image.

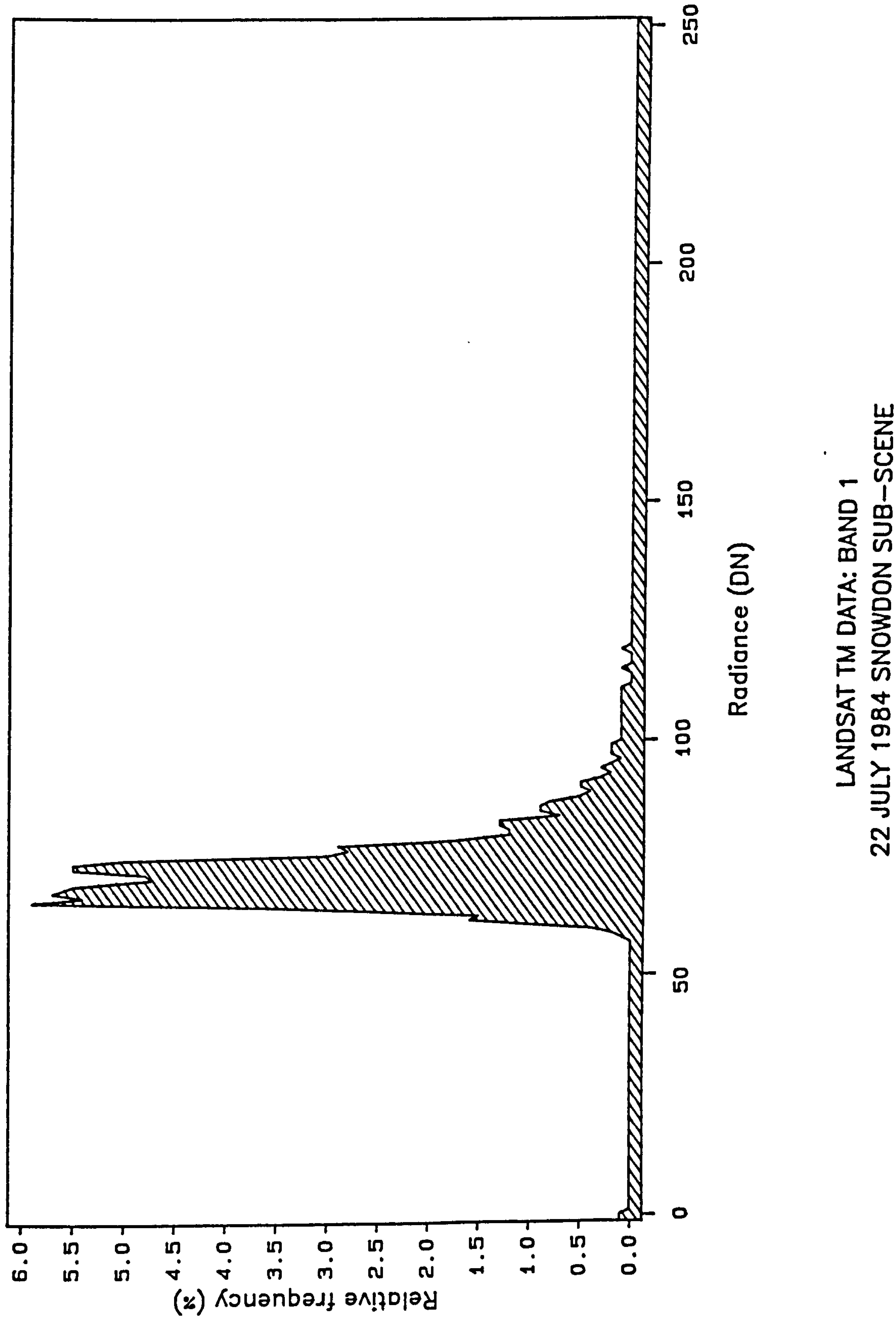


Figure 4.2 b
The histogram shows the frequency distribution of digital numbers (DN) from the Landsat Thematic Mapper image.

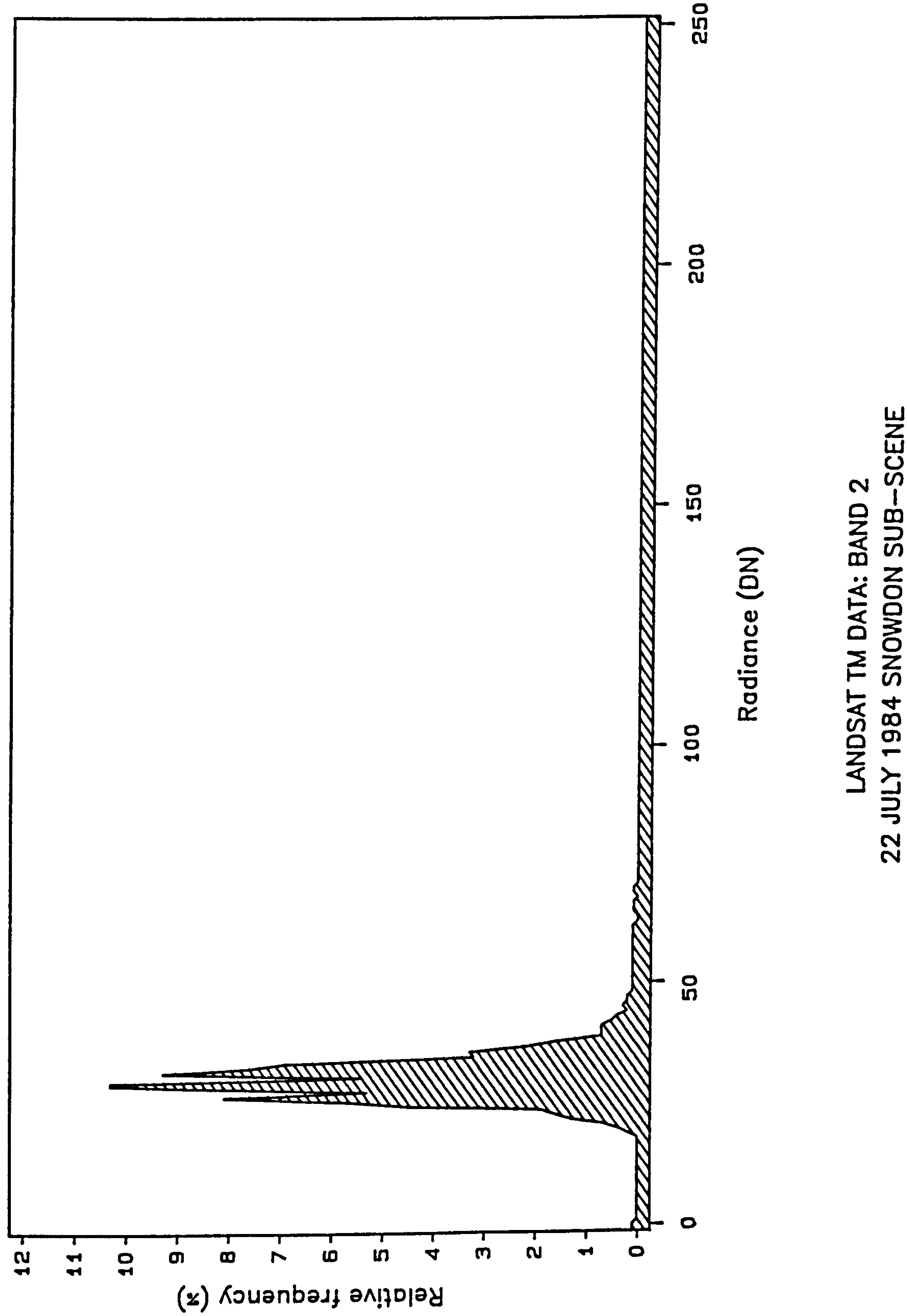


Figure 4.2 c
The histogram shows the frequency
distribution of digital numbers (DN)
from the Landsat Thematic Mapper image.

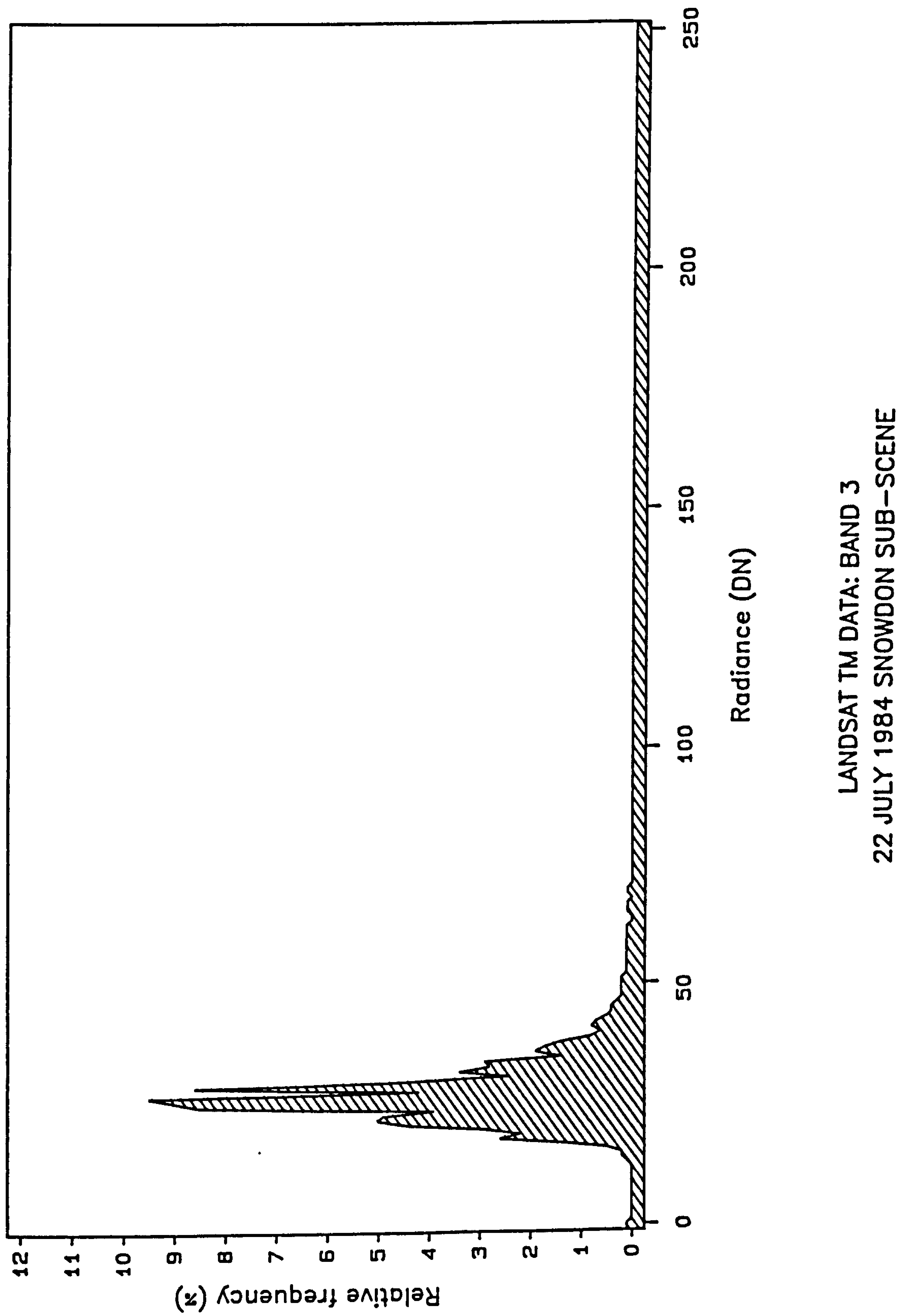


Figure 4.2 d
The histogram shows the frequency
distribution of digital numbers (DN)
from the Landsat Thematic Mapper image.

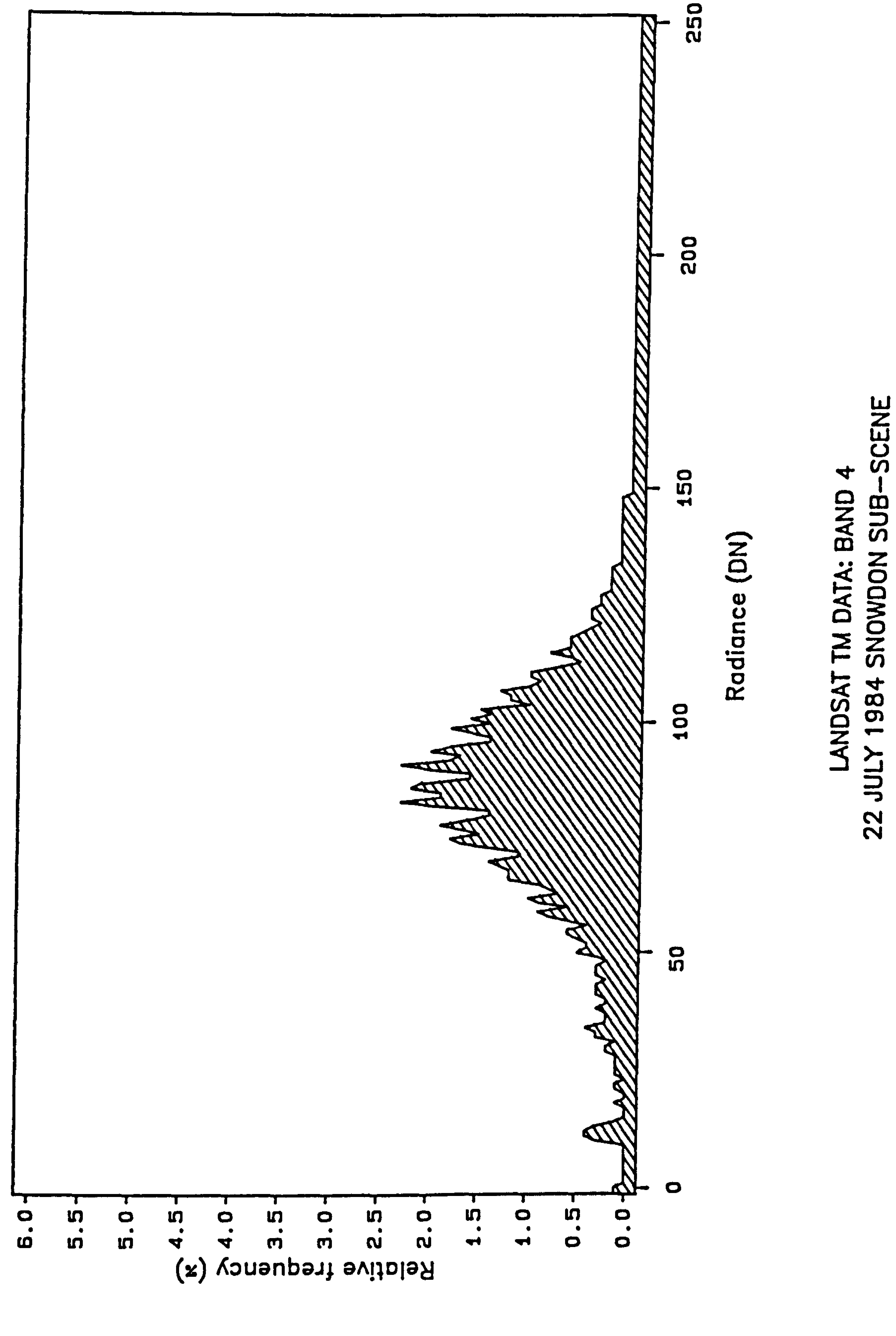


Figure 4.2 e
The histogram shows the frequency
distribution of digital numbers (DN)
from the Landsat Thematic Mapper image.

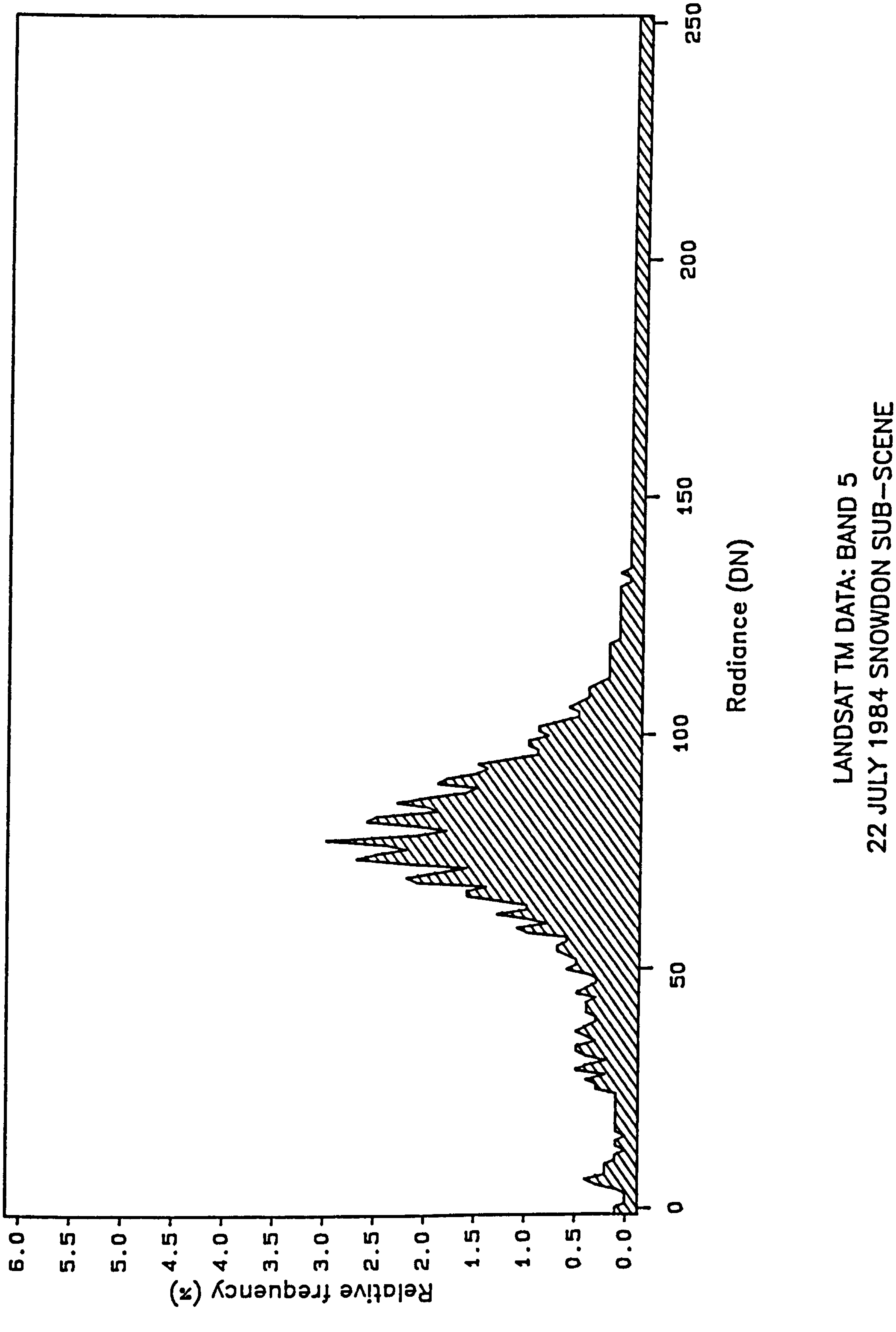


Figure 4.2 f
The histogram shows the frequency distribution of digital numbers (DN) from the Landsat Thematic Mapper image.

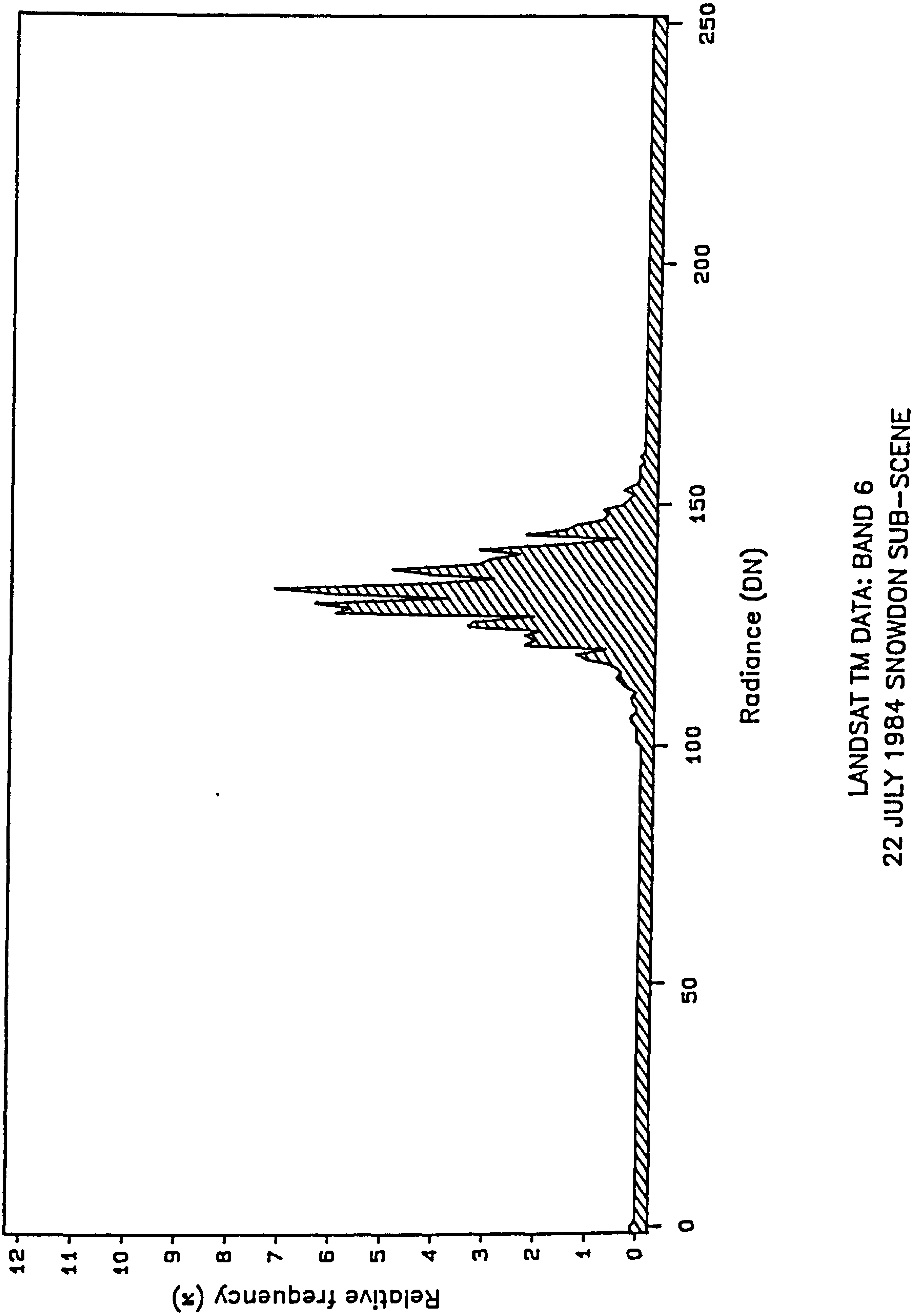


Figure 4.2 g
The histogram shows the frequency
distribution of digital numbers (DN)
from the Landsat Thematic Mapper image.

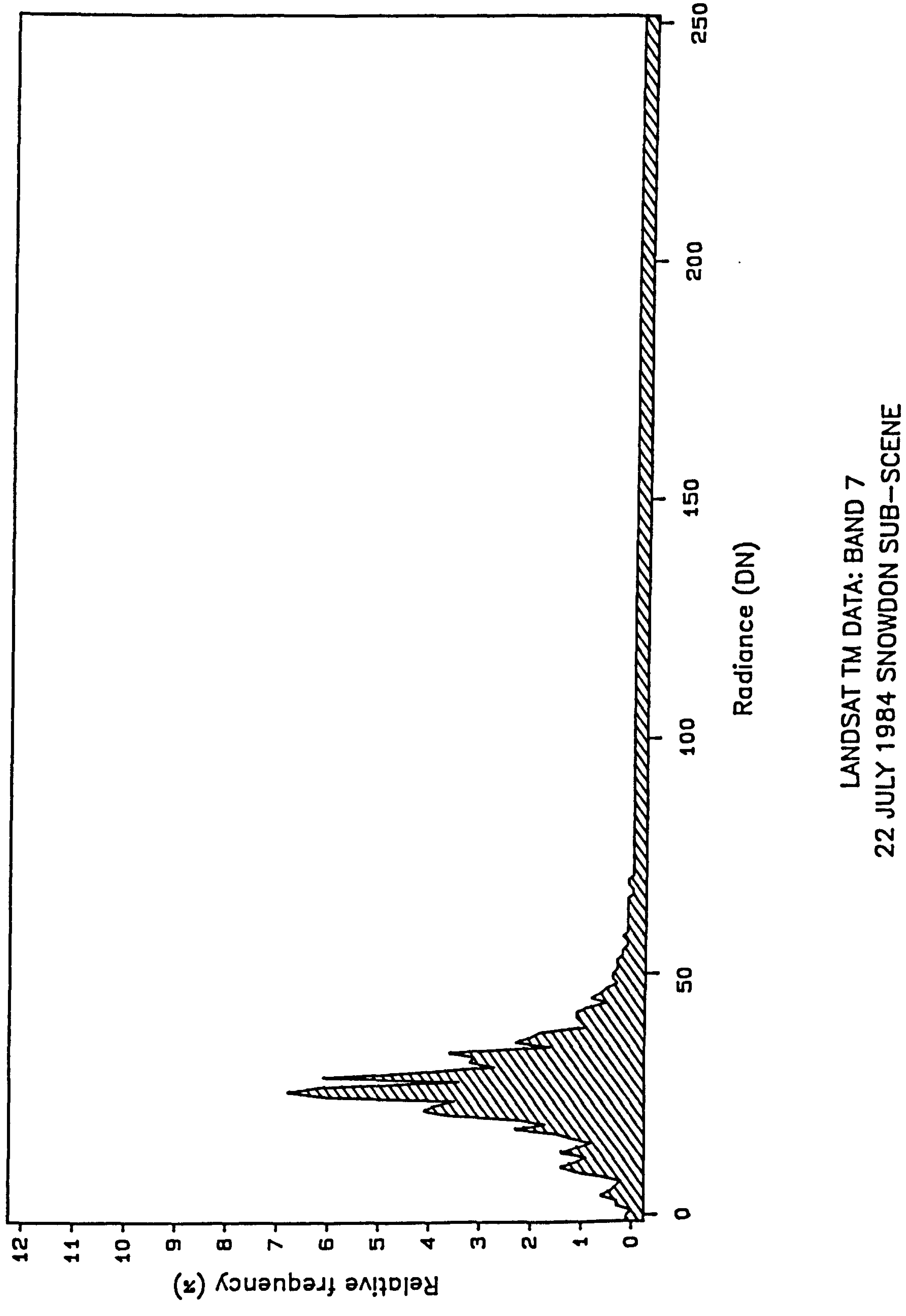
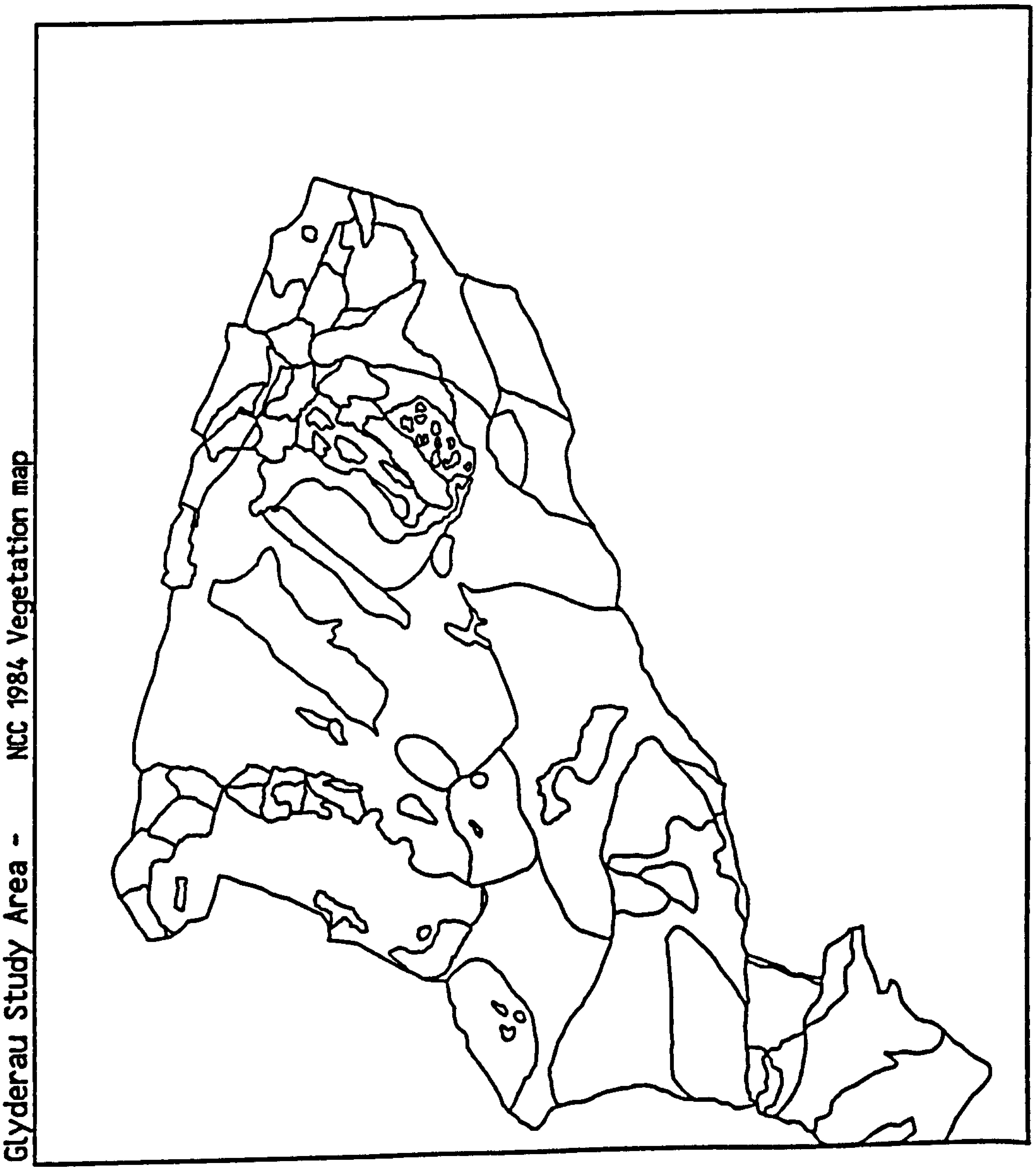


FIGURE 4.5
NCC Vegetation boundaries were transferred as vectors to the image analysis system for use as an overlay on the geometrically- corrected Thematic Mapper image. Map width is 7.7km; top of page is East.



FIGURES 4.6 a to g

The following seven histograms display the frequency distribution of digital numbers (DN) from the geometrically-corrected study area image.

The data were extracted from a sub-scene of 204/23 from the 22nd July 1984 resampled to a 15m x 15m pixel size. A 512 x 512 pixel image centred on the Glyderau study area.

Thematic Mapper waveband 1	Figure 4.6 a
Thematic Mapper waveband 2	Figure 4.6 b
Thematic Mapper waveband 3	Figure 4.6 c
Thematic Mapper waveband 4	Figure 4.6 d
Thematic Mapper waveband 5	Figure 4.6 e
Thematic Mapper waveband 6	Figure 4.6 f
Thematic Mapper waveband 7	Figure 4.6 g

Figure 4.6 a
The histogram shows the frequency distribution of digital numbers (DN) from the geometrically-corrected image.

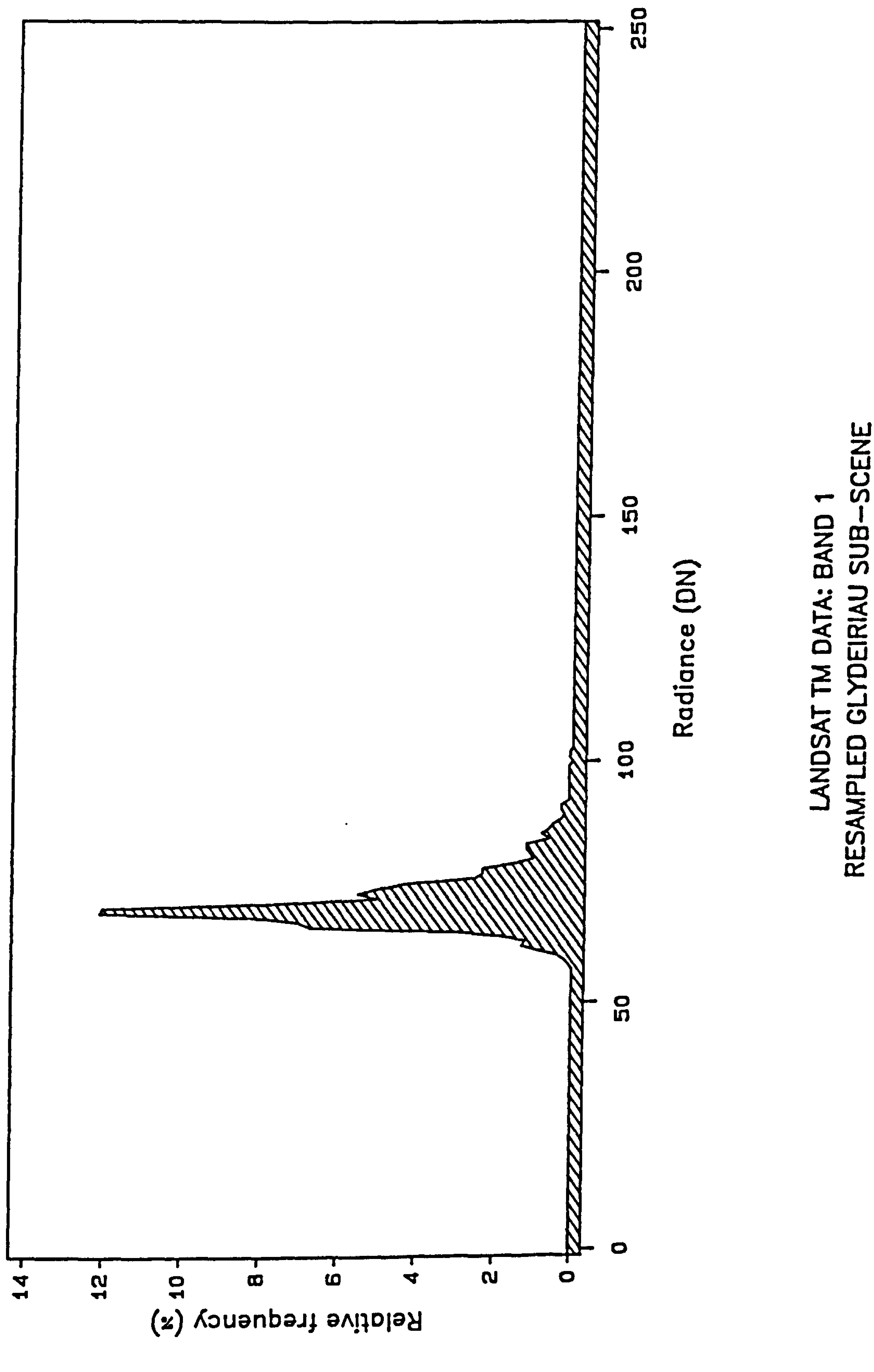


Figure 4.6 b
The histogram shows the frequency
distribution of digital numbers (DN)
from the geometrically-corrected image.

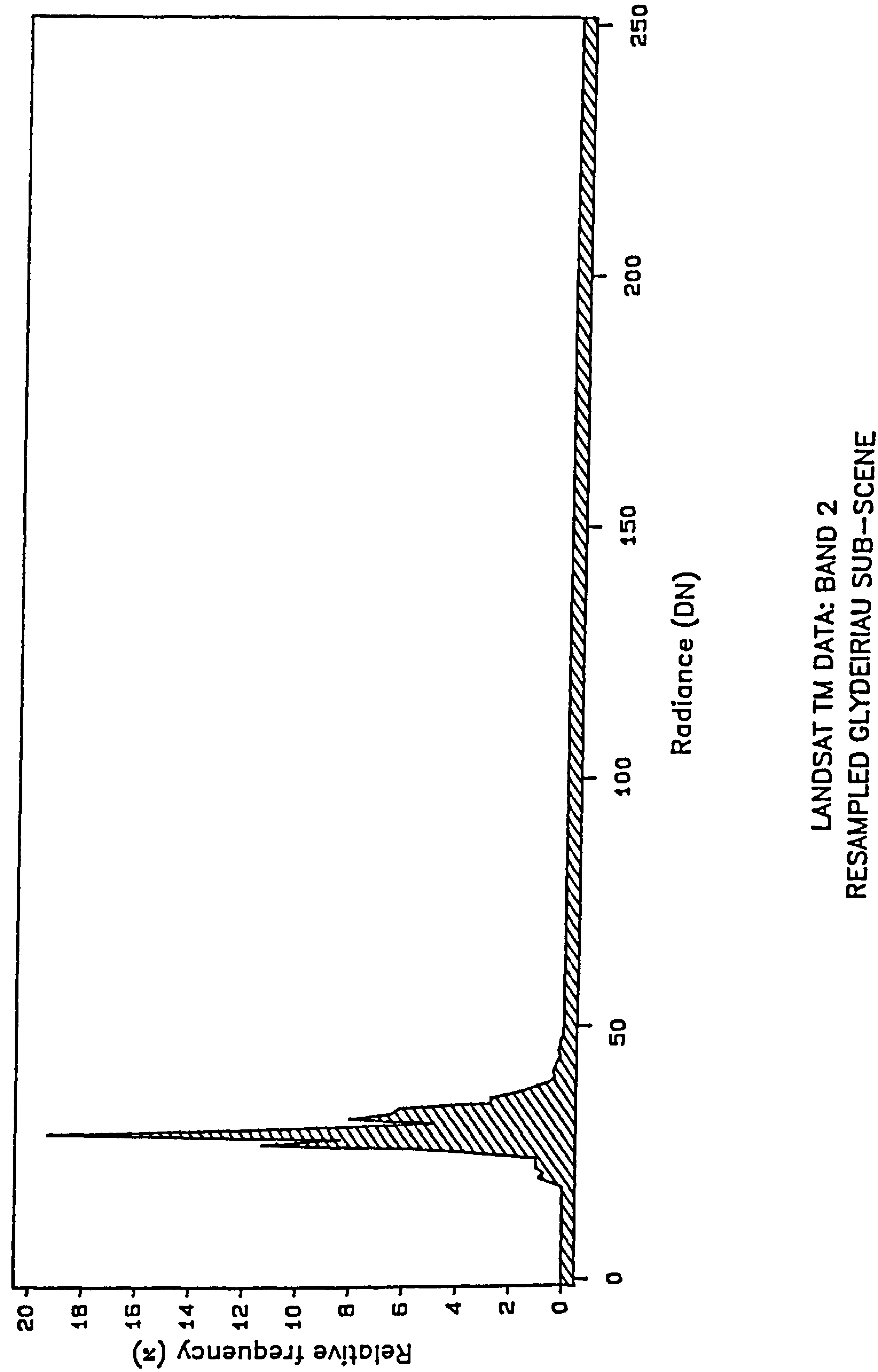


Figure 4.6 c
The histogram shows the frequency
distribution of digital numbers (DN)
from the geometrically-corrected image.

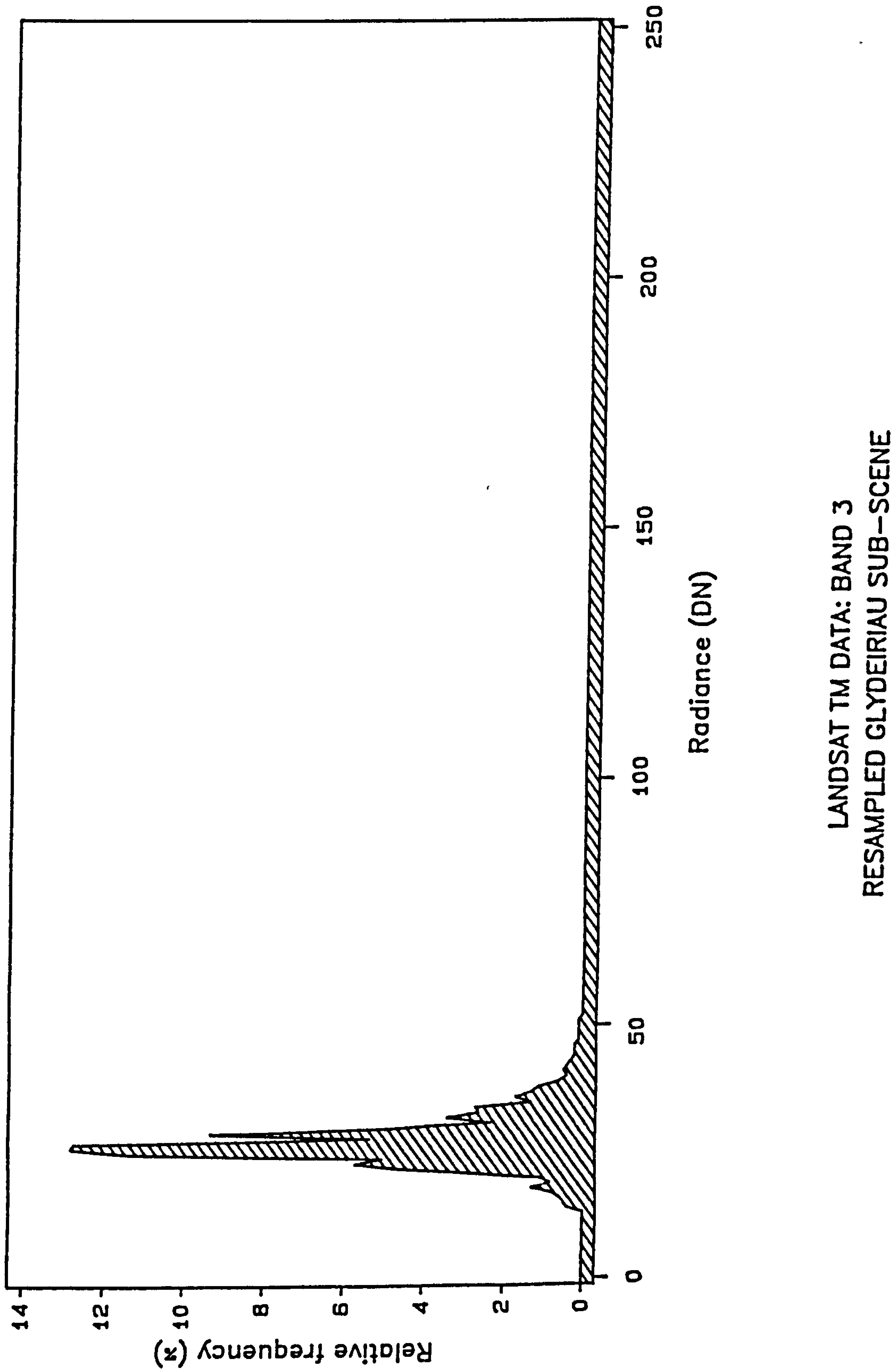


Figure 4.6 d
The histogram shows the frequency
distribution of digital numbers (DN)
from the geometrically-corrected image.

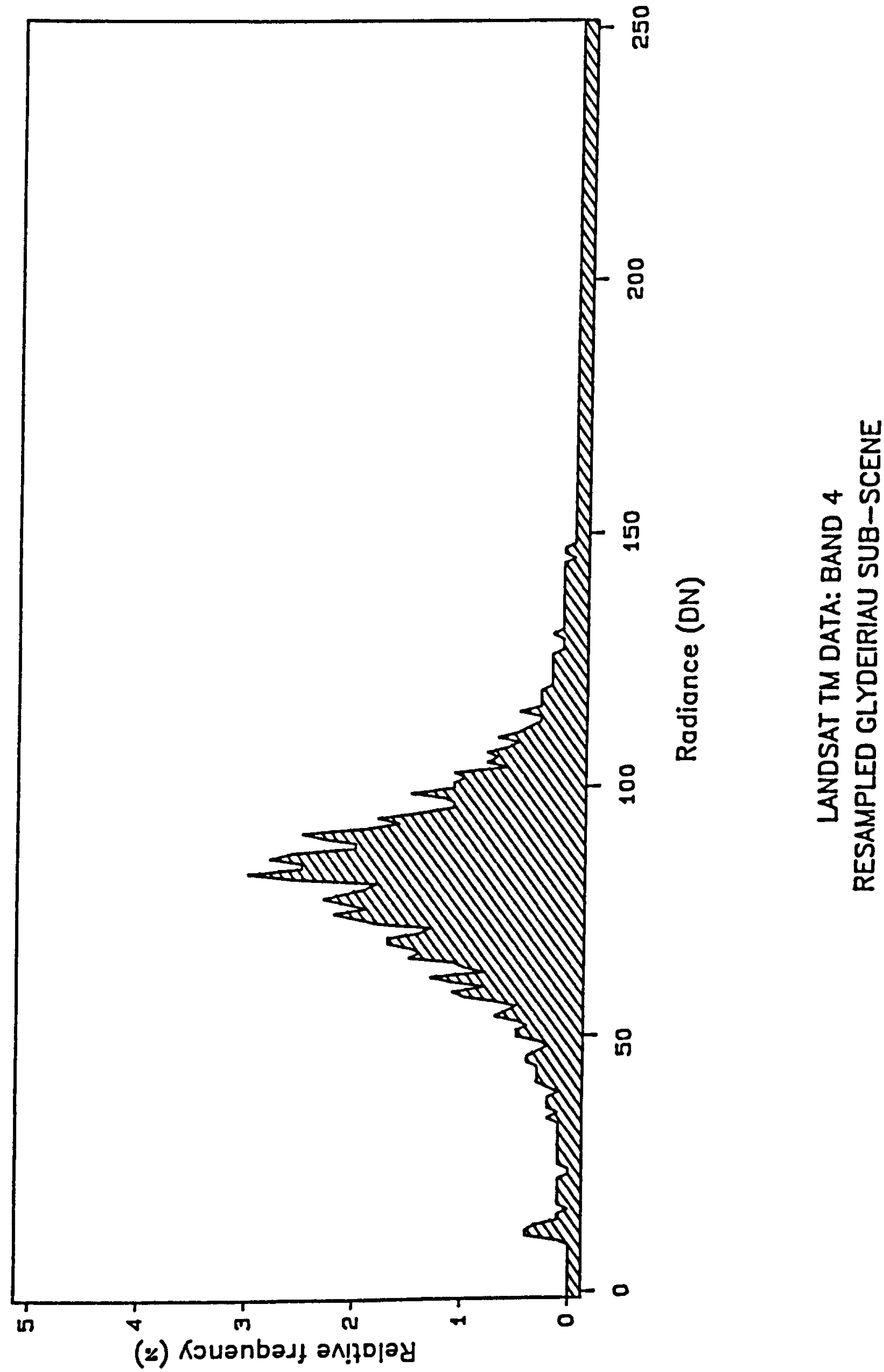


Figure 4.6 e
The histogram shows the frequency
distribution of digital numbers (DN)
from the geometrically-corrected image.

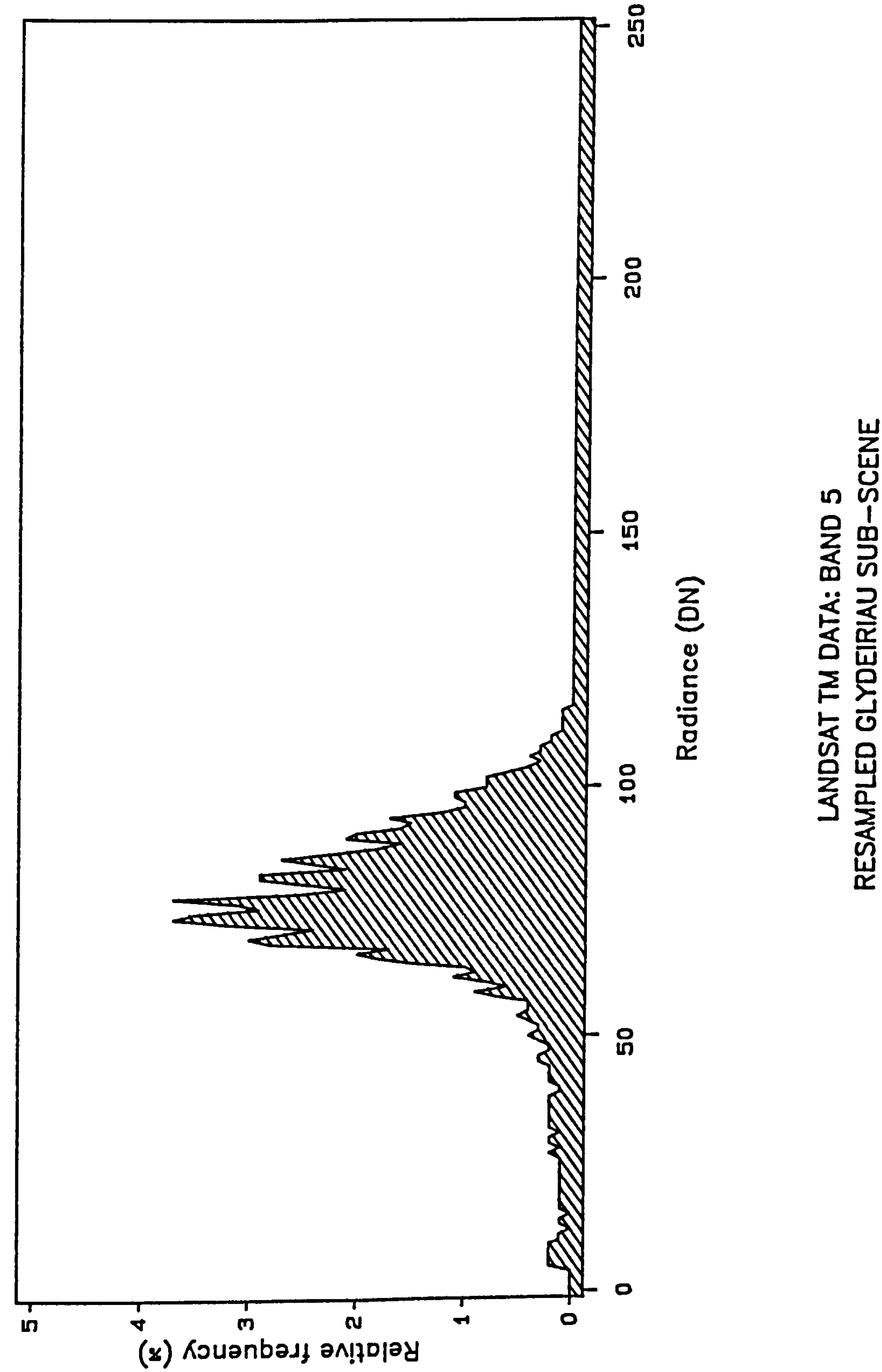


Figure 4.6 f
The histogram shows the frequency
distribution of digital numbers (DN)
from the geometrically-corrected image.

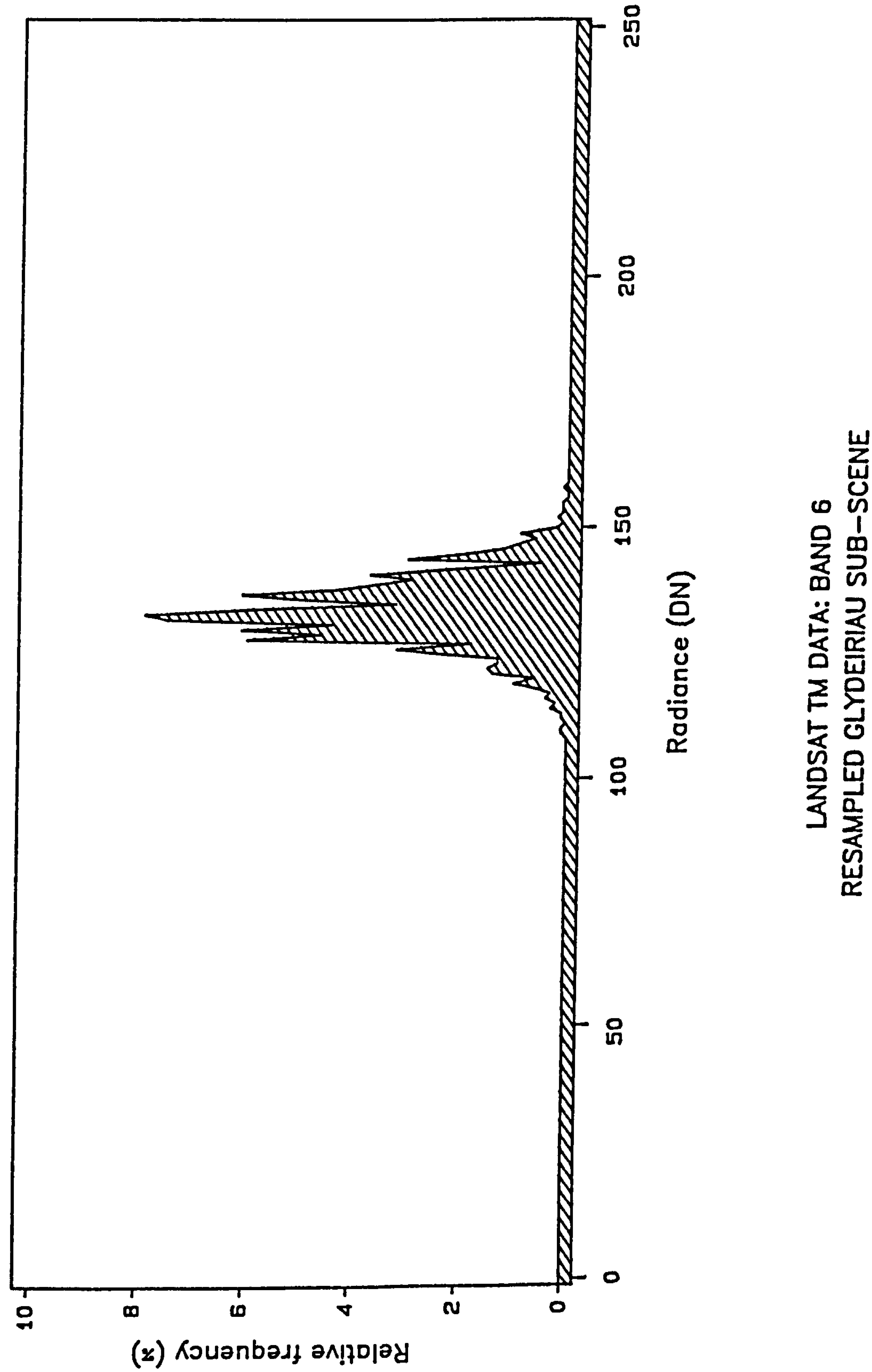
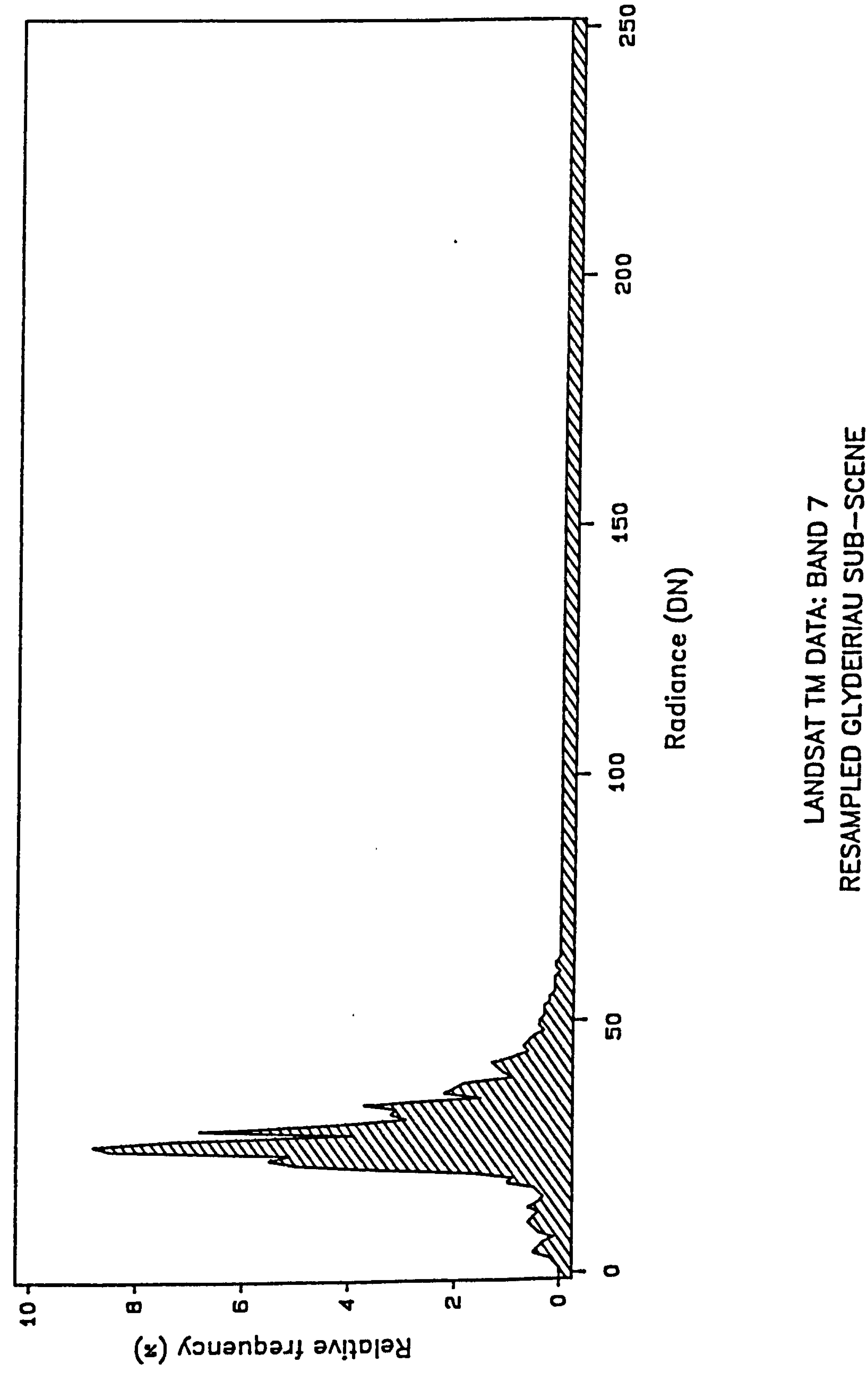


Figure 4.6 g
The histogram shows the frequency
distribution of digital numbers (DN)
from the geometrically-corrected image.



FIGURES 4.7 a to g

Graphs showing vegetation class statistics.
Class codes refer to aspect sub-classes, Table 4.1, Level I.
Figures show class mean and standard deviation.

Thematic Mapper waveband 1	Figure 4.7 a
Thematic Mapper waveband 2	Figure 4.7 b
Thematic Mapper waveband 3	Figure 4.7 c
Thematic Mapper waveband 4	Figure 4.7 d
Thematic Mapper waveband 5	Figure 4.7 e
Thematic Mapper waveband 6	Figure 4.7 f
Thematic Mapper waveband 7	Figure 4.7 g

Figure 4.7 a
Graph showing vegetation class statistics.
Class codes refer to Table 4.1, Level I.

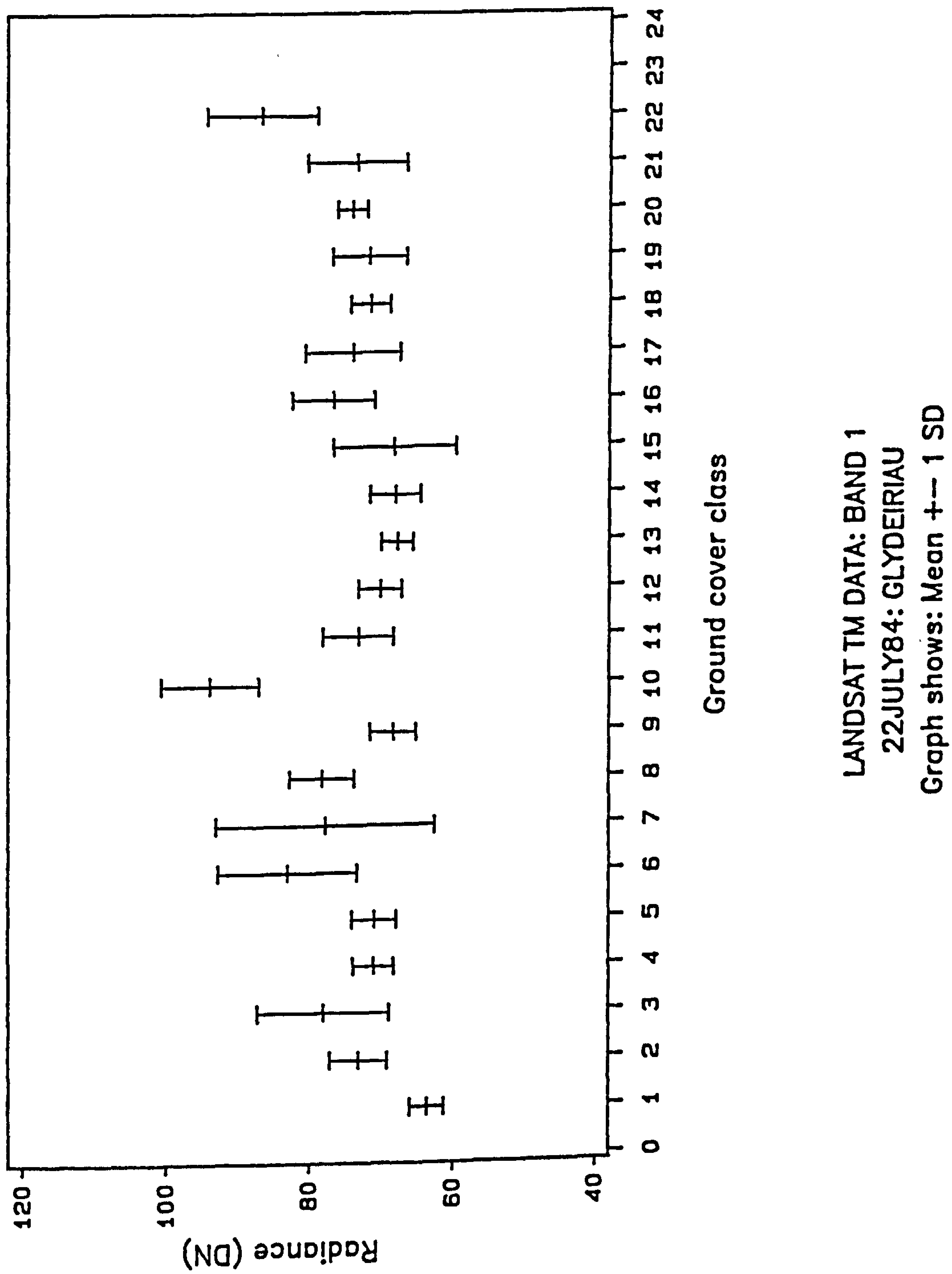


Figure 4.7 b
Graph showing vegetation class statistics.
Class codes refer to Table 4.1, Level I.

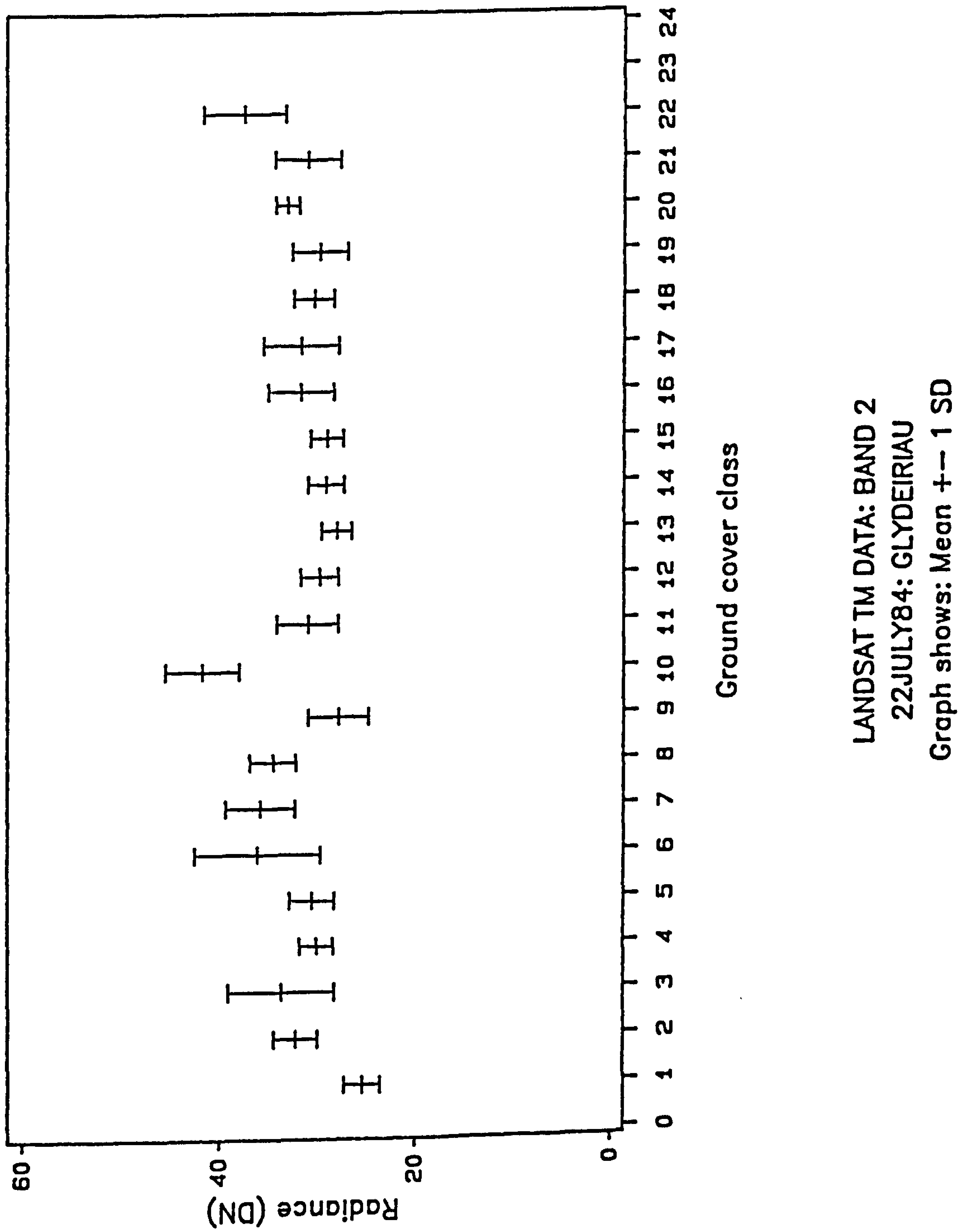


Figure 4.7 c
Graph showing vegetation class statistics.
Class codes refer to Table 4.1, Level I.

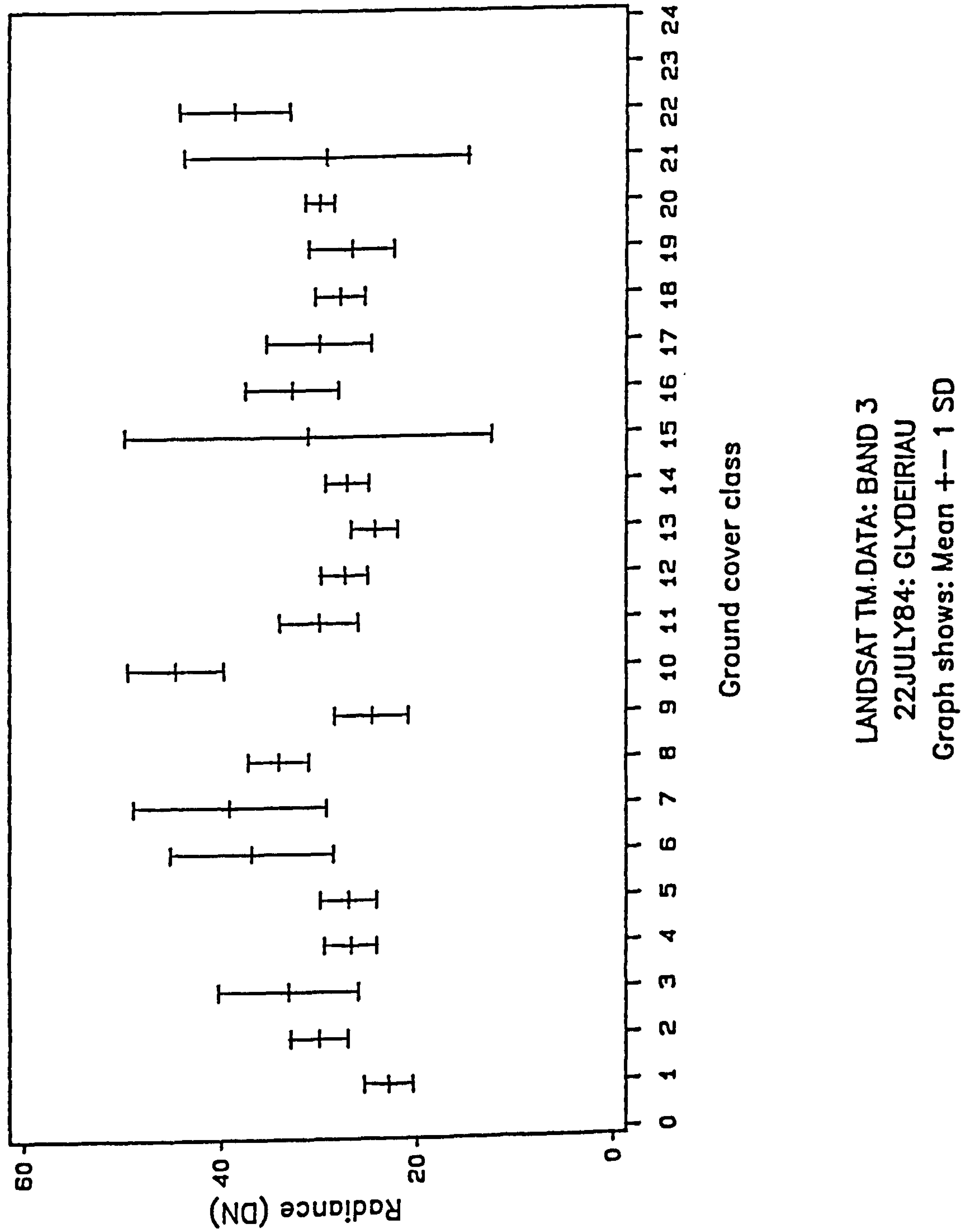


Figure 4.7 d
Graph showing vegetation class statistics.
Class codes refer to Table 4.1, Level I.

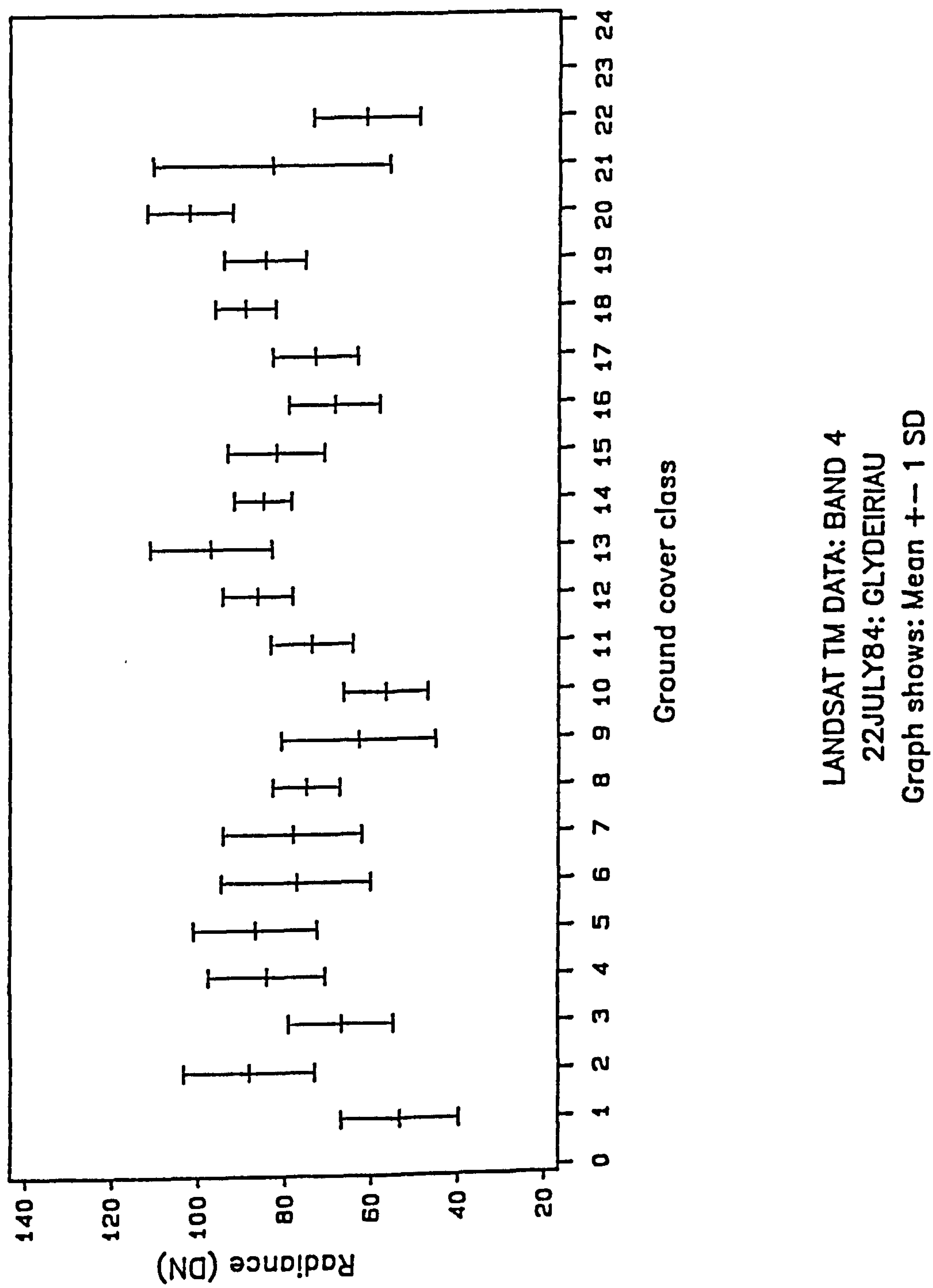


Figure 4.7 e
Graph showing vegetation class statistics.
Class codes refer to Table 4.1, Level I.

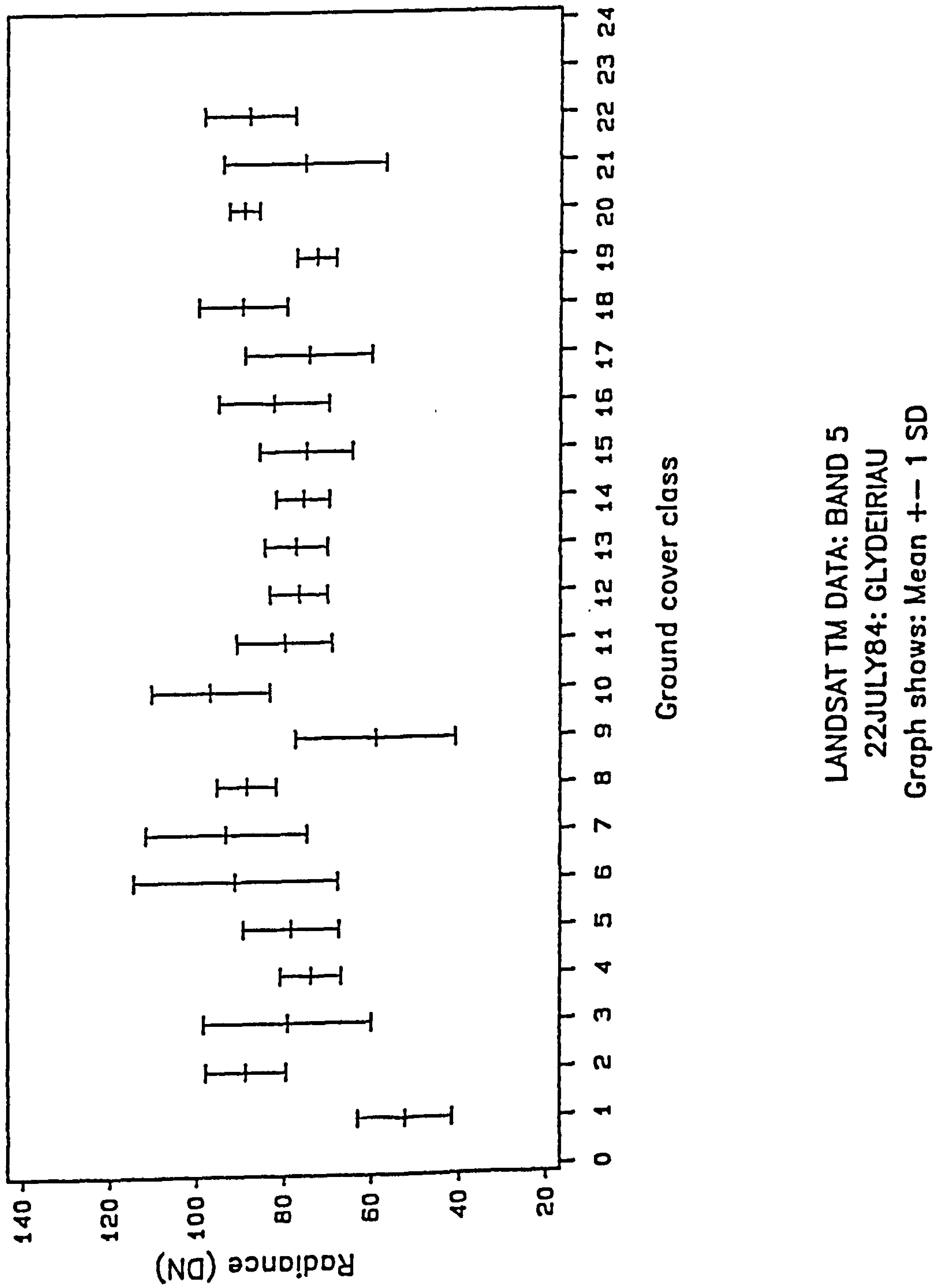


Figure 4.7 f
Graph showing vegetation class statistics.
Class codes refer to Table 4.1, Level I.

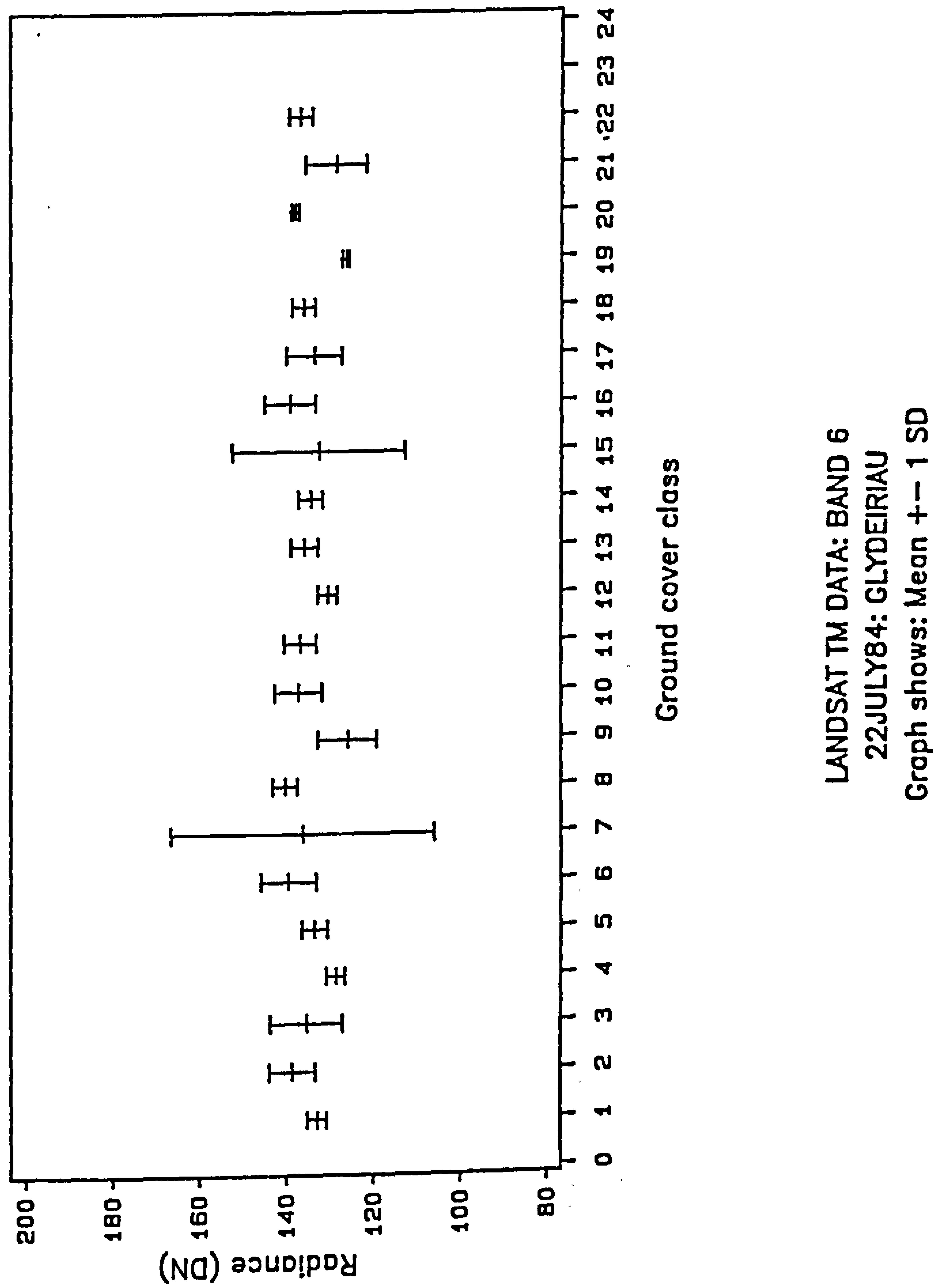
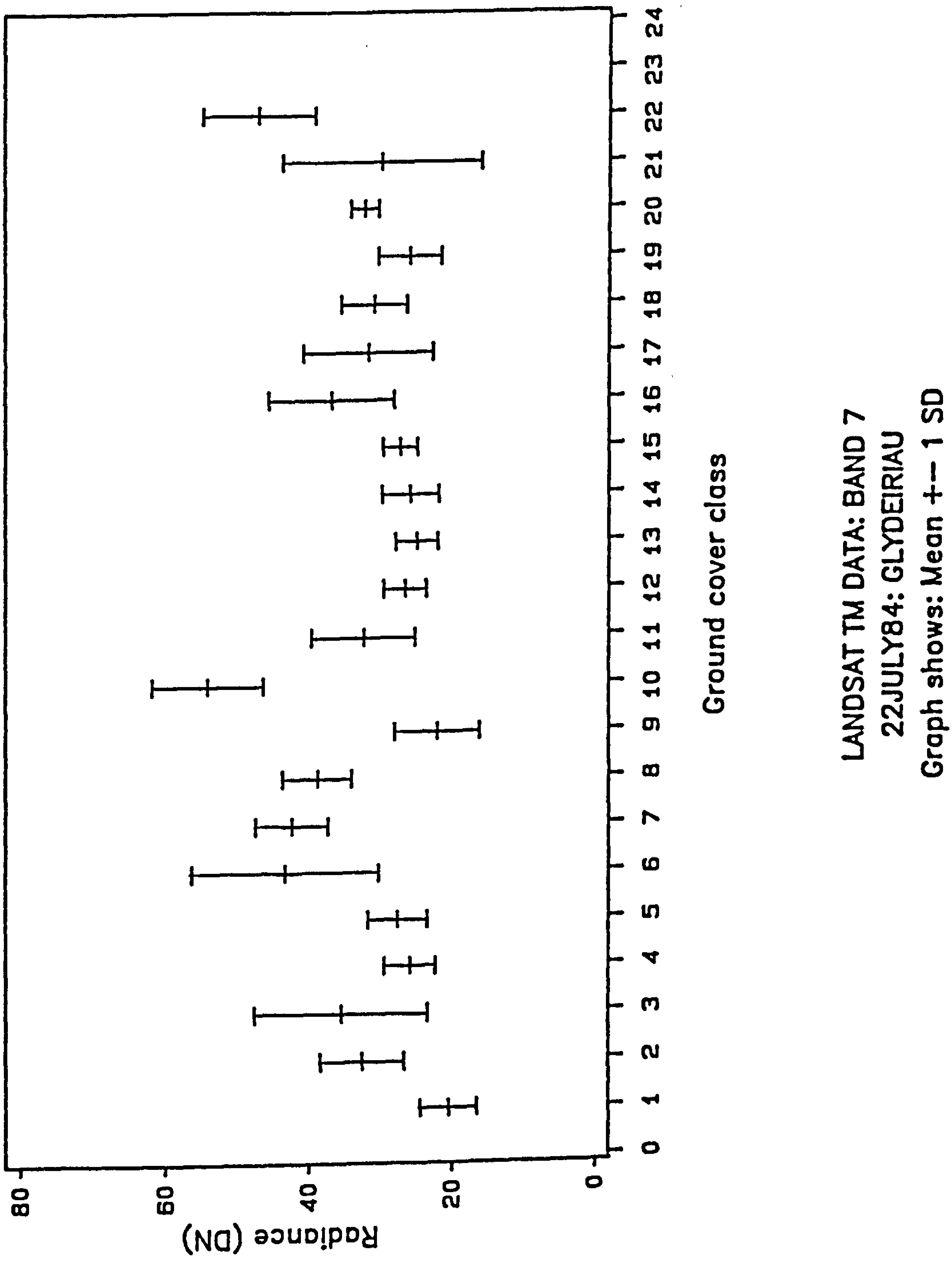


Figure 4.7 g
Graph showing vegetation class statistics.
Class codes refer to Table 4.1, Level I.



FIGURES 4.8 a to g

Graphs showing vegetation class statistics.
Class codes refer to aspect sub-classes, Table 4.1, Level I.
Figures show class mean, minimum and maximum.

Thematic Mapper waveband 1	Figure 4.8 a
Thematic Mapper waveband 2	Figure 4.8 b
Thematic Mapper waveband 3	Figure 4.8 c
Thematic Mapper waveband 4	Figure 4.8 d
Thematic Mapper waveband 5	Figure 4.8 e
Thematic Mapper waveband 6	Figure 4.8 f
Thematic Mapper waveband 7	Figure 4.8 g

Figure 4.8 a
Graph showing vegetation class statistics
Class codes refer to Table 4.1, Level I.

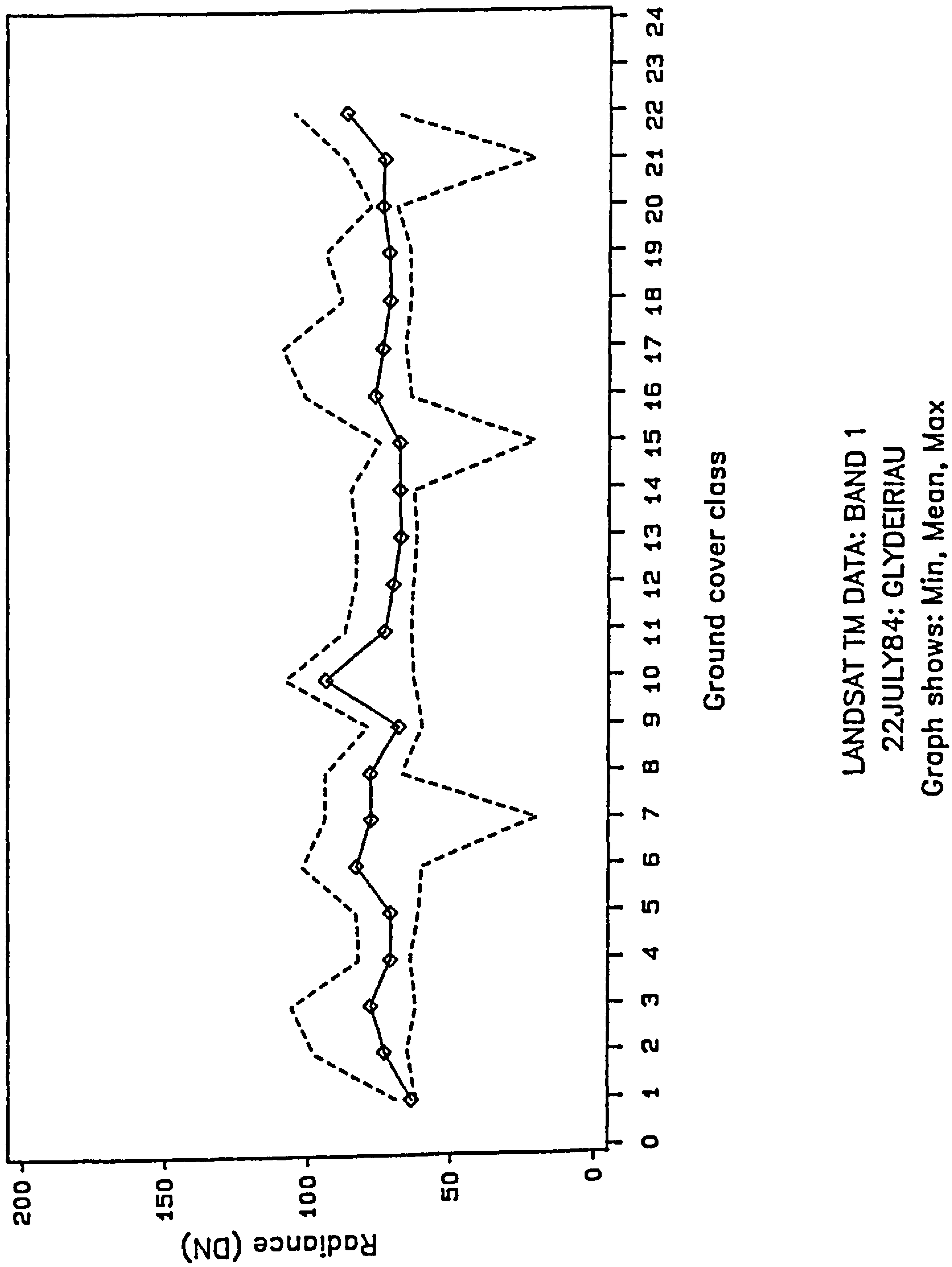


Figure 4.8 b
Graph showing vegetation class statistics
Class codes refer to Table 4.1, Level I.

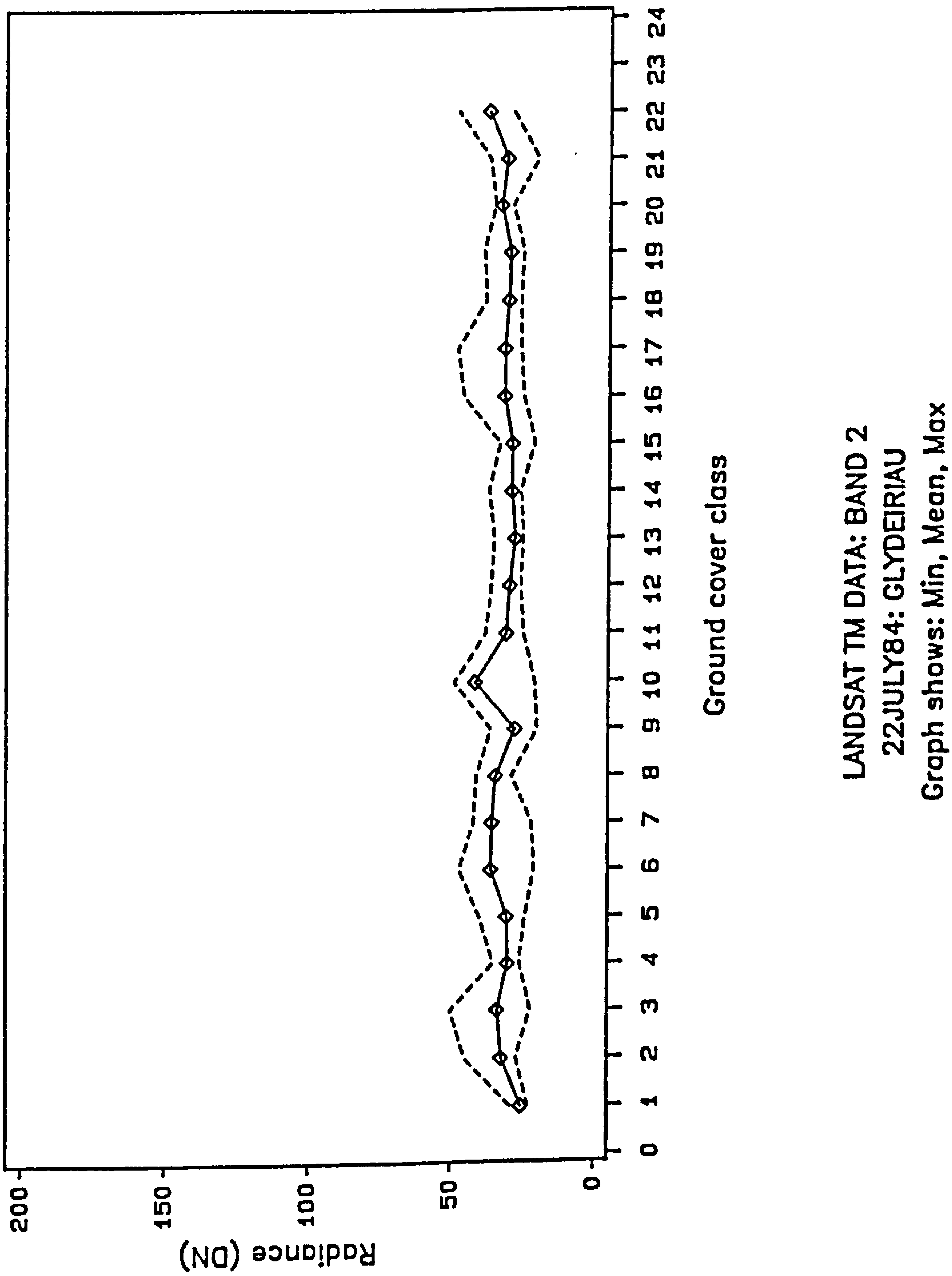


Figure 4.8 c
Graph showing vegetation class statistics
Class codes refer to Table 4.1, Level I.

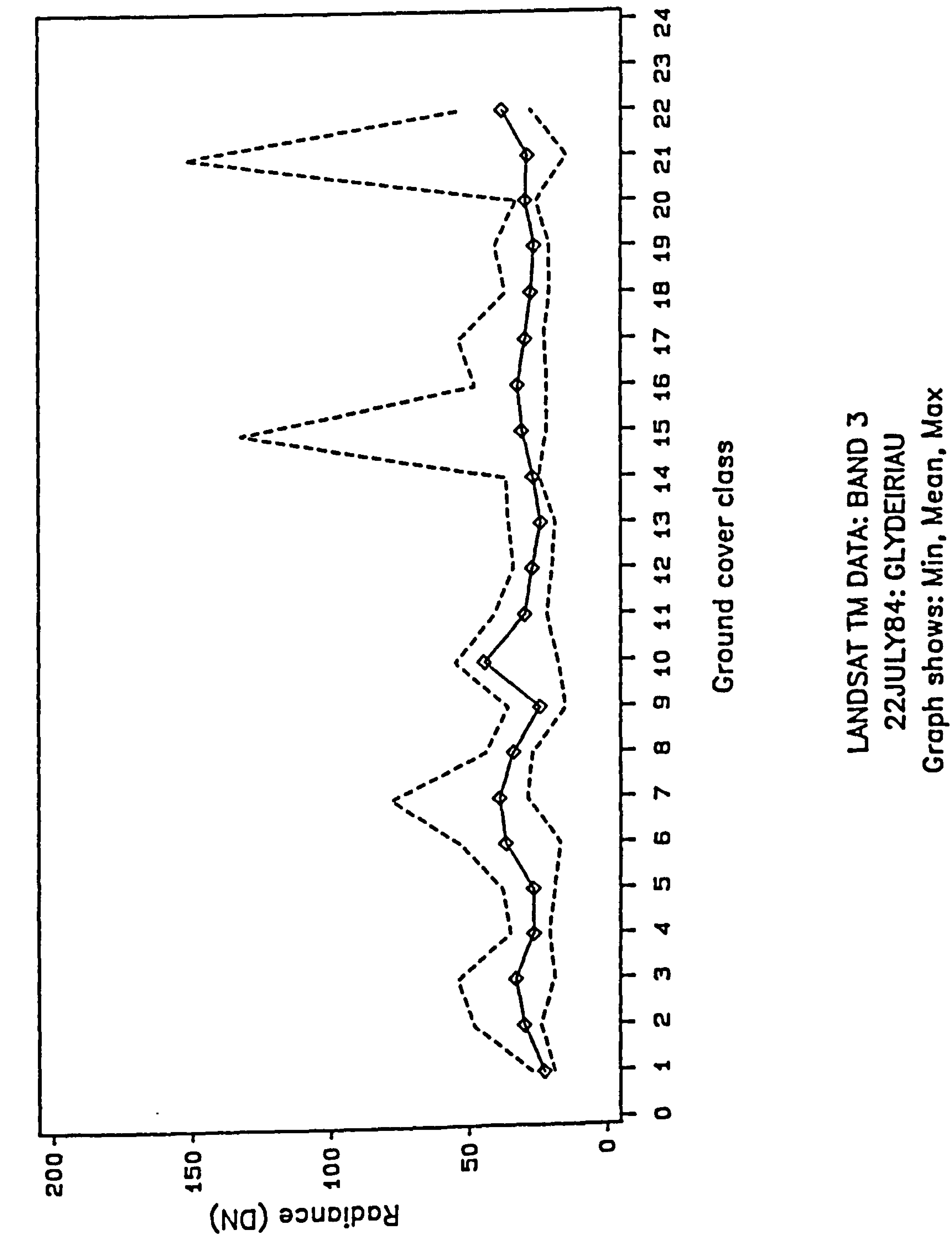


Figure 4.8 d
Graph showing vegetation class statistics
Class codes refer to Table 4.1, Level I.

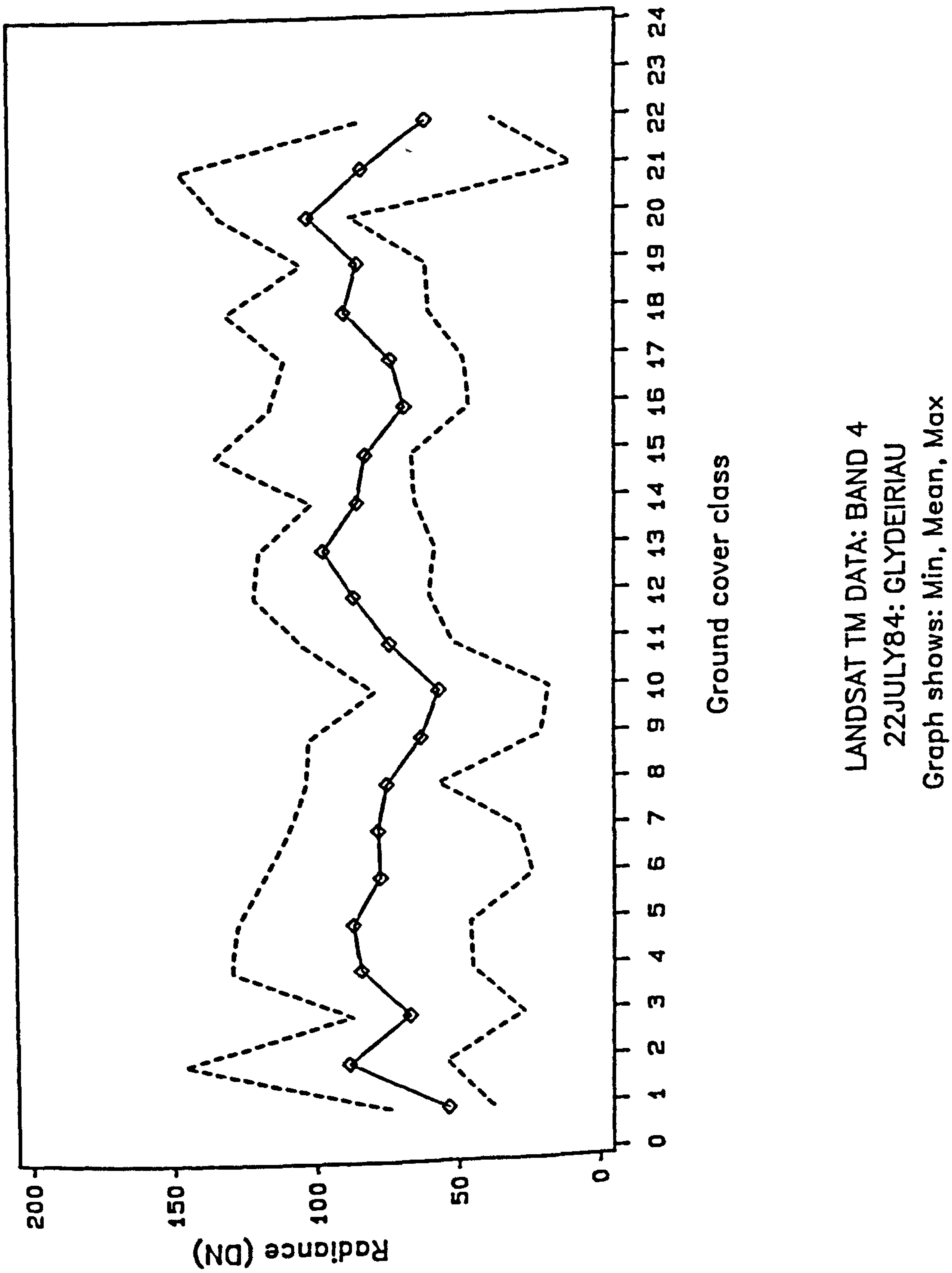


Figure 4.8 e
Graph showing vegetation class statistics
Class codes refer to Table 4.1, Level I.

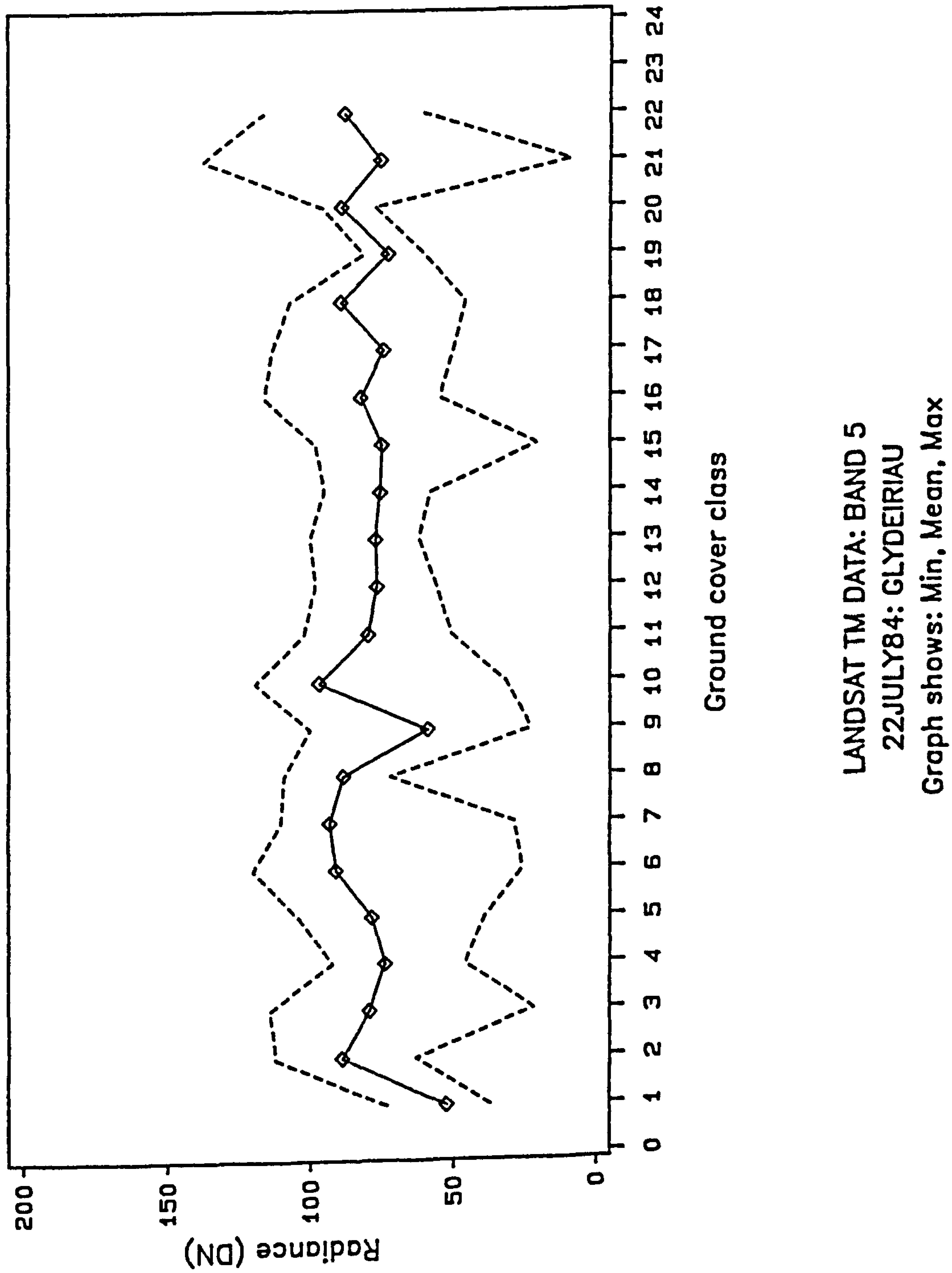


Figure 4.8 f
Graph showing vegetation class statistics
Class codes refer to Table 4.1, Level I.

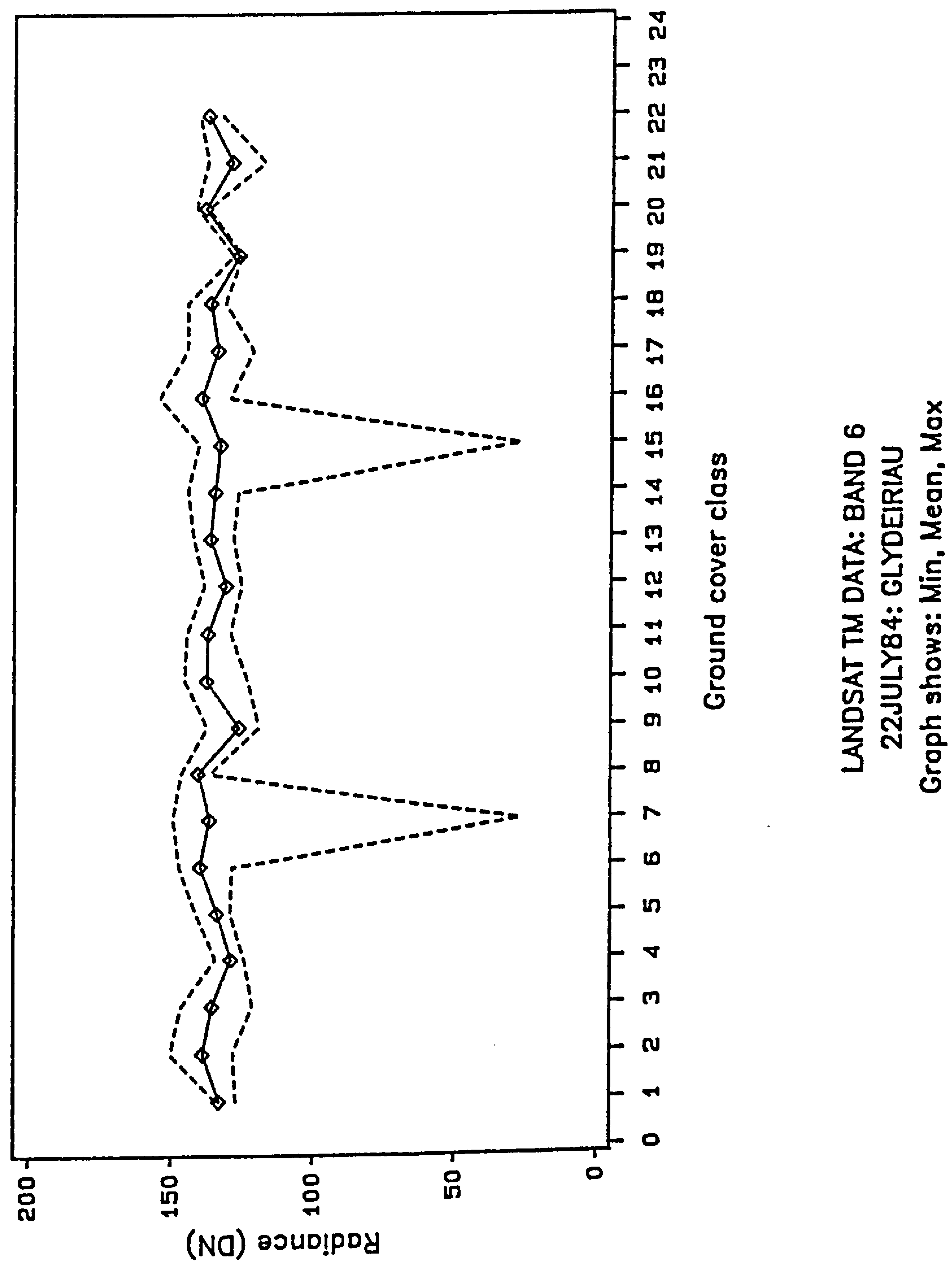
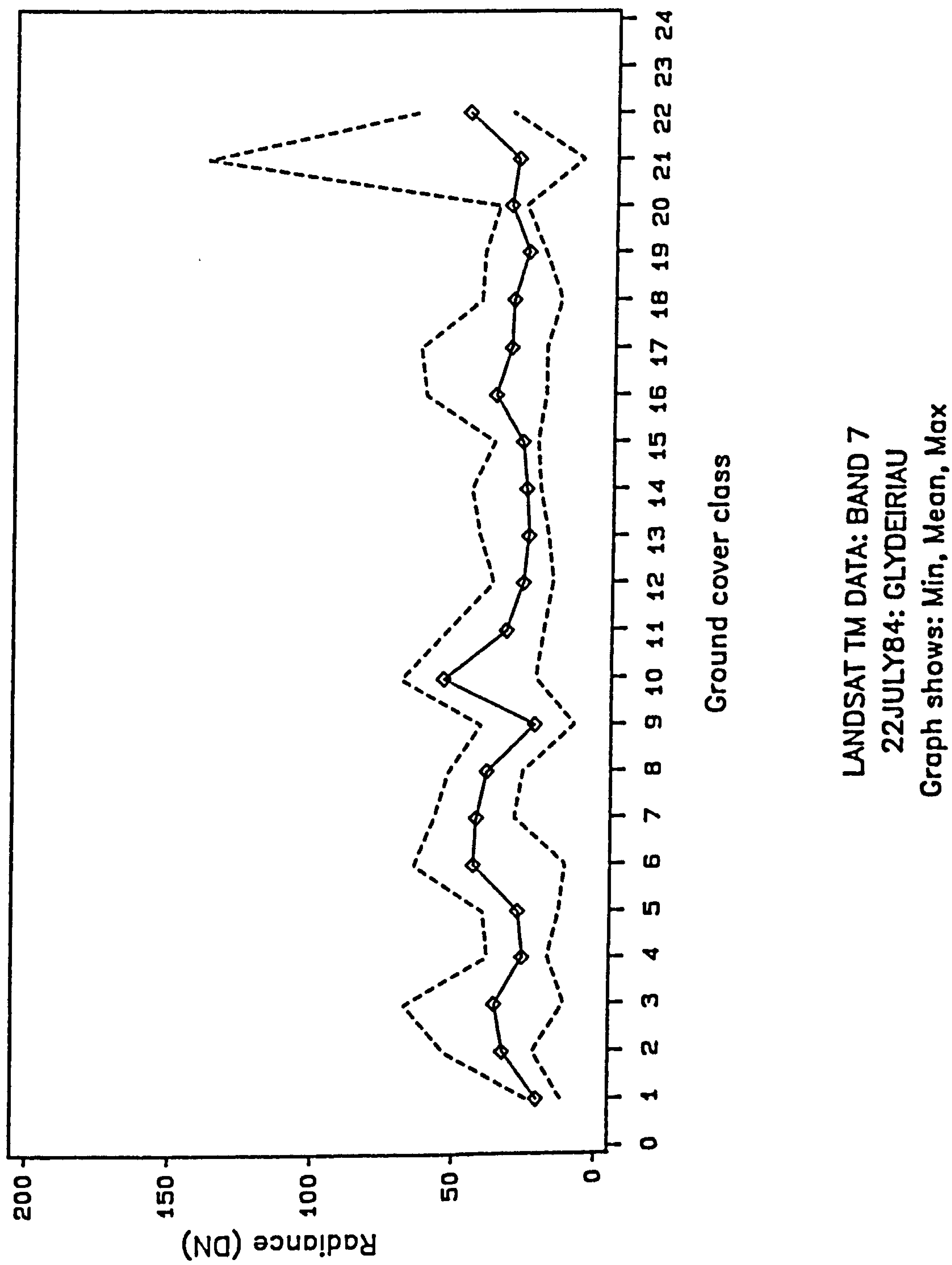


Figure 4.8 g
Graph showing vegetation class statistics
Class codes refer to Table 4.1, Level I.



FIGURES 4.9 a to d

Graphs showing the change in correspondence for each vegetation class between the NCC field survey map and the classified Thematic Mapper data after image spatial filtering.

Class codes refer to vegetation classes, Table 4.1, Level II.

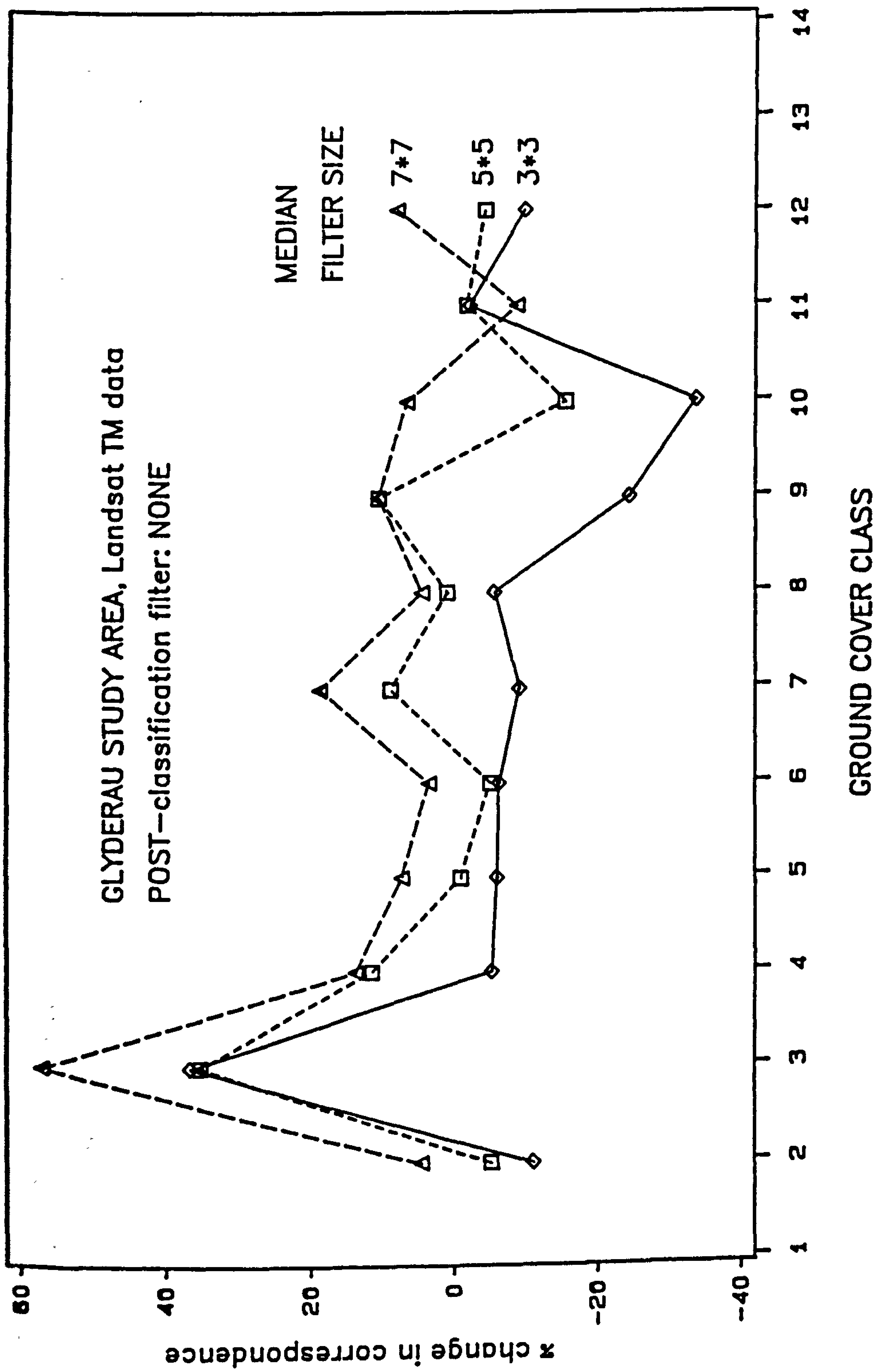
Graphs show the changes resulting from:

an increase in the level of PRE-Classification filtering,

for each level of POST-Classification filter.

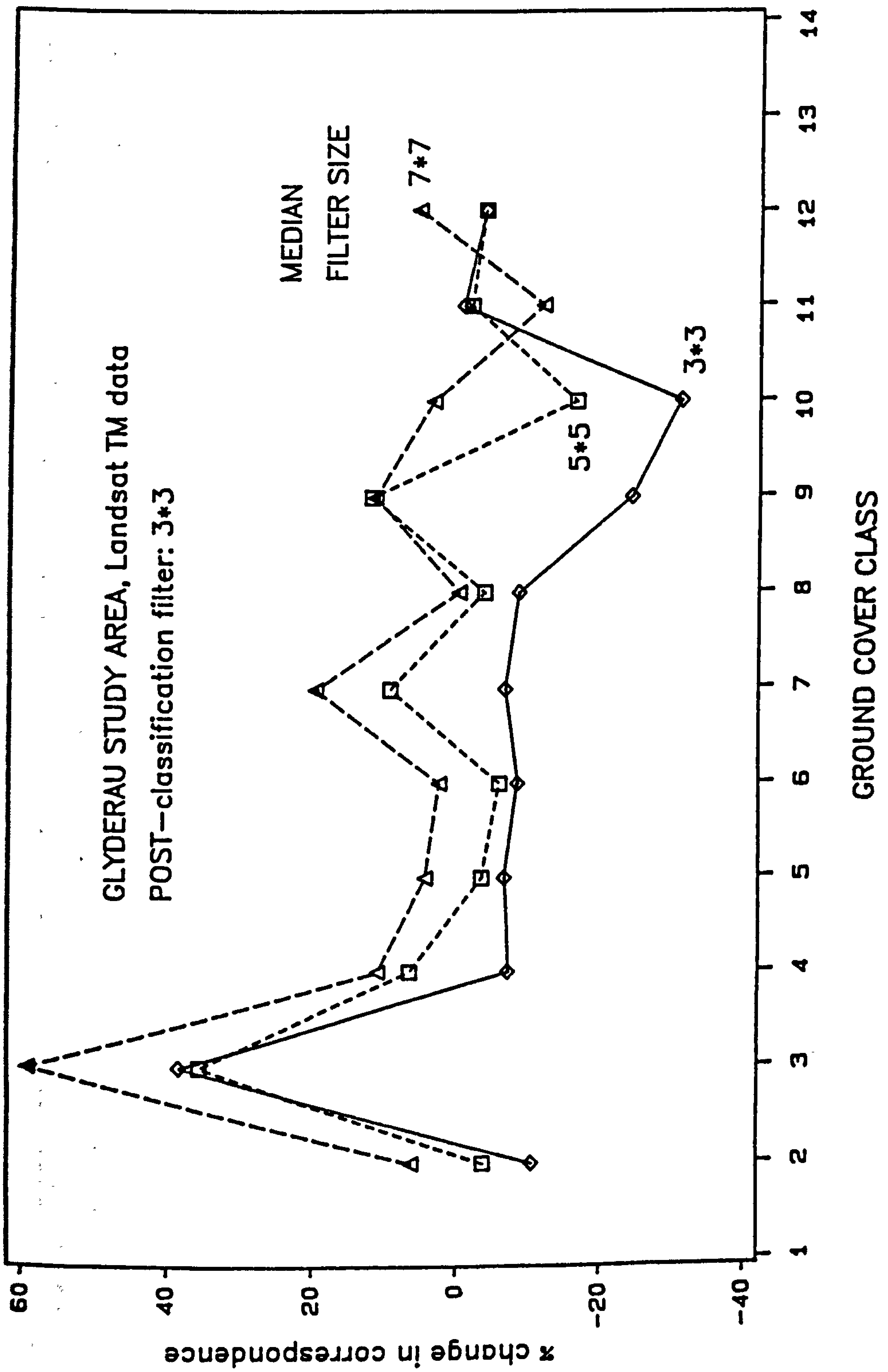
Post-classification filter: NONE	Figure 4.9 a
Post-classification filter: 3x3	Figure 4.9 b
Post-classification filter: 5x5	Figure 4.9 c
Post-classification filter: 7x7	Figure 4.9 d

Figure 4.9 a
Graph showing the change in correspondence resulting from an increase in the level of PRE-Classification spatial filtering. Class codes refer to Table 4.1, Level II.



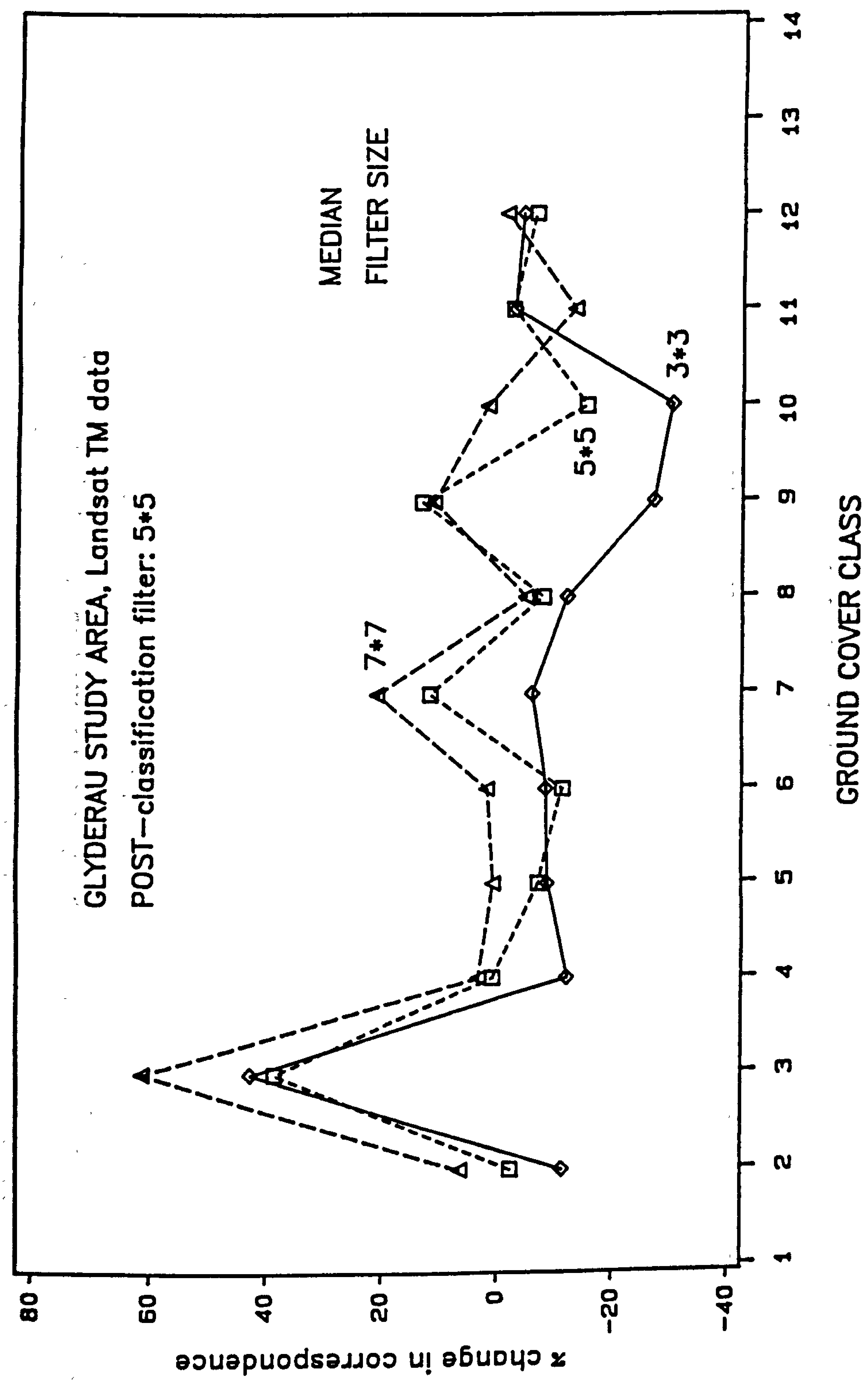
Graph showing the change in correspondence between ground and classified TM data resulting from an increase in the level of PRE–classification filtering

Figure 4.9 b
Graph showing the change in correspondence
resulting from an increase in the level
of PRE-Classification spatial filtering.
Class codes refer to Table 4.1, Level II.



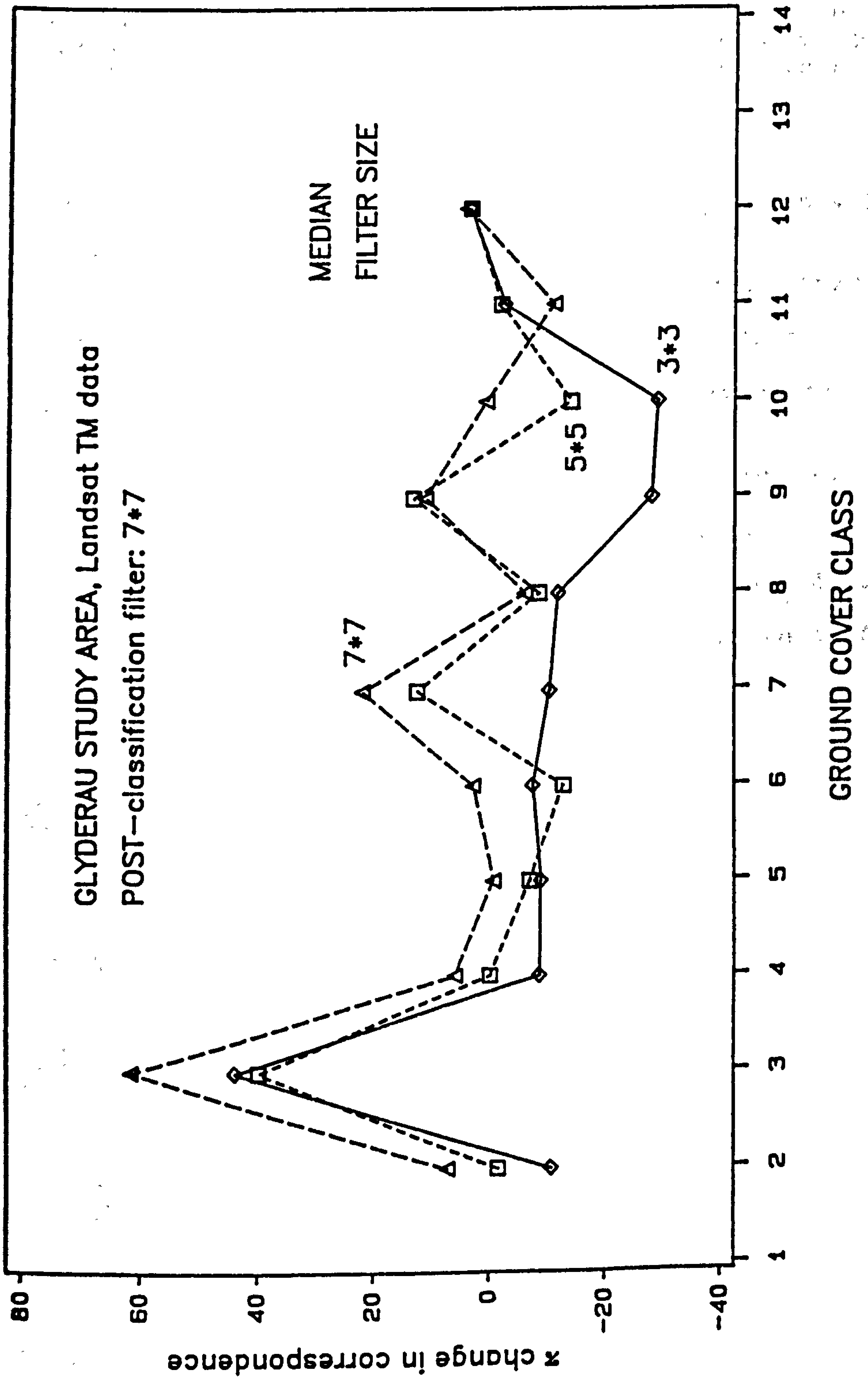
Graph showing the change in correspondence
between ground and classified TM data resulting from
an increase in the level of PRE–classification filtering

Figure 4.9 c
Graph showing the change in correspondence
resulting from an increase in the level
of PRE-Classification spatial filtering.
Class codes refer to Table 4.1, Level II.



Graph showing the change in correspondence between ground and classified TM data resulting from an increase in the level of PRE—classification filtering

Figure 4.9 d
Graph showing the change in correspondence
resulting from an increase in the level
of PRE-Classification spatial filtering.
Class codes refer to Table 4.1, Level II.



Graph showing the change in correspondence
between ground and classified TM data resulting from
an increase in the level of PRE—classification filtering

FIGURES 4.10 a to d

Graphs showing the change in correspondence for each vegetation class between the NCC field survey map and the classified Thematic Mapper data after image spatial filtering.

Class codes refer to vegetation classes, Table 4.1, Level II.

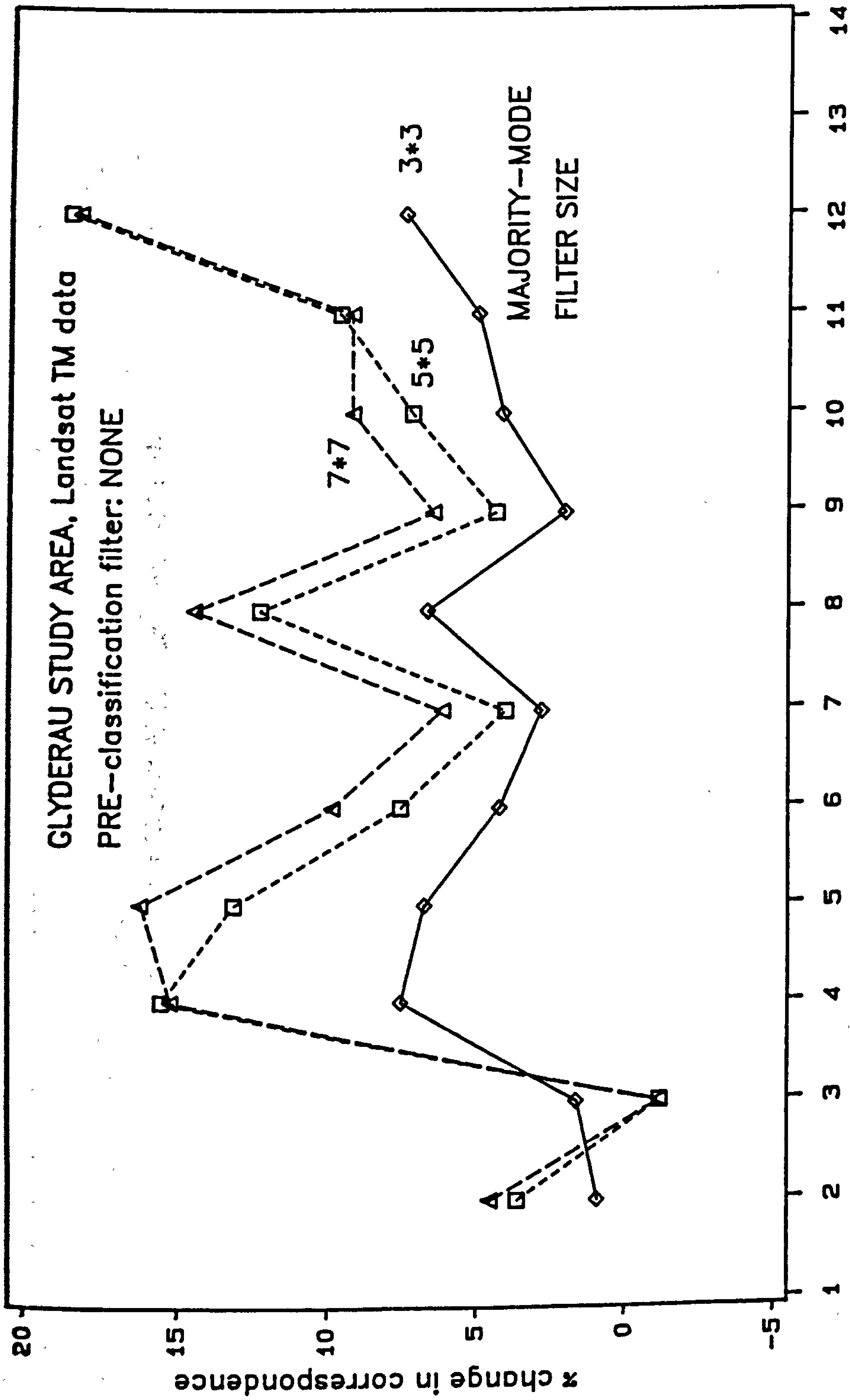
Graphs show the changes resulting from:

an increase in the level of POST-Classification filtering,

for each level of PRE-Classification filter.

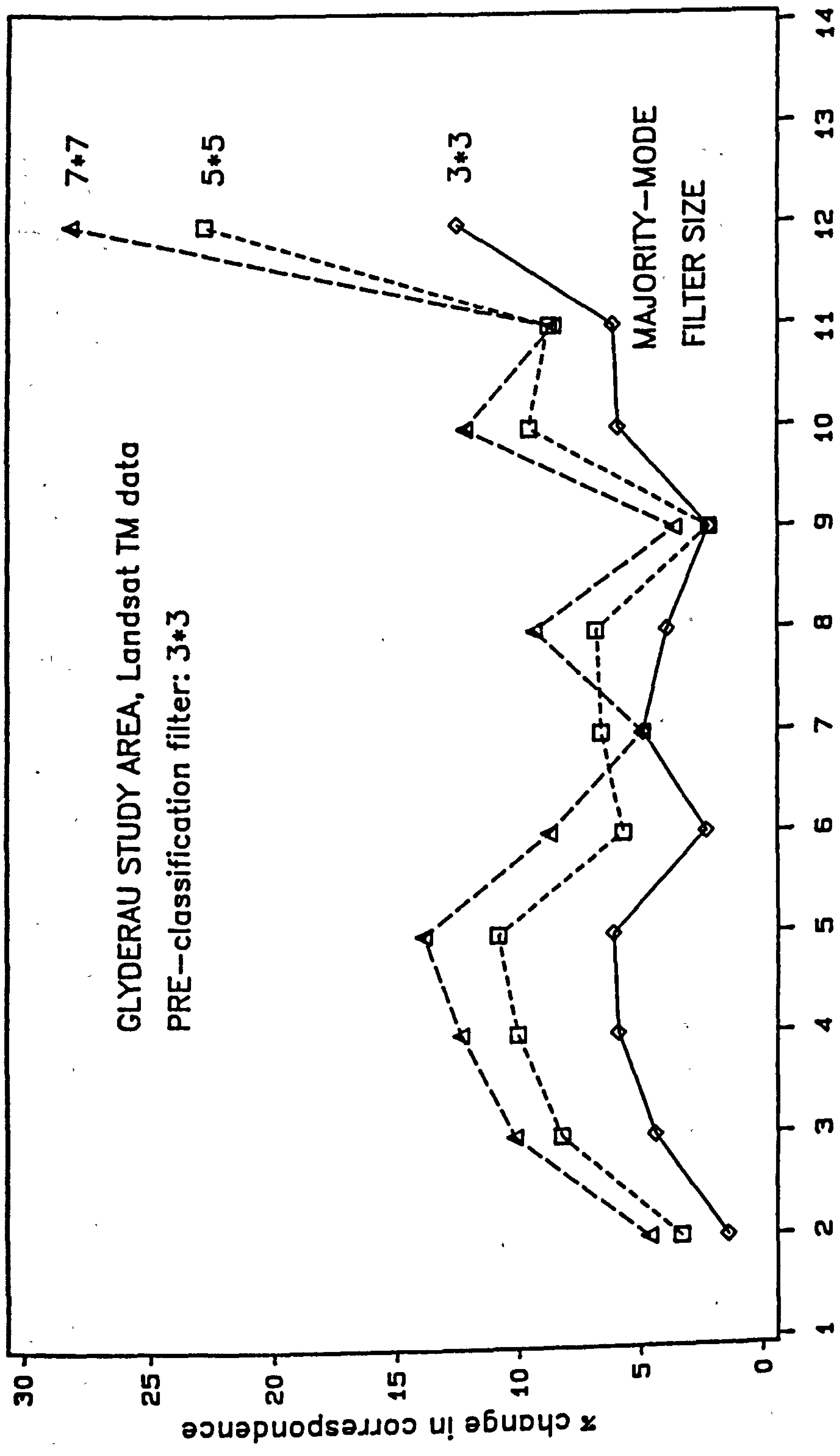
Pre-classification filter: NONE	Figure 4.10 a
Pre-classification filter: 3x3	Figure 4.10 b
Pre-classification filter: 5x5	Figure 4.10 c
Pre-classification filter: 7x7	Figure 4.10 d

Figure 4.10 a
Graph showing the change in correspondence
resulting from an increase in the level
of POST-Classification spatial filtering.
Class codes refer to Table 4.1, Level II.



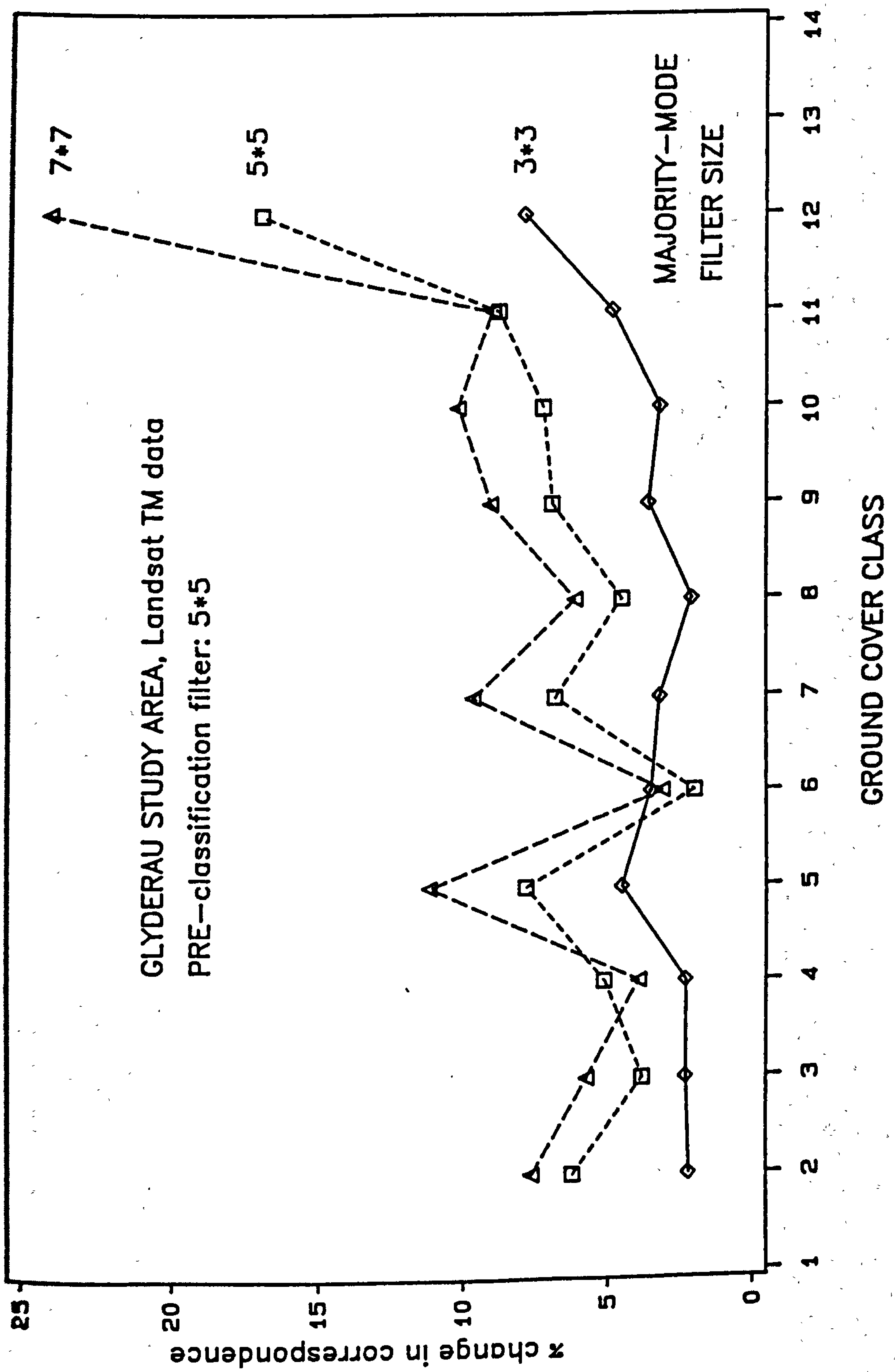
Graph showing the change in correspondence
between ground and classified TM data resulting from
an increase in the level of POST-classification filtering

Figure 4.10 b
Graph showing the change in correspondence resulting from an increase in the level of POST-Classification spatial filtering. Class codes refer to Table 4.1, Level II.



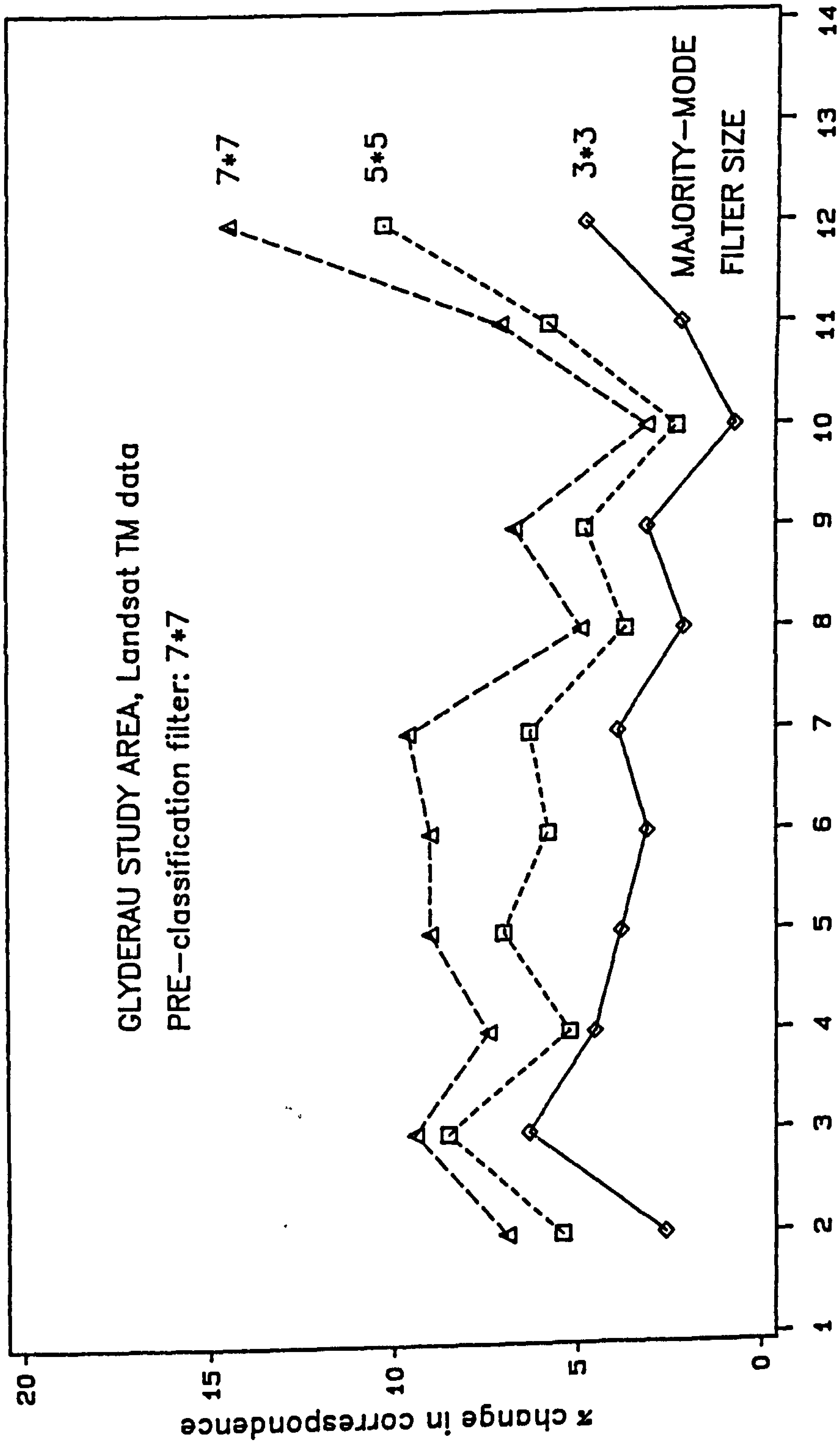
Graph showing the change in correspondence between ground and classified TM data resulting from an increase in the level of POST—classification filtering

Figure 4.10 c
Graph showing the change in correspondence resulting from an increase in the level of POST-Classification spatial filtering. Class codes refer to Table 4.1, Level II.



Graph showing the change in correspondence between ground and classified TM data resulting from an increase in the level of POST-classification filtering

Figure 4.10 d
Graph showing the change in correspondence resulting from an increase in the level of POST-Classification spatial filtering. Class codes refer to Table 4.1, Level II.



Graph showing the change in correspondence between ground and classified TM data resulting from an increase in the level of POST–classification filtering

FIGURES 4.11 a to k

Graphs showing the change in correspondence for each vegetation class between the NCC field survey map and the classified Thematic Mapper data after image spatial filtering.

Graphs show the changes resulting from each combination of:

PRE-Classification median filter and

POST-Classification majority-mode filter.

Figure 4.11 a	Nardus/Juncus
Figure 4.11 b	Agrostis/Festuca
Figure 4.11 c	Crags
Figure 4.11 d	Vaccinium heath
Figure 4.11 e	Rhacomitrium heath
Figure 4.11 f	Soligenous flushes
Figure 4.11 g	Blanket bog
Figure 4.11 h	Calluna heath
Figure 4.11 i	Molinia grassland
Figure 4.11 j	Bracken
Figure 4.11 k	Scree

Figure 4.11 a
Graph showing the correspondence between the NCC field map and the TM classmaps.

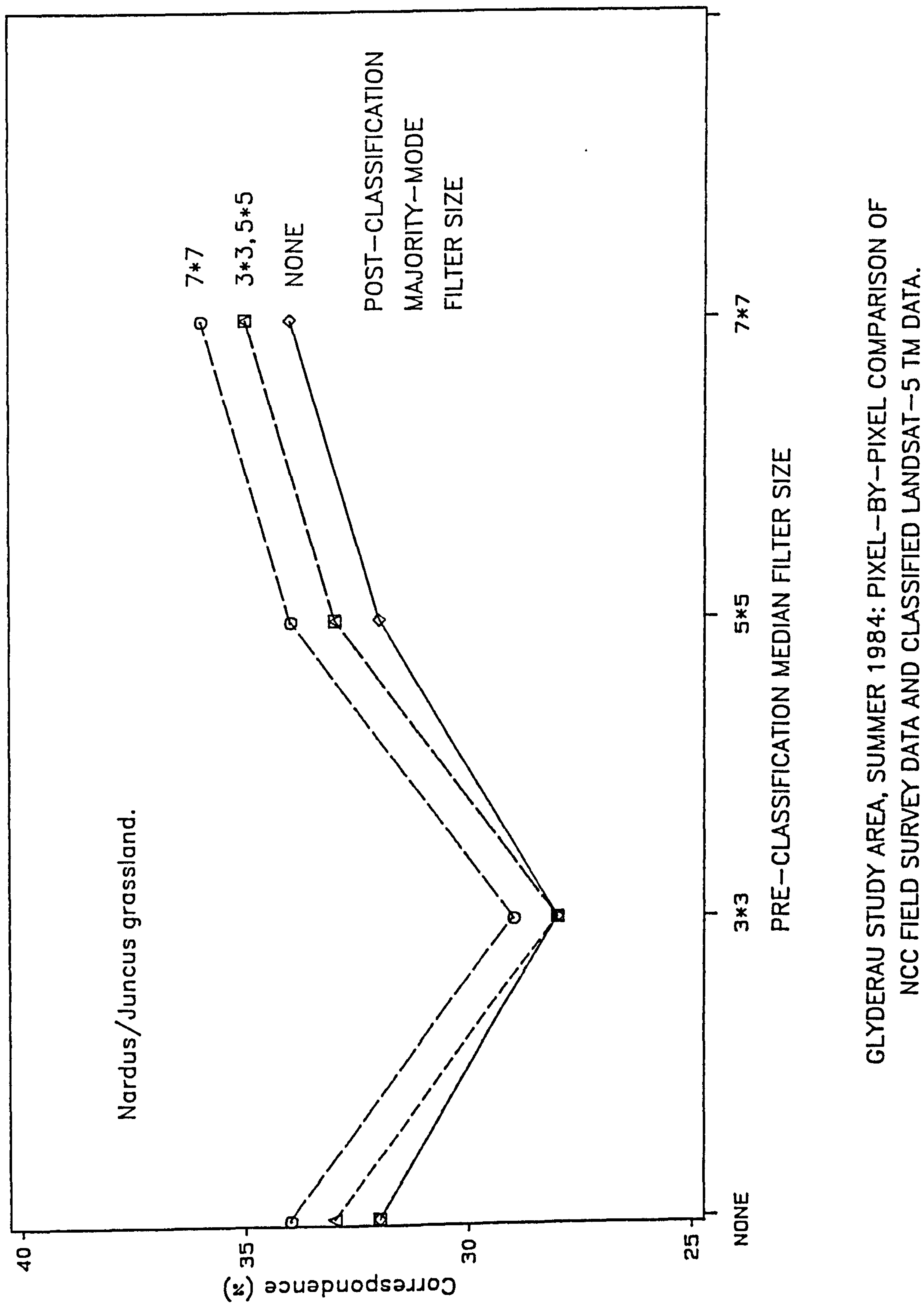


Figure 4.11 b
Graph showing the correspondence between the NCC field map and the TM classmaps.

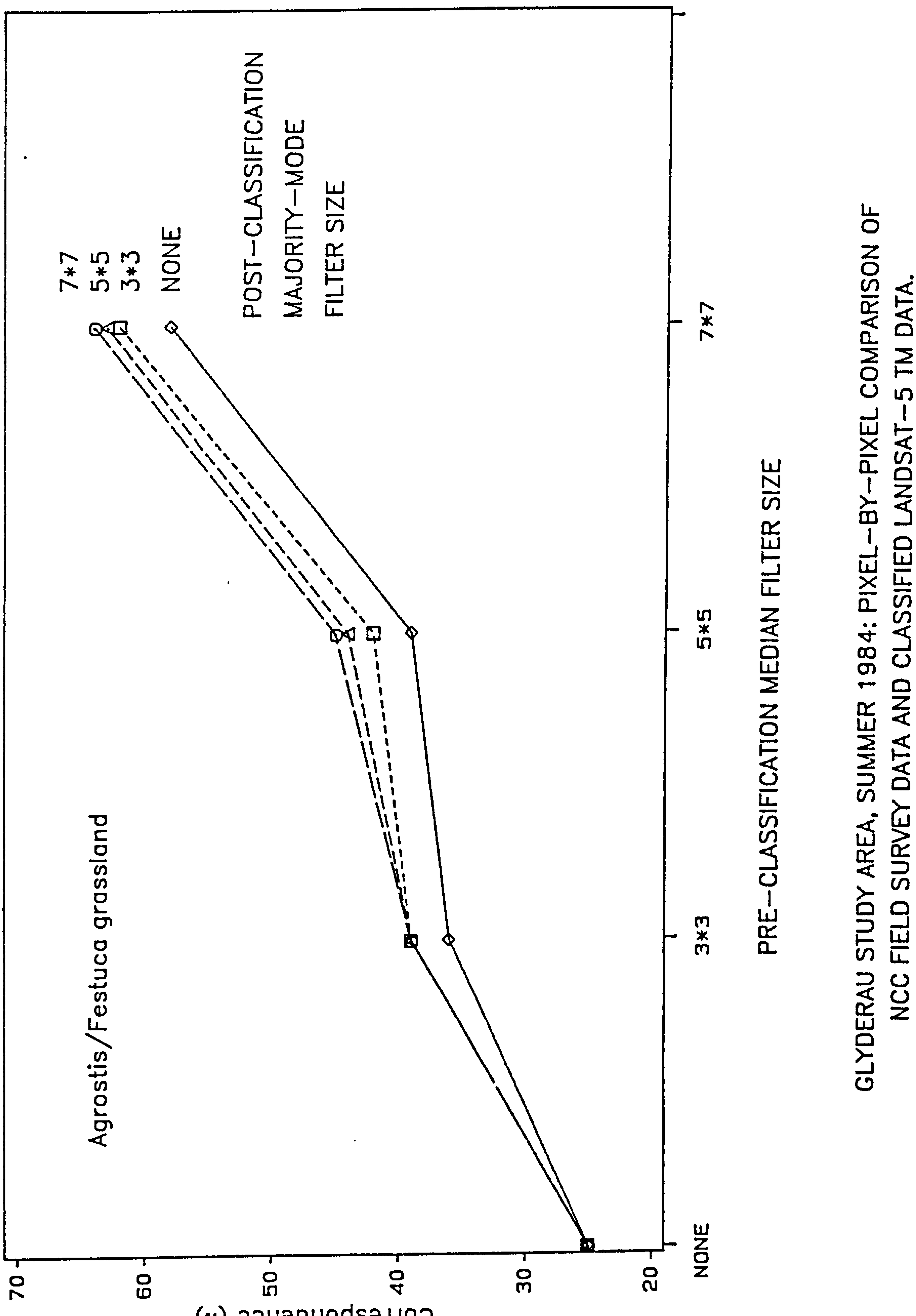


Figure 4.11 c
Graph showing the correspondence between the NCC field map and the TM classmaps.

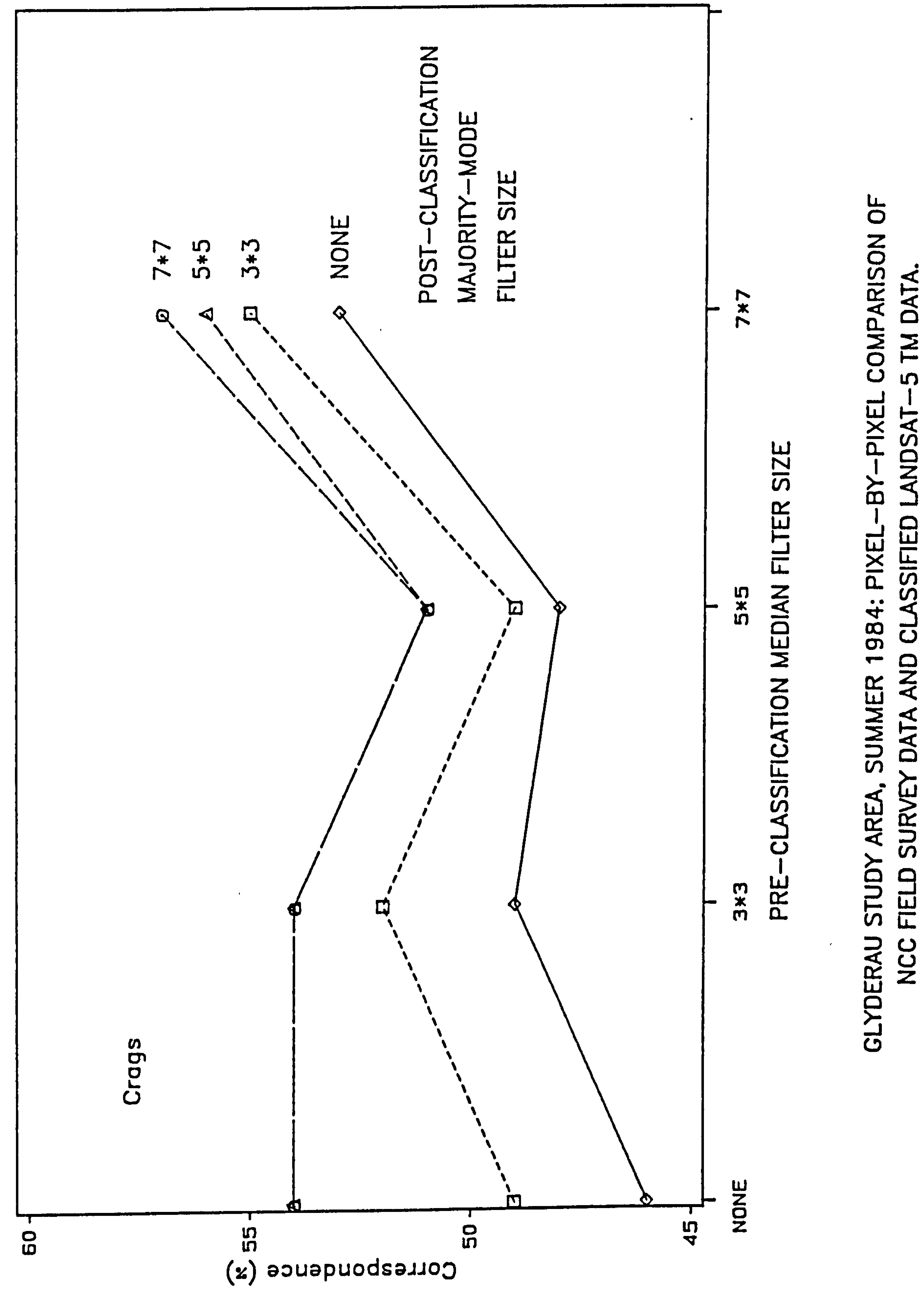


Figure 4.11 d
Graph showing the correspondence between the NCC field map and the TM classmaps.

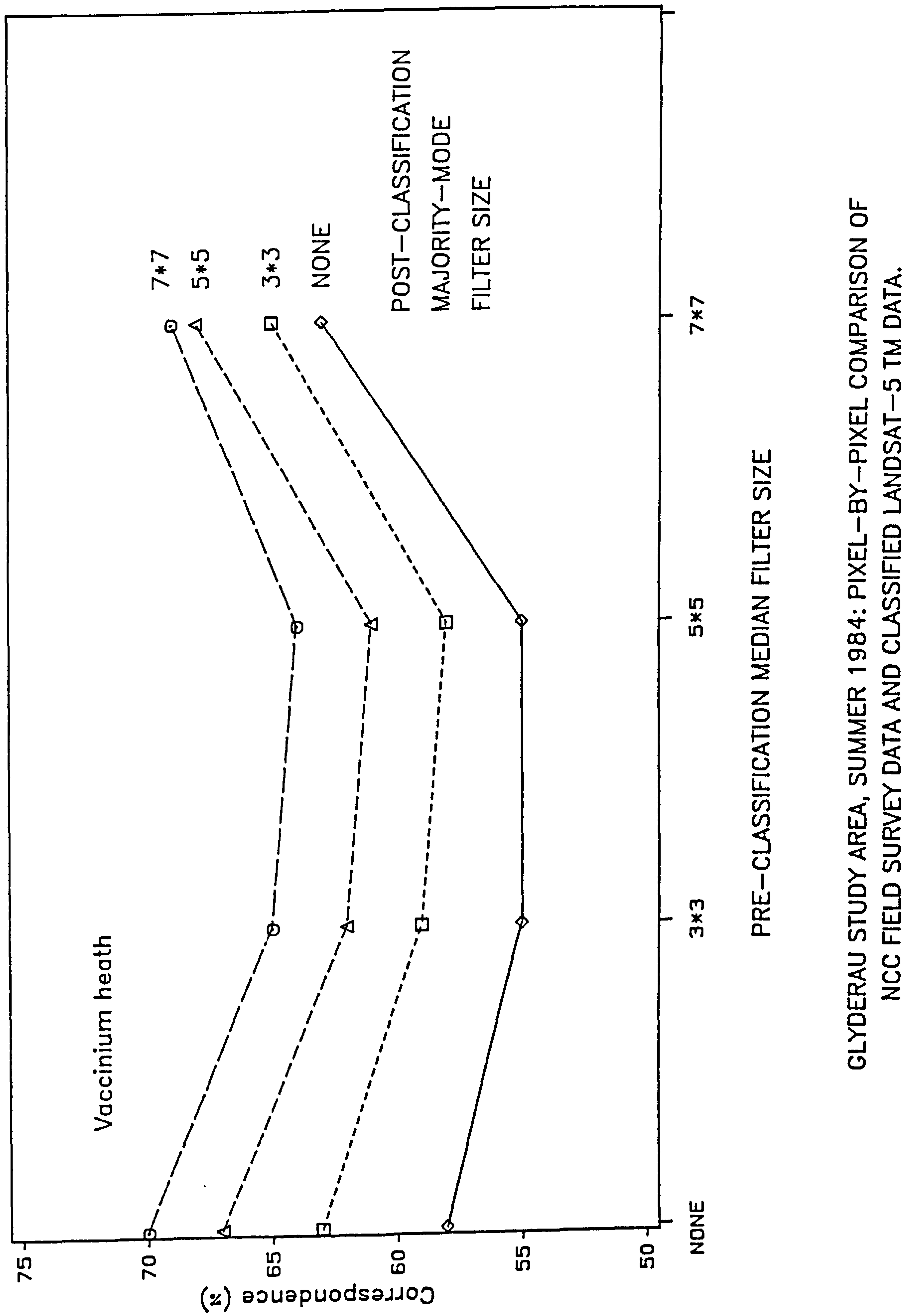


Figure 4.11 e
Graph showing the correspondence between the NCC field map and the TM classmaps.

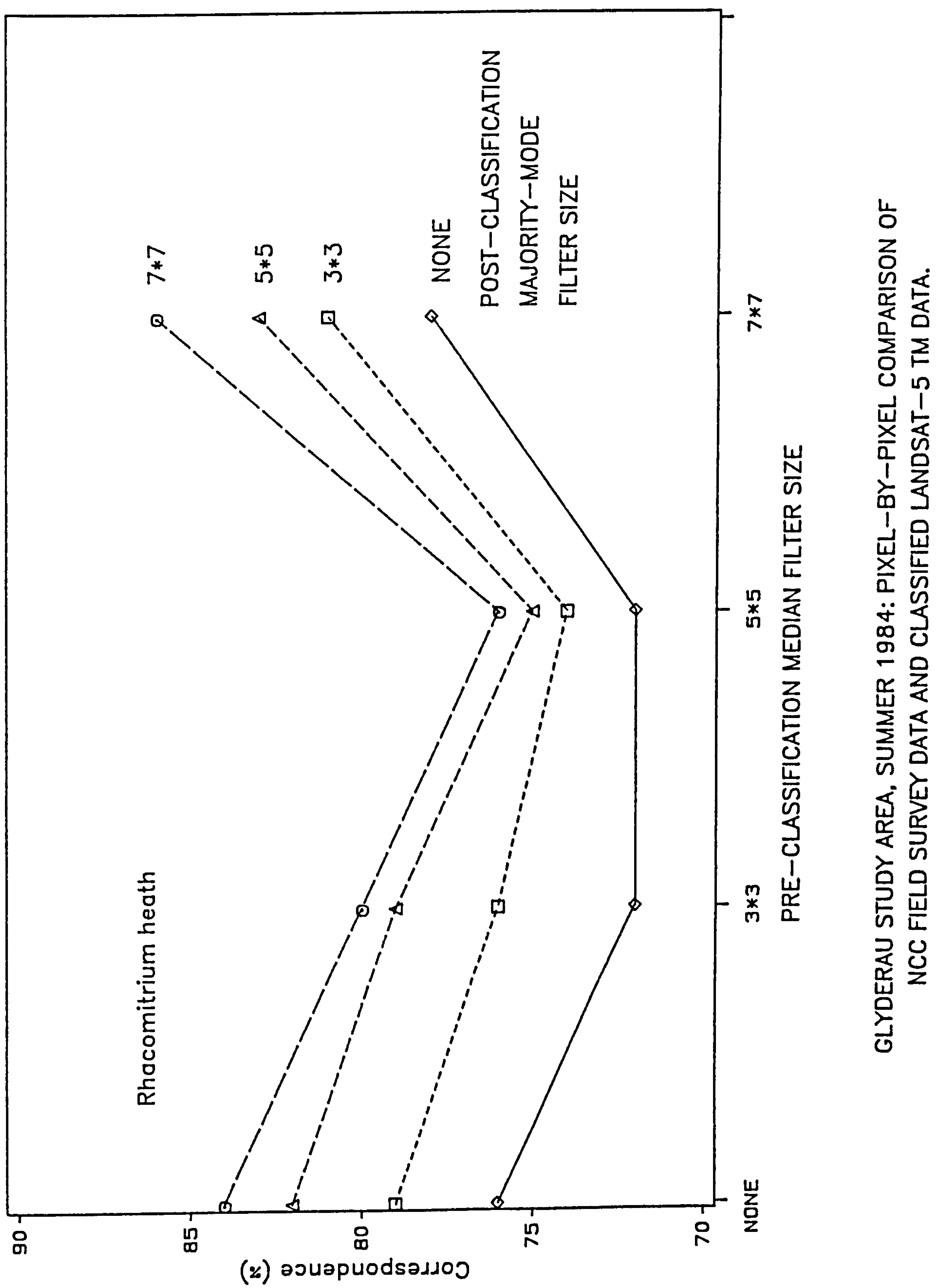


Figure 4.11 f
Graph showing the correspondence between the NCC field map and the TM classmaps.

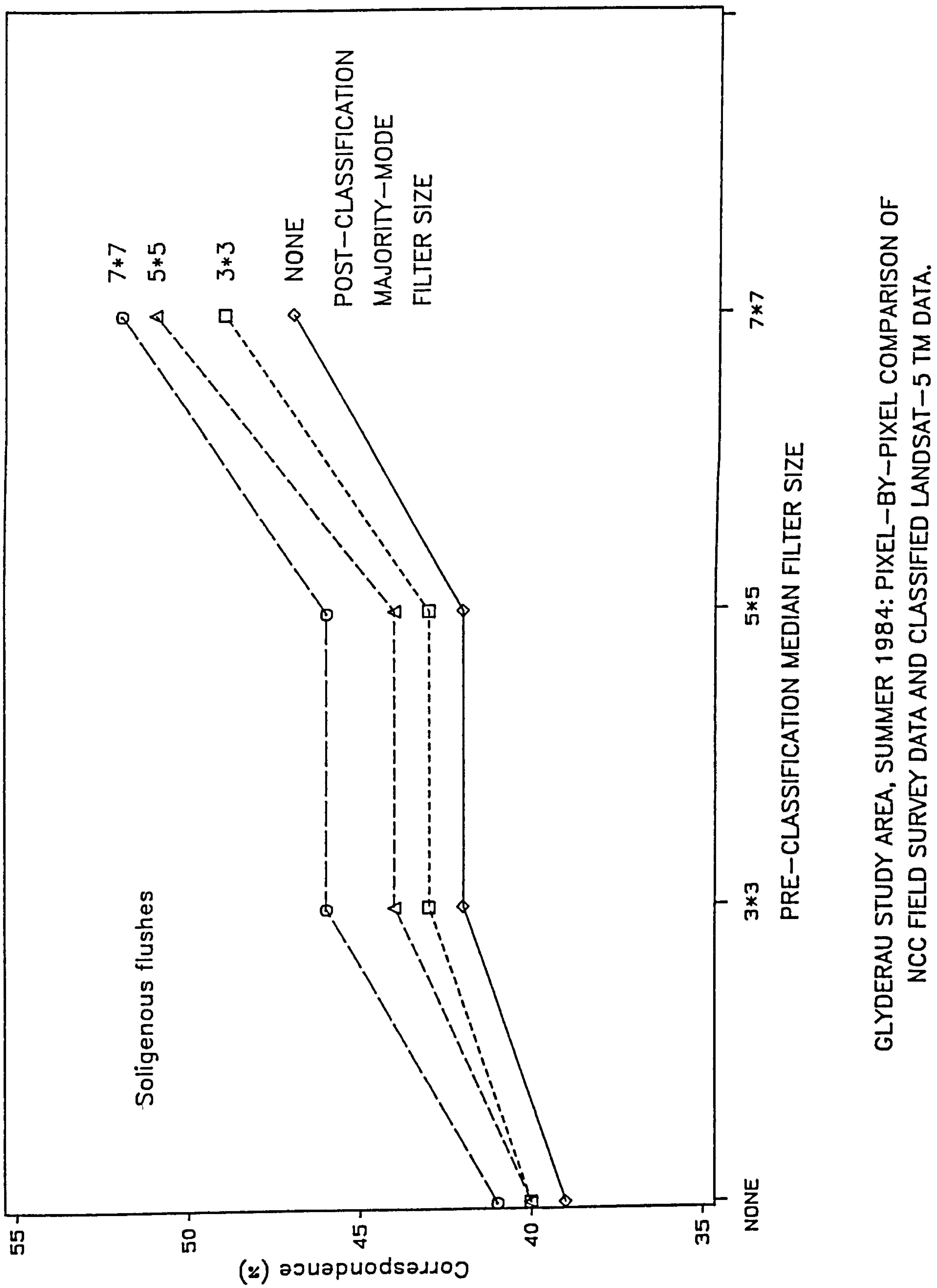


Figure 4.11 g
Graph showing the correspondence between the NCC field map and the TM classmaps.

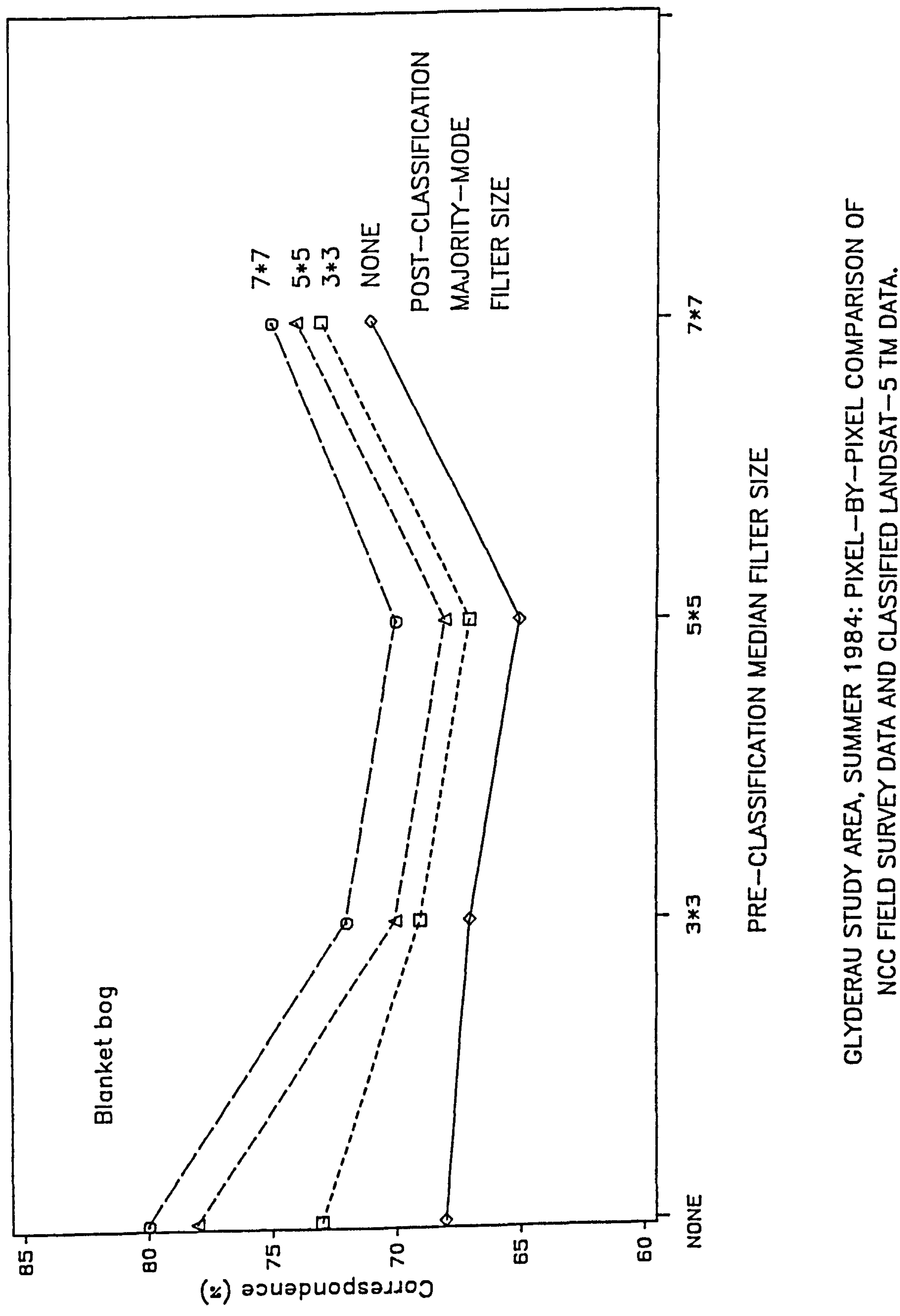


Figure 4.11 h
Graph showing the correspondence between the NCC field map and the TM classmaps.

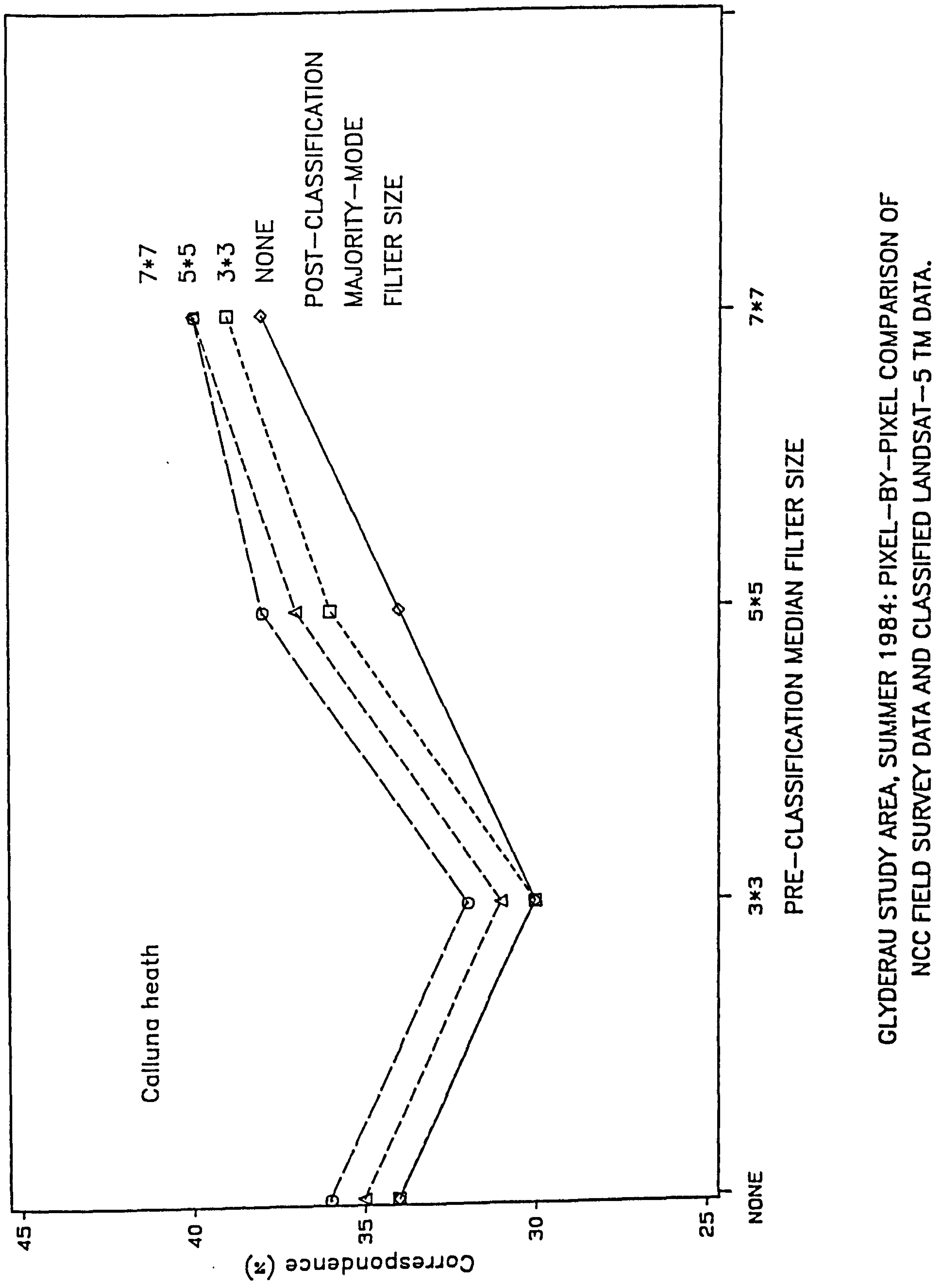


Figure 4.11 i
Graph showing the correspondence between the NCC field map and the TM classmaps.

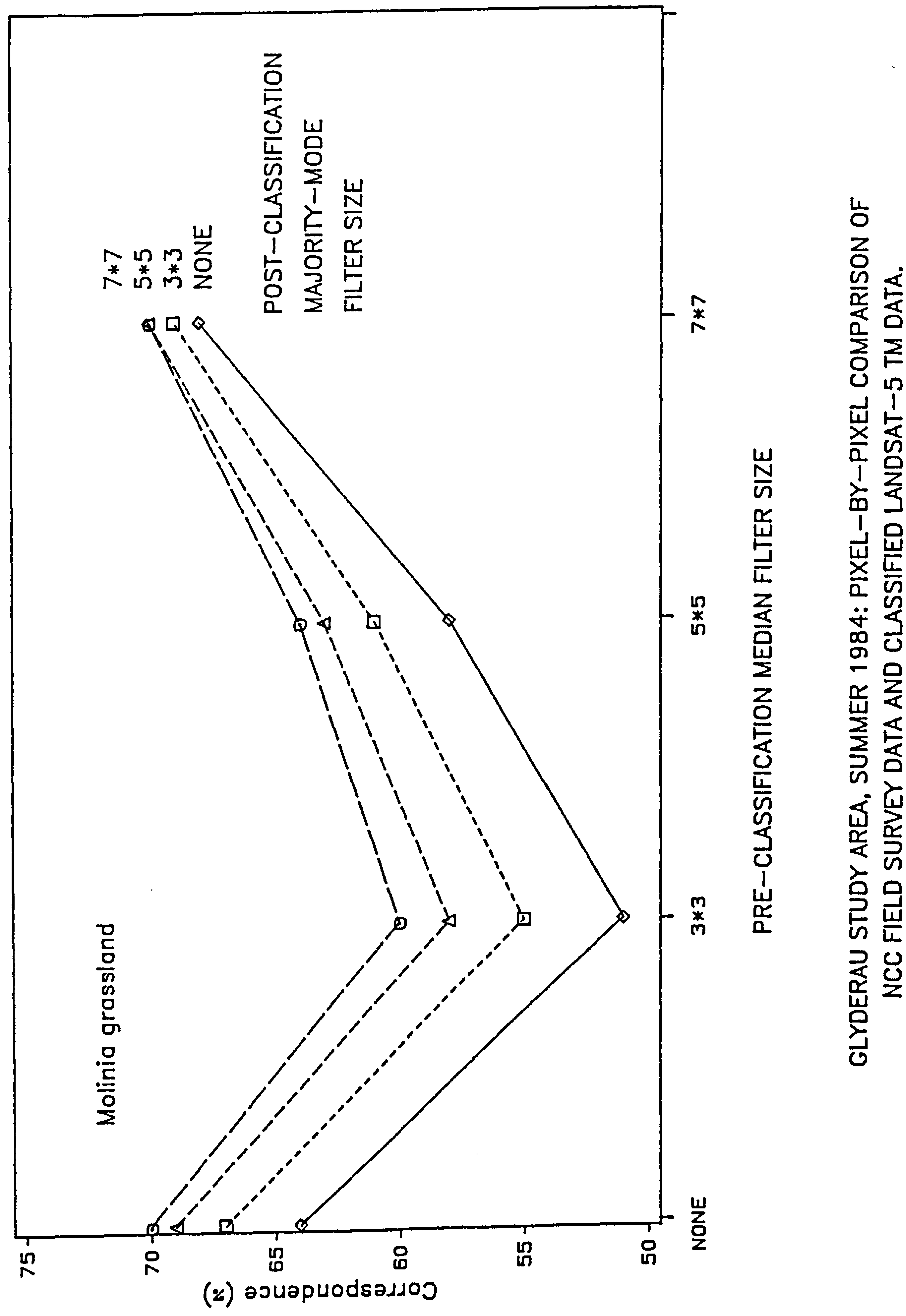


Figure 4.11 j
Graph showing the correspondence between the NCC field map and the TM classmaps.

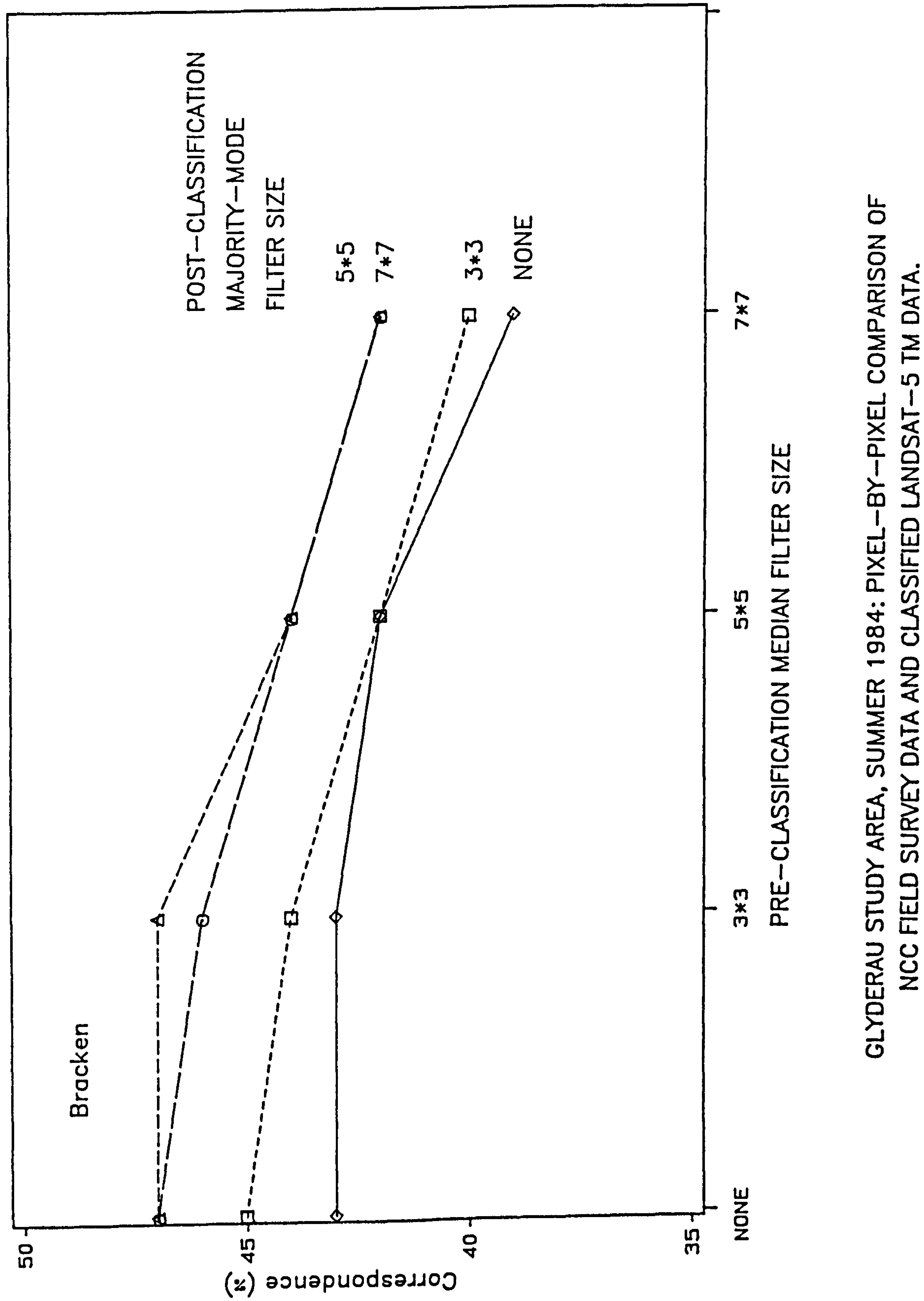


Figure 4.11 k
Graph showing the correspondence between the NCC field map and the TM classmaps.

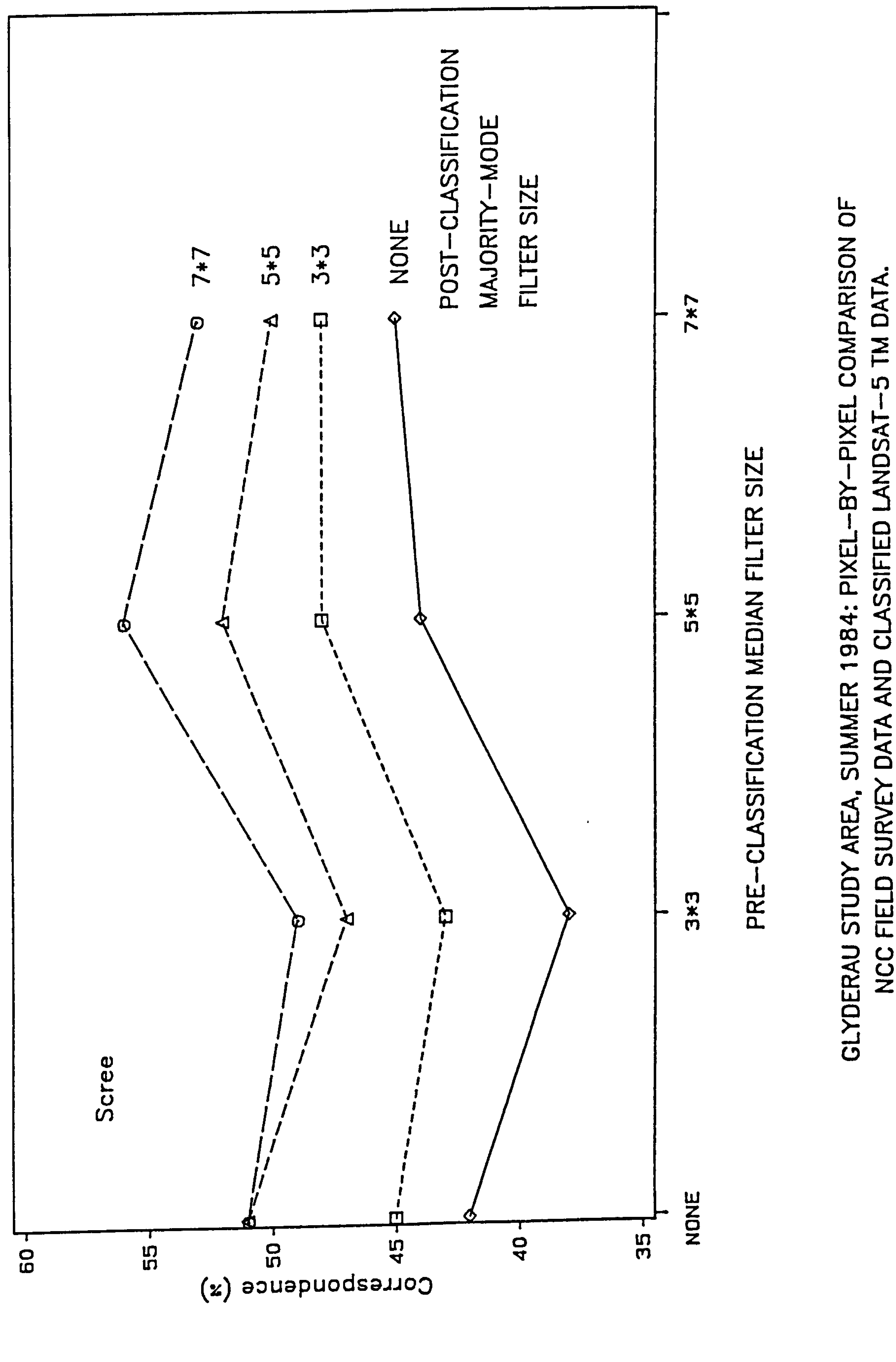


FIGURE 4.12

Land ownership boundaries within the study area.
Map width is 5.9km; top of page is East.

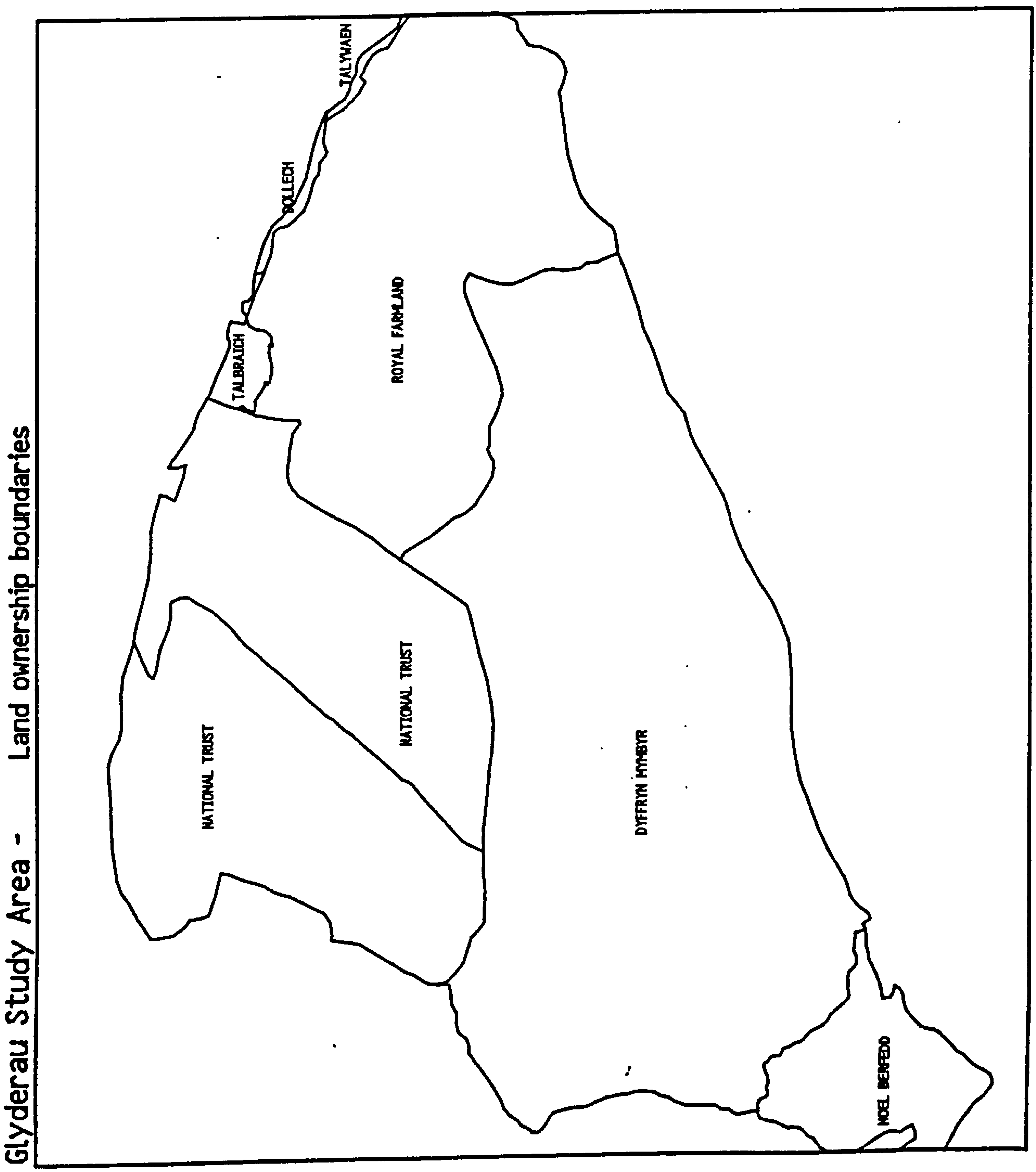


FIGURE 4.13

NCC 1984 Field survey vegetation boundaries.
Vector linework for overlay on Thematic Mapper data.
Map width is 7.7km; top of page is East.

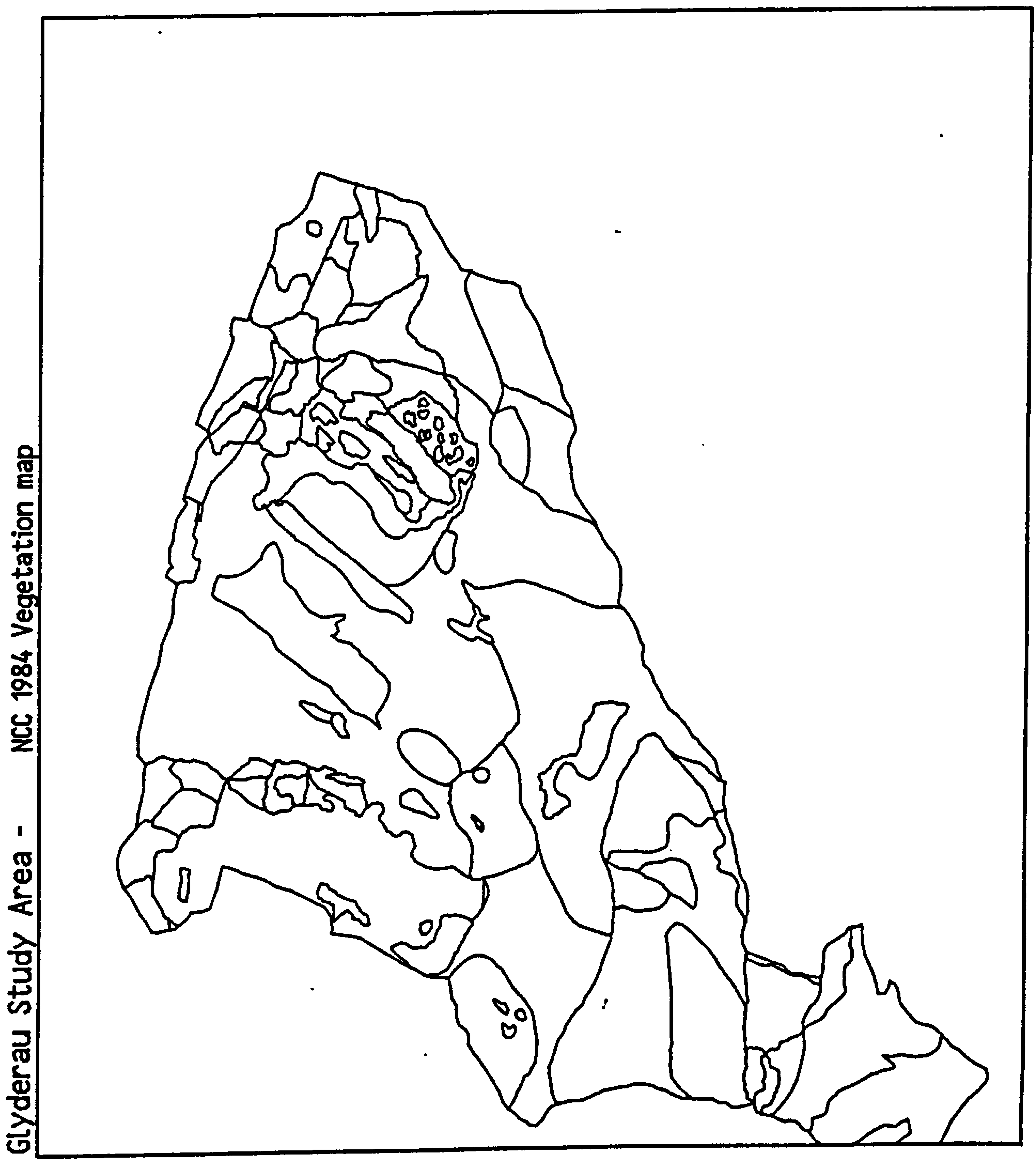


FIGURE 4.14

Vector representation of polygon overlay.
Owner 13 (National Trust) cut through NCC vegetation map.
Map width is 3km; top of page is East.

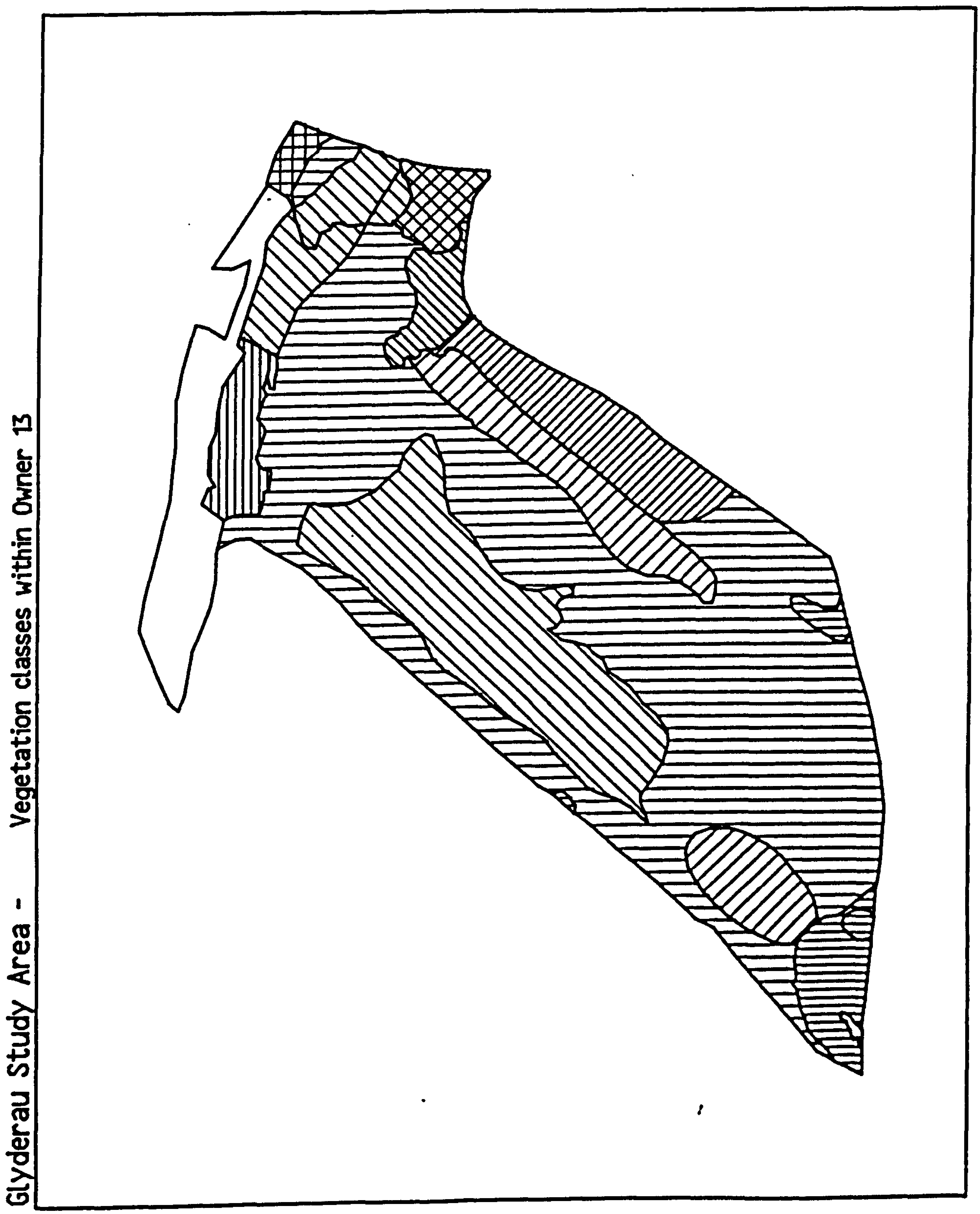


TABLE 4.1

The upland vegetation types and their aspect sub-classes found in the Glyderau study area.

Vegetation types refer to Ratcliffe and Birks (1980).

CLASS I	Level II	ASPECT	DESCRIPTION
1	1		Open water
2	2	SE	Nardus-Juncus grassland
3	2	TOP	Nardus-Juncus grassland
4	2	NW	Nardus-Juncus grassland
5	3		Agrostis-Festuca grassland
6	4		Crags
7	5	SE	Vaccinium heath
8	5	TOP	Vaccinium heath
9	5	NW	Vaccinium heath
10	6		Rhacomitrium heath
11	7	SE	Soligenous flushes
12	7	NW	Soligenous flushes
13	8	SE	Blanket bog
14	8	TOP	Blanket bog
15	8	NW	Blanket bog
16	9	SE	Calluna heath
17	9	NW	Calluna heath
18	10	SE	Molinia grassland
19	10	NW	Molinia grassland
20	11	SE	Bracken
21	11	NW	Bracken
22	12		Scree

TABLE 4.2

The wavebands of the Landsat TM sensor

TM Band	Waveband (μm)	Region
1	.45 - .52	green
2	.52 - .60	blue
3	.63 - .69	red
4	.76 - .90	near-IR
5	1.55 - 1.75	near middle-IR
6	10.40 - 12.50	thermal-IR
7	2.08 - 2.35	middle-IR

TABLE 4.3

The four extremes of filter combination
are shown in Plates 4.8 to 4.11

		PRE-Classification MEDIAN filter			
		0	3x3	5x5	7x7
	0	4.8			4.10
POST	3x3				
Classification	5x5			*PLATE*	
MAJORITY-MODE	7x7	4.9			4.11
filter					

TABLE 4.4

The sixteen treatments resulting from
pre- and post-classification filtering of
the Landsat Thematic Mapper data and classmaps.

POST-classification MAJORITY-MODE filter	PRE-classification MEDIAN filter NONE	3x3	5x5	7x7
NONE	1	2	3	4
3x3	5	6	7	8
5x5	9	10	11	12
7x7	13	14	15	16

TABLE 4.5
Classes refer to Level I, Table 4.1

GLYDERAU VEGETATION MAPPING using Landsat 5 TM 22 July 1984 data.

Table showing transformed divergence scores for the separability of 22 spectral classes (12 cover types).

Pre-classification filter: NONE.

CLASS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2	*	-	84	94	58	94	*	75	84	*	60	84	75	71	*	84	77	72	*	98	81	97
3	*	84	-	97	93	52	*	69	95	80	54	99	*	93	*	55	34	99	*	*	91	72
4	*	94	97	-	71	99	*	99	85	*	93	37	93	91	*	98	89	89	81	*	89	*
5	*	58	93	71	-	97	*	90	81	*	61	50	59	66	*	91	74	52	*	*	85	*
6	*	94	52	99	97	-	*	85	99	88	65	*	*	99	*	65	43	*	*	*	89	79
7	*	*	*	*	*	*	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
8	*	75	69	99	90	85	*	-	99	97	40	99	99	76	*	52	71	96	*	98	99	85
9	*	84	95	85	81	99	*	99	-	*	88	86	95	97	*	98	78	95	*	*	90	*
10	*	*	80	*	*	88	*	97	*	-	98	*	*	*	*	97	95	*	*	*	*	60
11	*	60	54	93	61	65	*	40	88	98	-	89	92	66	*	46	41	85	*	99	93	86
12	*	84	99	37	50	*	*	99	86	*	89	-	67	58	*	99	90	74	95	*	89	*
13	*	75	*	93	59	*	*	99	95	*	92	67	-	78	*	99	97	70	*	99	97	*
14	*	71	93	91	66	99	*	76	97	*	66	58	78	-	*	86	81	74	*	99	99	99
15	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-	*	*	*	*	*	*	*
16	*	84	55	98	91	65	*	52	98	97	46	99	99	86	*	-	51	99	*	*	95	95
17	*	77	34	89	74	43	*	71	78	95	41	90	97	81	*	51	-	94	*	*	83	86
18	*	72	99	89	52	*	*	96	95	*	85	74	70	74	*	99	94	-	*	97	97	*
19	*	*	*	81	*	*	*	*	*	*	*	95	*	*	*	*	*	*	-	*	*	*
20	*	98	*	*	*	*	*	98	*	*	99	*	99	99	*	*	*	97	*	-	*	*
21	*	81	91	89	85	89	*	99	90	*	93	89	97	99	*	95	83	97	*	*	-	*
22	*	97	72	*	*	79	*	85	*	60	86	*	*	99	*	95	86	*	*	*	*	-

TABLE 4.6
Classes refer to Level I, Table 4.1

GLYDERAU VEGETATION MAPPING using Landsat 5 TM 22 July 1984 data.

Table showing transformed divergence scores for the separability of 22 spectral classes (12 cover types).

Pre-classification filter: MEDIAN 3*3.

CLASS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2	*	-	66	95	63	83	*	64	84	99	59	88	77	80	99	65	71	71	*	*	67	85
3	*	66	-	97	93	41	*	68	96	85	50	99	99	94	*	40	41	97	*	*	77	76
4	*	95	97	-	67	*	*	99	85	*	93	38	94	90	*	98	90	87	80	*	82	*
5	*	63	93	67	-	98	*	93	81	*	71	37	74	70	98	92	82	54	*	*	77	*
6	*	83	41	*	98	-	*	77	99	91	53	*	*	98	*	63	47	99	*	*	89	72
7	*	*	*	*	*	*	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
8	*	64	68	99	93	77	*	-	*	97	38	99	99	85	*	39	71	93	*	*	96	81
9	*	84	96	85	81	99	*	*	-	*	88	87	93	97	*	99	79	96	*	*	77	*
10	*	99	85	*	*	91	*	97	*	-	98	*	*	*	*	93	98	*	*	*	*	54
11	*	59	50	93	71	53	*	38	88	98	-	93	95	75	*	42	46	80	*	*	87	83
12	*	88	99	38	37	*	*	99	87	*	93	-	77	72	*	*	95	74	95	*	83	*
13	*	77	99	94	74	*	*	99	93	*	95	77	-	64	*	98	96	77	*	*	93	*
14	*	80	94	90	70	98	*	85	97	*	75.	72	64	-	*	85	85	58	*	*	99	*
15	*	99	*	*	98	*	*	*	*	*	*	*	*	*	-	*	*	*	*	*	*	*
16	*	65	40	98	92	63	*	39	99	93	42	*	98	85	*	-	50	98	*	*	86	87
17	*	71	41	90	82	47	*	71	79	98	46	95	96	85	*	50	-	92	*	*	84	91
18	*	71	97	87	54	99	*	93	96	*	80	74	77	58	*	98	92	-	*	99	97	*
19	*	*	*	80	*	*	*	*	*	*	*	95	*	*	*	*	*	*	-	*	*	*
20	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	99	*	-	*	*
21	*	67	77	82	77	89	*	96	77	*	87	83	93	99	*	86	84	97	*	*	-	99
22	*	85	76	*	*	72	*	81	*	54	83	*	*	*	*	87	91	*	*	*	99	-

TABLE 4.7
Classes refer to Level I, Table 4.1

GLYDERAU VEGETATION MAPPING using Landsat 5 TM 22 July 1984 data.

Table showing transformed divergence scores for the separability of 22 spectral classes (12 cover types).

Pre-classification filter: MEDIAN 5*5.

CLASS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2	*	-	72	96	70	89	*	71	83	99	60	91	84	84	99	70	82	78	*	*	70	89
3	*	72	-	97	95	45	*	75	95	86	52	*	*	96	*	40	51	99	*	*	81	79
4	*	96	97	-	71	*	*	99	86	*	93	43	96	94	*	99	92	90	96	*	84	*
5	*	70	95	71	-	99	*	94	83	*	68	42	82	76	98	94	86	59	*	*	83	*
6	*	89	45	*	99	-	*	80	99	95	61	*	*	99	*	65	54	*	*	*	95	82
7	*	*	*	*	*	*	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
8	*	71	75	99	94	80	*	-	*	99	42	*	*	90	*	42	73	96	*	*	97	88
9	*	83	95	86	83	99	*	*	-	*	86	93	94	97	*	98	79	98	*	*	76	*
10	*	99	86	*	*	95	*	99	*	-	99	*	*	*	*	95	99	*	*	*	*	59
11	*	60	52	93	68	61	*	42	86	99	-	94	96	75	*	41	49	82	*	*	88	85
12	*	91	*	43	42	*	*	*	93	*	94	-	82	86	*	*	97	82	99	*	87	*
13	*	84	*	96	82	*	*	*	94	*	96	82	-	60	*	99	99	84	*	*	96	*
14	*	84	96	94	76	99	*	90	97	*	75	86	60	-	*	89	89	62	*	*	99	*
15	*	99	*	*	98	*	*	*	*	*	*	*	*	*	-	*	*	*	*	*	*	*
16	*	70	40	99	94	65	*	42	98	95	41	*	99	89	*	-	55	99	*	*	87	90
17	*	82	51	92	86	54	*	73	79	99	49	97	99	89	*	55	-	96	*	*	88	96
18	*	78	99	90	59	*	*	96	98	*	82	82	84	62	*	99	96	-	*	*	99	*
19	*	*	*	96	*	*	*	*	*	*	*	99	*	*	*	*	*	*	-	*	*	*
20	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-	*	*
21	*	70	81	84	83	95	*	97	76	*	88	87	96	99	*	87	88	99	*	*	-	*
22	*	89	79	*	*	82	*	88	*	59	85	*	*	*	*	90	96	*	*	*	*	-

TABLE 4.8
Classes refer to Level I, Table 4.1

GLYDERAU VEGETATION MAPPING using Landsat 5 TM 22 July 1984 data.

Table showing transformed divergence scores for the separability of 22 spectral classes (12 cover types).

Pre-classification filter: MEDIAN 7*7.

CLASS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2	*	-	87	97	78	96	*	83	91	*	80	95	97	88	*	91	86	86	*	*	76	97
3	*	87	-	97	98	58	*	77	99	97	78	*	*	97	*	55	59	*	*	*	92	83
4	*	97	97	-	84	*	*	99	91	*	97	43	98	96	*	99	93	95	98	*	84	*
5	*	78	98	84	-	99	*	96	94	*	87	65	95	89	*	98	90	76	*	*	91	*
6	*	96	58	*	99	-	*	90	*	99	80	*	*	*	*	78	55	*	*	*	98	86
7	*	*	*	*	*	*	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
8	*	83	77	99	96	90	*	-	*	*	58	*	*	92	*	56	73	99	*	*	98	94
9	*	91	99	91	94	*	*	*	-	*	95	95	*	99	*	*	91	99	*	*	87	*
10	*	*	97	*	*	99	*	*	*	-	*	*	*	*	*	*	*	*	*	*	*	80
11	*	80	78	97	87	80	*	58	95	*	-	97	*	87	*	68	50	97	*	*	94	98
12	*	95	*	43	65	*	*	*	95	*	97	-	89	82	*	*	96	88	*	*	91	*
13	*	97	*	98	95	*	*	*	*	*	*	89	-	93	*	*	*	95	*	*	98	*
14	*	88	97	96	89	*	*	92	99	*	87	82	93	-	*	95	93	86	*	*	99	*
15	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-	*	*	*	*	*	*	*
16	*	91	55	99	98	78	*	56	*	*	68	*	*	95	*	-	66	*	*	*	96	97
17	*	86	59	93	90	55	*	73	91	*	50	96	*	93	*	66	-	98	*	*	90	98
18	*	86	*	95	76	*	*	99	99	*	97	88	95	86	*	*	98	-	*	*	98	*
19	*	*	*	98	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-	*	*	*
20	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-	*	*
21	*	76	92	84	91	98	*	98	87	*	94	91	98	99	*	96	90	98	*	*	-	*
22	*	97	83	*	*	86	*	94	*	80	98	*	*	*	*	97	98	*	*	*	*	-

TABLE 4.9
Classes refer to Level I, Table 4.1

Table showing the increase in Transformed Divergence scores resulting from moving from no filtration to an nXn pre-classification median filtration.

Only the changes in highest separability are shown.

Class	Score increase after using 3*3	5*5	7*7	% score increase after using 3*3	5*5	7*7
2	7	16	22	10	21	34
3	1	17	25	1	50	74
4	1	10	17	1	27	21
5	17	27	36	29	46	61
6	0	9	15	0	21	28
7	0	0	0	0	0	0
8	7	13	18	9	20	45
9	3	8	13	3	10	17
10	1	11	20	1	14	33
11	1	15	26	1	23	48
12	9	19	24	14	33	41
13	17	27	36	29	46	61
14	8	19	24	14	33	41
15	0	0	0	0	0	0
16	0	7	22	0	15	48
17	1	17	25	1	50	74
18	6	17	25	9	24	46
19	1	10	17	1	12	21
20	3	3	3	3	3	3
21	0	8	9	0	10	10
22	0	9	20	0	10	33

TABLE 4.10

The maximum reductions and increases in transformed divergence scores resulting from the pre-classification median filtering of Thematic mapper data.

Maximum changes (%) in transformed divergence score.		Reduction	Increase
Median Filter Size	3x3	-37%	+29%
	5x5	-18%	+50%
	7x7	-6%	+74%

TABLE 4.12
Classes refer to Level II, Table 4.1

GLYDEIRIAU VEGETATION MAPPING using Landsat 5 TM 22 July 1984 data.

Table showing correspondence (%) between ground survey and classified TM data from methodologies using combinations of no image filtration, and pre- and post-classification image filtration.

Median filter used! PRE	0	0	0	0	3*3	3*3	3*3	3*3	5*5	5*5	5*5	5*5	7*7	7*7	7*7	7*7		
POST	0	3*3	5*5	7*7	0	3*3	5*5	7*7	0	3*3	5*5	7*7	0	3*3	5*5	7*7	min	max
Class																		
2	32.1	29.1	26.4	24.6	27.6	24.7	22.7	21.1	31.9	30.0	28.1	26.6	33.6	32.2	31.1	30.1	21.1	33.6
3	24.9	21.9	20.0	17.7	36.3	37.3	38.4	36.5	39.3	43.6	46.7	48.3	57.8	64.0	65.7	66.9	17.7	66.9
4	45.7	53.0	59.3	62.2	48.9	54.5	57.9	56.1	47.7	53.6	55.8	54.7	52.9	58.9	60.8	61.4	45.7	62.2
5	58.4	65.4	70.4	73.6	55.0	61.5	66.5	68.4	55.1	60.5	65.8	71.5	62.9	67.2	70.7	73.2	55.0	73.6
6	75.6	80.6	84.4	88.7	72.2	76.7	80.3	82.7	71.7	75.4	77.5	79.4	78.3	82.2	85.6	89.6	71.7	89.6
7	38.5	43.4	47.2	50.8	41.9	48.3	53.4	59.4	41.8	45.3	48.5	51.6	47.3	50.6	52.4	54.3	38.5	59.4
8	68.1	75.2	81.5	85.0	67.0	69.8	72.3	74.9	65.3	67.6	69.6	70.8	71.2	73.0	74.4	75.6	65.3	85.0
9	33.7	32.7	31.8	31.3	29.5	28.4	27.1	25.9	34.4	34.4	34.0	34.0	37.6	38.0	38.1	38.3	25.9	38.3
10	63.9	66.8	68.6	70.3	51.1	55.9	59.1	60.1	58.0	61.1	63.0	64.2	68.3	68.9	70.8	71.7	51.1	71.7
11	42.7	42.9	41.3	37.6	42.5	41.1	40.1	37.9	41.5	40.8	38.5	36.9	39.2	38.4	37.6	36.9	36.9	42.9
12	41.8	41.6	44.9	45.1	37.7	41.6	45.9	45.7	44.1	47.0	51.3	54.9	45.3	47.2	49.8	52.2	37.7	54.9

Improvement from no filtration to best combination! mean 36%, range 1% - 169%.
Improvement from worst combination to best combination! mean 52%, range 16% - 278%.

TABLE 4.13
Classes refer to Level II, Table 4.1

GLYDERAU VEGETATION MAPPING using Landsat 5 TM 22 July 1984 data.

Table showing the change in correspondence resulting from increasing the level of PRE-classification filtering, for each level of POST-classification filtration.

Pre- / Post-	3*3 / 0 v	5*5 / 0 v	7*7 / 0 v	3*3 / 3*3 v	5*5 / 3*3 v	7*7 / 3*3 v	3*3 / 5*5 v	5*5 / 5*5 v	7*7 / 5*5 v	3*3 / 7*7 v	5*5 / 7*7 v	7*7 / 7*7 v	General trend
Class													
2	-4	0	2	-4	1	3	-4	2	5	-4	2	6	+
3	11	14	33	15	22	42	18	27	46	19	31	49	+
4	3	2	7	2	1	6	-1	-4	2	-6	-8	-1	+-
5	-3	-3	5	-4	-5	2	-4	-5	0	-5	-2	0	-
6	-3	-4	3	-4	-5	2	-4	-7	1	-6	-9	1	-
7	3	3	9	5	2	7	6	1	5	9	1	4	+
8	-1	-3	3	-5	-8	-2	-9	-12	-7	-10	-14	-9	-
9	-4	1	4	-4	2	5	-5	2	6	-5	3	7	+
10	-13	-6	4	-11	-6	2	-10	-6	2	-10	-6	1	-
11	0	-1	-4	-2	-2	-5	-1	-3	-4	0	-1	-1	-
12	-4	2	4	0	5	6	1	6	5	1	10	7	+

Table showing the change in correspondence resulting from increasing the level of POST-classification filtering, for each level of PRE-classification filtration.

Pre- / Post-	0 / 3*3 v	0 / 5*5 v	0 / 7*7 v	3*3 / 3*3 v	3*3 / 5*5 v	3*3 / 7*7 v	5*5 / 3*3 v	5*5 / 5*5 v	5*5 / 7*7 v	7*7 / 3*3 v	7*7 / 5*5 v	7*7 / 7*7 v	General trend
Class													
2	-3	-6	-8	-3	-5	-7	-2	-4	-5	-1	-2	-3	-
3	-3	-5	-7	1	2	0	4	7	9	6	8	9	+
4	7	14	17	6	9	7	6	8	7	6	8	9	+
5	7	12	15	7	12	13	5	11	16	4	8	10	+
6	5	9	13	5	8	11	4	6	8	4	7	11	+
7	5	9	12	6	12	18	4	7	10	3	5	7	+
8	7	13	17	3	5	8	2	4	6	2	3	4	+
9	-1	-2	-2	-1	-2	-4	0	0	0	0	1	1	-=
10	3	5	6	5	8	9	3	5	6	1	3	3	+
11	0	-1	-5	-1	-2	-5	-1	-3	-5	-1	-2	-2	-
12	0	3	3	4	8	8	3	7	11	2	5	7	+

TABLE 4.14
General trend in correspondence for each vegetation class after application of the filter types

+ improved, - decreased, = little change

CLASS	DESCRIPTION	General trend for --- Pre-	Post- filtration
2	Nardus-Juncus grassland	+	-
3	Agrostis-Festuca grassland	+	+
4	Crags	+-	+
5	Vaccinium heath	-	+
6	Racomitrium heath	-	+
7	Soligenous flushes	+	+
8	Blanket bog	-	+
9	Calluna heath	+	-=
10	Molinia grassland	-	+
11	Bracken	-	-
12	Scree	+	+

TABLE 4.15

Area (hectares) of each vegetation type lying within the boundary of Owner 13 (National Trust) on the Glyderau.

CLASS	DESCRIPTION	AREA (Ha)
1	Open water	0.1
2	Nardus-Juncus grassland	129.8
3	Agrostis-Festuca grassland	8.1
4	Crags	5.2
5	Vaccinium heath	20.0
6	Rhacomitrium heath	0.0
7	Soligenous flushes	49.1
8	Blanket bog	10.0
9	Calluna heath	16.4
10	Molinia grassland	1.5
11	Bracken	5.3
12	Scree	0.0

TABLE 4.16

Areal estimates for the vegetation cover in each ownership Owner12 to Owner20 from the NCC field survey.

Comparison of areal estimates for Owner13

from the NCC field survey OWNER13
and from the TM classification IISML13

ITE/NCC GLYDEIRIAU OWNERSHIP/VEGETATION TYPE AREA ESTIMATION.

CELL CONTENTS: AREA (Ha).

CLASS	OWNER12	OWNER13	OWNER14	OWNER15	OWNER16	OWNER20
1	*	0.1	*	*	*	*
2	146.8	129.8	136.8	82.2	1.9	47.4
3	*	8.1	*	12.9	*	*
4	*	5.2	*	17.5	*	*
5	131.8	20.0	6.6	*	*	*
6	29.0	*	*	*	*	*
7	14.6	49.1	5.3	7.5	*	2.4
8	77.8	10.0	6.8	76.4	*	*
9	186.8	16.4	105.9	13.5	*	*
10	9.5	1.5	7.8	*	13.0	47.9
11	5.3	5.3	5.2	14.3	*	*
12	*	*	11.3	4.9	*	*

CLASS	DESCRIPTION	OWNER13	IISML13
1	Open water	0.1	*
2	Nardus-Juncus grasslands	129.8	124.7
3	Agrostis-Festuca grasslands	8.1	12.6
4	Crags	5.2	0.1
5	Vaccinium heaths	20.0	15.6
6	Rhacomitrium heath	*	*
7	Flush bogs	49.1	22.2
8	Blanket bogs	10.0	51.3
9	Calluna heaths	16.4	26.5
10	Molinia grasslands	1.5	12.8
11	Bracken	5.3	1.5
12	Scree	*	0.1

OWNER	NAME
12	Dyffryn Mymbyr
13	National Trust
14	National Trust
15	Royal Farmland
16	Talbraich
20	Moel Berfedd

CHAPTER 5

REMOTE SENSING AND GEOGRAPHICAL INFORMATION SYSTEMS: AN INTEGRATED APPROACH TO MONITORING THE CONDITION OF SEMI-NATURAL VEGETATION

5.1 COMBINING THE REMOTE SENSING TECHNOLOGIES

Radiometry, airborne scanning and satellite data collection have been considered in Chapters 2, 3 and 4 respectively. The technologies are complementary and can be combined to improve the eventual outcome of research and terrestrial applications. Radiometry, for example, provides the technology for detailed investigation of plant leaf sections and portions of plant canopies. With the precise field-of-view inherent in radiometry it is possible to obtain relatively 'pure' radiance measurements from the target vegetation. Extraneous surfaces that may contribute to the mixed signal in satellite data (soil background, rocks and stones, water pools, for example) can be excluded from the radiometer field-of-view. These other surfaces can then be measured separately in order to examine their likely contribution to the total radiance of a mixed scene. The information obtained from radiometry can be useful when predicting the ground cover responsible for the radiance of the larger field-of-view (pixel) in airborne scanner and satellite sensor data.

Radiometry is also useful when only limited areas of plant canopy are available for investigation. Under laboratory conditions, for example, it may be difficult to prepare the experimental treatment of large areas of plant canopy. Radiometry can thus prove useful when examining the effect of changing environmental conditions on plant material. The 'chlorotic yellowing' of plants under nutrient stress or airborne pollution can be quantified in terms of specific radiance changes in particular wavebands. This information can be used when attempting to quantify the significance of forest or grassland canopy radiance variation as observed in airborne scanner and satellite sensor data.

The potential impact of airborne pollution on the extensive swathes of semi-natural grassland in the UK uplands and lowlands is significant. Farming enterprises are at the limit of financial stability in these areas and any reduction in the quality and productivity of the vegetation could affect the already low animal stocking densities. The impact of airborne pollutants was a major concern for the Welsh Office who initiated the experiments reported in chapter 2.

While air pollution was of particular interest the early 1980s, when the experiments reported in chapter 2 were completed, there are many other potential applications for radiometry in the study of semi-natural vegetation in the UK uplands. In terms of management information, grazing pressure and its impact has always been of key interest. It would be most useful to investigate the effect on radiance of the gradual thinning and eventual destruction of the grassland canopy under the influence of actual or simulated grazing. This information would be of considerable use in analysing airborne or satellite scanner data from extensive tracts of rural land. A prime concern of the organisations involved in the management of these areas is sheep stocking density and the early detection of areas liable to soil erosion.

Airborne scanner data are essential in the intermediate stratum between radiometry and satellite scanner survey. During the development of new technology, data from airborne scanners simulating the specifications of new satellite sensors have been released early to allow research teams to prepare for the next phase of remote sensing. Prior to the launch of the Landsat Thematic Mapper and SPOT HRV missions, for example, airborne scanners were used to collect and prepare digital simulation data. In early 1992, EOSAT released data simulating the modified scanner data which should soon be available from Landsat-6.

Airborne scanner data have other applications. Research flights can be controlled with regard to location, time-of-day, date, weather conditions, height (and thus resolution) enabling unique data sets to be prepared. The extensions to laboratory-based experiments are field trials and experiments. Research field plot sizes can, typically, be 30m x 30m to 50m x 50m; these plot sizes are close to the ground resolution of Landsat TM and SPOT HRV data. It can be difficult or impossible to collect a significant number of pixel samples from an experimental plot when using data at these resolutions. Low-altitude (500m - 1000m) airborne sorties, however, can produce digital scanner data with nominal resolutions of 1m x 1m upwards. These data allow adequate (>30) numbers of samples to be obtained from within the centre of each field plot.

In Snowdonia, for example, ATM data were collected from research plots with tightly-controlled grazing regimes. Several location were used including one on the upland fringe of the Carneddau mountains. An initial examination of the data indicated that both available organic matter and sheep stocking density could be accurately characterised from the multispectral ATM data (Williams, 1987).

Conclusions and models of plant growth and reaction to changing environmental conditions under field plot conditions can be extrapolated for use in the analysis and interpretation of satellite data. The high cost of airborne scanner sorties precludes the routine operational collection of data. However, the surveying of high-value resources such as petroleum, minerals and water in some regions has made use of airborne scanner data. Airborne scanner data have also been collected for the study of unusual and worrying phenomena such as the 'forest death' in central Europe.

Satellite sensor data remain the main focus of digital earth-observation surveys. The stability of the satellite platforms, repeating synoptic coverage, relative simplicity of data processing and geometric correction and relative low operational cost make this source attractive to end-users. The increased spatial resolution of non-military sensors to the 10 metre benchmark (SPOT Panchromatic) has made the use of satellite data realistic for many applications specialists. Furthermore, the development of a world-wide series of radar satellite sensors starting with the launch of ERS-1 in July 1991 has, to some extent, overcome one of the major obstacles for applications scientists - cloud cover.

The resolution and coverage of satellite images should be appropriate for the monitoring of extensive tracts of upland vegetation; this is clear from the range of applications cited in section 4.3. While the routine monitoring of these areas continues on a 5-year basis using aerial photography and fieldwork, there are many dynamic changes in vegetation which occur on a seasonal and annual cycle. The interpretation of satellite images should be able to detect the progress of seasonal phenology, the cyclical nature of vegetation condition in relation to weather and grazing and many other dynamic processes of importance to the integrity of the uplands.

This information will be of considerable use when building and developing a GIS model of the extent and condition of the upland grasslands and wider environment. Many pressing management problems will be easier to resolve through the interrogation of this qualitative, quantitative and accurate areal information base. The application of these technologies is considered for a large upland region - Snowdonia - in section 5.3.

5.2 REMOTE SENSING AND G.I.S.

Geographical Information Systems (G.I.S.) have gained wide acceptance as a complementary technology to remote sensing. Fisher and Lindenberg (1989) attempted to clarify the distinction between remote sensing, cartography, and GIS. After considering a linear model with GIS linking remote sensing and cartography, followed by models with cartography and then GIS dominant, the authors proposed a three-way model. All disciplines were presented as equals, each being recognised as having unique and overlapping spheres of activity.

Remote sensing appears to be the clearest sphere of activity. The area which appears to require distinction is cartography, digital mapping and GIS. From the work involved in the experiments described in the previous chapters, the functionality required of a true GIS system was clear. GIS must be able to perform polygon overlay with recognition of the effects and interactions of so doing, as described in sections 4.14 and 4.16.

GIS functionality has been used in many research methodologies throughout the 1970s and 1980s. Much was achieved by the manipulation of image analysis software functions (as in Chapter 4), and also by the production of user-written functions and programs. However, the development of early commercial specialist software such as Arc/Info and Spans and the launch of learned journals such as the International Journal of Geographical Information Systems in 1987 signalled the arrival of this new technology. Software has also been written for specific purposes such as the relational image-based GIS MAP/INFO research project for use in arid land resource studies described by Zhou (1989).

Organisations and institutes concerned with rural land use inevitably store much of their spatial information as paper maps. When applying this information to management and decision-making applications it is usual to have to combine multiple dissimilar polygon and vector overlays. This is difficult in practical terms, and the new GIS technology simplifies the overlay process. GIS, however, has many other valuable properties. One of the simplest, and yet conventionally very time-consuming, is areal estimation. To calculate the areal extent of the polygons on one map (land cover, for example) was an arduous task; and yet much areal information is sought from map cross-tabulations (land cover by land owner, for example). These processes are fast and straightforward using GIS; the only cautionary note is the initial data entry or digitising overhead which must be completed in advance of the interrogation of the digital maps.

GIS functionality now provides the technology for the manipulation of spatial data. Proximity zones around points, vectors and polygons are now easily and rapidly generated; areal estimates of the zones created follow quickly. The implementation of many water and pollution guide-lines will make extensive use of these functions. More interestingly, the modelling of rural resource management through the manipulation and combination of several map overlays is now possible. Maps can be weighted to control the influence of their information on the model, and each class on each map can be considered for its contribution to the model.

There remain considerable problems in machine processing and automating the conversion of image data to information ready for incorporation and use in a natural resource GIS. Some of the developments in this field were considered in section 4.3. Trotter (1991) reviewed the particular problems of image interpretation and the difference between the continuous-tone image and the cartographic representation of geographic space in the choropleth thematic map.

When considering the integration of remote sensing with GIS, Ehlers, Edwards and Bedard (1989) described three levels of integration: separate but equal, seamless integration and total integration. The first level covers the useful and complementary display of, for example, GIS vectors on remotely sensed images as shown in chapter 4 (Plates 4.1, 4.3 and 4.4). The second level of integration covers the incorporation of rasterised GIS vector data, for example, directly in the image analysis process as described in sections 4.8.2 and 4.11.3, and shown on Plates 4.5, 4.12, 4.13 and 4.14. The third level, total integration, recognises the need and potential for a GIS capable of handling both vector and raster data structures, but, more importantly, also field-based and object-based representations.

5.3 THE APPLICATION OF G.I.S. TECHNOLOGY

The Remote Sensing and GIS Unit at the University of Wales in Bangor has adopted a stepwise approach to GIS modelling (Fig. 5.1). Five levels of spatial overlay combination have been found to be generally applicable in the development of Rural Resource Management Indicative GIS Strategies.

In the study of rural resources, it has been found useful to combine and consider the map and other spatial information in five stages. It can be possible to combine all the information in one large and complex model linking all the source data to the eventual modelled outcome. However, it is difficult to visualise or check the influence of any particular input and modification is more complex and more time-consuming. With the stepwise approach, each data input can be visualised after it has been included in a relatively simple sub-model. This approach was used by Fehr (1990) in modelling appropriate land use in Dominica, W.I. and for Belize (Tovar, 1991). Nath (1991) studied the wildlife population viability for elephants in the Rajaji National Park in India and Hunt (1992) modelled interzone and edge conservation habitats in a Welsh upland forest.

Much of the work in Chapter 4 considered the problems of providing information for a land management organisation such as the Snowdonia National Park (SNP). The implementation of GIS is discussed with particular reference to an area such as Snowdonia.

The rural communities within the Park depend heavily on agricultural enterprises. Individual farm and collective farm or parish management is responsible for the nature and diversity of land use and landscape within the Park. The farm, parish and district structure of the Park forms the framework for areal analyses and indicative strategies at the core of future land use planning. GIS can provide the management authority with a recording and decision making methodology.

The spatial nature of GIS can improve the examination and quantification of the extent and distribution of land use categories and linear landscape elements by farm, parish, district and Park. This will assist managers in preparing environmental schemes, in encouraging and discouraging certain land uses, in controlling recreation pressure, in resolving planning applications in the rural environment and in developing priority models for action within the Park. GIS is also likely to be used to develop practical and effective recording and decision making methodologies for use in other rural areas in Wales.

5.4 GENERAL RURAL RESOURCE MANAGEMENT RESEARCH

5.4.1 The fundamental need

The increasing impact of complex external factors will, over the next decade, have serious implications for maintaining the integrity of much of the Snowdonia National Park. The major external factors involved are changes in Welsh, British and European policies affecting urban and rural areas. These matters, considered with local developments, such as the improvement of the A55 coastal road, will have major consequences for agriculture, forestry, conservation and recreation in the Park. In the longer term, the impact of airborne pollutants and climatic change will have implications for the flora, fauna, hydrology and rural enterprise within the Park.

The management authorities within the Park will be able to exert considerable control over some of the policies, implementations and effects involved. However, with regard to other factors, there will be a need to examine resource management strategies which will diffuse, divert and limit the effects of anthropogenic and environmental impacts on the Park.

There is urgent need, therefore, for the development of a workable, effective and holistic methodology to assist decision making processes and the implementation of management proposals.

5.4.2 Appropriate use of GIS modelling

Computer databases have become accepted as an efficient and flexible means of storing information about resources. Increasingly there is a need to examine and model the spatial relationships between factors which interact and affect the rural areas concerned. Geographic information systems have been developed to meet this exacting need and provide an effective medium for landscape and environmental modelling. Examples include:

(a) the rapid calculation of land surface area having specific and common characteristics or the length of linear features such as hedges, stone-walls, footpaths;

(b) the inclusion of many factors in the spatial modelling of indicative rural resource management strategies;

(c) predicting, quantifying and illustrating the effects of change on the three-dimensional landscape.

Indicative rural resource management strategies result from the consideration and combination of basic spatial information. Indicative strategies generally present the suitability of land for individual activities such as grazing, arable production, recreation or urban development. The strategies are developed by careful and progressive consideration of the many factors which impinge on activities within rural areas such as the SNP. Policy implementation and economic analysis can be included in the process. The effects of both of these major factors on the Park environment can be estimated in terms of spatial distribution, areal extent and visual impact.

The factors which contribute to GIS modelling at each stage can be published and examined in detail. This flexibility simplifies the preparation of models predicting the outcome of a range of scenarios and speeds the examination of the effects of new information as it becomes available.

5.5 SPECIFIC NEEDS IN THE SNOWDONIA NATIONAL PARK

5.5.1 Operational requirements

In many organisations, there is need for a comprehensive management information system containing data about the rural environment. GIS will make feasible the exchange and combination of information for this purpose and would promote the rapid development of data resources in an organisation such as the Snowdonia National Park.

5.5.2 Implementation of existing Park policies

GIS will be useful for supporting current Park policies and their implementation in agriculture, forests and woodlands, archaeological and wildlife conservation sites, recreation and amenity, and developments in the rural environment and on the urban fringe. GIS will also help in assessing cost effectiveness and in identifying priorities; this implementation is currently being reviewed for use in the control of Rhododendron in Snowdonia. The methodology would support the preparation of whole farm plans such as those proposed in the CCW Tir Cymen (land stewardship) initiative.

5.5.3 Implementation of new external policies

Examples include:

European:	changes in agricultural policy and rates of grant aid and the consequent likely effects on farm enterprises in the Park;
British:	new farm woodland schemes and their impact and incorporation within the Park;
Welsh:	the introduction of Tir Cymen and its impact and integration within the Meirionnydd region of the Park - also its implication in other areas of the Park.

5.6 IMPLEMENTATION

Natural resource data for an area such as Snowdonia would be considered and combined through GIS modelling in a series of stages. At each stage the model can be inspected, refined and developed. Each intermediate stage would also provide spatial information and areal estimates which can be of considerable use to management organisations.

Level I	Baseline data
Level II	Baseline derivatives
Level III	Functional themes
Level IV	Indicative strategies
Level V	Appropriate management

Level I data represent basic features of the Park such as soil type, weather, altitude, vegetation and the road network; this level would also include remote sensing data such as thematic maps portraying vegetation type and grassland condition.

Level II data are derivatives from level I. Altitude data, for example, can be used to derive slope and aspect which are crucial in most spatial models. The road network can be used to derive corridors of proximity for use in transport and accessibility modelling; the river network is used to generate a proximity map showing riparian zones.

Level III data result from the first combination of level I and II thematic overlays (Figure 5.1). Level III data are produced through simple GIS models involving the weighting of level I and II maps and the ranking of classes within each map. The result is a set of functional themes which are absolutely crucial in the day-to-day management of the Park and in the development of indicative strategies. Common examples are overlays showing accessibility, general capability for crop growth, erosion risk on hill slopes, protection needs for conservation areas, landscape value and many others.

The level III functional themes are used to identify areas appropriate for a specific land use such as livestock farming, grazing, forestry, conservation or recreation. These are the level IV indicative strategies. Current local, regional, national and EC policy objectives and guide-lines can be built into the indicative strategies. When policies change, the GIS model can be adjusted at level III and the effects on Park management would be recalculated. The indicative strategies are indexed so that each land use would have a number of classes showing, for example, high, medium and low suitability for grazing and, where necessary, a number of contra-indication classes. A contra-indication class might be used where grazing would be harmful on slopes prone to erosion.

Level V maps provide expression to the final judgement of the most appropriate balance of land use for elements within a farm, parish, district or complete region. GIS modelling is used to combine the indicative strategies for the full range of options for land use. Policy objectives can be used to put a high positive weight on favoured land uses; low or negative weights can be used conversely to minimise the areas indicated for discouraged land uses. This flexibility simplifies the preparation of models predicting the outcome of a range of scenarios and speeds the examination of the effect of new information as it becomes available.

5.7 CONCLUSION

Land managers now have a considerably expanded choice of technology to draw on when attempting to cope with the vast quantity of spatial data relating to extensive rural areas. The traditional sources of spatial and attribute information: maps, aerial photographs, point and plot survey data can now be combined in a computer-based GIS. The flexibility of input, combination, processing and output with GIS makes the provision of information relating to these areas considerably simpler.

It is now possible to add to the GIS dataset from sources of remote sensing data. Visible and infra-red data provide information on the type and condition of vegetation, suitable for combining and modelling with soil and topographic map information, for example. Radar data are yet to be fully tested and understood for terrestrial vegetation survey, but their all-weather advantages will be significant for areas such as the UK uplands.

There are considerable initial barriers to be overcome when establishing comprehensive GIS datasets. However, the increasing and ready provision of public-domain datasets and the availability of commercial datasets is already helping to reduce this burden.

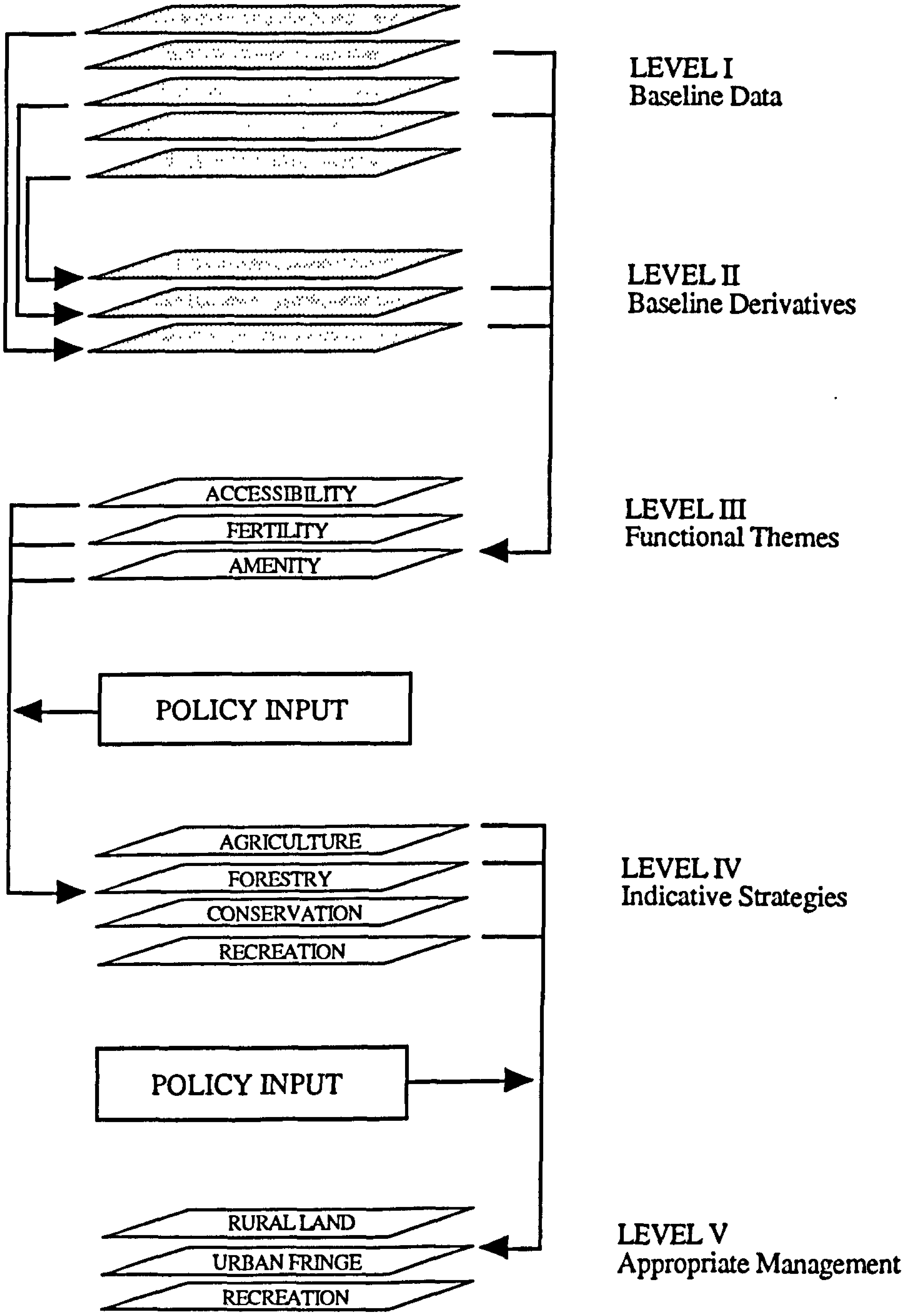
Land managers can look forward with confidence to a future which promises a greater awareness of the condition and extent of our extensive rural resources, and the opportunity to protect and repair sensitive areas.

CHAPTER FIVE

FIGURE

FIGURE 5.1

Rural Resource Management Indicative GIS Strategies



REFERENCES

Allan, J.A. (1990). Sensors, platforms and applications; acquiring and managing remotely sensed data. In: *Applications of remote sensing in agriculture*, (Eds. J A Clark and M D Steven), pp. 1-18. Butterworths, London.

Amthor, J.S. (1984). Does acid rain directly influence plant growth ? : Some comments and observations. *Environmental Pollution (Series A)*, **36**: 1-6.

Anon. (1985). *SAS User's guide: Statistics, Version 5 Edition*. SAS Institute Inc., Cary, North Carolina, USA.

Ashenden, T.W. and Bell, S.A. (1987). Yield Reductions in winter barley grown on a range of soils and exposed to simulated acid rain. *Plant and Soil*, **98**: 433-437.

Ashenden, T.W. and Bell, S.A. (1988). Growth responses of birch and Sitka spruce exposed to acidified rain. *Environmental Pollution*, **51**: 153-162.

Ashenden, T.W. and Williams, J.H. (1988). Differences in the spectral characteristics of birch canopies exposed to simulated acid rain. *New Phytologist*, **109**: 79-84.

Atkinson, P., Cushnie, J.L., Townshend, J.R.G. and Wilson, A. (1985). Improving Thematic Mapper land cover classification using filtered data. *International Journal of Remote Sensing*, **6**: 955-961.

Baker, J.R., Briggs, S.A., Gordon, V., Jones, A.R., Settle, J.J., Townshend, J.R.G. and Wyatt, B.K. (1991). Advances in classification for land cover mapping using SPOT HRV imagery. *International Journal of Remote Sensing*, **12**: 1071-1085.

Barrett, C.F., Atkins, D.H.F., Cape, J.N., Fowler, D., Irwin, J.G., Kallend, A.S., Martin, A., Pitman, J.I., Scriven, R.A. and Tuck, A.F. (1983). *Acid deposition in the United Kingdom*. Warren Spring Laboratory, Stevenage.

Barrett, E.C. and Martin, D.W. (1981). *The use of satellite data in rainfall monitoring*. Academic Press, London.

Bell, J.N.B. (1982). Sulphur dioxide and the growth of grasses. In: *Effects of gaseous air pollution in agriculture and horticulture*, (Eds. M.H. Unsworth and D.P. Ormrod), pp. 225-246. Butterworth Scientific, London and Boston.

Belward, A.S., Taylor, J.C., Stuttard, M.J., Bignal, E., Mathews, J. and Curtis, D. (1990). An unsupervised approach to the classification of semi-natural vegetation from Landsat Thematic Mapper data - A pilot study on Islay. *International Journal of Remote Sensing*, **11**: 429-445.

Belward, A.S. and Valenzuela, C.R. (Eds.). (1991). *Remote sensing and geographical information systems for resource management in developing countries*. Kluwer Academic, London.

Bibby, J.S. and Thomas, M.F. (Eds.) (1990). *Evaluation of land resources in Scotland.* Macaulay Land Use Research Institute, Aberdeen.

Black, C.R. and Black, V.J. (1979). Light and scanning electron microscopy of SO_2-induced injury to leaf surfaces of field bean (*Vicia faba L.*). *Plant, Cell and Environment*, 2: 329-333.

Booth, D.J. and Oldfield, R.B. (1989). A comparison of classification algorithms in terms of speed and accuracy after the application of a post-classification modal filter. *International Journal of Remote Sensing*, 10: 1041-1047.

Briggs, S.A. and Settle, J.J. (1985). A fast Maximum Likelihood classifier. Proc (poster sessions): *Remote sensing: data acquisition, management and applications*, pp. 249-255. Remote Sensing Society, Univ. of Reading, U.K.

Budd, J.T.C. (1987). Remote sensing applied to the work of the NCC in upland areas. In: *The ecology and management of upland habitats: the role of remote sensing*, B1-B7. Remote Sensing Special Publication No.2, Department of Geography, University of Aberdeen.

Cape, J.N. and Fowler, D. (1981). Changes to epicuticular wax of *Pinus sylvestris* exposed to polluted air. *Silva Fennica*, 15: 457-458.

Ciesla, W.M. (1989). Aerial photos for assessment of forest decline a multinational overview. *Journal of Forestry*, 87: 37-41.

Congalton, R.G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, 37: 35-46.

Conway, V.M. (1942) Biological flora of the British Isles: *Cladium mariscus (L.). Journal of Ecology*, 30: 211-216.

Cross, A. and Mason, D.C. (1985). Segmentation of remotely- sensed images by a split-and-merge process. Proc: *Advanced technology for monitoring and processing global environmental data*, pp. 177-189. Remote Sensing Society, University of Reading, U.K.

Cross, A., Mason, D.C. and Dury, S.J. (1988). Segmentation of remotely- sensed images by a split and merge process. *International Journal of Remote Sensing*, 9: 1329-1345.

Curran, P.J. (1985). *Principles of remote sensing*. Longman, London.

Curran, P.J. and Williamson, H.D. (1987). Airborne MSS data to estimate GLAI. *International Journal of Remote Sensing*, 8: 57-74.

Cushnie, J.L. (1984). Improving the accuracy of computer classification of Thematic Mapper data. In: *Satellite remote sensing - review and preview.* (Eds. J. Hardy and J. Brookling), pp. 329-338. Remote Sensing Society, University of Reading, U.K.

Cushnie, J.L. (1987). The interactive effect of spatial resolution and degree of internal variability within land-cover types on classification accuracies. *International Journal of Remote Sensing*, **8**: 15-29.

Cushnie, J.L. and Atkinson, P. (1985). Effect of spatial filtering on scene noise and boundary detail in Thematic Mapper imagery. *Photogrammetric Engineering and Remote Sensing*, **51**: 1483-1493.

Dollard, G.J., Unsworth, M.H. and Harve, M.J. (1983). Pollutant transfer in upland regions of occult precipitation. *Nature*, **302**: 241-243.

Drury, S.A. (1990). *A guide to remote sensing: Interpreting images of the Earth.* Oxford University Press.

Dutra, V.L. and Mascarenhas, N.D.A. (1984). Some experiments with spatial feature extraction methods in multispectral classification. *International Journal of Remote Sensing*, **5**: 303-313.

Ehlers, M., Edwards, G. and Bedard, Y. (1989). Integration of remote sensing with geographic information systems: a necessary evolution. *Photogrammetric Engineering and Remote Sensing*, **55**: 1619-1627.

Evans, D.F. (1988). Personal communication. Institute of Terrestrial Ecology, Bangor, Wales, U.K.

Evans, L.S., Gmur, N.F. and Da Costa, F. (1977). Leaf surface and histological perturbations of leaves of *Phaseolus vulgaris* and *Helianthus annuus* after exposure to simulated acid rain. *American Journal of Botany*, **64**: 903-913.

Evans, L.S., Gmur, N.F. and Da Costa, F. (1978). Foliar responses of six clones of hybrid poplar to simulated acid rain. *Phytopathology*, **68**: 847-856.

Evans, L.S., Lewin, K.F., Cunningham, E.A. and Patti, M.J. (1982). Effects of simulated acid rain on yields of field grown crops. *New Phytologist*, **91**: 429-441.

Evans, L.S., Lewin, K.F., Patti, M.J. and Cunningham, E.A. (1983). Productivity of field grown soybeans exposed to simulated acid rain. *New Phytologist*, **93**: 377-388.

Fehr, C. (1990). *A GIS to study cash cropping agroforestry in the perennially moist tropics of Dominica, W.I.* MSc Thesis. University of Wales, Bangor.

Ferenbaugh, R.W. (1976). Effects of simulated acid rain on *Phaseolus vulgaris L. (Fabaceae)*. *American Journal of Botany*, **63**: 283-288.

Ferns, D.C. and McLeod, A.R. (1984). Field spectroradiometry to detect subtle effects of SO_2 on wheat in an outdoor field fumigation experiment In: *Satellite remote sensing - review and preview*. (Eds. J. Hardy and J. Brookling), pp. 275-288. Remote Sensing Society, University of Reading, U.K.

Fischer, W.A. (1975). History of remote sensing. In: Reeves, R.G. (Ed.), *Manual of Remote Sensing*, pp. 27-50. American Society of Photogrammetry, Falls Church, Virginia, USA.

Fisher, P.F. and Lindenberg, R.E. (1989). On distinctions among cartography, remote sensing, and geographic information systems. *Photogrammetric Engineering and Remote Sensing*, **55**: 1431-1434.

Foody, G.M. (1992). A fuzzy sets approach to the representation of vegetation continua from remotely sensed data: an example from lowland heath. *Photogrammetric Engineering and Remote Sensing*, **58**: 221-225.

Franklin, S.E. and Peddle, D.R. (1989). Spectral texture for improved class discrimination in complex terrain. *International Journal of Remote Sensing*, **10**: 1437-1443.

Fuller, R.M. (1981). Aerial photographs as records of changing vegetation patterns. In: *Ecological Mapping from Ground, Air and Space*, 57-68. Institute of Terrestrial Ecology, Huntingdon, U.K.

Fuller, R.M., Jones, A.R., Groom, G.B., Thomson, A.G. and Brown, N.J. (1992). *Countryside survey 1990. Mapping the land cover of Great Britain using satellite remote sensing: a demonstrator project in remote sensing*. Second interim report to the British National Space Centre. Environmental Information Centre, Institute of Terrestrial Ecology, Huntingdon, U.K.

Fuller, R.M. and Parsell, R.J. (1990). Classification of TM imagery in the study of land use in lowland Britain: practical considerations for operational use. *International Journal of Remote Sensing*, **11**: 1901-1917.

Gastellu-Etchegorry, J.P. (Ed.). (1990). *Satellite remote sensing for agricultural projects*. World Bank Technical Paper Number 128. World Bank, Washington, USA.

Gausman, H.W., Escobar, D.W., Rodriquez, R.R., Thomas, C.E. and Bowen, R.L. (1978). Using reflectance and photography to detect ozone damage on cantaloupe plants. *Photogrammetric Engineering and Remote Sensing*, **44**: 481-485.

Girard, C.M., Benoit, M., De Vaubernier, E. and Curran, P.J. (1990). SPOT HRV data to discriminate grassland quality. *International Journal of Remote Sensing*, **11**: 2253-2267.

Glaser, P.H. (1989). Detecting biotic and hydrogeochemical processes in large peat basins with Landsat TM imagery. *Remote Sensing of Environment*, **28**: 109-119.

Gorham, E, and Pearsall, W.H. (1956) Production ecology. III. Shoot production in *Phragmites* in relation to habitat. *Oikos*, **7**: 206-14.

Gurney, C.M. and Townshend, J.R.G. (1983). The use of contextual information in the classification of remotely sensed data. *Photogrammetric Engineering and Remote Sensing*, **49**: 55-64.

Guyot, G. (1990). Optical properties of vegetation canopies. In: *Applications of remote sensing in agriculture*, (Eds. J A Clark and M D Steven), pp. 19-43. Butterworths, London.

Hall-Konyves, K. (1987). The topographic effect on Landsat data in gently undulating terrain in southern Sweden. *International Journal of Remote Sensing*, **8**: 157-168.

Harcourt, S.A. and Farrar, J.F. (1980). Some effects of simulated acid rain on the growth of barley and radish. *Environmental Pollution (Series A)*, **22**: 69-73.

Haslam, S.M. (1969). The reed: a study of *Phragmites communis (Trin.)* in relation to its cultivation and harvesting in East Anglia for the thatching industry. *Norfolk Reed Growers Association I*, Norwich.

Haslam, S.M. (1970) The performance of *Phragmites communis* in relation to water supply. *Annals of Botany*, **34**: 867-77.

Haslam, S.M. (1972) Biological flora of the British Isles: *Phragmites communis*. *Journal of Ecology*, **60**: 585-610.

Headley, A.D. (1986). *Plant ecology of Crymlyn Bog, W. Glamorgan*. Interim report to BP Group Environmental Services, October 1986. Botany Department, University of Sheffield, U.K.

Headley, A.D. (1987a). *Plant ecology of Crymlyn Bog, W. Glamorgan*. Interim report No.2 to BP Group Environmental Services, January 1987. Botany Department, University of Sheffield, U.K.

Headley, A.D. (1987b). *Plant ecology of Crymlyn Bog, W. Glamorgan*. Interim report No.3 to BP Group Environmental Services, June 1987. Botany Department, University of Sheffield, U.K.

Heit, M. and Shortreid, A. (Eds.). (1991). *GIS Applications in natural resources*. GIS World Inc., Fort Collins, Colorado, USA.

Hill, A.C., Pack, M.R., Treshow, M., Downs, R.F. and Transtrum, L.G. (1961). Plant injury induced by O_3. *Phytopathology*, 51: 356-363.

H.M.S.O. (1981). *Wildlife and Countryside Act*, and 1985 amendment. HMSO, London.

Hoffer, R.M. (1978). Biological and physical considerations in applying computer-aided analysis techniques to remote sensor data. In: *Remote sensing: the quantitative approach*, (Ed. by P.H. Swain and S.M. Davies), pp. 227-289. McGraw-Hill, New York.

Howard, J.A. (1991). *Remote sensing of forest resources: Theory and application.* Chapman and Hall, London.

Hume, E., McMorrow, J. and Southey, J. (1986). Mapping semi-natural grassland communities from panchromatic aerial photographs and digital images at SPOT wavelengths. In: *Mapping from modern imagery*, pp. 386-395. Remote Sensing Society, University of Nottingham, U.K.

Hunt, S. (1992). *Identifying the extent of interzone and edge habitat for conservation in a Welsh upland forest using GIS.* BSc Project. University of Wales, Bangor.

Huttunen, S and Soikkeli, S. (1984). Effects of various gaseous pollutants on plant cell ultrastructure. In: *Gaseous air pollutants and plant metabolism*, (Eds. M.J. Koziol and F.R. Whatley), pp. 117-127. Proceedings of the 1st international symposium on air pollution and plant metabolism 1982, Oxford.

Ioka, M. and Koda, M. (1986). Performance of Landsat-5 TM data in land cover classification. *International Journal of Remote Sensing*, 7: 1715-1728.

Irons, J.R., Markham, B.L., Nelson, R.F., Toll, D.L., Williams, D.L., Latty, R.S. and Stauffer, M.L. (1985). The effects of spatial resolution on the classification of Thematic Mapper data. *International Journal of Remote Sensing*, 6: 1385-1403.

Irving, P.M. (1983). Acidic precipitation effects on crops: a review and analysis of research. *Journal of Environmental Quality*, 12: 442-453.

Jewell, N. and Brown, R.W. (1987). The use of Landsat TM data for vegetation mapping in the North York Moors National Park. In: *The ecology and management of upland habitats: the role of remote sensing*, E1-E8. Remote Sensing Special Publication No.2, Department of Geography, University of Aberdeen.

Jones, A., Settle, J.J. and Wyatt, B., (1988). Use of digital terrain data in the interpretation of SPOT-1 HRV multispectral imagery. *International Journal of Remote Sensing*, 9: 669-682.

Jones, A., Wyatt, B., Settle, J. and Robinson, G. (1987). The use of a DTM for topographic correction and classification of SPOT HRV data for ecological mapping in upland environments. In: *Advances in digital image processing*, 488-497. Remote Sensing Society, University of Nottingham, U.K.

Justice, C. and Townshend, J.R.G. (1982). A comparison of unsupervised classification procedures on Landsat MSS data for an area of complex surface conditions in Basilicata, Southern Italy. *Remote Sensing of Environment*, 12: 407-420.

Koch, B. and Kritikos, G. (1984). Integrative investigation on forest damage detection based on air-borne multispectral scanner data. Proc: *Integrative approaches in remote sensing*, EARSel/ESA (ESA SP-214) Symposium (Eds. N. Longdon and O. Melita), pp. 109-113. European Space Agency, Paris.

Law, R.M. and Mansfield, T.A. (1982). Oxides of nitrogen and the greenhouse atmosphere. In: *Effects of gaseous air pollution in agriculture and horticulture*, (Eds. M.H. Unsworth and D.P. Ormrod), pp. 93-112. Butterworth Scientific, London.

Malingreau, J.P. and Tucker, C.J. (1990). Ranching in the Amazon Basin; Large-scale changes observed by AVHRR. *International Journal of Remote Sensing*, 11: 187-189.

Mansfield, T.A., Lucas, P.W. and Wright, E.A. (1988). Interactions between air pollutants and other limiting factors. In: *Effects of air pollution on terrestrial and aquatic ecosystems*. Proceedings of Commission of the European Communities Workshop, Grenoble, 1987.

McMorrow, J. and Hume, E. (1986). Problems of applying multispectral classification to upland vegetation. In: *Mapping from modern imagery*, pp. 610-620. Remote Sensing Society, University of Nottingham, U.K.

Megier, J., Hill, J. and Kohl, H. (1991). Land use inventory and mapping in a mountainous area: the Ardeche experiment. *International Journal of Remote Sensing*, 12: 445-462.

Milton, E.J. (1980). A portable multiband radiometer for ground data collection in remote sensing. *International Journal of Remote Sensing*, 1: 153-165.

Milton, N.M., Ager, C.M., Eiswerth, B.A. and Power, M.S. (1989). Arsenic- and Selenium-induced changes in spectral reflectance and morphology of soybean plants. *Remote Sensing of Environment*, 30: 263-269.

Narendra, P.M. (1981). A separable median filter for image noise smoothing. *I.E.E.E. Trans. on Pattern Analysis and Machine Intelligence*, V PAMI-3, 1: 20-29.

Nath, L. (1991). *A wildlife population viability model using GIS: Elephant conservation in the Rajaji National Park, India.* MSc Thesis. University of Wales, Bangor.

Nature Conservancy Council. (1986). *Upland vegetation survey Eryri*. Wales field unit, Nature Conservancy Council, Bangor, Gwynedd.

Nichol, D.G. (1990). Region adjacency analysis of remotely sensed imagery. *International Journal of Remote Sensing*, 11: 2089-2101.

Nobel, P.S. and Wang, C.T. (1973). O_3 increases the permeability of isolated pea chloroplasts. *Archives of biochemistry and biophysics*, 157: 388-394.

Paris, J.F. (1990). On the uses of combined optical and active microwave image data for agricultural applications. In: *Applications of remote sensing in agriculture*, (Eds. J A Clark and M D Steven), pp. 355-374. Butterworths, London.

Pearce, F. (1982). The menace of acid rain. *New Scientist*, 95: 419-424.

Pedley, M.I. and Curran, P.J. (1991). Per-field classification: an example using SPOT HRV imagery. *International Journal of Remote Sensing*, 12: 2181-2192.

Phillips, M.E. (1954) Biological flora of the British Isles: *Eriophorum angustifolium (Roth.)*. *Journal of Ecology*, 42: 612-622.

Pratt, W.K. (1978). *Digital image processing*, pp. 330-333. Wiley, New York.

Prince, S.D. (1990). High temporal frequency remote sensing of primary production using NOAA AVHRR. In: *Applications of remote sensing in agriculture*, (Eds. J A Clark and M D Steven), pp. 169-183. Butterworths, London.

Proy, C., Tanre, D. and Deschamps, P.Y. (1989). Evaluation of the topographic effects in remotely sensed data. *Remote Sensing of Environment*, 30: 21-32.

Ratcliffe, D.A. and Birks, H.J.B. (1980). *A classification of upland vegetation types in Britain*. Internal report. Nature Conservancy Council, Peterborough, U.K.

Richards, P.W. (1973). Plant life. In: *Snowdonia National Park*, (Ed. G. Rhys Edwards), pp. 58-63. H.M.S.O., London.

Rock, B.N., Hoshizaki, T and Miller, J.R. (1988). Comparison of in-situ and airborne spectral measurements of the blue shift associated with forest decline. *Remote Sensing of Environment*, 24: 109-128.

Rock, B.N., Vogelmann, J.E., Williams, D.L., Vogelmann, A.F. and Hoshizaki, T. (1986). Remote detection of forest damage. *Bioscience*, 36: 439-445.

Rosenfield, G.H. (1986). Analysis of thematic map classification error matrices. *Photogrammetric Engineering and Remote Sensing*, 52: 681-686.

Rosenfield, G.H. and Fitzpatrick-Lins, K. (1986). A coefficient of agreement as a measure of thematic classification accuracy. *Photogrammetric Engineering and Remote Sensing*, 52: 223-227.

Rudeforth, C.C., Hartnup, R., Lea, J.W., Thompson, T.R.E. and Wright, P.S. (1984). *Soils and their use in Wales*. Bulletin No. 11. Soil Survey of England and Wales, Harpenden, U.K.

Runeckles, V.C. and Resh, H.M. (1975). The assessment of chronic ozone injury to leaves by reflectance spectrophotometry. *Atmospheric Environment*, 9: 447-452.

Sabaratnam, S., Gupta, G. and Mulchi, C. (1988). Effects of nitrogen dioxide on leaf chlorophyll and nitrogen content of soybean. *Environmental pollution*, 51: 113-120.

Schowengerdt, R.A., (1983). *Techniques for image processing and classification in remote sensing*. Academic Press, London.

Schutt, J.B., Rowland, R.A. and Heggestad, H.E. (1984). Identification of injury resulting from atmospheric pollutants using reflectance measurements. *Journal of Environmental Quality*, 13: 605-608.

Settle, J. (1987). Contextual classification. In: *NERC Unit for Thematic Information Systems, Current Research 1987*, pp. 4-5. NUTIS, Department of Geography, University of Reading, U.K.

Silva, L.F. (1978). Radiation and instrumentation in remote sensing. In: *Remote sensing: the quantitative approach*, (Eds. P.H. Swain and S.M. Davies), pp. 112-135. McGraw Hill, New York.

Singh, A. (1984). Some clarifications about the pairwise divergence measure in remote sensing. *International Journal of Remote Sensing*, 5: 625-627.

Soikkeli, S. and Tuovinen, T. (1979). Damage in mesophyll ultrastructure of needles of Norway spruce in two industrial environments in central Finland. *Annales Botanici Fennici*, 16: 50-64.

Spence, D.H.N. (1964). *The macrophytic vegetation of freshwater lochs, swamps, and associated fens: The vegetation of Scotland*, (Ed. J. H. Burnett), pp 306-425. Oliver and Boyd, Edinburgh.

Steven, M.D. and Clark, J.A. (Eds.). (1990). *Applications of remote sensing in agriculture.* Butterworths, London.

Swain, P.H. (1978). Fundamentals of pattern recognition in remote sensing. In: *Remote sensing: the quantitative approach*, (Eds. P.H. Swain and S.M. Davies), pp. 164-174. McGraw-Hill, New York.

Thomson, A.G. and Jones, C. (1990). Effects of topography on radiance from upland vegetation in North Wales. *International Journal of Remote Sensing*, 11: 829-840.

Thomson, A.G. and Milner, C. (1989). Population densities of sheep related to Landsat Thematic Mapper radiance. *International Journal of Remote Sensing*, 10: 1907-1912.

Tovar, M. (1991). *An indicative strategy for agroforestry in Belize using GIS*. MSc Thesis. University of Wales, Bangor.

Townsend, F.E. (1986). The enhancement of computer classifications by logical smoothing. *Photogrammetric Engineering and Remote Sensing*, 52: 213-221.

Townshend, J.R.G. and Justice, C. (1981). Information extraction from remotely sensed data: a user view. *International Journal of Remote Sensing*, 2: 313-329.

Trotter, C.M. (1991). Remotely-sensed data as an information source for geographical information systems in natural resource management: a review. *International Journal of Geographical Information Systems*, 5: 225-239.

Vogelmann, J.E. and Rock, B.N. (1988). Assessing forest damage in high elevation coniferous forests in Vermont and New Hampshire using Thematic Mapper data. *Remote sensing of environment*, 24: 227-247.

Ward, S.A., Weaver, R.E. and Brown, R.W. (1987). Monitoring heather burning in the North York Moors National Park using multi-temporal Thematic Mapper data. In: *The ecology and management of upland habitats: the role of remote sensing*, F1-F4. Remote Sensing Special Publication No.2, Department of Geography, University of Aberdeen.

Wardley, N.W., Milton, E.J. and Hill, C.T. (1987). Remote sensing of structurally complex semi-natural vegetation - an example from heathland. *International Journal of Remote Sensing*, 8: 31-42.

Weaver, R.E. (1984). Integration of remote sensing data for moorland mapping. In: *Satellite remote sensing- review and preview*. Remote Sensing Society, University of Reading, U.K., 191-200.

Weaver, R.E. (1987a). Using multi-spectral scanner data to study vegetation succession in upland Scotland. In: *The ecology and management of upland habitats: the role of remote sensing*, H1-H11. Remote Sensing Special Publication No.2, Department of Geography, University of Aberdeen.

Weaver, R.E. (1987b). Spectral separation of moorland vegetation in airborne Thematic Mapper data. *International Journal of Remote Sensing*, 8: 43-55.

Williams, D.F. (1984). Overview of the NERC Airborne Thematic Mapper Campaign of September 1982. *International Journal of Remote Sensing*, 5: 631-634.

Williams, J.H. (1986). Remote sensing in the UK. *BBC Domesday Project*, National Disc. BBC Enterprises Ltd, London, U.K. 59 text pages, 55 colour images.

Williams, J.H. (1987). Assessing upland grassland condition from airborne multispectral data. In: *The NERC 1986 Airborne Campaign Results*. Natural Environment Research Council, Swindon, UK.

Williams, J.H. (1988). Vegetation survey in upland Wales: reconciling ground and satellite surveys. *Ecological change in the uplands*. British Ecological Society, Special Publication No.7. Blackwell, Oxford.

Williams, J.H. and Ashenden, T.W. (1992). Differences in the spectral characteristics of white clover exposed to gaseous pollutants and acid mist. *New Phytologist*, 120: 69-75.

Williams, J.H., Brown, N.J. and Norris, D. (1987). An experimental GIS for upland management information in Snowdonia. In: *Applications of remote sensing*, Postgraduate workshop, 6th May 1987, Department of Geography, University of Durham.

Wilson, A.K. (1986). Calibration of ATM data. Proceedings of the *NERC 1985 Airborne Campaign Workshop*, E: 25-40. Institute of Terrestrial Ecology, Huntingdon, U.K.

Wood, T. and Bormann, F.H. (1975). Increases in foliar leaching caused by acidification of an artificial mist. *Ambio*, 4: 169-171.

Woodhead, N. (1933). Alpine plants of the Snowdon range. *Journal of the Alpine Gardens Society*, 12-51.

Wyatt, B.K. (1987). Remote sensing applications in upland ecology: a review of research at ITE. In: *The ecology and management of upland habitats: the role of remote sensing*, C1-C9. Remote Sensing Special Publication No.2, Department of Geography, University of Aberdeen.

Wyatt, B.K., Parsell, R.J. and Evans, D F. (1986). *A multi-spectral survey of Crymlyn Bog*. Report to BP Group Environmental Services, December 1986. Institute of Terrestrial Ecology, Bangor, Gwynedd, U.K.

Wyatt, B.K. and Williams, J.H. (1987). *Monitoring the condition of Crymlyn Bog using remote sensing*. Interim report No.1 to BP Group Environmental Services, December 1987.

Zhou, Q. (1989). A method for integrating remote sensing and geographic information systems. *Photogrammetric Engineering and Remote Sensing*, 55: 591-596.