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Remote Sensing of Bog Surfaces

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Contents

List of Tables

List of Figures

1. Summary of Main Findings

The aims of this contract were to:

- review the current approaches to raised lowland bog classification and to identify how remote sensing might provide an information source for such classifications;
- develop a cost-effective method of using the best currently available civilian satellite sensor data to produce habitat maps for raised bogs, to a level of accuracy appropriate for management;
- investigate the opportunities offered by advanced airborne sensors currently available for hire in the UK (e.g. ATM, lidar).

The project focused on three lowland raised bogs: Wedholme Flow in Cumbria, Cors Caron (Tregaron Bog) in mid-Wales and Ballynahone Bog in Northern Ireland.

Ikonos satellite sensor data were found to be highly suited to the task of lowland raised bog habitat classification. Although this sensor has only four relatively broad spectral bands, they are located in parts of the spectrum which were well able to identify the major raised bog land cover classes. Most of the spectral information required for the task was found to be contained within the three visible bands. The near infra-red band, which is often so useful in vegetation mapping and monitoring, was found be of little use, although data in this band could be used to identify the outer limits of a lowland raised bog. The most important attributes of Ikonos data for this task were found to be its high spatial resolution (4 metres in multispectral mode) and its excellent geometric properties. These properties made it possible to interpret the Ikonos image as one would a small scale colour aerial photograph. Indeed, one of the outcomes of this project has been a renewed sense of the importance of visual image interpretation, albeit based upon digital data which have been manipulated and enhanced to maximise their information content.

The project also investigated the potential of airborne lidar data for lowland bog habitat assessment, and we concluded that this data source has a great deal to offer. Unfortunately, the archived lidar data coverage of our sites was very limited, but we have no hesitation in stating that it has a major role to play in both the qualitative categorisation of lowland bog habitats and the quantification of surface microrelief. The combination of Ikonos satellite sensor data and airborne lidar data would be a very powerful tool to monitor and map lowland bog habitats.

We also investigated the potential of remote sensing in other spectral regions for lowland raised bog habitat mapping and monitoring, and concluded that the short-wave infra-red (SWIR) region (around 1.55 – 1.75 m) contained significant additional information not found in the visible wavelengths. However, an operational system reliant upon data collected in the SWIR band would be problematic as there are very few such systems in operation and data from them tend to be expensive. In essence, we felt that the SWIR band was a useful and interesting addition to the visible wavelengths, but its additional utility would not justify the additional cost if the aim was purely to meet the EU Habitats Directive.

Our aim has been to recommend an approach which is reliable, cost-effective, and achievable with minimal additional staff training in remote sensing and Geographical Information System (GIS). Furthermore, we have explicitly considered the need to base any operational method on remote sensing systems which have a reasonable expectation of long-term availability and have alternative sources of data supply. For example, the Ikonos data could be replaced with data from many different visible and near infra-red sensors, including the CASI airborne imaging spectrometer or digital aerial photography. In the same way, the lidar data could be replaced with data from an interferometric synthetic aperture radar (e.g. NEXTMap).

In conclusion, there are two areas which warrant further investigation. The first concerns the use of airborne imaging spectrometry to estimate directly the proportion of an area dominated by 'colourful *Sphagnum* species'. Our research indicates that this should be possible using the CASI instrument, which is operated by the Environment Agency on the same aircraft as the lidar system provided the data we used for this project. The second area of further research concerns the use of an expert system to codify the various approaches to lowland bog habitat classification and to provide a robust means of resolving conflicts when they occur. Remotely sensed data could provide a rich source of information for such an expert system, with the added advantage inherent in this approach that it would be just one of many data streams informing the decision making process.

2. Introduction

Lowland raised bogs are an important and declining habitat throughout Western Europe. The majority of lowland raised bogs in the UK have been damaged to varying degrees and by various human activities over a very long period. The classification and categorisation of the extent of this damage, the extent of natural or near natural active peat growth and the ability to restore active peat formation is central to the management of remaining sites and the application of appropriate restoration measures on degraded sites.

Existing categorisations are varied and based largely on field inventories and surveys. The adoption of remote sensed techniques allows the potential for consistent assessment of the condition of sites over a wider area. However, such approaches will only be effective if the level of discrimination and classification is appropriate to the determination of the impacts and the indicators of the land cover classes (in terms of degree of degradation). This project seeks to assess the capability of remote sensing to discriminate these classes or to generate classes that approximate closely to those of the Lowland Bog Resource Inventory (LRBI) and EU Habitat Directive classes.

Raised bog surfaces pose a significant challenge to current remote sensing techniques. The areas involved are relatively small, and the spectral differences between plant communities are very subtle and change seasonally. However, in the UK at least, the major part of the raised bog habitat is characterised by a short, open sward that lends itself to detailed analysis using remote-sensing techniques. The habitat is thus more intrinsically amenable to such investigation than more structurally complex habitats such as woodland, scrubland or even tall sedge-fen. Raised bog is also a habitat generally characterised by low surface gradients. Consequently the typical problems associated with remote sensing in upland areas, such as extreme slope angles, markedly differing aspects, and hill shadows, do not generally arise. Indeed there is every reason to believe that as remote sensing becomes more capable, so raised bog sites will yield to the unique advantages that it offers. In particular, remote sensing has the potential to determine the surface extent and configuration of bogs, their species composition, and physical variables such as surface moisture content and the degree of humification of exposed peat. This report describes the results from a contract which set out to achieve three things:

- to review the current approaches to raised lowland bog classification and to identify how remote sensing might provide an information source for such classifications;
- to develop a cost-effective method of using the best currently available civilian satellite sensor data to produce habitat maps for raised bogs, to a level of accuracy appropriate for management;
- to investigate the opportunities offered by advanced airborne sensors currently available for hire in the UK (e.g. ATM, lidar);

3. Raised Bog Habitat Condition Classifications and Remote Sensing

The aim of this section is to review the definitions relating to the Lowland Raised Bog Inventory (LRBI) and European Union Habitats Directive classification systems. The two systems will be evaluated in terms of their potential for discrimination by remotely sensed methods.

3.1 European Commission 'Habitats' Directive classification system

3.1.1 Introduction

The European Union 'Habitats' Directive (Council Directive, 1992) establishes a common framework for the conservation of wild plant and animal taxa and natural habitats of importance to the European Community. The directive provides for the establishment of special areas of conservation (Natura 2000). The aim of these conservation areas is to "*maintain and restore, at favourable conservation status, natural habitats and species of wild fauna and flora…*" (European Commission, 1996). Annex I of the 'Habitats' Directive lists 198 European natural habitat types, which includes 65 labelled as priority "*habitat types in danger of disappearance whose natural range falls mainly within European Union territory*", European Commission, 1996).

The CORINE Biotopes project, led by Professor Noirfalise, was used as the basis for the list of habitats in Annex 1 of the Habitats Directive published in May 1992 (EUR12). The CORINE hierarchical classification of European habitats was subsequently updated, whilst the original Habitats Directive was being adopted. The revision introduced various changes to codes and habitat types, such that Annex I of the 'Habitats' Directive (version EUR12) no longer matches the CORINE classification. The Task Force/European Environment Agency later produced a paper describing the differences between Annex I and the revised CORINE classification (Task Force Agency, 1992). EUR12 has since been updated to EUR15, which incorporates habitat types from Austria, Finland and Sweden.

3.1.2 Interpretation Manual of European Habitats

The interpretation manual that accompanies Annex I of the 'Habitats' Directive (Council Directive, 1992) is primarily focused on the 65 'priority habitats'. The manual includes full descriptive sheets for each of these habitats, which "*establish clear, operational scientific definitions of habitat types, using pragmatic descriptive elements (e.g. characteristic plants).*" (European Commission, 1999). Similar descriptive sheets are provided for a further 36 non priority habitat types, which commonly cause interpretation problems. The remaining habitat types are represented by the CORINE Biotopes definitions (1991 version), which are considered to be "*a minimal interpretation*" (European Commission, 1999). The simple biotope definitions omit subtypes and regional varieties.

3.1.3 The Classification of Ombrotrophic Bogs in Annex I of the ‘Habitats’ Directive

Lowland Raised Bogs appear under the ‘*Sphagnum* acid bogs’ classification in Annex I. Two habitats are relevant to the present literature, namely ‘Active Raised Bogs’ (habitat code: 7110), which are priority habitats and ‘Degraded raised bogs still capable of natural regeneration’ (habitat code: 7120). Three further ombrotrophic bog types appear in Annex 1; Blanket Bogs (habitat code: code 7130), Transition Mires and Quaking Bogs (habitat code: 7140) and Depressions on peat substrates of the *Rhynchosporion* (habitat code: 7150). These latter three habitats fall outside of the scope of the present review.

***Active Raised Bogs (priority habitat)**
The EU interpretation manual defines ‘Active Raised Bogs’ as acid bogs, which are poor in mineral nutrients and mainly sustained by rainwater (ombrotrophic), with a water table level generally higher than the surrounding water table. “*The bogs are characterised by colourful Sphagna hummocks allowing for the growth of the bog*” (EUR15 /2, 1999). The interpretation manual is specific in defining the term ‘active’.

> “*The term ‘active’ must be taken to mean still supporting a significant area of vegetation that is normally peat forming, but bogs where active peat formation is temporarily at a standstill, such as after a fire or during a natural climatic cycle e.g., a period of drought, are also included*”. (European Commission, 1999).

The main plant species considered to be characteristic of oceanic ‘active’ raised bogs listed in Annex I include the following indicator species: *Andromeda polyfolia*, *Carex pauciflora*, *Cladonia* spp., *Drosera rotundifolia*, *Eriophorum vaginatum*, *Odontoschisma sphagni*, *Sphagnum magellanicum*, *S. imbricatum*, *S. fuscum*, and *Vaccinium oxycoccos*.

‘Active’ raised bog may be further defined using the Nation Vegetation Classification system (NVC) (Rodwell, 1991). Annex 1 of the habitats directive identifies four NVC communities as corresponding to ‘active’ raised bog (M1, M3, M18 and M20a). However, classification schemes used in the guidelines produced by the British conservation agencies differ to varying degrees with respect to the NVC communities recorded as ‘active raised bog’.

Table 1 provides a comparison of the classifications used by the different organisations and the Habitats Action Plan (HAP).

Table 1. Comparison of NVC categories included in 'active raised bog' by different authors

Phase 1	NVC communities	EU habitat	Comments
E1.6.2 raised bog	EU HD M1, 3, 18, 20a JNCC (1994) M1-4, 15, 16, 18, 20, 21 HAP (1999) M1-3, 15, 18, 19, 25 CCW (1999) M1-3, 18, 20, 25	'active raised bog'	Colourful *Sphagnum* Peat forming Acid Mineral nutrient poor Include M15, 16 only if peat >0.5m deep
E1.7 wet modified bog (derived from raised bog with *Sphagnum* spp. present at surface)	Dargie and Maier (2001) M15, M19, M20	'active raised bog'	Colouful *Sphagnum* Peat forming Degraded raised bog Include M15, only if peat >0.5m deep

Modified from Dargie and Maier (2001)

The EU 'Habitats' Directive recognises that some marginal areas of lowland raised bogs of relatively low quality will need to be identified and included in special areas of conservation to ensure that the active portions of the raised peatland systems can be secured. This may also require the regeneration of degraded areas.

3.1.4 Remote sensing of 'active raised bog'

The distinctive features of 'active raised bogs' identified by the 'Habitats Directive' are that they are peat forming, they maintain a raised water table and contain colourful Sphagna. The field guidance notes produced by Countryside Council for Wales (CCW) adds another important feature, namely that active raised bog has a characteristic hummock / hollow topography (CCW, 1999). Remote sensing techniques such as lidar may be able to characterise the topography of the mire surface, whilst CASI data could be used to explore the proportion of colourful Sphagna present.

3.1.5 Degraded raised bogs still capable of natural regeneration

This habitat type (habitat code 7120) includes raised peat bogs that have suffered damage to the natural hydrology of the peat body, usually as a consequence of anthropogenic disturbance such as hand and machine turf cutting, ditching and peripheral extraction. The plant communities of sites in this category usually contain species typical of the drier parts of raised bogs as there main constituent. But the cover of individual species may differ from the natural state. (European Commission, 1999).

The degraded category is considered to include sites where the damage to the hydrology can be repaired to the extent that peat forming communities re-establish within a timeframe of 30 years.

Management strategies might include ditch blocking and the installation of bunds or staggered sets of pools around the periphery of the intact raised peat dome.

3.1.6 Remote sensing of Degraded raised bogs still capable of natural regeneration

Degraded raised bogs are usually but not always a result of major anthropogenic disturbance to the bog hydrology. Old damage from hand peat cutting is usually restricted to the periphery of sites but this may still have a major impact on the raised water mound across the whole site. By contrast industrial scale modern exploitation may involve ditch cutting right across a site or stripping of vegetation from large sections of a raised mire. Bog bursts, such as the one that occurred at Solway Moss in the late nineteenth century are an example of a natural disturbance to a raised bog system that could disrupt the surface hydrology to the extent that long term changes occur to the vegetation communities. In all cases the damage leaves very distinctive traces long after peat surfaces have begun to re-vegetate. These signs of disturbance are readily detected from the air by simple manual interpretation techniques using either air photographs or Ikonos imagery. Lidar may also prove to be a highly affective method of surveying the surface topography of degraded bogs, since this technique has sufficient resolution to detect even subtle changes in relief. More complicated automatic techniques are probably not necessary for detecting damage that is sufficient to disrupt the overall site hydrology of raised bogs.

3.2 The Lowland Raised Bog Inventory (LRBI) (Lindsay and Immirzi, 1996)

3.2.1 Background to the Inventory

The Inventory of Lowland Raised Bogs in Great Britain was compiled in 1996 to provide a synthesis of information on the condition and conservation status of identifiable lowland raised bogs (Lindsay and Immirzi, 1996). The Inventory provides a general assessment of land cover, and it reports the extent of peatland types in Britain as well as their conservation status (e.g. SSSI, NNR or SAC).

The Lowland Raised Bog Inventory is only concerned with ‘confined’ raised bogs, which are systems that have developed solely or largely through terrestrialisation. As the lowlands of Britain are now generally subject to various degrees of agricultural activity, the concept of ‘lowland raised bog’ in practice was applied to those areas that currently form discrete units of ombrotrophic peat within an otherwise non-peat (*i.e.* agricultural) landscape. The lists of bog sites and their descriptions published by Lindsay and Immirzi (1996) consequently focus on a relatively small proportion of the overall national peatland resource. ‘Semi-confined’ lowland bogs are also listed by the Inventory. This latter peatland type consists of raised bog systems that may have a main peat dome contained within a basin and fringing mires that have developed via paludification of mineral ground beyond the confines of the original basin. The semi-confined mire systems are termed ‘intermediate’.

Lindsay and Immirzi (1996) recognise three broad conditions of raised bog: primary, secondary, and archaic. ‘Primary’ raised bog represents those parts of a raised bog that have developed through natural growth. Fires and drier climate periods may have caused the surface to cease peat accumulation for a time, but the stratigraphic profile is otherwise intact. 'Secondary' raised bog represents those parts of a raised bog that have lost part of the stratigraphic profile through peat removal, generally as a result of peat cutting or agricultural land-claim. The habitat is clearly still ombrotrophic peat, but the surface morphology is determined largely by the activities of peat removal and surface lowering. 'Archaic' peat was defined as ombrotrophic peat deposits that are now so subject to human activity as to be unrecognisable as ombrotrophic peat. Leys of *Lolium perenne* sown onto peat soils, for example, or the extensive tracts of root-crops dominating the Lancashire coastal plain, both represent 'archaic' peat areas.

The Lowland Raised Bog Inventory assumes that cutover bogs originally derived from raised bogs unless there is specific evidence to suggest otherwise (Lindsay and Immirzi, 1996). Oligotrophic peat found on blanket bogs and raised bogs is readily distinguishable from eutrophic to mesotrophic fen and fen carr peat on the basis of macrofossil remains. The latter peat types normally contain obvious remains of reeds (*Phragmites australis*), sedges (e.g. *Carex* spp. and *Cladium mariscus*) and wood remains (carr peat) whereas the former two categories of acidic peat are often rich in Ericaceous remains and Sphagna, or they may be humified to the point where plant remains are not readily distinguishable.

The definitions of 'lowland' and 'upland' used by the Inventory are deliberately flexible and not based on altitude alone. Instead Lindsay and Immirzi (1996) have adopted the 'traditional' definition of 'upland' as being land that extends either above or beyond the enclosed land. Generally though, most raised bogs lie at low altitude and they are most often found below 200m elevation.

3.2.2 Classification used by the Lowland Raised Bog Inventory

Table 2 presents the condition class scheme devised by Lindsay and Immirzi (1996), while Table 3 sets out the vegetation modifiers subsequently used by the Scottish Wildlife Trust for the Scottish Raised Bog Land Cover Survey (Parkyn & Stoneman 1997).

Table 2 : The Lowland Raised Bog Inventory (LRBI) uses the following land cover classes.

Class	Name	Description
P1*	Primary natural / near-natural	A primary peat dome with an extensive cover of colourful Sphagna, with the ability to accumulate peat.
P2*	Primary degraded	Primary surface where the vegetation has been modified by factors other than drainage (e.g. grazing).
P3*	Primary drained	Primary drained bog in which a regular drainage pattern exists.
P4	Primary open canopy	Primary bog supporting open canopy woodland or scrub.
P5	Primary closed canopy	Bogs supporting closed canopy woodland. Trees may have 'self-seeded' but often they are present because of deliberate planting. Self-seeding is often a symptom of damage. Tree cover enhances oxidation and drying of the peat surface.
S1*	Secondary re-vegetating	Surface layers of peat have been removed. Following abandonment of the site vegetation has re-established mainly through natural regeneration.

Class	Name	Description
S2	Secondary, commercial / domestic peat extraction	Large expanses of bare peat for modern industrial-scale peat extraction. Block getting and milling maintain a largely bare peat surface.
A1	Archaic (agriculture)	Bogs drained for agriculture. The peat is oxidised with a lowered surface. Eventually fen peats will be exposed.
A2	Built development	Peatland covered by structures such as buildings, roads or railway lines.
U	Not determined	Condition not yet classified.

Table 3. Vegetation modifiers used in land cover classification

Drainage Modifiers	Vegetation Modifiers	Erosion Modifiers
I irregular	BP broadleaf plantation	MIC micro-broken
N narrow	CP coniferous plantation	Y gully erosion
M moderate	MP mixed plantation	
W wide	PF plantation felled	
A absent	PFR plantation felled and replanted	
U unknown	BS broadleaf self-sown	
	CS coniferous self-sown	
	MS mixed self-sown	
	GS gorse, bramble etc	
	O or C open or closed canopy	
	L low shrub dominated	
	H herb dominated	
	SPH *Sphagnum* dominated	
	BRY bryophyte dominated	
	BAR bare peat dominated	
	BBA bryophyte / bare peat co-dominant	
	BS bryophyte / *Sphagnum* co-dominant	
	BAS bare peat / *Sphagnum* co-dominant	

* denotes condition classes that are considered to be ‘active’ under Annex I of the EC Habitats Directive.

3.3 A Remote Sensing Framework for Lowland Raised Bog Classification

Having established the current best practice in respect of bog habitat classification, the next step was to identify a set of procedures which would deliver these classes in an accurate, reliable and cost-effective manner, based as much as possible on remotely sensed data manipulated in a geographic information system (GIS). Additional requirements were that the overall processing chain be robust, so that alternative sources of data could be substituted if necessary, and so that high-level technical skills in remote sensing and GIS were not necessary to achieve a reliable and repeatable outcome.

3.3.1 Identification of lowland raised bogs on remotely sensed images

Although not strictly part of this project, it should be noted that remote sensing provides a simple means of identifying the extent of many lowland raised bogs, as the contrast between the area of bog and the surrounding agricultural land is often very high, especially in the near infra-red region. Many satellite sensors include a spectral band in the near infra-red, so, depending upon the spatial resolution required, it would be possible to map the extent of lowland peat bogs using data from Ikonos, SPOT HRV, Landsat ETM+ and many other systems.

3.3.2 Identification of physiographic units within lowland raised bogs

For the purpose of this project, the most important physiographic features were those related to past drainage of the bog and evidence of active or abandoned peat cutting. Ideally, mapping such features would be achieved using a sensor which responded to subtle variations in surface micro relief, such as radar, lidar or stereo air photo interpretation, but in the absence of data from these systems, it would be possible to use data from the visible, near infra-red and thermal infra-red wavelengths. The reason for this is that the spatial variation within land parcels, although primarily due to variation in topography, would also be expected to be mirrored in the land cover on a raised bog. Spatial patterns of healthy vegetation, saturated ground and standing water would be expected to have an expression in the spectral domain as well as the spatial domain.

3.3.3 Identification of plant communities on lowland raised bogs

Clearly, one of the most important indicators of active raised bog is the presence of ‘colourful *Sphagnum* species’ and it is very likely that these will have a characteristic spectral response within the visible and near infra-red wavelengths. There is also some evidence from the literature that reflectance in the short wave-infra-red, around the shoulders of the water absorption features at 1.4µm and 1.9µm, varies considerably for different plant species commonly found on raised bogs. Although very few remote sensing systems exist that could measure these spectral features in detail, most sensors have some spectral capability in the visible and near infra-red region.

3.3.4 Summary of remote sensing data requirements

The minimum requirement to achieve the task would appear to be data from a high spatial resolution sensor operating in visible and near infra-red wavelengths. Satellite sensor data are preferable to airborne data for the task as they have much better geometric properties and also cover larger areas of ground for lower cost. However, cloud cover is a major limitation on the operational use of satellite sensor data in the UK.

4. Site Selection and RS Data Availability

4.1 Site Selection

Our initial selection of sites proposed for study included Wedholme Flow in Cumbria, the priority site identified by English Nature, Cors Caron (Tregaron Bog) in mid-Wales, and one or more sites from the Vale of York, for example Thorne Moors. Following discussion with the client, Ballynahone Bog in Northern Ireland was substituted for the site in the Vale of York.

Our previous experience with Landsat TM and SPOT XS/Pan suggested that neither of these systems would be suitable as the basis for a nationwide operational system for mapping raised peat bogs. Problems of cloud cover in the British Isles and the coarse spatial resolution of these sensors relative to the features of interest on peat bogs would be the main problems, but, following the review of raised bog habitat classifications presented above, we also anticipated needing information on surface micro relief which could not be provided either by Landsat or SPOT. Nonetheless, Landsat has shown itself capable of providing useful assessments of ‘active bog’ over large geographic areas at a resolution of around 30 metres (Quarmby, Everingham & Reid 1997), so offers the possibility of operating as a relatively inexpensive initial coarse filter covering a wide area, provided cloud-free images can be obtained.

Remote sensing methods (Table 4) which could provide sufficiently detailed information on bog surface topography include analogue or digital stereo photogrammetry from an aerial platform, airborne interferometric synthetic aperture radar (InSAR) and airborne LIDAR. Photogrammetry would be the most accurate method, but also the most labour intensive, requiring specialist skills to extract the necessary information from the imagery. The main problem with InSAR was its limited availability for the sites of interest. However, this situation is about to change markedly due to the NEXTMap programme which is planning to acquire InSAR data for most of England and Wales during 2003. With this in mind, we have included a InSAR-based approach in the relative costings presented in Section 8.2.

Table 4. RS data availability for the main sites

	Wedholme Flow	Cors Caron	Ballynahone	Comment
High resolution satellite sensor data	Three Ikonos images were available from September and October 2001.		None available	Infoterra, the UK agent for Ikonos originally stated that Ikonos data were available for Ballynahone, but this proved not to be the case
Airborne multispectral data	CASI data possibly available for part of the site from the Environment Agency.	Daedalus Airborne Thematic Mapper and CASI data available for three dates from NERC	None available	
Airborne LIDAR	Partial coverage available from the Environment Agency.		None available	
Airborne InSAR	The NextMap programme is currently acquiring interferometric SAR data for England and Wales (February 2003).			
Comment			Copies of colour aerial photographs of Ballynahone Bog were made available in January 2003	

4.2 Ikonos Satellite Sensor Data

Ikonos multispectral imagery, which has been commercially available since early 2000, (www.spaceimaging.com, 2002), was chosen as the main data source for the Wedholme Flow test site. It is a reliable source of high resolution data with the sensor acquiring panchromatic imagery (1 band) at one metre resolution and multispectral imagery (4 bands) at four metre resolution (Table 5). The multispectral data were found to be more useful as the different bands contain more information concerning surface cover than panchromatic data for the present purpose.

Table 5. The spectral range of the 4 Ikonos bands. (Source: Infoterra, 2002)

Band	Region	Spectral Range (nm)
1	Blue	445-516
2	Green	506-595
3	Red	632-698
4	Near Infrared	757-853

The data were obtained from Infoterra, a company specialising in geographic information and who offer a range of remotely sensed data from both airborne and satellite sources.

The precise location of the area of interest was given as 54.5212° latitude and -3.1329° longitude as this is the centre of the Wedholme Flow lowland raised bog. Archive data was stipulated as a preferable source as it would be readily available and cheaper than obtaining a new data set. Infoterra offered three archive images which were acquired in September and October 2001. The October image, dated 24 October 2001, is the only one in which the area of immediate interest (i.e. the peat bog itself) is completely cloud free and was thus preferable over the other two, the exact geographical reference of this image is 54.9151° latitude and -3.32404° longitude. The data were provided on a CD-ROM in a format which preserved the maximum dynamic range (11 bits per pixel).

4.3 Airborne Multispectral Data

Several data sets were available for the Cors Caron site as a result of it having been used for a PhD research project within the University of Southampton. These are described in Table 6 and Table 7. Aerial photographs were also collected during each flight and a large number of ground spectra were collected from vegetation communities on the raised bog.

Table 6. Airborne Multispectral Data available for the Cors Caron site

Date	Sensor	Nominal Pixel Size (metres)	Wavebands
8 May 2001	CASI	3	Up to 288 spectral bands between blue and near infra-red.
27 June 2001	CASI	3	
12 Oct 2001	CASI	3	
8 May 2001	ATM	4	10 bands in the visible, near infra-red and thermal wavelengths.
27 June 2001	ATM	4	
12 Oct 2001	ATM	4	

Table 7. Bands sensed by the Daedalus Airborne Thematic Mapper (Source: NERC, 2003)

Channel	Wavelength (μm)	Corresponding Landsat TM Band
1	0.42-0.45	
2	0.45-0.52	1
3	0.52-0.60	2
4	0.60-0.62	
5	0.63-0.69	3
6	0.69-0.75	
7	0.76-0.90	4
8	0.91-1.05	
9	1.55-1.75	5
10	2.08-2.35	7
11	8.5-13.0	6

4.4 Lidar Data

Airborne lidar data covering part of the Wedholme Flow site were purchased from the archive maintained by the Environment Agency. These data were provided as a 2km x 2km tile, with a nominal pixel size of 2 metres, and covered only part of the complete bog area (see Figure 1). The stated precision of height was ±25 cm. Both filtered and unfiltered data were provided. Due to the additional height uncertainty introduced by the filtering process it was decided to use only the unfiltered data.

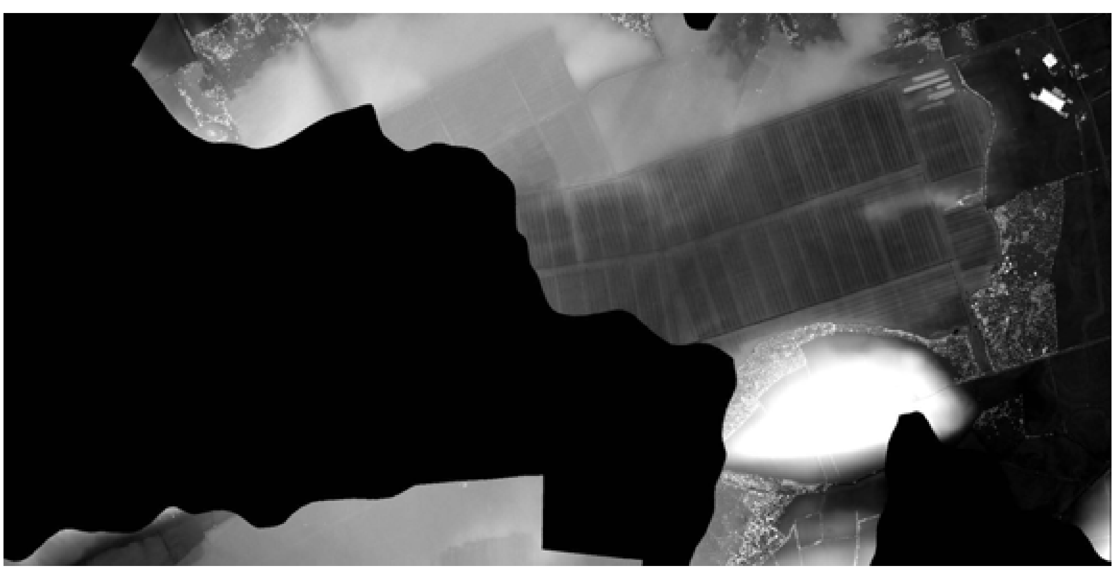

Figure 1. A grey scale image of the LIDAR coverage available from the Environment Agency archive covering part of Wedholme Flow

The initial plan was to use the lidar data as the primary source of quantitative information on surface micro relief over the whole bog area, and it would have been very useful for this task. However, the limited spatial extent of the available lidar coverage meant that this was not possible. Instead, we investigated a number of ways in which lidar data may be processed so as to provide useful information for bog habitat classification, and in particular as a means of discriminating primary from secondary bog surfaces. Various digital processing techniques were applied to the lidar coverage, including fourier transform analyis and geostatistical techniques designed to extract repetitive patterns from digital image arrays. Although these were reasonably successful, the results they produced required specialist knowledge to interpret and it was felt that they added little to what could be achieved by simple visual interpretation of a relief-enhanced lidar image (Figure 2). This image was produced by first colour-coding the lidar image according to the height value (green = low, red = high), and then illuminating the colour-coded image from the north-east, at a low elevation angle so that the relief features on the bog were enhanced. In this example, a single illumination geometry was sufficient to enhance the surface relief features within the land parcels on the bog. However, in other cases it may be necessary to produce several images, each illuminated from a different direction in order to optimise the visual interpretation of microrelief.

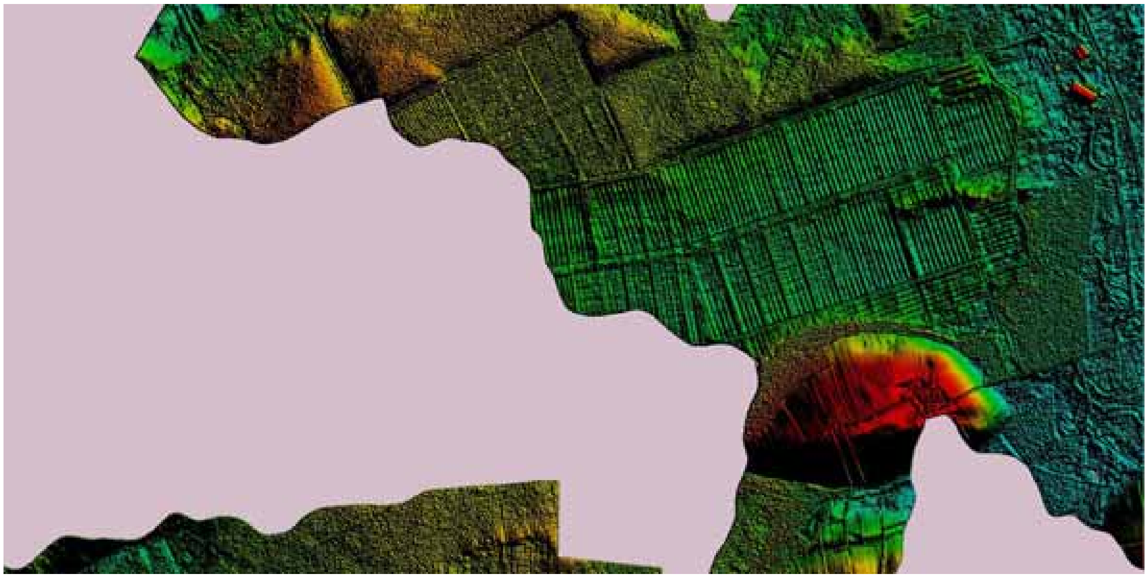

Figure 2 : Enhanced lidar image of part of Wedholme Flow. The lidar data have been colour coded according to altitude and then relief shading applied. Blank areas indicate no lidar data

5. Field Sites and Ecological Methods

5.1 Wedholme Flow, Cumbria (Grid Reference: NY 2253)

Wedholme Flow, an extensive lowland raised bog, is situated at the head of the Solway Firth in Cumbria at an altitude of 13 m. Annual rainfall is about 900 mm /yr and evapotranspiration 471 mm/yr (McMullen, 2000) The peat deposits, whose thickness reaches over 7 m overlie reddish till and marine alluvium (Burton and Hodgson, 1987). Wedholme Flow covers 780 ha[1]. The area of uncut *Sphagnum*-rich raised bog of 125 ha is still among the largest in England. Wedholme Flow includes several existing "Sites of Special Scientific Interest" and is also proposed as a Special Area of Conservation (SAC) as part of the Natura 2000 network under the EC Habitats Directive. The Scotts Company undertook peat extraction in an east-west direction, separating two big uncut areas in the northern part of the site and in the south. In early 2002 the peat extraction ceased, after Scotts agreed to sell 1,526 ha of lowland raised bog to English Nature for £17.3 million[1]. Wedholme Flow is managed by English Nature as part of the South Solway Mosses NNR.

The site was visited for fieldwork 13 until 15 September 2002. To obtain an overview of the vegetation cover of Wedholme Flow, 20 quadrats of 3 x 3 m were mapped at representative locations according to the land cover classes of the Lowland Raised Bog Inventory (LRBI) (Lindsay and Immirzi, 1996). Additionally the mapped areas had to be representative of the surrounding vegetation in terms of colour and reflectance. Therefore, areas which are distinctive because of the growth of vegetation patches with a contrasting reflectance (e.g. *Narthecium ossifragum* hollows) within the uncut areas were excluded from mapping.

The northern and southern uncut areas possess active peat forming vegetation dominated by *Sphagnum,* which covers 30 to 70 % of the ground. The most common *Sphagnum* species in the uncut areas are *S. magellanicum*, *S. papillosum* and *S. tenellum* along with *S. subnitens* and *S. capillifolium.* Accompanying vascular plants include *Calluna vulgaris*, *Erica tetralix*, *Andromeda polifolia*, together with *Eriophorum vaginatum*, *E. angustifolium, Rhynchospora alba* and *Drosera rotundifolia. Narthecium ossifragum* is also present, growing in clusters. In the Southern part of the bog some *Sarracenia purpurea* plants were encountered. This carnivorous species is a North American native and was introduced to Wedholme Flow (McMullen, 2000). Altogether the southern part of the uncut areas possesses a much higher *Sphagnum* cover and is in better condition than the northern part, which has to be considered as somewhat degraded. All uncut areas are drier along their edges, which are dominated by vigorous growth of *Calluna vulgaris*. In the north eastern part of the northern section of uncut bog the vegetation is disturbed and modified due to an air accident in the Second World War (Frank Mawby, site manager, personal communication).

1 http://www.defra.gov.uk/news/2002/020227a.htm

Adjacent to the east side of the southern uncut compartment, there are domestic peat cuttings which have been re-vegetated by peat forming plant communities. Areas where sod-cut peat has been extracted are mainly situated in the western part of the central cut area. Vegetation there is quite heterogeneous varying between very wet artificial hollows to dry baulks, which lie adjacent to each other. In the hollows *Sphagnum cuspidatum* and *Eriophorum vaginatum* are dominant, whereas the ridges are mainly covered by *Calluna vulgaris*. Along the western slope where the ground rises towards to the mineral soil the area becomes generally dryer and *Calluna vulgaris* is predominant. The central / eastern part of the site has been excavated until very recently and consists mainly of a bare milled peat surface without vegetation.

At the northern edge of the bog there are minerotrophic fringes of cut-over peat, which are now wooded. These woodlands consist mainly of *Betula pubescens* and have a *Sphagnum*-rich field layer. At the southern edge the wooded fringes are probably uncut peat and could be related to a former lagg zone.

5.2 Cors Caron, Ceredigion, West Wales (Grid Reference: SN 685622)

Cors Caron, also known as Tregaron Bog, is situated near Tregaron village in the Teifi valley in Ceredigion, west Wales. The bog complex developed from a late glacial lake, which was formed behind an end-moraine (Godwin and Conway, 1939). It is an extensive lowland raised bog complex of 816 ha, consisting of three hydrologically independent peat domes. All three suffer from marginal peat cutting at different scales. There may have been three further raised peat domes, which are destroyed now due to peat extraction for domestic fuel (CCW, 1994). The least disturbed bog is the West Bog, stretching 2 km parallel to the Teifi river on its western side. At the eastern side of the Teifi are the Northeast Bog and the Southeast Bog, separated by a mineral ridge. These two bogs are more affected by peripheral peat cutting, but the central peat domes of all three bogs are still structurally intact. In contrast to many other raised bog remnants they still show the ecological differentiation of plant communities typical of the crown (mire expanse), rand and (partly) lagg (Fojt, 1995). Peat cutting occurred only for domestic purposes and ceased in 1960 (CCW, 1995). The composition of the surface vegetation at Cors Caron underwent a dramatic change over the last 65 years. On the West Bog Godwin and Conway (1939) noted, in the field seasons of 1936 and 1937, numerous pool features and extended *Sphagnum*-rich areas that appear to have been largely replaced by 'drier' communities sixty-five years on, despite an annual rainfall of about 1600 mm/yr (Paul Culyer, site manager, pers. communication). Comparisons of the vegetation data of Godwin and Conway (1939) with recent surveys (Schulz, in preperation) reveal a substantial retreat of the *Sphagnum* cover and a significant increase of ericaceous dwarf shrubs.

Cors Caron became a National Nature Reserve (NNR) in 1955 and it was added to the Ramsar site list in 1993. It supports a range of rare plant species such as the nationally rare bog moss *Sphagnum pulchrum* and rare animals such as the rosy marsh moth *Coenophida subrosea*. The Cors Caron NNR is managed by the Countryside Council for Wales.

Fieldwork was carried out in August and September 2002 using the same methodology as on Wedholme Flow. The uncut areas are mainly dominated by a degraded M18 community (National Vegetation Classification, NVC; Rodwell, 1991), with very little *Sphagnum* (2-23 %) and a high cover of ericaceous dwarf shrubs. The eastern slope of the West Bog is chiefly covered by *Molinia caerulea*. This species also forms an extensive canopy on most cut-over areas of the Northeast and the Southeast Bogs. Despite peripheral peat cutting, these two peat domes also possess an altogether higher *Sphagnum* cover (about 20 %) and less ericaceous shrubs than the West Bog. Wooded areas occur on cut-over peat, especially in the north-western compartment (willow carr) and along the edges of the eastern peat domes. In recent years many dams around the crowns of the bogs have been built in order to prevent surface runoff. Behind these dams, bodies of standing water have formed, which support renewed colonisation by *Sphagnum cuspidatum*

5.3 Ballynahone Bog, Co. Londonderry, Northern Ireland (Grid Reference: H 860980)

Ballynahone Bog, which is one of the largest lowland raised bogs in Northern Ireland, formed as a basin mire in the valley of the Moyola River, to the south of the Glenshane Pass. The raised peat dome, which extends to 243 ha, is structurally undisturbed over central parts but exhibits, on its southern half, a regular pattern of recently blocked drains. Marginally, the bog has been cut for domestic fuel supply and there is no natural rand left[2]. The cut parts are mostly minerotrophic and covered with carr woodlands. The domed part of Ballynahone Bog possesses characteristic *Sphagnum*-rich raised bog vegetation with hummock, hollow and pool complexes, supporting species which have became scarce. Rare species include *Sphagnum pulchrum* and the liverwort *Pleurozia purpurea* as well as the Large Heath butterfly *Coenonympha tullia*[2]. In 1991 a peat extraction company called Bulrush dug 13 miles of drains on the southern part of the bog in preparation for future peat extraction. Due to public action and pressure from several organisations, including the Ulster Wildlife Trust and Friends of the Earth, planning permission was revoked[3] and the site declared a NNR in 1993. Further declarations of the bog as an Area of Special Scientific Interest (ASSI) in 1995 and as a Ramsar site in 1998[2] followed.

Fieldwork on Ballynahone Bog took place 15 and 16 October 2002, using the same methods as on Wedholme Flow and Cors Caron. At the South-eastern part of the bog the vegetation has been almost completely killed off due to lead contamination. About 15 tons of lead was deposited on the site when it was used as a clay pigeon shooting ground (Dermot Hughes, Ulster Wildlife Trust, pers. communication). The pellets, which dispersed onto the bare peat, are still visible and are a significant threat to the surrounding vegetation and ground water.

The central part of the peat dome is characterised by a high percentage cover of *Sphagnum tenellun, S. cuspidatum* and *S. papillosum* along with *S. capillifolium* and *S. subnitens*. However, there is also vigorous growth of young *Calluna vulgaris* shoots, which often cover more than 30 % of the ground. In some hollows in the western half of the bog *S. pulchrum* was encountered and in the northern area, occasionally *Vaccinium oxycoccus*. At the cut margins mature *Calluna vulgaris* dominates and reaches nearly 1m in height.

2 http://www.ehsni.gov.uk/natural/designated/ramsar/ramsar_ballynahone.shtml

3 http://www.geographyinaction.co.uk/Landscapes/Landscapes_bog.html

There are some areas at the margin of the peat dome where sod cutting took place. They have re-vegetated forming a pattern of *Sphagnum cuspidatum*-rich pits adjacent to *Calluna vulgaris* dominated balks as on Wedholme Flow. The wooded areas closed to the uncut peat dome are covered by *Betula pubescens* carr with *Sphagnum palustre*, *S. fimbriatum* and *Polytrichum* commune in the moss layer.

5.4 Methodology of the vegetation survey at the investigated sites

To gain an overview of the vegetation cover of the investigated sites, approximately 20 quadrats of 3 x 3 m were surveyed in representative areas, according to the land cover classes of the Lowland Raised Bog Inventory (LRBI) (Lindsay and Immirzi, 1996). Additionally, the mapped areas had to be representative of the surrounding vegetation in terms of colour and spectral reflectance. Therefore, some distinctive patches with contrasting reflectance had to be excluded from mapping. (For example, *Narthecium ossifragum* patches) The areas to be surveyed where chosen with the aid of aerial photographs and after consultation with the site managers.

In the vegetation tables the plant frequency was noted as percentage cover of the ground and the location of each quadrat within the National Grid was acquired using a handhold GPS. On Wedholme Flow, Ballynahone and some parts of the Cors Caron West Bog digital photographs of each quadrat were taken.

Nomenclature follows Stace (1991) for vascular plants, Daniels and Eddy (1990) for *Sphagnum*, Smith (1978) for non-*Sphagnum* bryophytes, Hodgetts (1992) for *Cladonia* and Molberg and Holmasen (1992) for Lichens.

6. Results from Wedholme Flow

6.1 Preliminary Image Interpretation

Prior to the field visit to the site, a preliminary interpretation of the available image data for the site was undertaken. Recent colour air photographs of the site were available on the internet[4], and, despite their high degree of data compression, these proved to be very useful in planning the field survey. The Ikonos data were delivered shortly before the field survey, which gave us sufficient time to make laminated colour hardcopy for use in the field. Two colour combinations were used: simulated true colour created from Ikonos bands 3, 2, and 1 (Figure 3); and false-colour infra red created from Ikonos bands 4, 3, and 2 (Figure 4). Our initial impression was that, in visual terms at least, the near infra-red band added little to the information available in the visible wavelength bands.

The Environment for Visualising Images (ENVI) Research Systems software version 3.5 (2001 edition) was used for the image processing. Although some of the terms discussed here may be specific to this system, the principles are relevant to all image processing software packages.

The initial digital processing of the Ikonos data revealed two minor problems. First, the geometric fidelity of the data as supplied by Infoterra was not good enough to use in conjunction with Ordnance Survey map data and so an additional image warping using ground control points had to be undertaken (Table 8). Second, there was evidence of slight radiometric mismatch where adjacent swaths of image data met. This is shown as a ‘step’ in the image colour running north-south slightly west of easting 85000 on and may be due to a sensor calibration problem or it may be due to the difference in sensor view geometry between the two swaths interacting with the ground surface bidirectional reflectance properties. It would have been possible to apply an arbitrary correction for this defect by scaling the data from the western portion of the bog to match that from the east, but this was not done as it only affected a small part of the area of interest and we were interested so see whether such a minor radiometric defect would affect the reliability of the automated classification. A human interpreter is easily able to discount this error in the data.

[4] multimap.com

Table 8. Ground control points used to refine the geometric correction of the Ikonos image

Map (X)	Map (Y)	Image (X)	Image (Y)
321167	552702	1509.25	1452.25
322540	551011	1855.60	1869.00
322809	552466	1919.17	1504.50
323691	553896	2132.75	1144.50
320170	555180	1251.63	834.50
322118	554389	1742.43	1027.43
320338	553897	1297.20	1154.60
321640	554704	1619.20	948.70

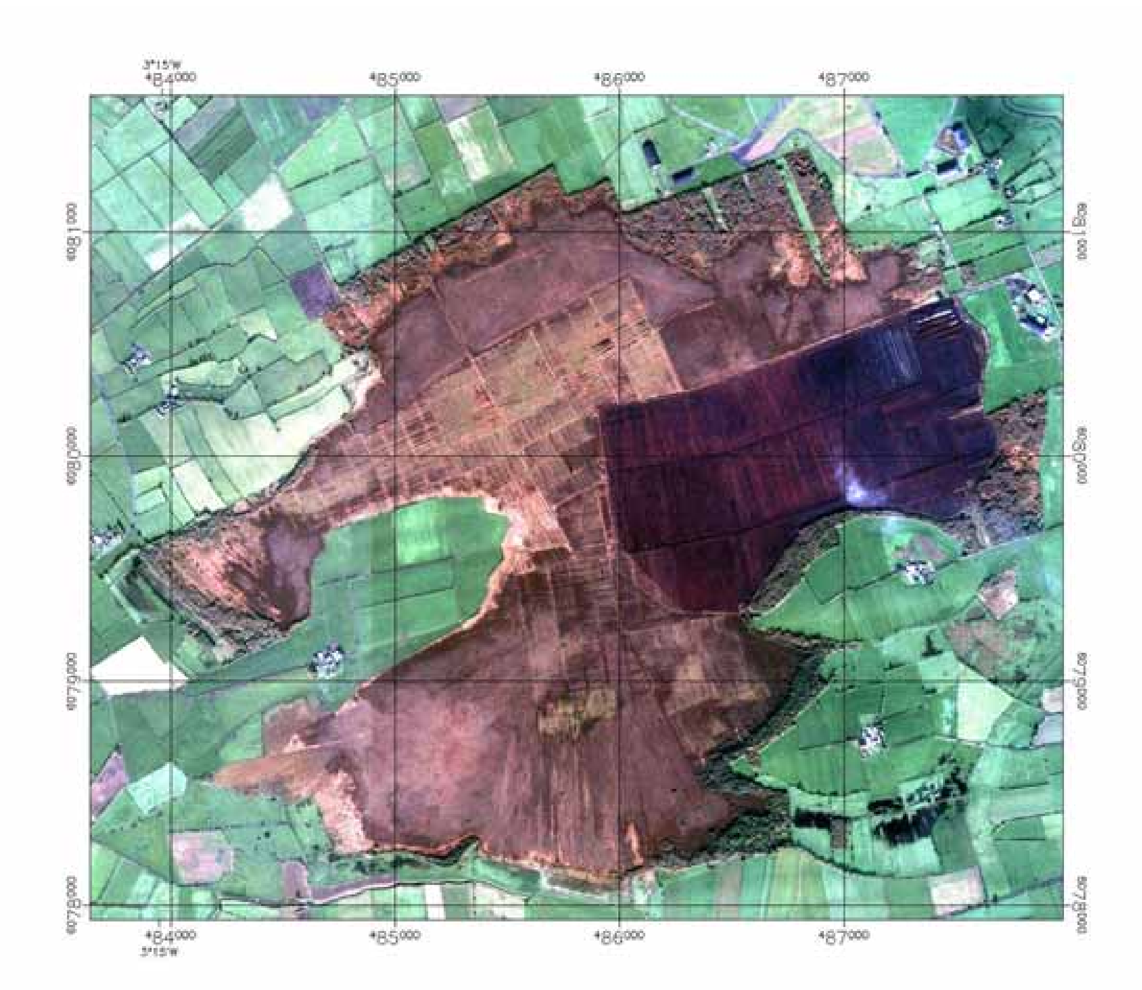

Figure 3. Simulated true colour composite of Ikonos bands 3, 2 and 1

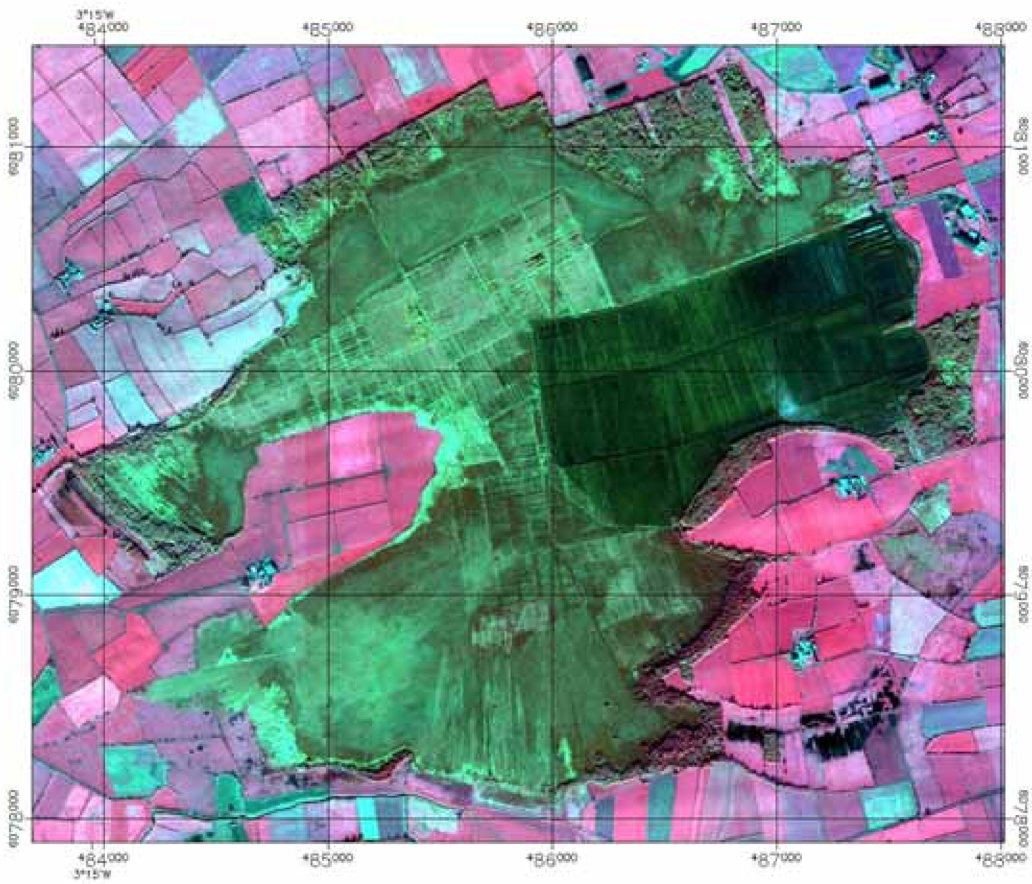

Figure 4. False-colour composite of Ikonos bands 4, 3, and 2

6.2 Colour Space Rotation

As part of the initial exploration of the image data, a colour space rotation was performed on the Ikonos red, green and blue spectral bands. This transformed the RGB image into three separate black-and-white images representing ‘Hue’, ‘Saturation’ and ‘Intensity’. Of these, the most informative was the intensity image, reproduced in Figure 5 below. The various compartment boundaries within the bog were picked out well in this image, especially those areas which had been subject to cutting or draining in the past, in which the linear channels were clearly visible. It was also possible to identify more subtle boundaries within relatively undisturbed areas of the bog. While these were also present in the colour image, they were visually clearer in the intensity image, free from the distracting effect of the colour information.

6.3 Identification of Photomorphic Regions

The final stage of the visual analysis of the Wedholme Flow Ikonos data was a test to see how easy it would be for someone with no knowledge of the site to identify ecologically consistent regions within the bog. A skilled remote sensing specialist with no background in bog ecology and no knowledge of the particular site was given the task of identifying photomorphic regions from the Ikonos image, based on the image attributes alone (colour, texture, shape, size, pattern/context, shadow). In total, 16 regions were created as distinct polygons (see Figure 6). Region 16 was created using the 'multi-part' option in ENVI as it encompasses a small area (region 8) that is visually distinct from it and should therefore be treated as a separate polygon.

Figure 5. Intensity image created from Ikonos bands 1, 2, and 3

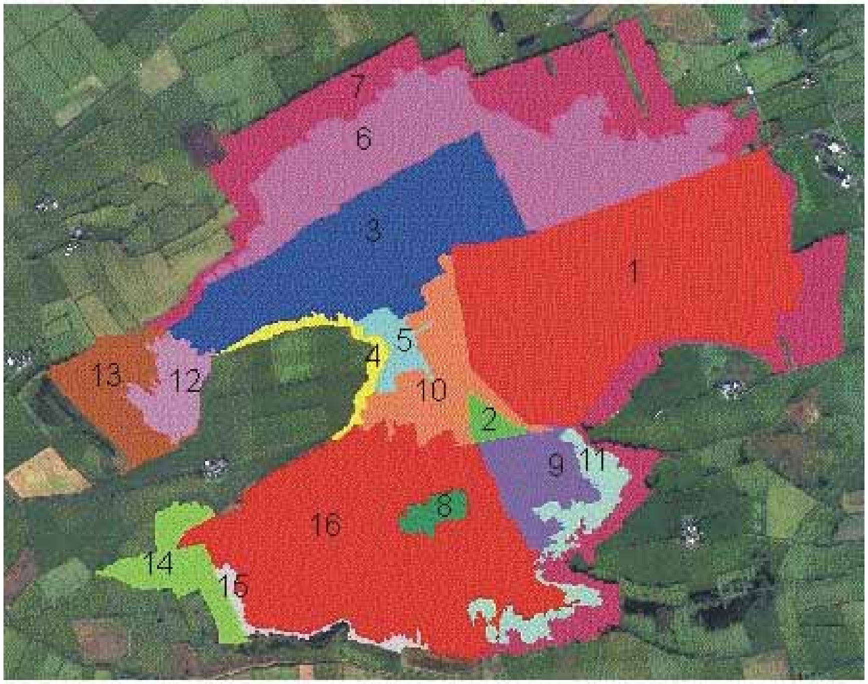

Figure 6. Photomorphic regions identified by visual analysis of the simulated true colour Ikonos image

6.4 Strategy Adopted for Digital Classification

The first aim of the digital image processing was to investigate the spectral properties of raised bog in the four Ikonos bands. In order to achieve this we needed first to isolate the area of raised bog from its surroundings by creating an image mask. The pixels from within the bog area were then clustered in spectral space in order to identify any natural groupings which might indicate information classes. The results from this 'unsupervised' classification were then used to inform a more sophisticated 'supervised' classification and analysis of the image data.

6.5 Masking the Area of Raised Bog

The first step in the unsupervised classification was to define the bog as an area of interest distinct from the rest of the data in the scene. The most efficient method by which to achieve this in ENVI is to use the masking tool. This results in a binary image (i.e. one that is made up of values of 0 and 1), any processing that employs this mask will only include the areas with a value of 1, the areas with a value of 0 not being processed. This simplifies the scene, easing interpretation of results and reducing the amount of data that is included in the calculations (which, in turn, increases the speed of processing and reduces data quantity for storage purposes).

In order to create a mask, the bog was defined as a region of interest (ROI), the zoom window was used in this process to provide a higher degree of accuracy than using the viewing window. The image was displayed in bands 3, 2 and 1 – a true colour simulation – and was enhanced using 2% linear stretching. These settings were chosen as they best highlight the contrast between the bog and the surrounding area.

Once the bog had been identified as a ROI it was converted into a mask (using the basic tools menu in ENVI). This mask could then be overlaid onto the image at any point during the image processing to ensure continuity in the area of interest.

6.6 Unsupervised Classification

As a preliminary approach, unsupervised classification was used to determine the number of spectral classes evident within the scene, based purely on the natural structure of the data (Campbell, 1996). This type of clustering procedure does not aim to identify what the different classes are on the ground but to establish whether or not different classes can, indeed, be distinguished spectrally.

There are two options for unsupervised classification in ENVI; these are ISOSDATA and K-Means. They are similar in that they are both minimum distance classifiers, the principle of which is that each pixel is grouped to the cluster to which there is the shortest distance (in spectral space) to the centre (i.e. to the mean pixel of that cluster). In unsupervised classifications the initial definition of the cluster centre is determined randomly, with each re-calculation the allocation of the new centre pixel should get closer to the truth. This is the extent of the K-means classifier.

There are two main assumptions with this with this method of classification. The first is that the number of classes is known (Mather, 1999) – the analyst is required to enter this value as a prerequisite to the 'unsupervised' classification. In this case this was simply determined through trial and error, the final number of classes (between 5 and 10) was decided on based upon the appearance of the classification after a variety of parameters – lower and higher numbers and fewer and more classes – were experimented with.

A second assumption is that the distinction between clusters is obvious, that is, that there is no overlap between different classes. If the distance from the centre of a cluster to a pixel is less than the user-defined threshold this will not be the case as it would be possible for that pixel to be allocated to more than one group.

ISODATA attempts to rectify this, ISODATA is an 'Interactive Self-Organising Data Analysis Technique' (Mather, 1999), the results of which are often regarded as superior to the basic minimum distance classifiers (Campbell, 1996). This classifier splits classes that have large standard deviations and merges classes that are closer to each other than the user defined parameter. This is repeated until there is no, or little, change in the mean class pixel between iterations. A limitation of this technique is the fact that the same class may be split and merged infinitely, supplying a maximum number of iterations (again, a user defined value) prevents this.

As the ISODATA classifier is considered to yield more satisfactory results than the less sophisticated K-means method it was chosen as the unsupervised classification method for this project.

As noted previously, a variety of different thresholds were experimented with in order to determine a suitable combination for the production of an unsupervised image. The final set of parameters used is presented below (see Table 9).

In total, 10 classes (or clusters) were defined (see Figure 7). The most striking is class 1, it is the largest homogeneous area in the scene with class 2 forming a well defined pattern over it (A). These two classes are spectrally distinct from the rest of the image. Around the edge of the bog there appears to be some spectral confusion – there is a high degree of mixing between classes (e.g. B). This may be due to the fact that the cover here is more varied than further into the bog, perhaps as the conditions get drier. Classes 4 and 5 frequently appear to be adjacent or overlapping (C); it may be that these could be classified as one class or, alternatively, that there is a marginal but detectable difference between them. The difference may be a reflection of vegetation health, or simply arise from the mixture of species present, but both of these would be relevant to this study.

Table 9. Parameters used in ISODATA Classification

PARAMETER	VALUE
Minimum number of classes	5
Maximum number of classes	10
Change threshold	5%
Maximum number of iterations	5
Minimum number of pixels in a class	20
Maximum class standard deviation	2
Minimum class distance	2
Maximum merge pairs	2

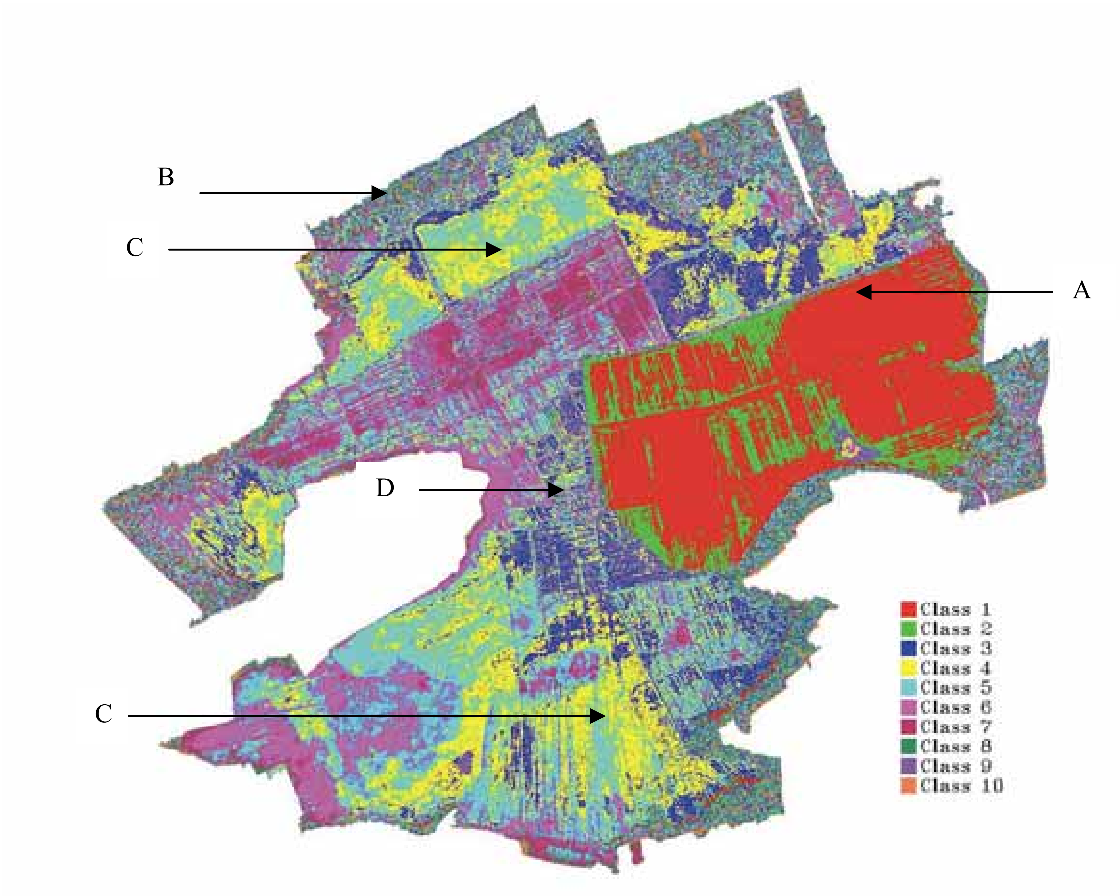

Figure 7. Results from the ISODATA unsupervised classification of Wedholme Flow

The most complicated area is the centre of the bog (D). Interpretation of this would prove difficult at this stage; post processing (see Section 6.7) may be particularly valuable here.

These preliminary results are encouraging as there appears to be clear differences in the spectral response of different areas of the bog. Some clusters are quite striking in that they are areas of homogeneous cover (e.g. class 1, and some areas of classes 2, 3, 4, 5 and 6). In other cases the pattern of the cover and proximity to other classes may carry more information on the bog habitat for management purposes.

6.7 Spatial Reclassification

A common problem encountered when classifying remotely sensed data from areas of semi-natural vegetation concerns the intermingling of classes and the uncertain membership of pixels to classes. Both of these problems result from the nature of the plant communities present on the ground and the transitional or gradational nature of boundaries between them. If the pixel size is large relative to the average ecological unit on the ground, then each pixel may be thought of as containing a mixture of 'pure' classes and strategies such as spectral unmixing may be used to estimate the proportions of each class within each pixel in the image. If the pixel size is of a similar size to (or smaller than) the average ecological unit on the ground, then it can be argued that there is a different situation, and that the pixels should be considered as individuals and assigned to classes accordingly. In this case, there are two further computational tools that can help maximise the information content of the classification. The first is fuzzy classification, which allow for each pixel to be a member of more than one information class. The second is spatial reclassification, which looks at the designated class of each pixel produced from a conventional classification method (e.g. ISODATA), and re-assigns pixels to classes based on their spatial context or some other measure of the local geography.

The result of the ISODATA classification was spatially reclassified using a number of different metrics, including clumping, combining and sieving classes. The one that produced the most visually satisfactory result was majority analysis which acts as a modal class filter, reclassifying pixels which are outliers within a large cluster of spectrally similar pixels. As with the classification stage, there are user-defined parameters for this process, and the optimum values are shown in Table 10. One of these is the kernel size; the larger it is, the smoother the final image. The default 3x3 size was chosen here after experimentation with both larger and smaller values as it resulted in a smoother image but did not cause a notable loss of detail.

Table 10. Parameters used for Majority Analysis

Parameter	Value
Classes selected	1-10
Analysis method	Majority
Kernel size	3x3
Centre pixel weight	1

The smoother image (Figure 8) can be directly compared to the original, classified image (Figure 7). In particular, the central area of the bog (Figure 7, B) is a lot less confused than before the spatial reclassification was carried out. This may aid interpretation of what the cover actually is on the ground – in its original state this area was too jumbled for any satisfactory interpretation. There was only a small loss of detail between the spectral classes, the contrast is good and patterning is still evident.

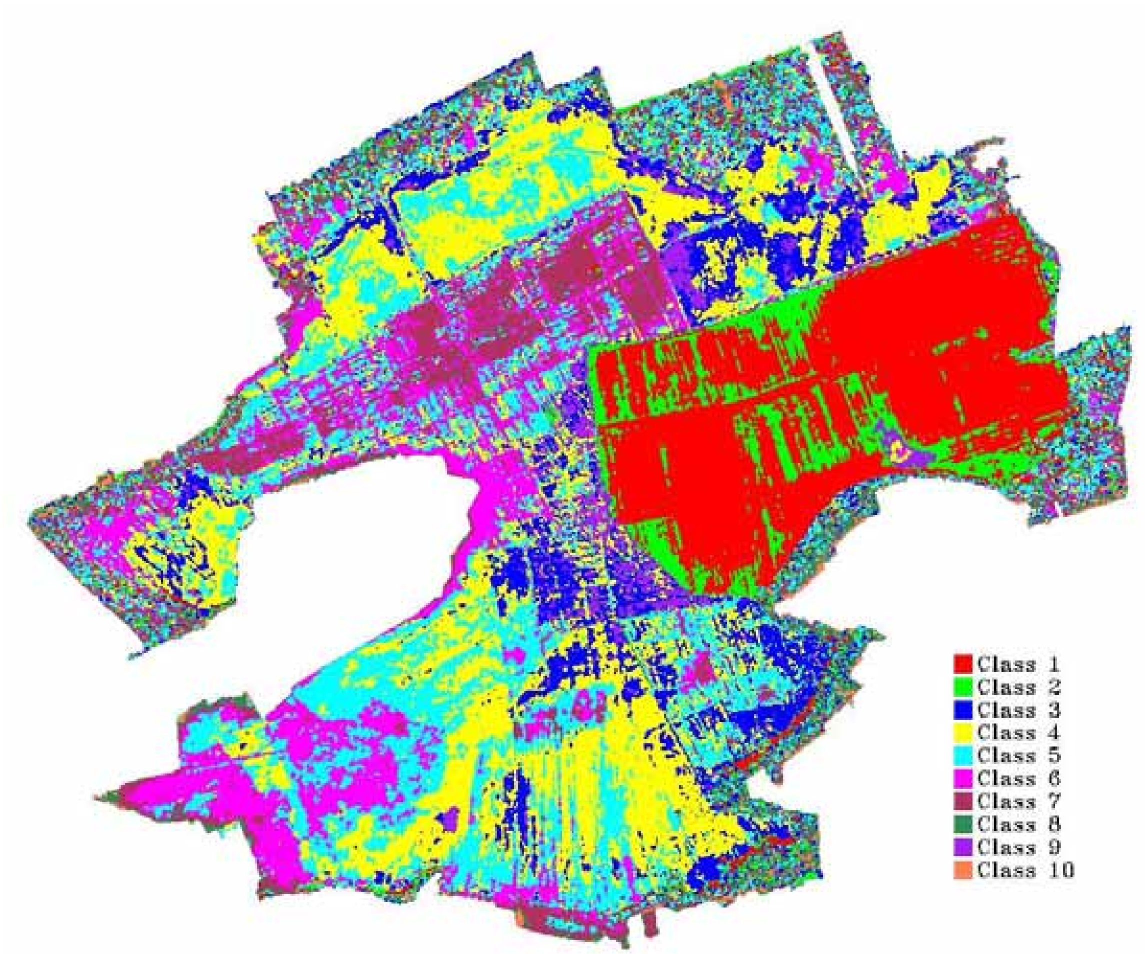

Figure 8. The ISODATA classification of Wedholme Flow after applying a 3x3 majority filter

6.8 Supervised Classification

6.8.1 Training site selection

Having established the extent and nature of the spectral classes present in Wedholme Flow from the unsupervised classification, we proceeded to identify training sites for the supervised classification. The relief-shaded, colour-coded, lidar image was used as the basis for training site selection within the open bog as it was felt that the boundaries shown on it related more clearly to the management units required in the final classified map than those shown in either the colour composite or the ISODATA classification. Additional training sites within those areas not covered by the lidar data were selected with reference to the Ikonos images and the field survey data (Figure 9). A total of seven classes were sampled (see Table 11).

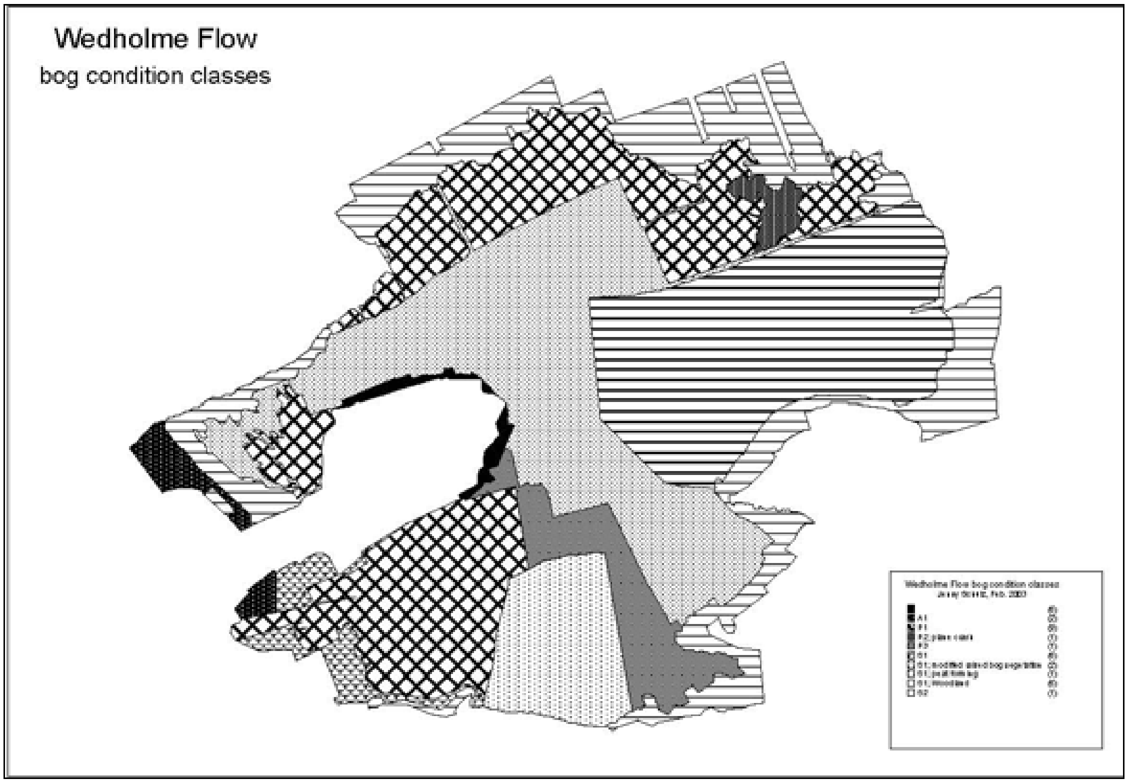

Figure 9. Bog condition classes for Wedholme Flow from field survey (larger version in Appendix, after Table 23)

Table 11. Land cover classes from which training sites were selected

1	Actively growing raised bog
2	Active, but degraded bog
3	Actively regenerating sod-cut peat
4	Milled, unvegetated peat
5	Drained and degraded bog
6	Carr woodland
7	Mire margin community

The training sites were inspected closely and refined where necessary using information collected during the field survey. These data were then used to perform a maximum likelihood classification of the Ikonos data. Many different classifications were performed on all four bands and on a subset of the three visible bands.

6.8.2 Results of the Supervised Digital Classification

Figure 10 shows the best classification, which was achieved using the maximum likelihood algorithm applied to all four Ikonos bands. At this stage, the allocation of pixels to land cover classes is simply based upon their spectral response in the four Ikonos bands; no information on the spatial arrangement of pixels, or of their context has been considered.

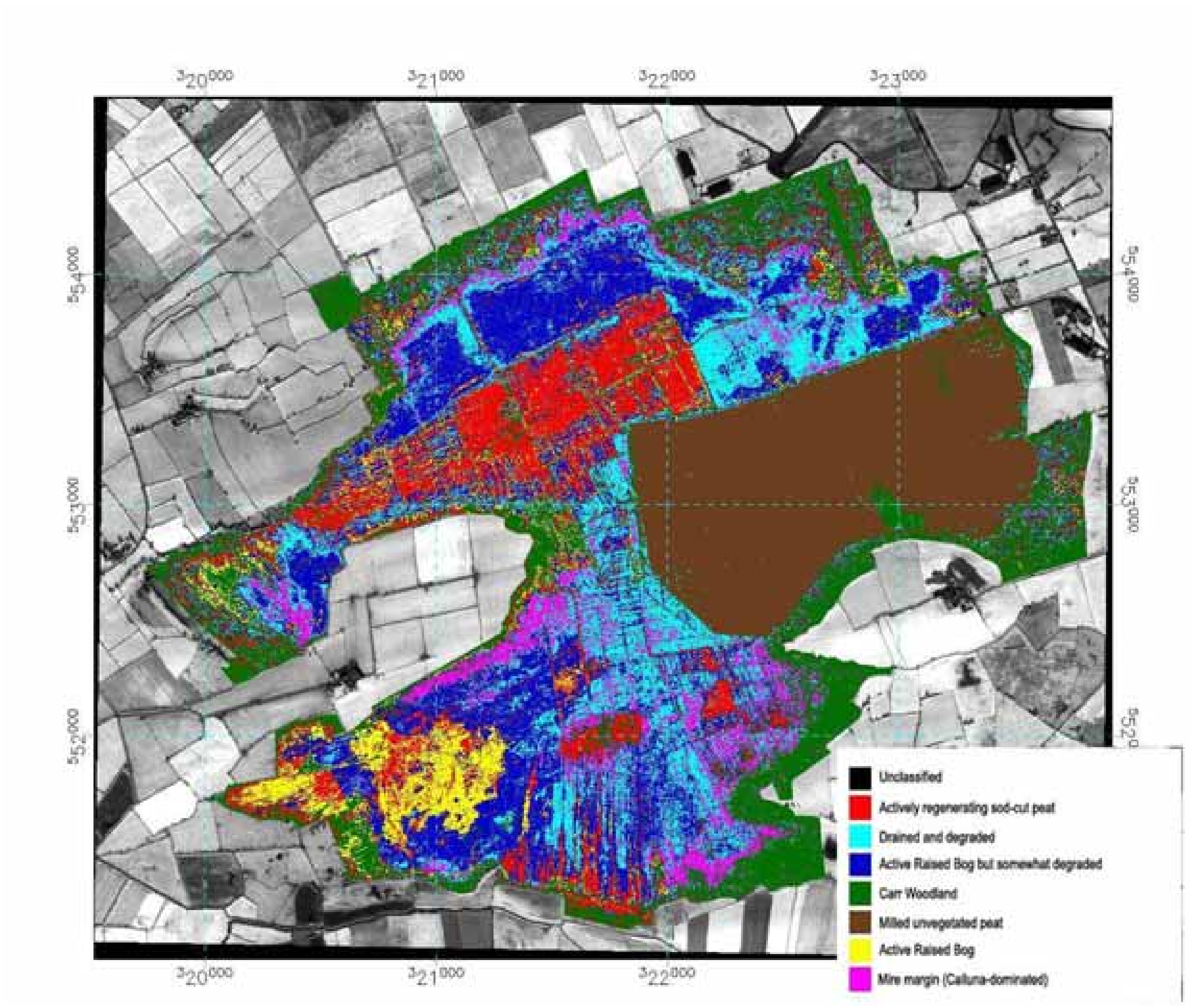

Figure 10. Maximum likelihood classification of Wedholme Flow

A 3 x 3 centre-weighted majority filter was applied to the classification in order to reduce the fine spatial detail within classes and to improve the definition of boundaries, with the result shown in Figure 11.

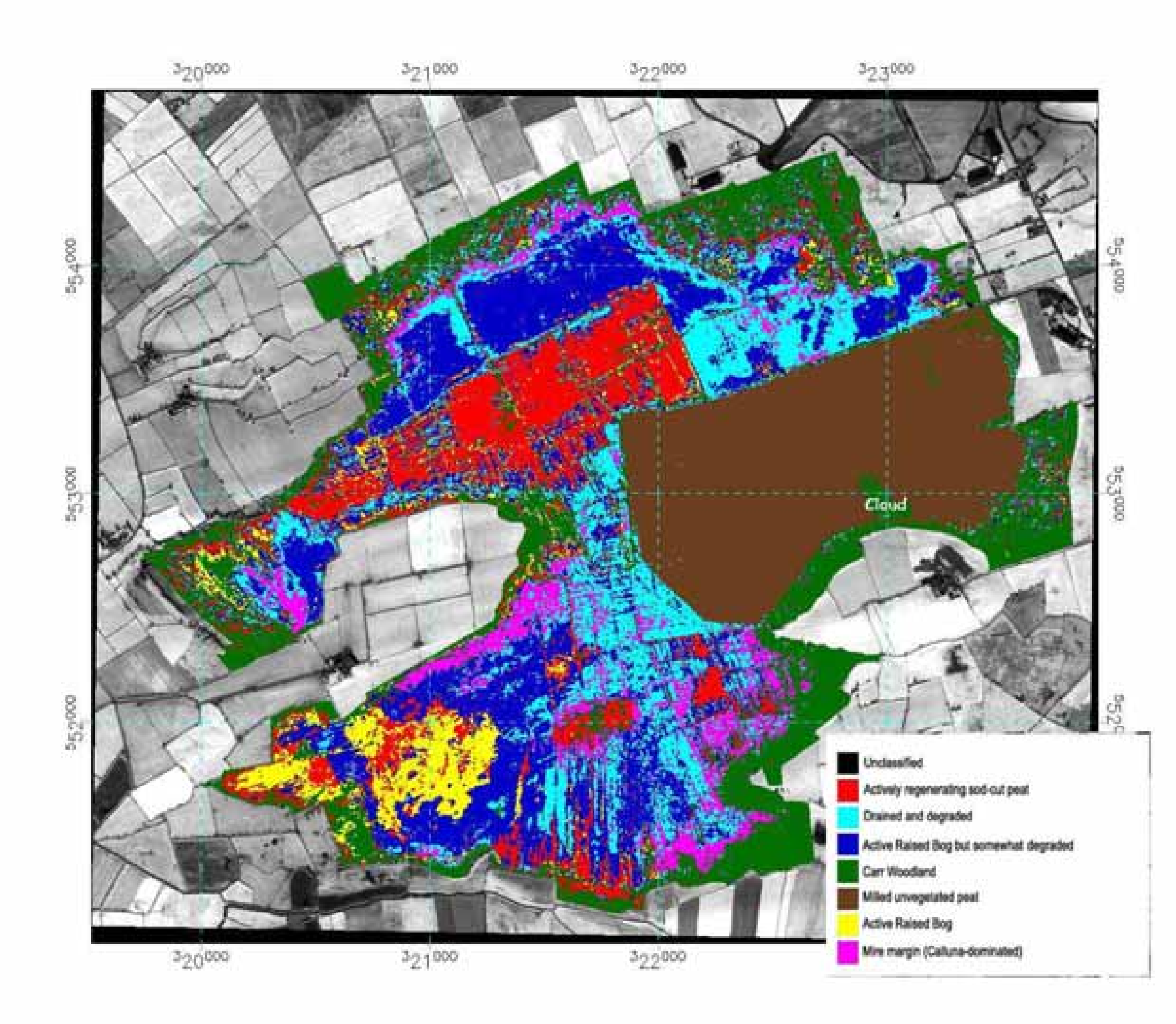

Figure 11. Maximum likelihood classification of Wedholme Flow. The classes have been aggregated by applying a centre-weighted majority filter to the classes shown in Figure 10.

6.8.3 Identification of LRBI categories

The spectral pixel-based classification was very successful, despite being based on just four spectral bands. However, it did not provide a clear-cut distinction between the 'primary' and 'secondary' raised bog habitats of the LRBI. This was not surprising as this distinction is largely based upon evidence of drainage and past management practices, and this is only indirectly accessible to a spectral-based classifier. Therefore, a second classification was created using visual interpretation of the lidar image, supplemented with interpretation of the Ikonos simulated colour composite. This produced a simple texture-based segmentation of the bog area into 'Undisturbed', 'Disturbed' and 'Mire margin' habitats, based upon the visual evidence of past and present disturbance and the presence of carr woodland, all of which were very clearly shown on these data sources (see Figure 2 and Figure 3). The texture mask was then used to constrain the spectral classifier, leading to the production of a series of maps showing the bog habitats classified according to the LRBI categories (see Figure 12, Figure 13, and Figure 14).

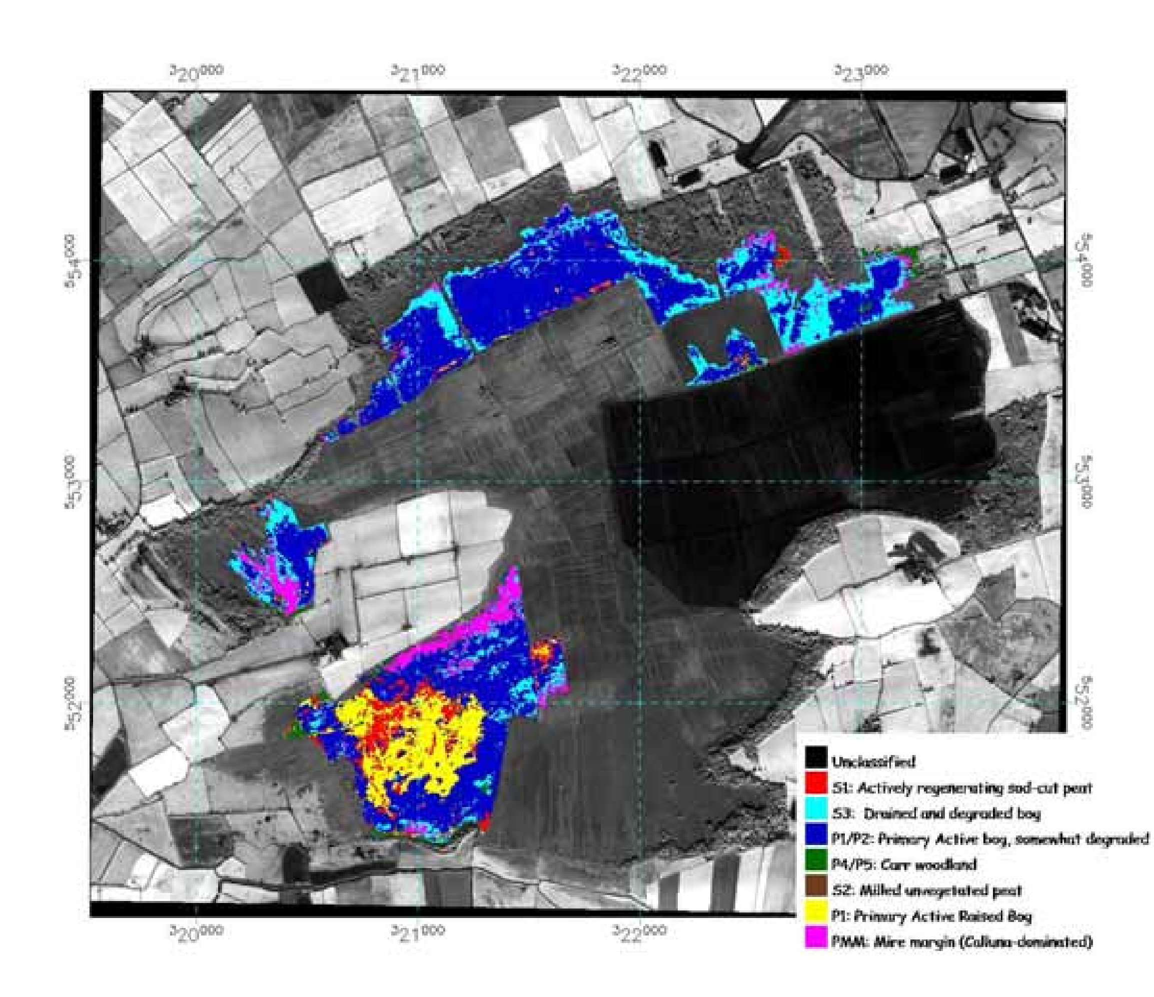

Figure 12. The relatively undisturbed habitats on Wedholme Flow, classified according to the LRBI categories

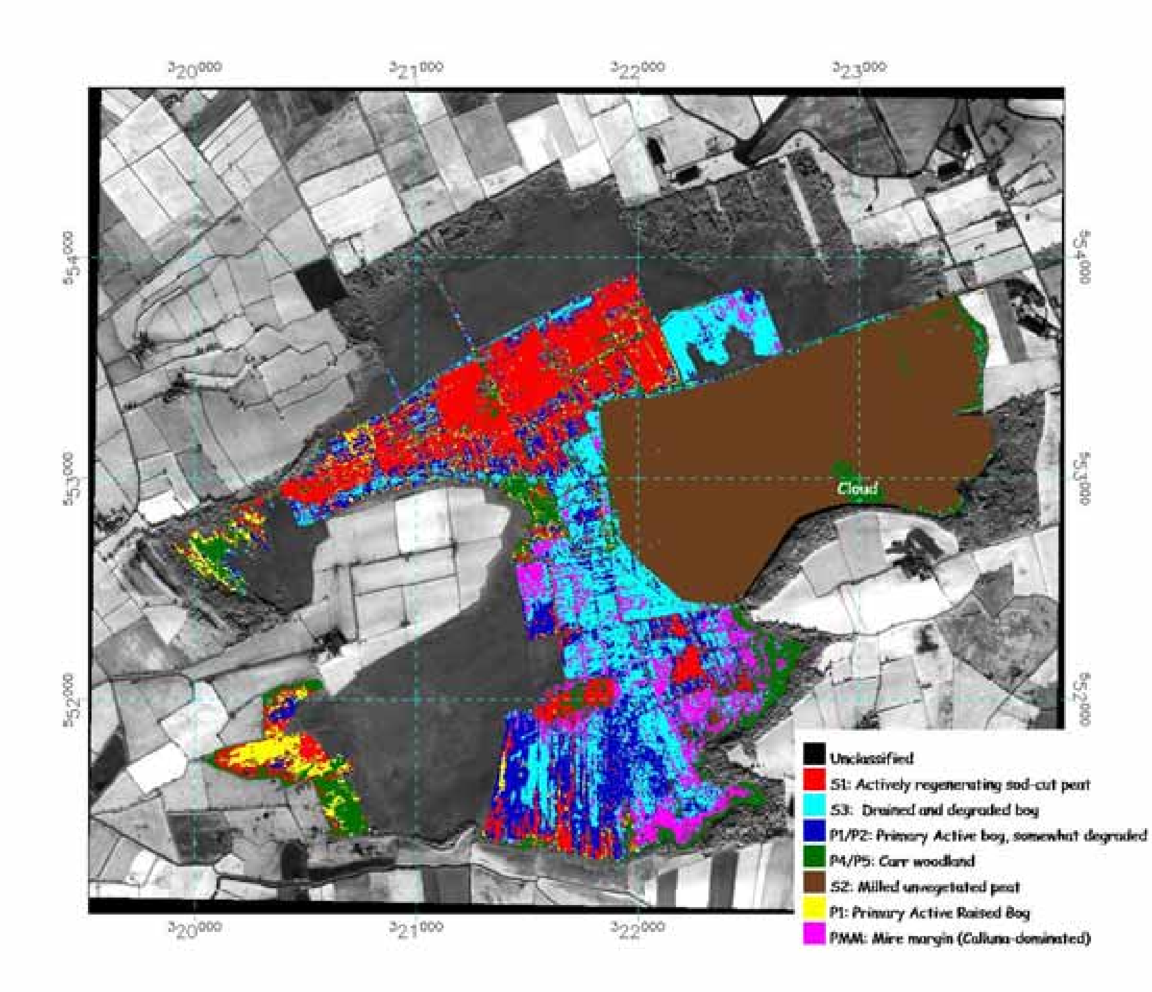

Figure 13. The disturbed habitats on Wedholme Flow, classified according to the LRBI categories

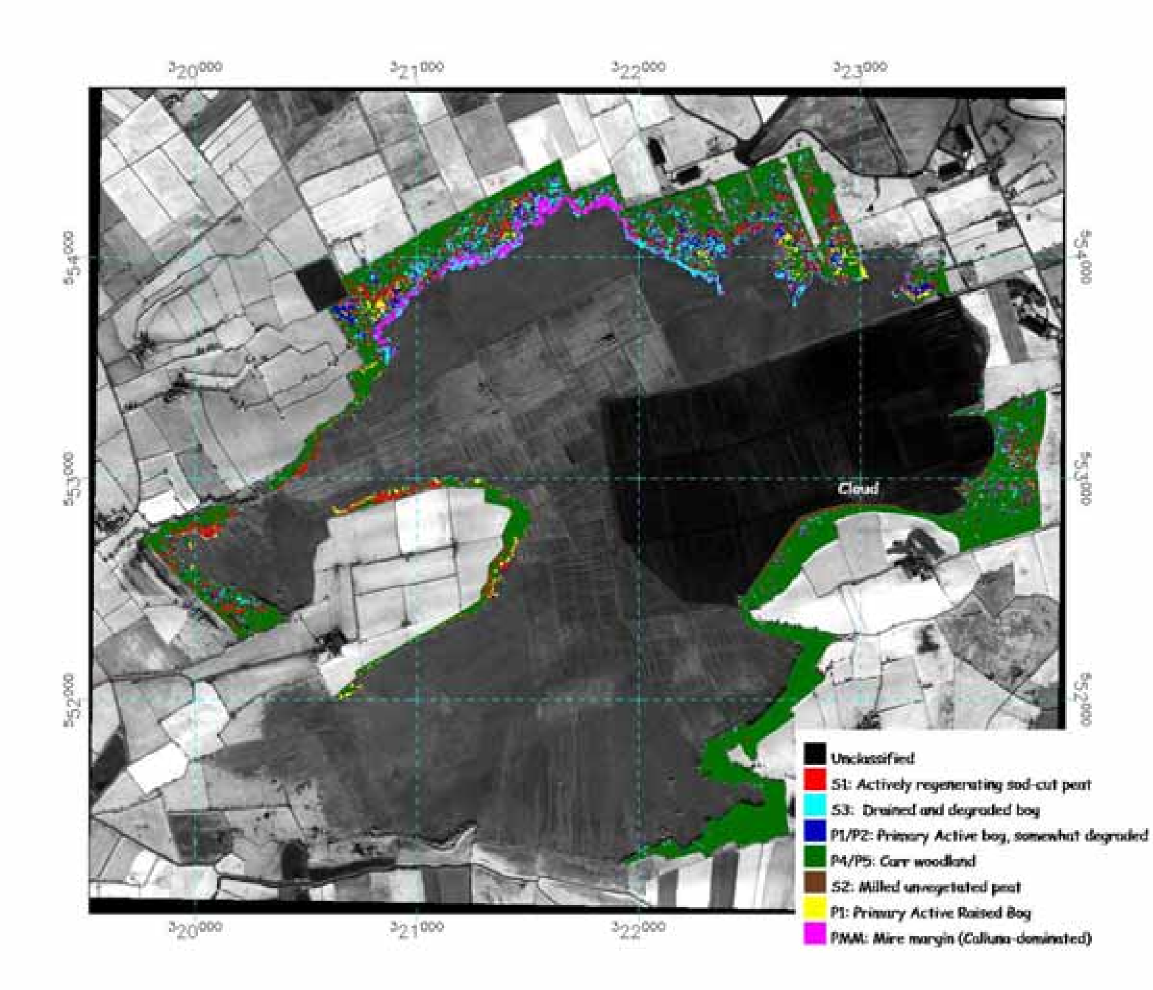

Figure 14. The mire margin habitats on Wedholme Flow, classified according to the LRBI categories

6.8.4 Beyond Maximum Likelihood Classification

The classified images presented so far represent the results of very many individual runs of the classification process, and we believe they represent a good indication of the best that could be achieved using data collected in the four Ikonos spectral bands. There are doubtless areas that are misclassified either by the maximum likelihood algorithm or by the visual interpretation of primary/secondary habitats, but it is questionable whether further refinement of these aspects would be either cost-effective or desirable, given that the aim is to produce a methodology that is robust and easily applied. Instead, we now turn our attention to the 'rule images' which are produced as a by-product of the maximum likelihood classification. There is a rule image for each class, and the data they contain are scaled from 0.0 – 1.0, indicating the probability that the pixel is a member of that class. The rule images for each of the seven classes are presented below in Figure 15 to Figure 22.

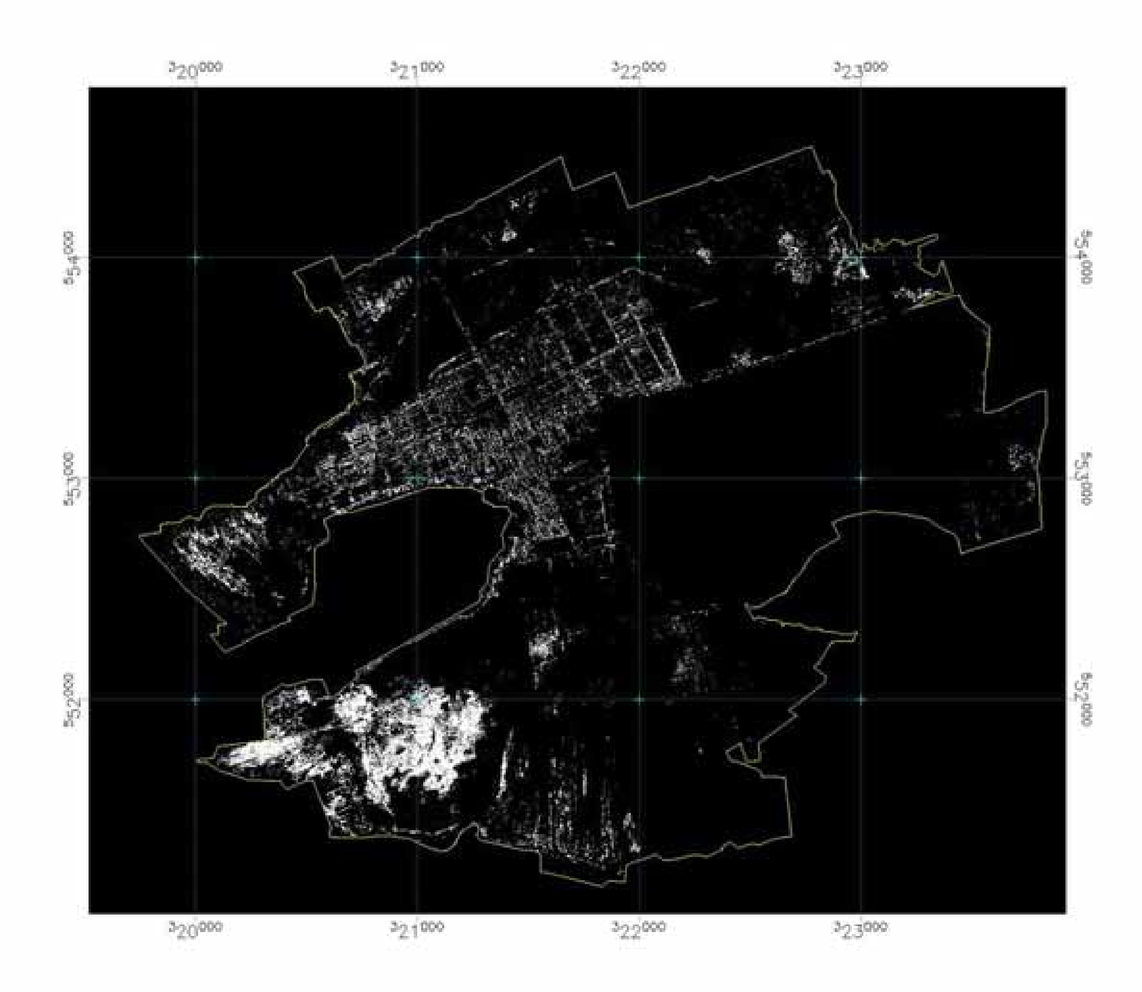

Figure 15. Rule image for Active Raised Bog

This image shows very high probability of active raised bog in the south-western arm of Wedholme Flow. There are also sites showing some of the characteristics of active raised bog in the area of re-wetted terrain trending across the north-western flank of the bog, as well as isolated patches elsewhere.

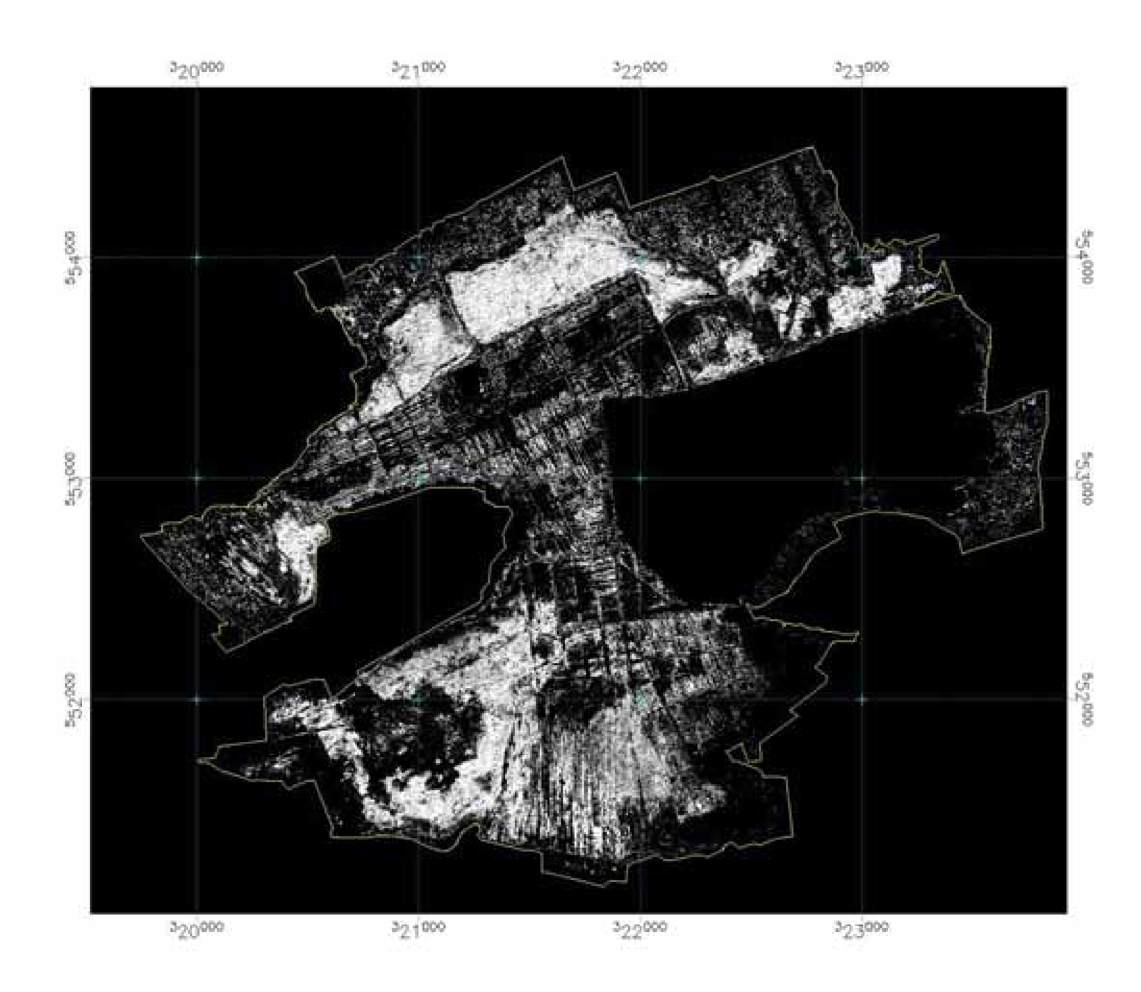

Figure 16. Rule image for Active, but degraded raised bog

This rule image identifies a large area of Wedholme Flow as comprising actively growing bog, but not of the highest quality. In LRBI terms, this class would be categorised as P1/P2.

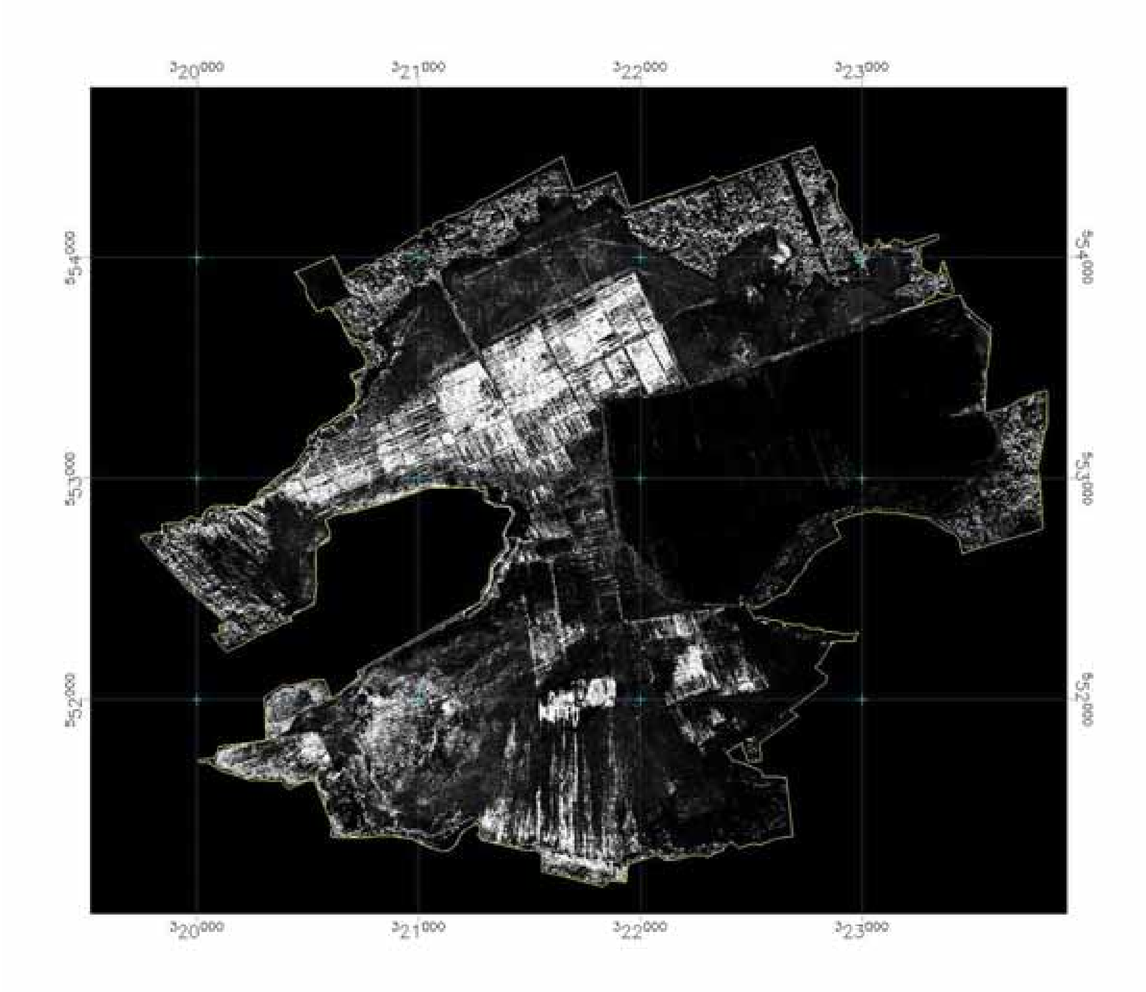

Figure 17. Rule image for actively regenerating sod cut peat

This image shows the broad area of successful regeneration across the older peat workings in the northern part of the bog. It also identifies actively regenerating bog associated with old drainage channels in the south-central part of the bog.

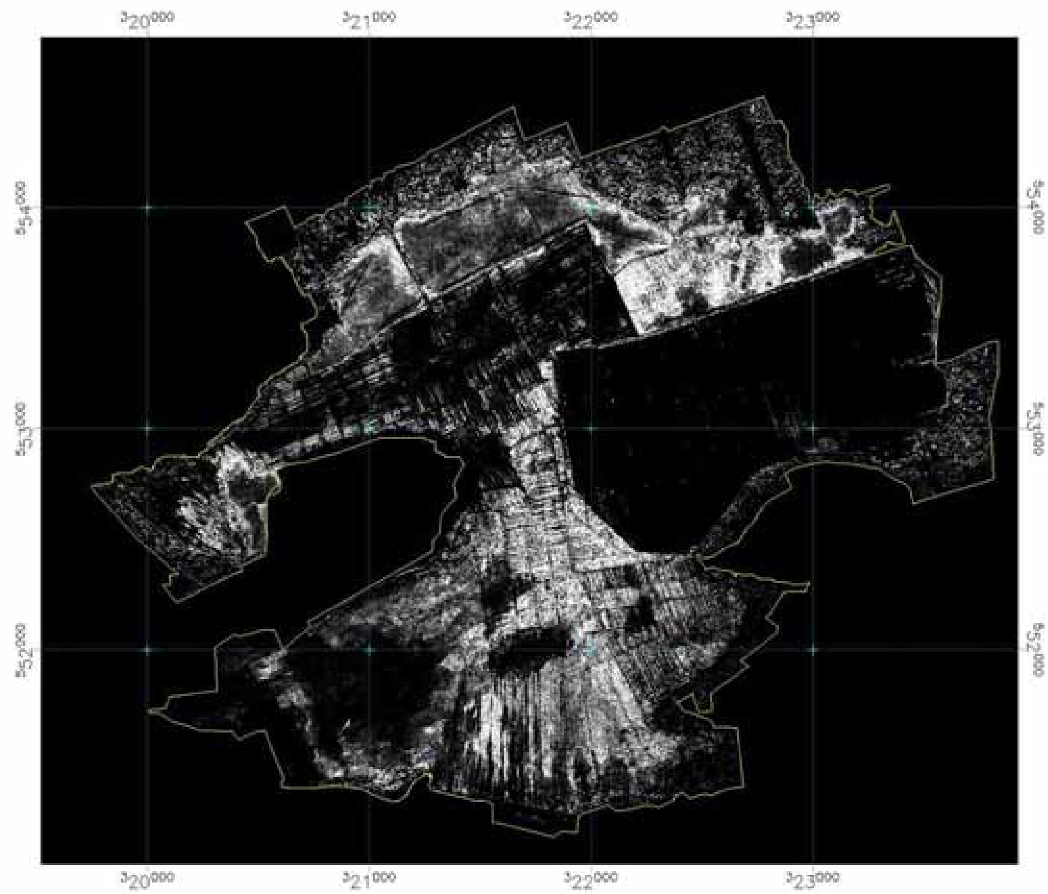

Figure 18. Rule image for drained and degraded bog

This rule image identifies a bog habitat that we have called S3. It is a secondary community affected by drainage and is widespread across the bog, and locally dominant around the northern margin adjacent to a major drainage channel and in the centre adjacent to the area of recent peat working.

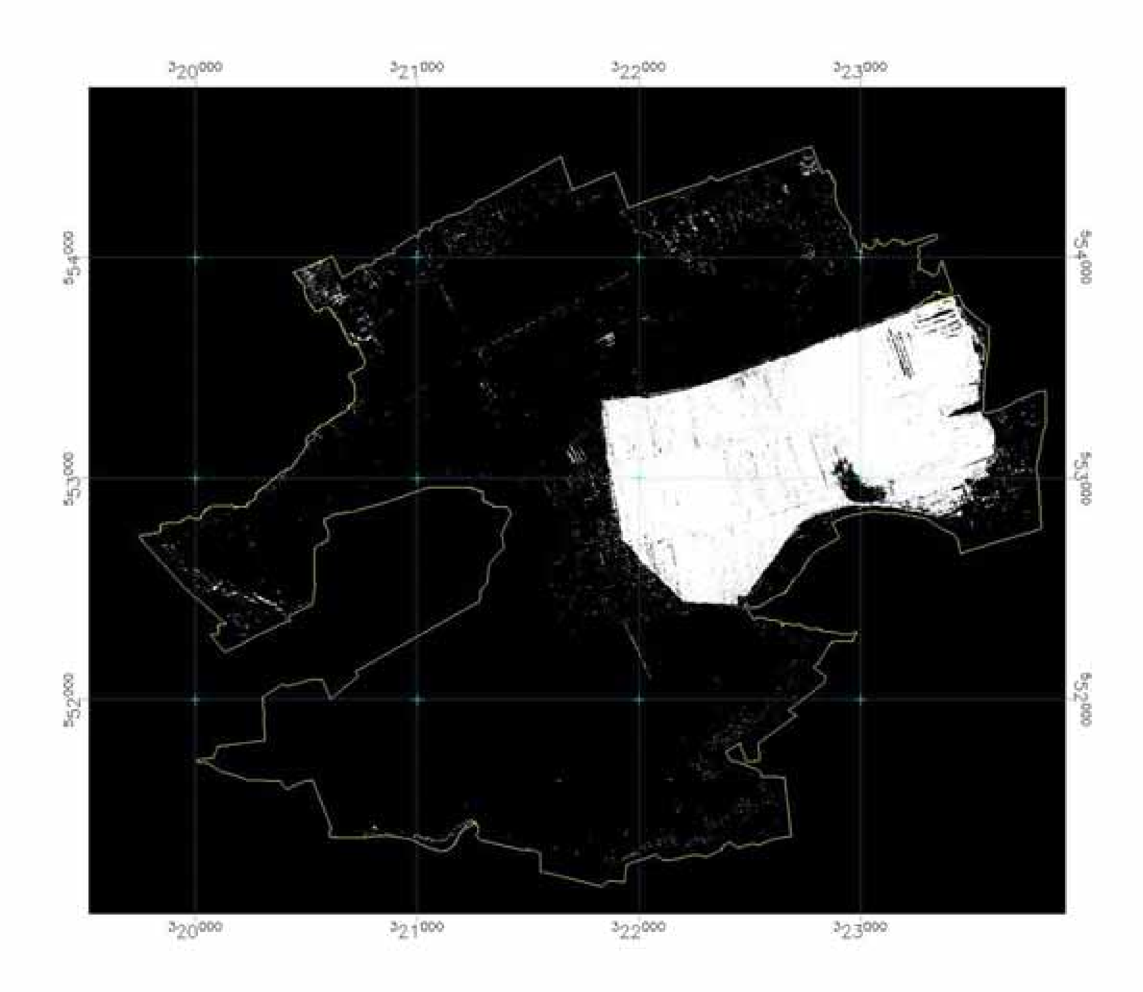

Figure 19. Rule image for milled, unvegetated peat

This image requires little comment, save to note that a cloud on the satellite image was responsible for the anomalous black patch within the area of bare peat. The fact that this area was milled peat, rather than sod-cut, was evident from the difference in texture on both the lidar image and the Ikonos simulated true colour composite (see Figure 20).

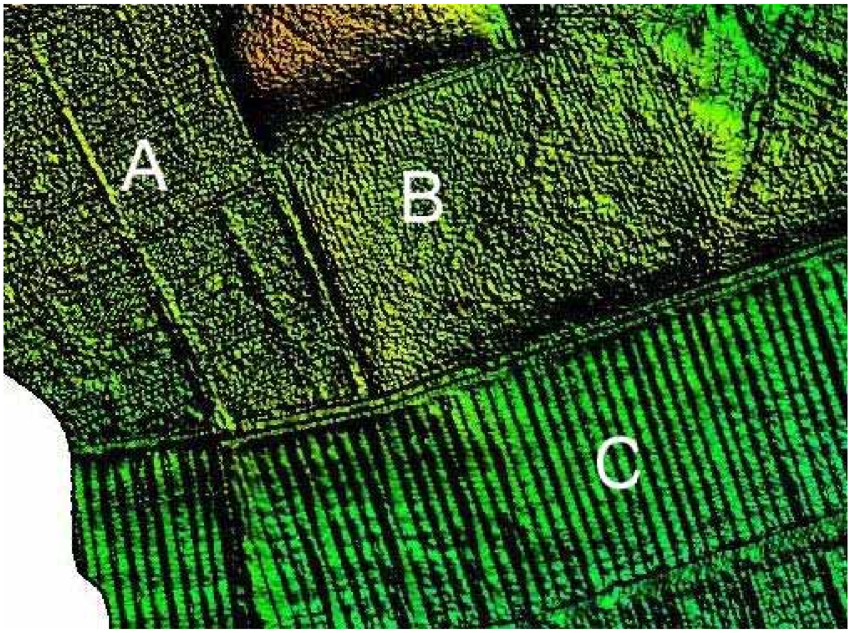

Figure 20. Differences between sod-cutting (A), degraded, drained bog (B) and milled peat extraction (C) shown on the relief-shaded lidar image

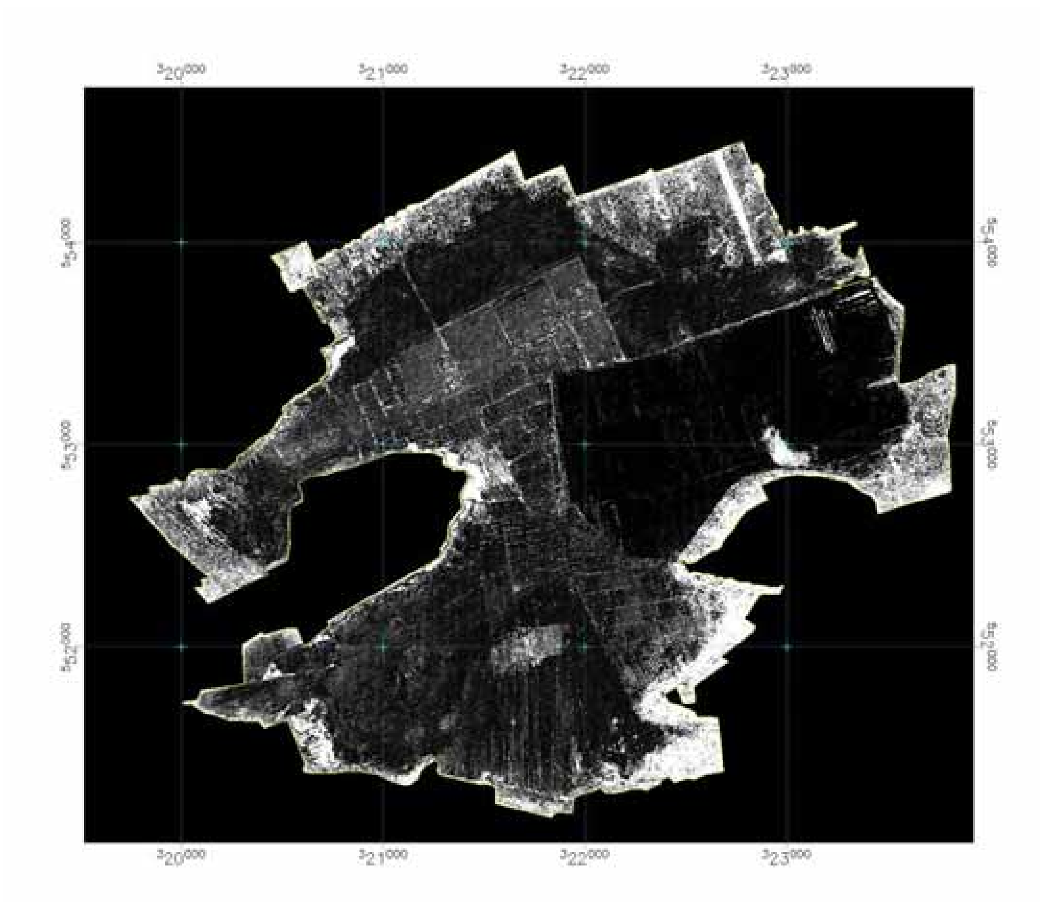

Figure 21. Rule image for Carr woodland

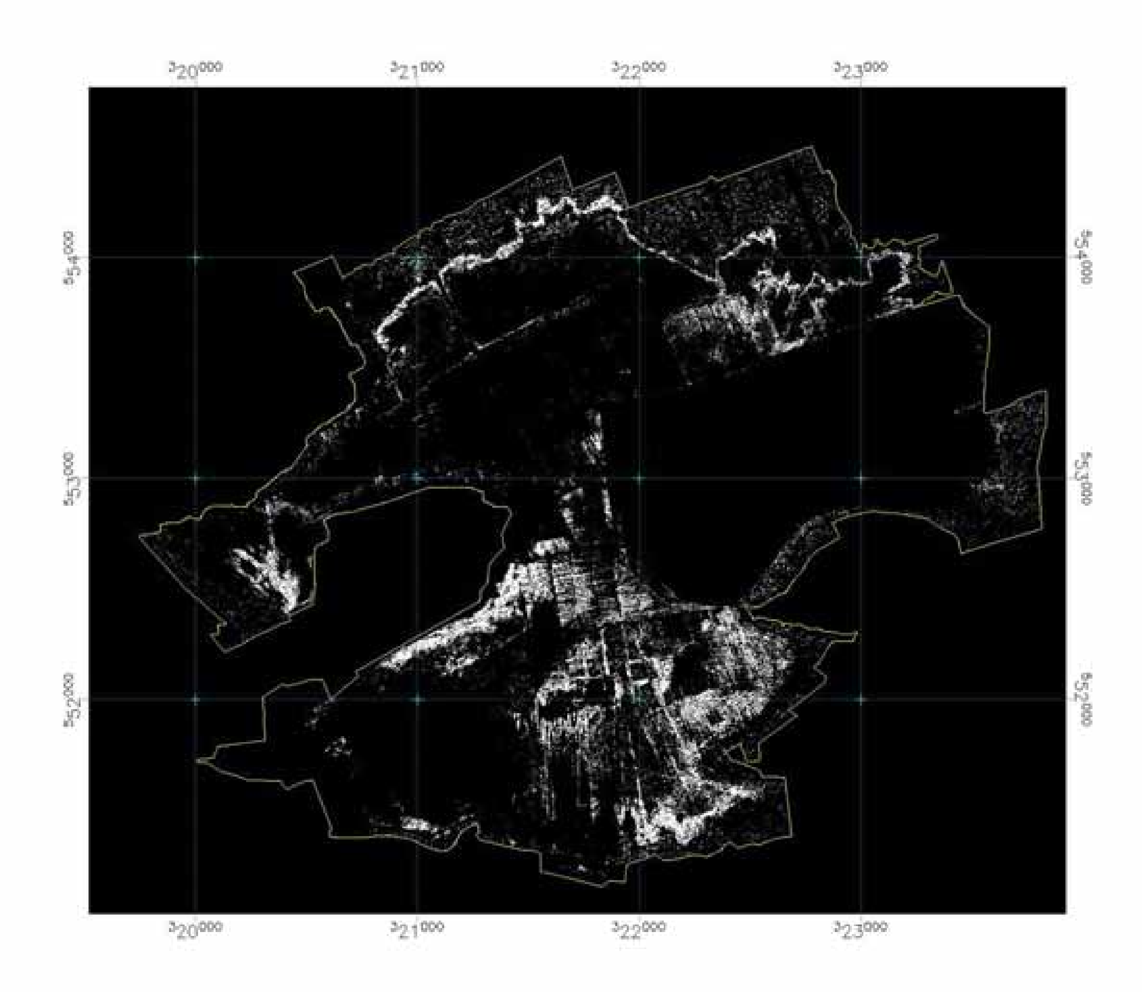

Figure 22. Rule image for mire margin (rand)

While this rule image shows very clearly the northern mire margin, it also shows patches within the secondary habitats in the southern part of the bog. It could be that this class is identifying drier, shrub-dominated areas of the bog as the northern mire margin has a dense stand of *Calluna*.

6.8.5 Making use of the rule images

Although it is beyond the scope of this project, it would be possible to use these rule images in an expert system to create a hybrid remote sensing / ecological information system. In order to do this, one would separate the largely technical process of identifying areas of similar characteristics on the images from the intellectual and discipline-specific process of allocating those areas to information classes. In practice, this means that a standardized, well-proven method (such as the maximum likelihood classifier) would be used to identify similar groups of pixels and an expert system then used to assign those groups to the classes required by the LRBI or EU Habitats Directive, based upon the rule images and other ancillary data. This two-stage approach has the advantage that the expert knowledge coded into the rule-base could be easily modified as classification systems evolve and the legislative requirements change.

An example of such an expert system would be the process known as ‘evidential reasoning’ or ‘weight-of-evidence modelling’. This process is based upon Dempster-Shafer theory, also known as the theory of belief functions (Dempster, 1968; Shafer, 1976). Whereas the Bayesian statistics which underpin the maximum likelihood algorithm require probabilities for each question of interest, belief functions allow us to base degrees of belief for one question on probabilities for a related question. Importantly, belief functions allow for the fact that we don’t always have full knowledge of the system of interest; in fact they explicitly allow for ignorance. Thus, in conventional statistics if we say that the probability of an area being active raised bog is 0.8, we imply that the probability of it not being active raised bog is 0.2. However, in reality, we often cannot say that. It may be that we just don’t know what the area is, so the probability of it not being active raised bog is actually less than 0.2, because of our ignorance. Within the limits of our knowledge, the probability may be 0.8, but the limits of our knowledge may represent only a small proportion of the full range of possibilities.

A further advantage of belief functions is that they allow the incorporation of anecdotal evidence and non-spatial information into the expert system. In essence, the user creates a ‘rule base’ which draws upon all the relevant knowledge of the system, whether it is a set of rule images such as those above, or a record from a historical map or archival source. Other contextual information such as whether the site receives sediment and nutrients from surrounding agricultural land could also be incorporated.

7. Results from Cors Caron

7.1 Aims of the Cors Caron study

The results from Wedholme Flow show that satisfactory class definition for the purpose of the LRBI/EUHD is achievable using a remote sensing methodology based upon a hybrid approach:

- visual interpretation of lidar and Ikonos data to identify the primary/secondary habitats, and
- maximum likelihood classification of high spatial resolution data collected in visible and near infra-red wavelengths in late-summer to identify the plant communities present.

The aim of the Cors Caron work was threefold. First, to test the methodology on a raised bog with vegetation communities, terrain type and management history that differed significantly from those at Wedholme Flow; second, to determine how suitable data collected at other times of the year would be to perform the same task; and third, to investigate whether spectral information in the longer wavelength infra-red and thermal regions improved the classification.

7.2 Influence of time of the year

ATM data from Cors Caron were available for three periods during the year, roughly corresponding to spring, mid-summer and late-summer. The data were flown by NERC specifically for a PhD project investigating the vegetation history of Cors Caron and these dates were chosen in relation to our knowledge of the phenological stages of the communities present. Logistical constraints due to cloud cover and aircraft availability meant that the precise dates of data acquisition were determined by practical reasons. Visible band colour composites of the data acquired are shown in Figure 23.

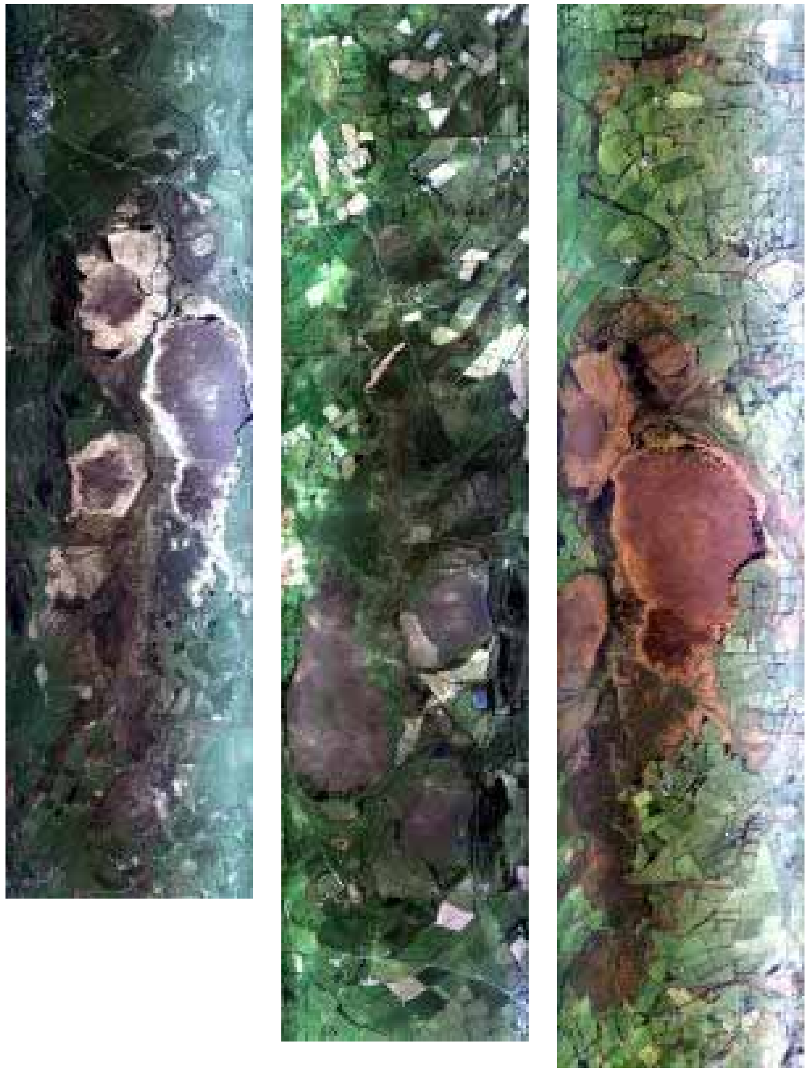

Figure 23. Visible band colour composites of the Airborne Thematic Mapper data acquired over Cors Caron

It is clear from the images above that their suitability for vegetation mapping varies considerably throughout the year. The spring image is dominated by the high reflectance from the *Molinia* and shows very little information for the mire surface. The mid-summer image is more informative, but has cloud shadows present which would make its use in a digital classification very problematic. The late-summer image shows the most discrimination between the vegetation classes of interest, confirming our choice of this time of the year for the Wedholme Flow data. Having inspected imagery from the three dates it was decided that only the data from the late-summer flight from NERC would be purchased.

The classification procedure adopted for Cors Caron was very similar to that used for Wedholme Flow, except that lidar data were not available for this site. This meant that the Primary / Secondary interpretation was achieved in a slightly different fashion. First, the ATM data had to undergo a series of pre-processing steps.

7.2.1 Pre-processing the ATM data

Unlike the Ikonos data, the ATM data had to have several pre-processing techniques applied before they were suitable for digital classification. First, a correction had to be applied for the cross-track shading because the flight line lies at an angle to the solar principal plane. This is seen in Figure 23 as a progressive brightening of the image from right to left. Second, the ATM also had to be screened for data quality to exclude any bands with sensor errors or any that were very noisy due to scattering in the atmosphere. The signal-to-noise ratio of ATM band 1 was very poor and so this was excluded from further analysis.

Airborne scanner data are notoriously prone to geometric distortions. These make it difficult to compare image data with maps and ground data. There are two types of geometric distortions: those associated with the attitude or orientation of the platform (roll, pitch and yaw), and those related to the optical characteristics of the sensor, and both of these have the potential to introduce distortions into the output image. In essence, platform motion and attitude instabilities will cause the sampled data to be projected in a shifted orientation in the reconstructed image. Therefore, before any of the classification techniques could be applied, it was necessary to register the image data to a geographical co-ordinate system and to correct for the motion of the aircraft during data acquisition.

Airborne data collected by the NERC ARSF were geometrically corrected to British National Grid co-ordinate systems post-flight using data collected from an on-board flight recorder called the "Integrated Data System" (IDS). The IDS has been developed to integrate the imagery provided by the airborne scanner with the navigation and attitude data from the aircraft. The AZGCORR post-processing software package provided by the NERC ARSF makes it possible to correct for these various errors and provide fully geo-referenced digital data without the use of ground control points. Precise geometric correction of the ATM data was not possible, however, as we did not have access to a digital elevation model (DEM) of the area. To overcome this problem we took the data as corrected for aircraft motion using AZGCORR and then used a number of ground control points to perform a conventional geometric correction to the OS National Grid.

7.2.2 Generating the mire mask

Masking is the process whereby areas of an image are eliminated from subsequent processing stages. A mask is a binary image consisting of values of 0 and 1 only. When a mask is used in a processing function, the areas with values of 1 are processed, and the areas with values of 0 are not. However, before a spatial mask can be applied to the data, it has to be constructed.

Using the Environment for Visualising Images (ENVI) software package, Regions of Interest (ROI's) were defined around the boundary of Cors Caron. Ms. Schulz was consulted during construction of this mask, which was defined with the aid of a map provided by the Countryside Council for Wales detailing the delineation of the NNR boundary. The ROI was then converted into a binary mask for use in subsequent processing stages (Figure 24).

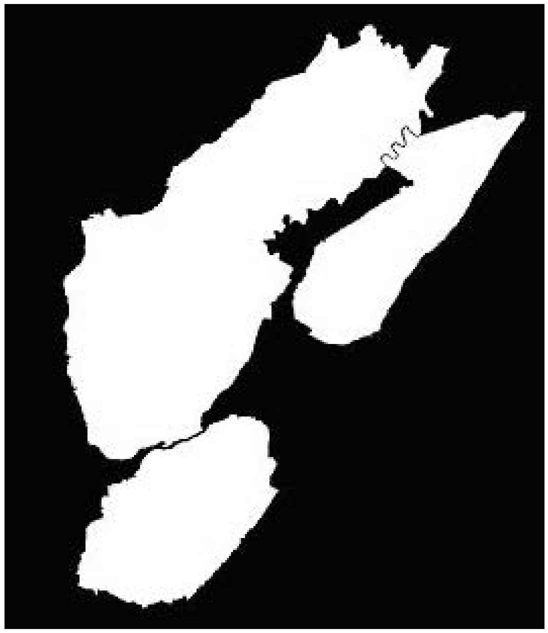

Figure 24. Binary mask of Cors Caron Region of Interest (ROI)

7.2.3 Training site location

Once the geocorrection had been implemented, it was necessary to locate training sites within the bog boundary upon which the classification would later be based. This was conducted through direct liaison with Jenny Schulz and Richard Lindsay. Training sites were positioned in areas of marsh corresponding to Ms. Schulz's classification map of the surface condition classes (Figure 25). Training sites were also positioned in other areas where there were clearly spectral differences in the plant communities present, but where these small-scale patterns had not been highlighted by the classification map. The training sites used for classification purposes are listed in Table 12.

Table 12. Training sites used for the Cors Caron classification

Training Site Name	Number of Pixels
Molinia cut	2693
Molinia uncut	1706
Uncut *Sphagnum* surface	4878
Standing water	193
Carr 1	522
Cut *Sphagnum*/Cottongrass	688
Disturbed bog surface	191
Dense *Calluna*	2098
Carr 2	1171
Wetter *Sphagnum*	699

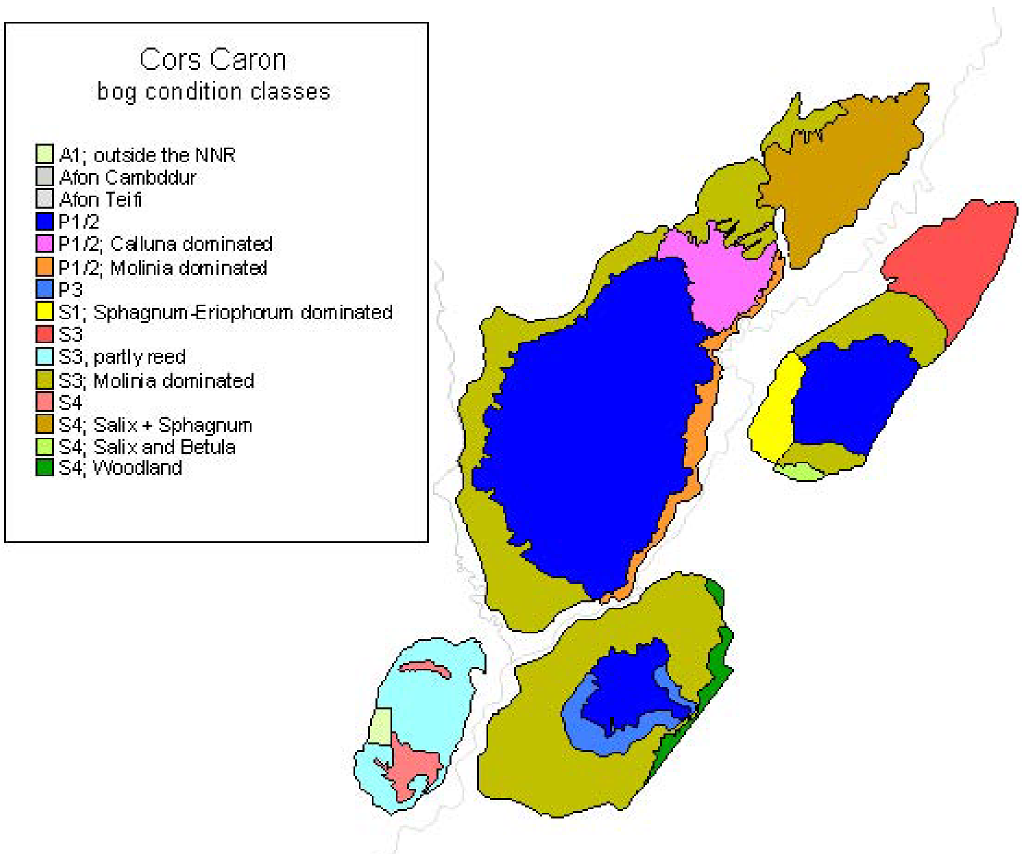

Figure 25. Bog condition map of Cors Caron derived from field survey (larger version in Appendix, after Table 24)

7.3 Results from the classification

7.3.1 Visible and Near Infra-red wavelengths

In order to provide a comparison with the Wedholme Flow results, the initial classifications were based upon data from those ATM bands which most closely matched the Ikonos bands: ATM bands 2, 3, 5 and 7. Many classifications were produced, and the best is shown in Figure 26.

Unlike Wedholme Flow, where we had the lidar image to identify the primary and secondary areas of the bog, for Cors Caron we had to include this distinction within the selection of training sites. Overall, this strategy was successful. However, it was found necessary to choose training sites from each of the three bogs as spatial extrapolation of the spectral signatures was not successful in general. The reason for this can be seen in Figure 27. This figure shows some residual haziness affecting the area along the southern edge of the swathe, which the cross-track shading correction had been unable to account for.

7.3.2 Incorporation of other spectral bands

Many earlier studies on terrestrial vegetation communities have utilised broad-band spectral data from instruments such as the Landsat Thematic Mapper (TM). Remote sensing at higher spectral and spatial resolutions, such as those offered by airborne scanner systems, offers the prospect of high quality land cover classification and mapping. However, one of the problems facing the analyst presented with data from these more advanced sensors is the wide choice of bands available. Decisions must be made about which of the bands might be suitable, and how many of these should be used. Simply using all the available bands for a classification is not only inefficient, in terms of the time taken to process the data, it also risks introducing error and uncertainty into the results. For every classification task there is an optimum number and combination of spectral bands; the question is how to determine this.

The pattern recognition technique known as ‘feature selection’ tackles this problem. This can be performed on the basis of probabilistic distance measures such as the *Transformed Divergence* which is calculated on the basis of the class mean vectors and the covariance matrices measured from a training sample (i.e. the spectral qualities of the LRBI classes). The transformed divergence measure therefore reflects the separability between the classes of interest. Feature selection differs from techniques such as principal components analysis in that it does not transform the bands into a new feature space, it simply analyses the classes to be separated (in this case, the bog condition classes) and finds the best original bandset combination to separate them.

Different feature selection methods give different results for the same data. Therefore, in order to test which method gives the best result, a combined approach was adopted. In this study, feature selection was followed by a maximum likelihood classification, whereby the classification error for each method gave a measure of the accuracy of the feature selected bands used. The best feature subset is therefore the one with the highest classification accuracy.

The feature selection algorithm was implemented on the bog class data from the October flightline, in order to determine the best band subset for spectrally separating the classes of interest. The training data input to the algorithm were derived through consultation with Jenny Schulz and Richard Lindsay, the consultant ecologists for this project. The map produced by Ms Schulz from field survey is shown in Figure 25.

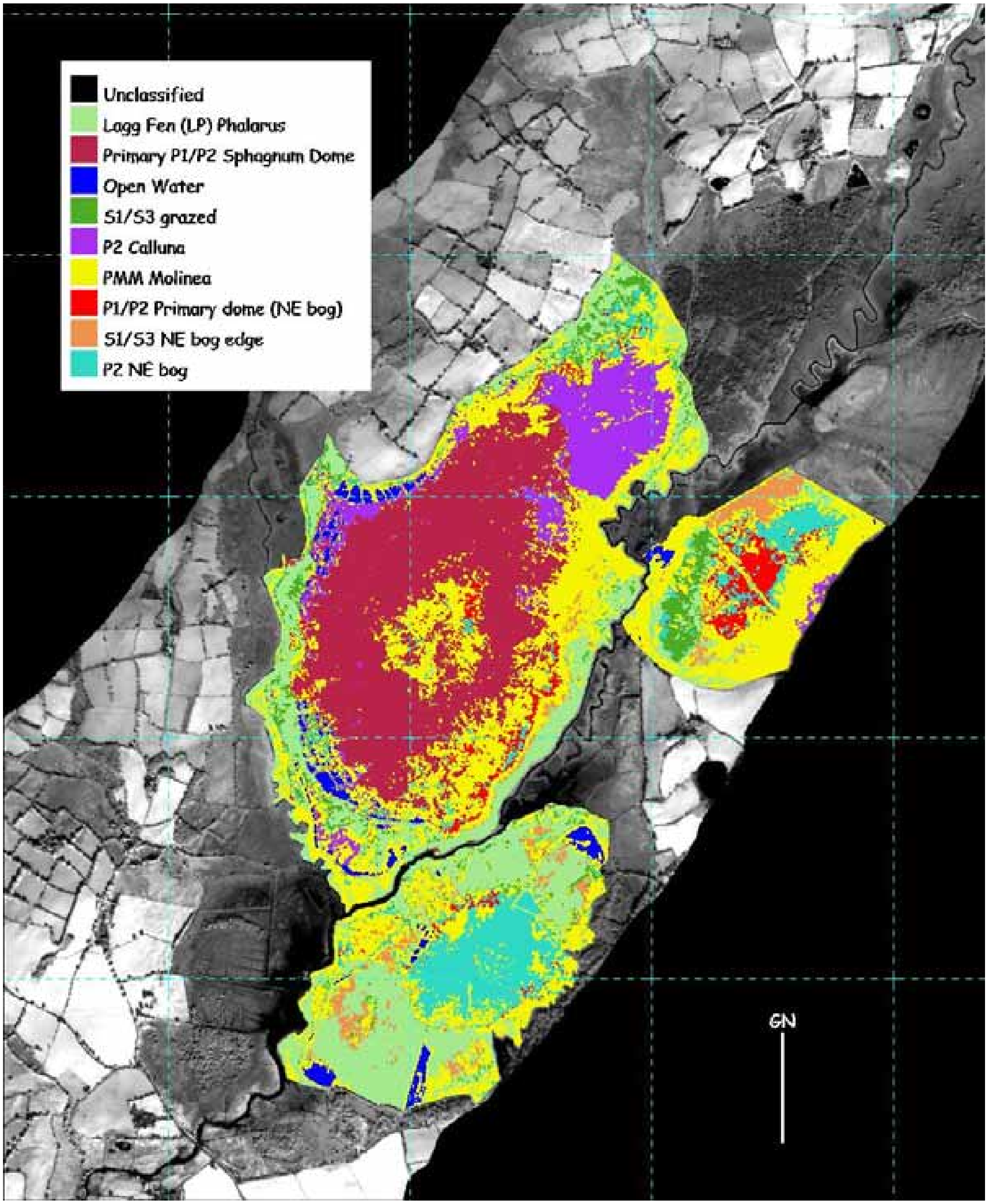

Figure 26. Maximum likelihood classification of Cors Caron based upon ATM bands 2,3,5 and 7 (Ikonos bands) [ATM data@NERC, 2001]

Figure 27. Simulated true colour composite of ATM bands 5, 3, and 2. Note the residual haziness affecting the two smaller bogs, despite the data having been corrected for cross-track shading. [ATM data © NERC, 2001]

Table 13 provides the results of the feature selection algorithm, when applied to all 11 bands of the October ATM image. The table lists the bands chosen from the original bandset in order of their importance for separating the classes defined during training site selection. It is apparent that this algorithm has highlighted a different bandset to the IKONOS bandset of 2, 3, 5, 7 used previously and suggests that a band combination of 3, 6, 9, 7 would better separate the classes, producing a higher classification accuracy. This ties in more closely with previous work by McMorrow *et. al.* (2002) on upland peat surfaces and Milton *et. al.* (2002) on valley mire communities in the New Forest. In these studies, spectral features in the 1500-1600nm wavelength region were shown to be indicative of depth to water table, and hence reflectance in this region is thought to act as a surrogate measure for the presence of species tolerant of waterlogged conditions.

Table 13. Results of the feature selection procedure applied to the October 2001 Cors Caron ATM data

Order of importance	ATM band	Centre Wavelength (nm)	Bandwidth (nm)
1	3	560	80
2	6	722.5	55
3	9	1650	200
4	7	830	140
5	8	980	140
6	5	660	60
7	2	485	70
8	11	10750	4500
9	4	615	20
10	10	2215	270
11	1	435	30

Figure 28 shows a colour composite created from the 'best' three feature selected bands. The first thing to note is that the haziness over the smaller bogs noted on Figure 27 is absent in this image, and this fact alone is likely to result in a more reliable classification. Furthermore, the distinction between a number of the classes of interest, such as the S1/S3 grazed area on the north-east bog and the boundaries between *Molinia* and lagg Fen on the main bog are much clearer in these spectral bands.

The best maximum likelihood classification created from these three ATM bands is shown in Figure 29. All of the major classes required for the LRBI/EU Habitats Directive are identified in this classification.

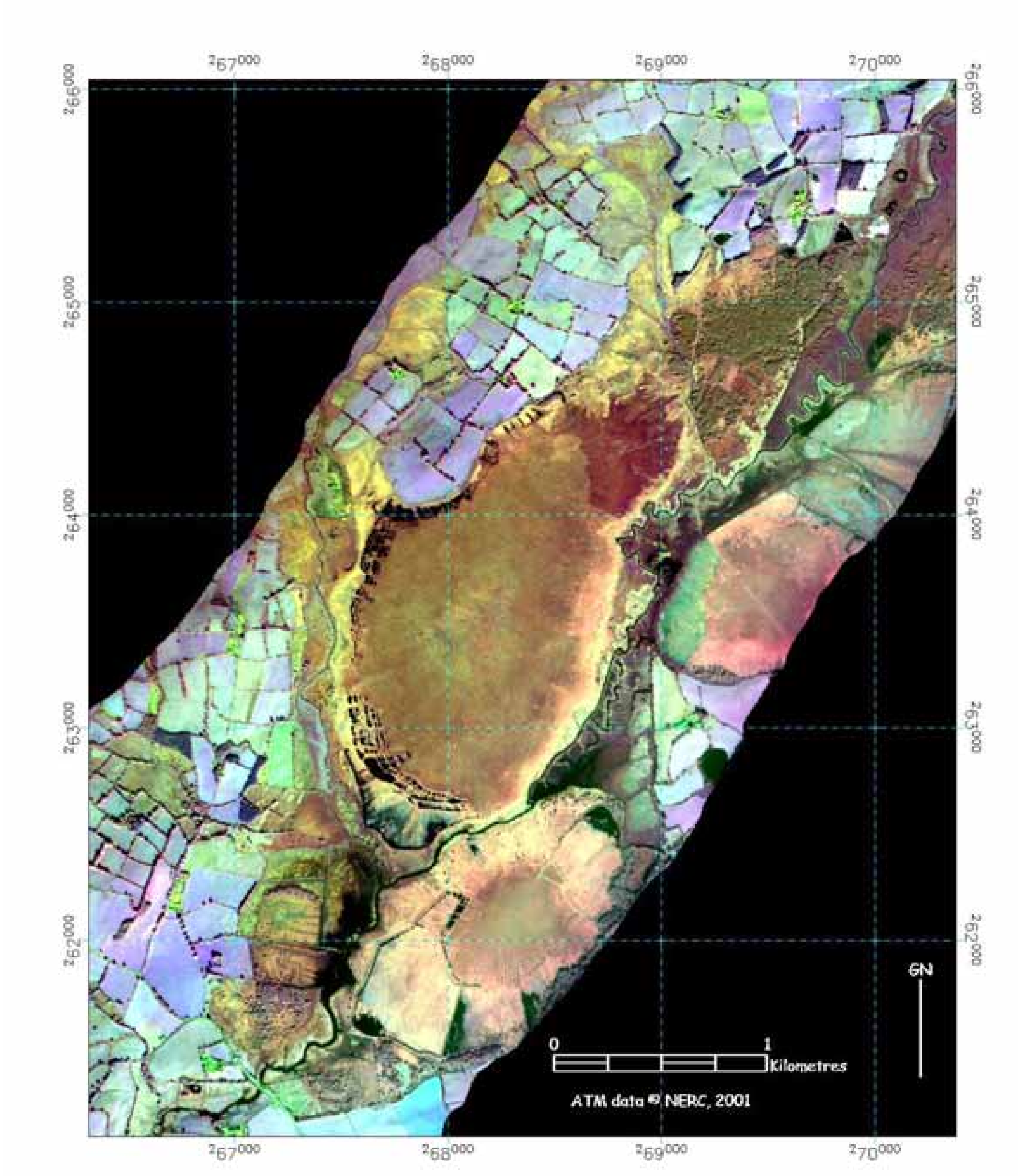

Figure 28. Colour composite of ATM bands 9, 3, and 6, the best three bands identified by the feature selection algorithm to separate the different raised bog habitat types. [ATM data © NERC, 2001]

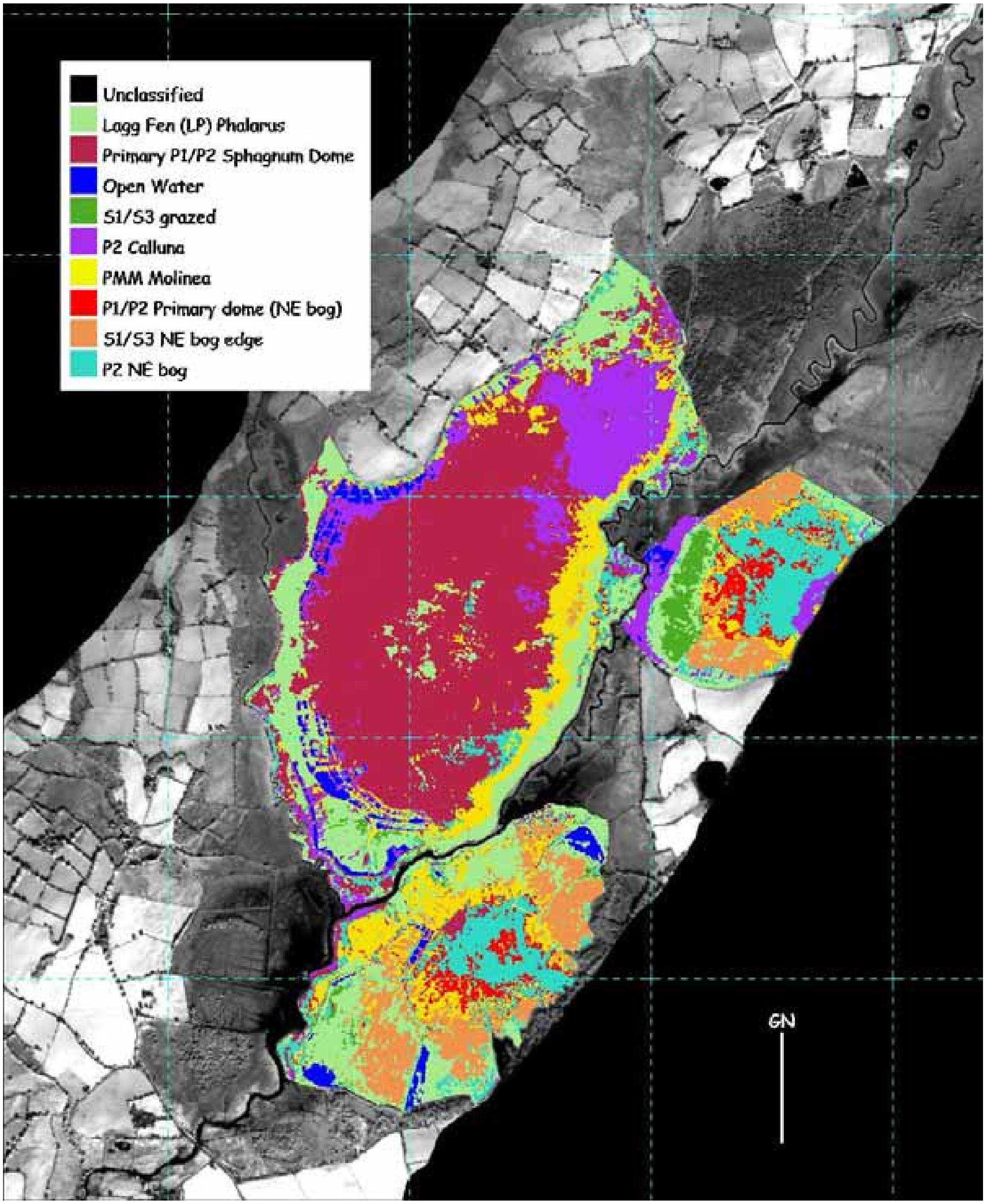

Figure 29. Maximum likelihood classification of the best three feature selected ATM bands. [ATM data © NERC, 2001]

8. Ballynahone Bog

8.1 Aims

Ballynahone Bog was included as a site at the client's request as it presented a more intact bog surface than either Wedholme Flow or Cors Caron. However, a major problem with this site concerned the lack of suitable remotely sensed data. The revised aim of the work at this site was to test the extent to which a meaningful bog condition classification could be obtained using digital image analysis of scanned aerial photographs. This was felt to be a useful exercise because cloud cover in the UK means that the widespread availability of high resolution satellite sensor data, such as Ikonos, cannot be guaranteed. Figure 46 shows the current availability of Ikonos data for raised bog SSSI sites and it is clear that many important sites currently lack coverage.

8.2 Data acquisition

Obtaining suitable remotely sensed data of the area was difficult. No Ikonos data were available in the Infoterra archive and it was not possible to acquire new data during the period of this contract, the main problem being cloud cover. No lidar or any other airborne multispectral data were available. The only existing remotely sensed data for Ballynahone Bog that it was possible to obtain were aerial photographs dated the 5 June 1996 (these were obtained from Keith Stanfield of Department of the Environment for Northern Ireland). Although they were adequate for this section of the study they were not optimum for a number of reasons:

- They were limited to three spectral bands, each of which was in the visible region of the spectrum (that is blue, green and red). As demonstrated through the feature selection carried out on the Cors Caron data, this may mean that some important information present in longer wavelengths is missing;
- The aerial photographs were at a scale that required three photos to encompass the whole of the area of interest. A digital image mosaic was created but the variability in colour and contrast between the individual photographs proved impossible to correct with sufficient accuracy and this introduced uncertainty into the classifications. For this reason it was decided that only the single photograph which contained most of the bog should be used. Although this resulted in a section to the north-west of the Bog being eliminated from the image processing, it was confirmed by Ms Schulz that this area does not contain any additional classes to those present in the photograph used.;
- The photographs were seven years old, and while they can still provide interesting results this should be kept in mind when comparing the classification results to the field survey as the situation on the ground may have changed. For instance, the burnt area near to the centre of the bog was distinct on the aerial photograph but when the fieldwork for this study was carried out the vegetation had recovered substantially. This type of change may be true for other areas of the bog;
- The time of year of the data acquisition was not optimum, the Cors Caron data showed late summer to be the best time of year for spectral discrimination between vegetation classes. The Ballynahone aerial photographs were acquired in early summer.

8.3 Pre-processing the aerial photograph

The photograph was scanned at a resolution of 300 dots per inch, so that it could be used for digital classification. As with the ATM data is was necessary to apply several pre-processing techniques to ensure that the aerial photograph would be suitable for the subsequent analysis.

Firstly, due to geometric distortions (as described in section 7.3.1) the image had to be registered to a geographical co-ordinate system. This proved problematic due to a lack of suitable map data available for the site. A number of sources were considered but the only map at a large enough scale (1:8 000) was provided by Dr A. McMullen courtesy of the Department of the Environment for Northern Ireland (Declaration dated 25 January 1995). However, this map did not contain information on co-ordinates (apart from an Irish grid reference of H 860980), nor did it encompass a complete grid square. For this reason the aerial photograph had to be corrected to an arbitrary co-ordinate system based on this map rather then to the OS national grid. This introduced error into the correction and the result is that the image is only corrected to within 3.9 meters of its true orientation.

There was also a change in the brightness across the image; the easterly section was much darker than the rest of the photograph which would introduce error into any classification (see Figure 30). This could not be corrected for using the standard enhancement options and so it was concluded that a cross-track illumination correction was necessary. This was applied to the whole image but with little effect. It was necessary to create a mask of the bog area (Ms Schulz was consulted as to which areas this should include) and to perform the correction based purely on the pixels contained within the masked area. This produced much more satisfactory results (as shown in Figure 31).

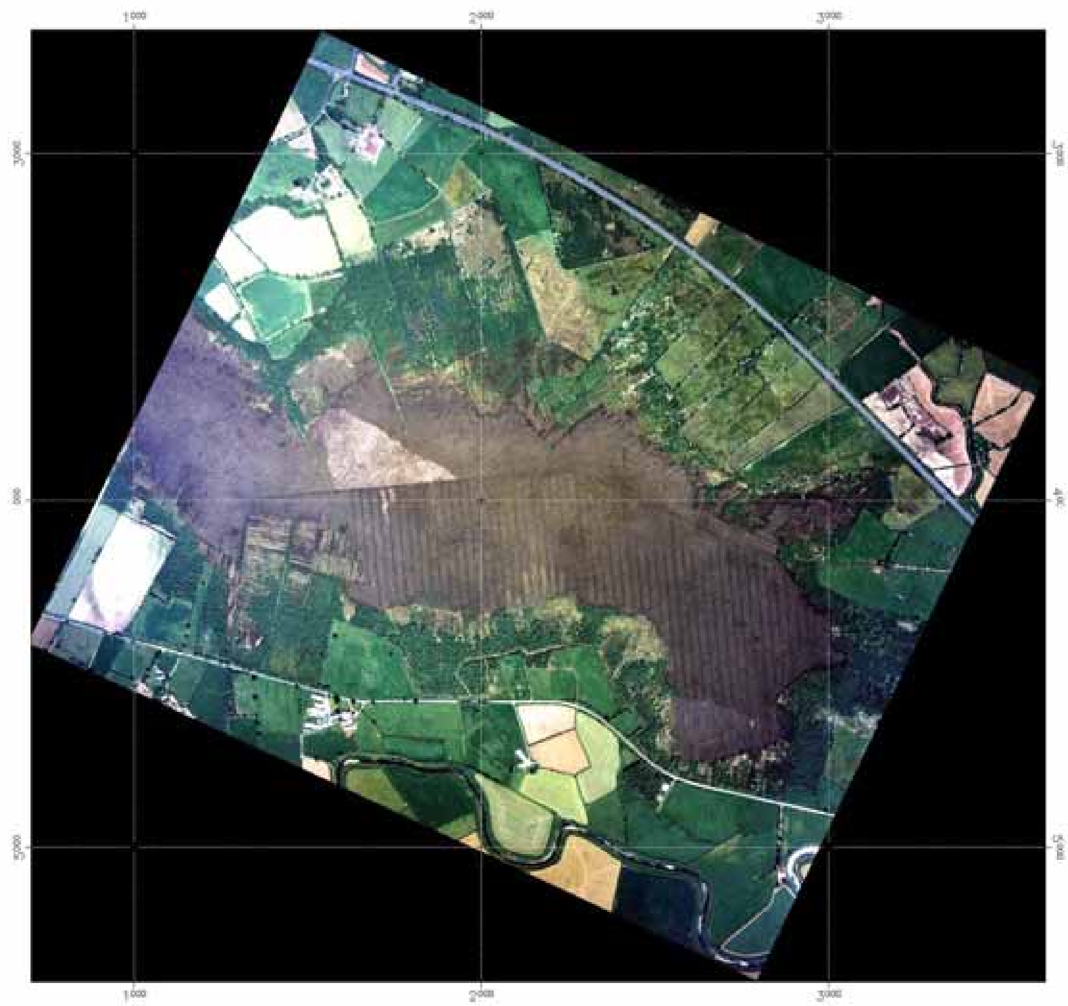

Figure 30. The aerial photograph of Ballynahone bog after geo-correction but before the cross-track shading had been corrected.

The mask that was used for the cross track correction is the same mask that was subsequently used in the classification to eliminate unnecessary data from the processing (as with Wedholme and Cors Caron classifications).

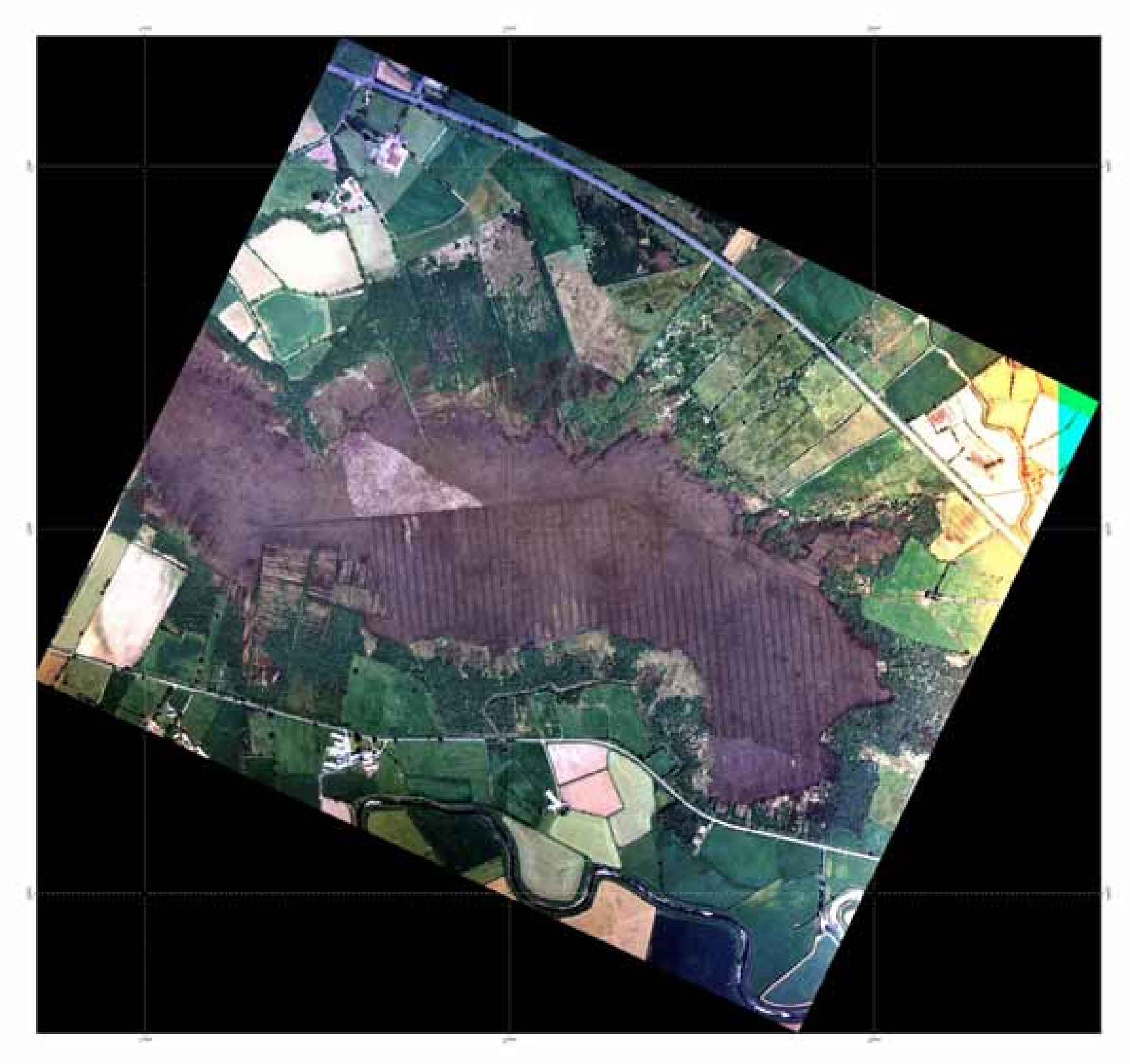

Figure 31. The aerial photograph of Ballynahone bog after the cross-track shading had been corrected.

8.4 Training site location

Once the necessary corrections had been implemented on the aerial photographs, a supervised classification was carried out. This involved the selection of suitable training sites on which the classification would be based. This was carried out in conjunction with Ms Schulz using her classification map (see Figure 32) based upon the surface condition classes presented in Table 17.

As with the Cors Caron training sites, additional sites were used where spectral differences, not separated by the classification map, were evident on the image. The training sites used for the classifications are presented in Table 14.

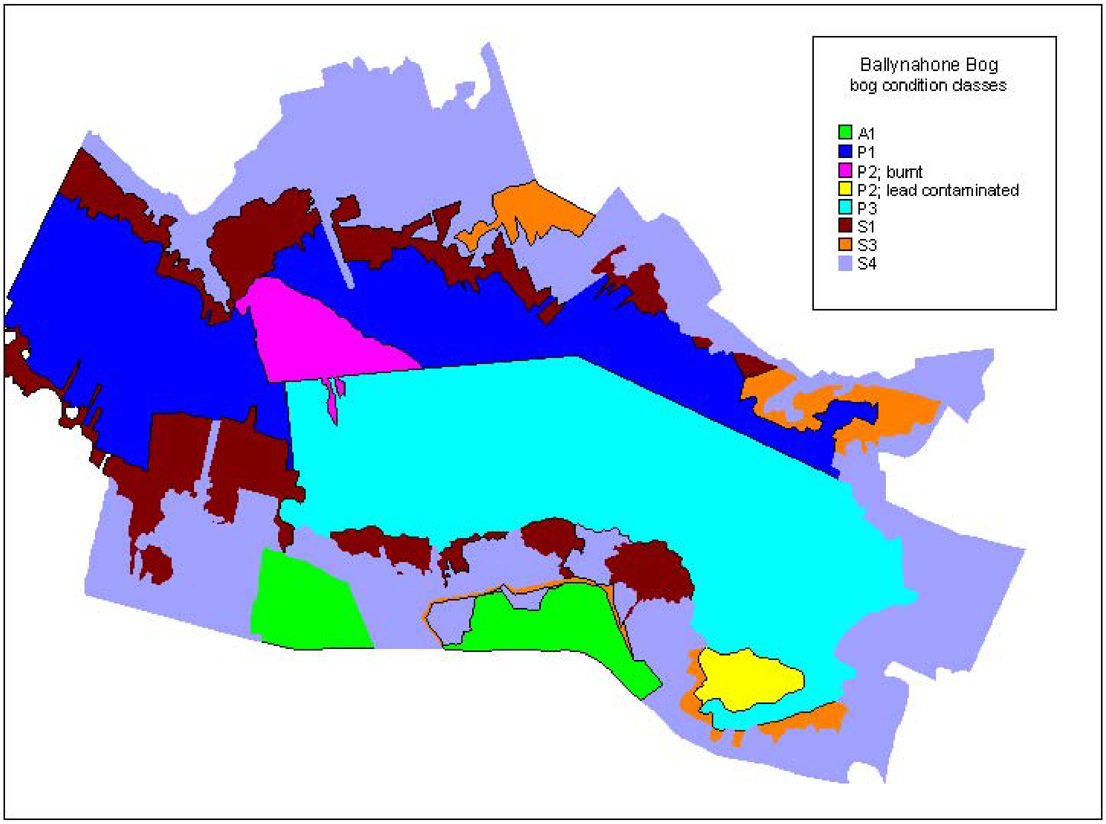

Figure 32. Bog condition map of Ballynahone Bog derived from field survey. Larger version in Appendix, after). Several of the classes identified from the field survey were not included in the automated classification (see Table 14).

Table 14. Training sites used for the Ballynahone classification

Training site name	Number of pixels
B-P2 burnt	237
L-P5	573
B-P1	1186
B-P3	1990
B-S1 cut1	1719
B-S1 cut2	370
B-P2 Pb	575
S3 : transitional class	not included
S4 : cut-over bog now woodland	not included
A1 : agricultural	not included

8.5 Classification

As there were only three bands available there was no choice as to which should be included in the classification. Bands 1, 2 and 3 (red, green and blue) were used in a maximum likelihood classification based upon the training sites shown in Table 14. Once the classification had been completed, regions 'B-P2 burnt' and 'B-P2 Pb' and regions 'B-S1 cut1' and 'B-S1 cut2' were merged to conform to the condition classes presented in Table 17. Therefore the final classification (see Figure 33) contains 5 classes that match the desired bog condition categories.

As with the Wedholme classification a 3 x 3 centre weighted majority filter was applied to the classification. This reduced the amount of spatial detail and resulted in a smoother classification (see Figure 34).

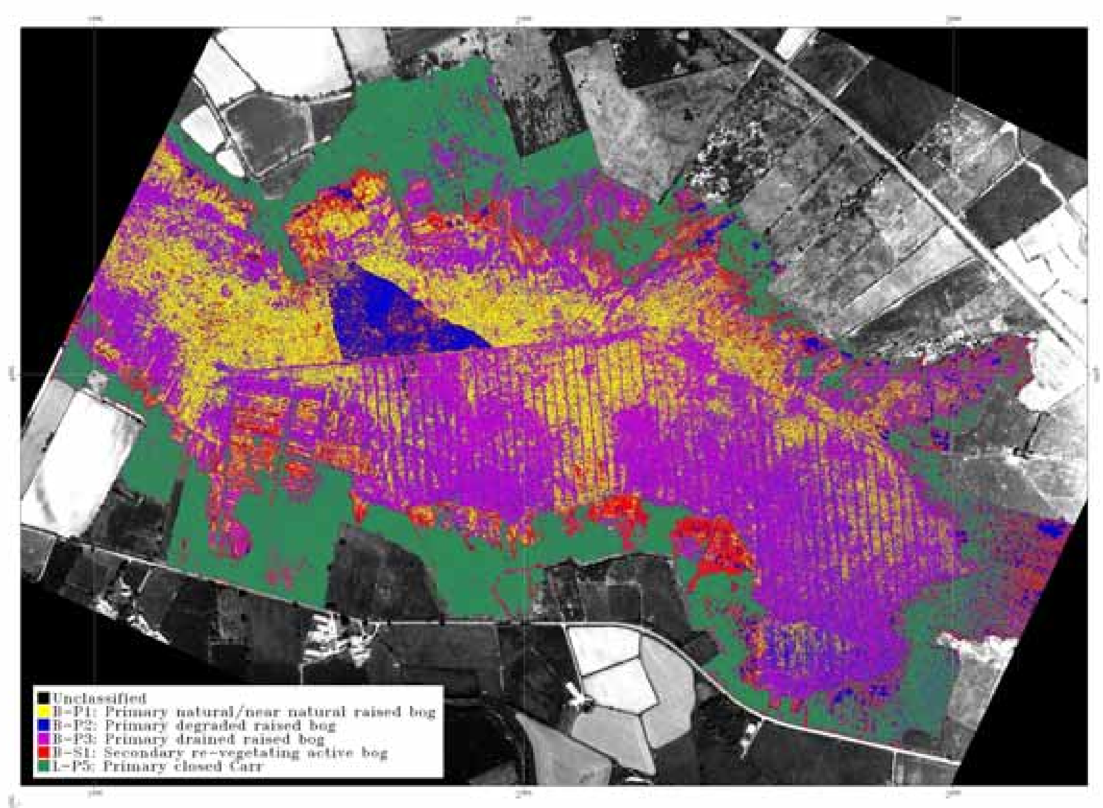

Figure 33. Maximum likelihood classification of Ballynahone Bog

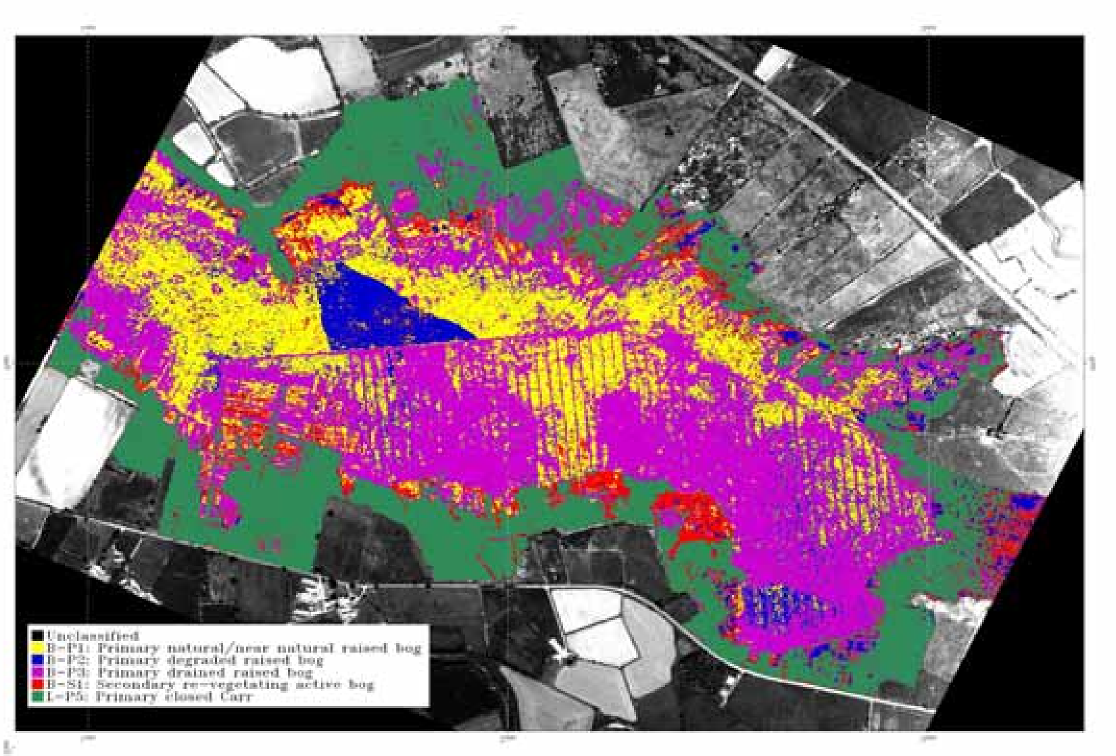

Figure 34. Maximum likelihood classification after the majority filter had been applied.

8.6 Accuracy of the supervised classification

The maximum likelihood classification generally proved successful – i.e. the distinct classes shown on the map based on the surface condition classes (Figure 34) are generally distinguishable. However, there is a lot of spectral confusion, of particular note is the mixing between the 'B-P1', 'B-P3' and 'B-S1' classes. To further investigate this mis-classification, a confusion matrix was used to evaluate the results of the classification. Surrogate ground data in the form of "testing sites" were chosen based upon a second set of regions of interest on the same aerial photograph. The testing sites used in the confusion matrix are shown in Table 15.

Table 15. The testing sites used in the confusion matrix

Testing site name	Number of pixels
Testing P2 burnt	278
Testing L5	543
Testing P1	1214
Testing P3	1962
Testing S1 cut1	2021
Testing S1 cut2	428
Testing P2 Pb	621

The number of pixels used for each training area roughly corresponds to the number of pixels used for each testing site.

The overall accuracy of the spectral classification was less than 50%. While this may initially appear low, most of the mis-classification was due to confusion between very similar classes. The confusion matrix clearly distinguishes which classes were the most difficult to classify on the basis of their spectral response in the visible wavelengths alone.

The category that proved easiest to classify was the L-P5 'Primary closed Carr' which was classified with an accuracy of 98%. This is because the green vegetation is very spectrally distinct from the rest of the area of interest. The burnt area (accuracy of 70%) and the 'B-S1 cut2' class (accuracy of 77%) were also well classified. These two classes were fairly bright so therefore contrasted with the rest of the bog. In each case, most of the misclassified pixels were assigned to the other class (i.e. 15.9% of the burnt area was classified as 'B-S1 cut2' and 10.27% of 'B-S1 cut2' was assigned to the burnt class). It is also possible that bright areas of *Molinia* mixed in with the 'B-P1' and 'B-P3' classes were assigned to these two classes.

As suspected from the results of the maximum likelihood classification, the 'B-P1', 'B-P3' and 'B-S1 cut 1' classes all have low classification accuracies (57.17%, 58.09% and 7.16% respectively). This is because these classes are all spectrally similar. Figure 35 shows a zoomed in area selected from each of these classes. These are taken from a colour composite of the three visible bands, as such they contain all of the information that is available in this data set. From this it is clear to see just how spectrally similar some of these categories can be.

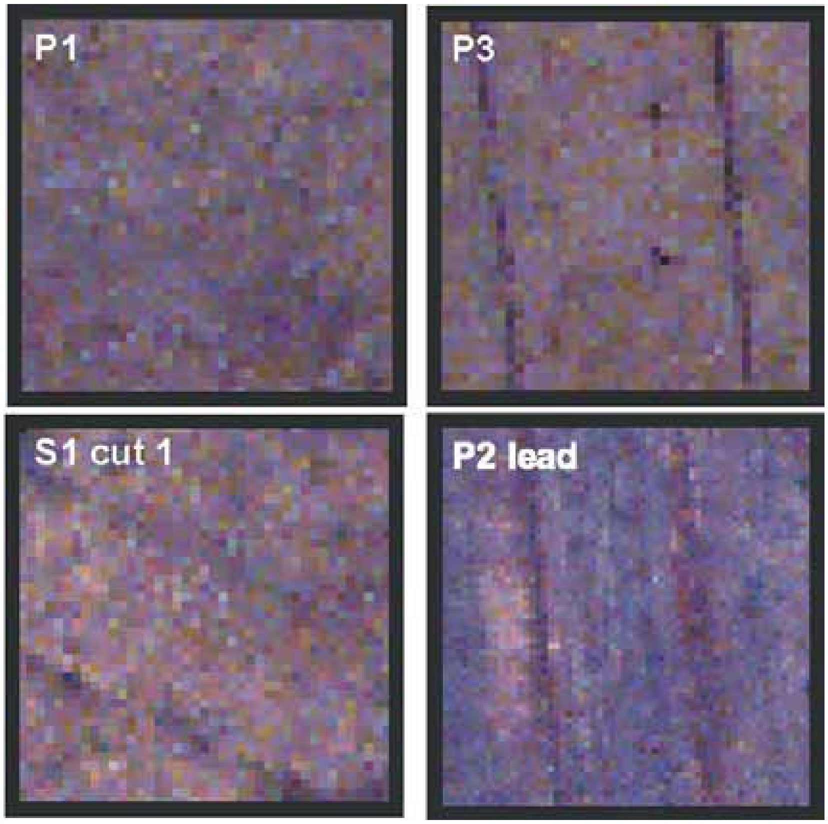

Figure 35. A comparison of the spectral responses of four of the condition classes

The P1, P3 and S1 classes are strikingly similar (note that the spectral response of these classes will vary over the image, these are just examples). It is not surprising, therefore, that a spectrally based classifier, such as the maximum likelihood classifier, would not be able to accurately distinguish between them. Table 16 shows the allocation of pixels per class from the testing sites.

Table 16. Percentage allocation of pixels to classes P1, P2 lead, P3 and S1 cut1

Class	B-P1	B-P3	B-S1 cut1	B-P2 lead
B-P1	**57.17**	17.14	41.94	25.57
B-P3	18.63	**58.09**	23.50	17.22
B-S1 cut1	4.22	1.61	**7.16**	0.70
B-P2 lead	10.29	18.44	8.49	**47.83**
Total (%)	**90.31**	**95.28**	**81.09**	**91.32**

This table shows that almost all of the error in the spectral classification lies in the misclassification between these classes. The numbers underlined are the percentage of pixels within each class allocated to these four condition classes. An original accuracy of 58.09% ('B-P3' classified as 'B-P3') is compared to 95.28% ('B-P3' classified as 'P-P1', 'B-S1 cut1', 'B-P2 lead' or 'B-P3'). The error in the classification is primarily due to the misclassification of pixels in these classes to one of the other three classes.

This spectral similarity is due to the homogeneous nature of the surface vegetation. The reason that the vegetation is so similar is because the bog is now a SSSI and drainage and cutting have been stopped. The drains were never fully operational and were blocked up soon after they were created, as such they have had a minimal effect on the vegetation surrounding them. Cutting is no longer taking place and the vegetation starting to recover. Thus, although past management practices have altered the condition of the bog, the vegetation is now recovering. This means that while there are still a number of condition classes on the ground they will be increasingly difficult to see from air or from space. This is especially the case if the only technique that is being used is a spectral classifier.

8.6 Contextual Classification

The evidence of draining and cutting on Ballynahone bog is clearly evident to the human eye as context and pattern can be taken into consideration as well as the spectral response of the surface. For this reason the area of interest has been split into undisturbed bog, disturbed bog and carr woodland. Differentiation between these was possible using the aerial photograph. As with the initial classification, a mask was created for each of these three new areas of interest and the same maximum likelihood classification was run on each area. Again a 3 x 3 centre weighted majority filter was applied to each classification. The following figures show the results of these classifications. (Figures 36 to 38).

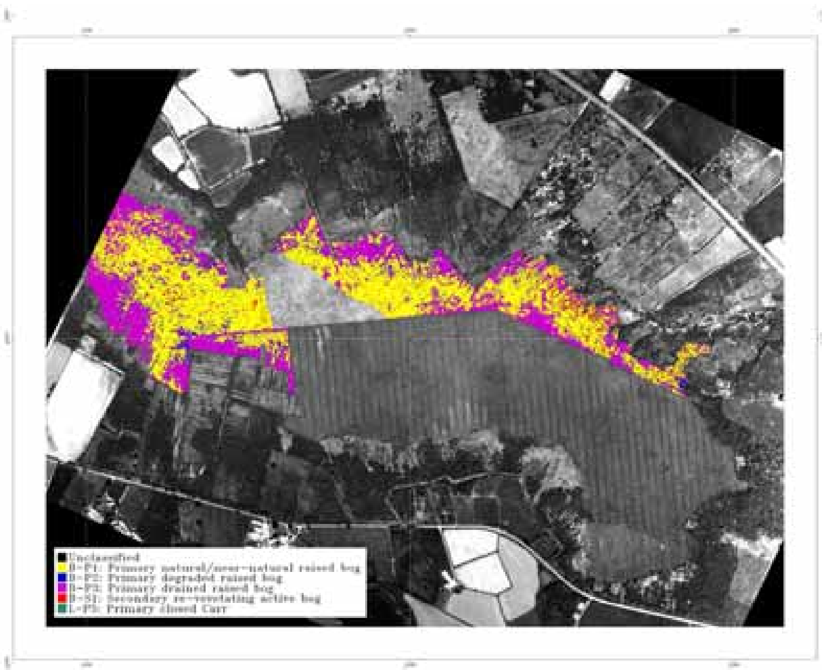

Figure 36. Maximum likelihood classification of the undisturbed areas of Ballynahone Bog

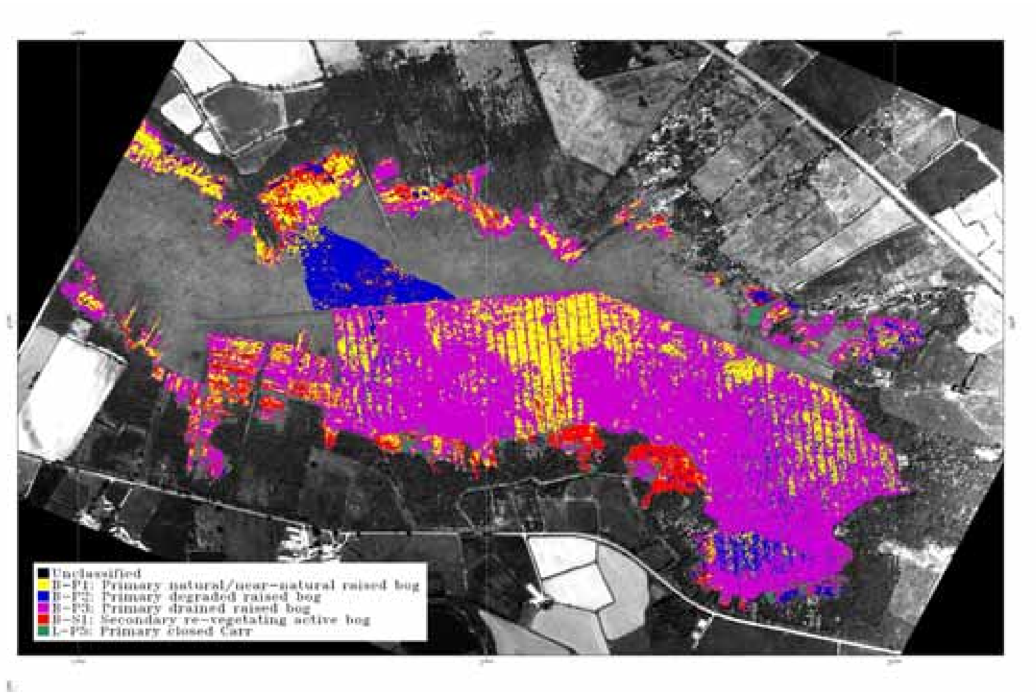

Figure 37. Maximum likelihood classification of the disturbed areas of Ballynahone Bog.

Figure 38. Maximum likelihood classification of the marginal communities on Ballynahone bog

These images are more useful than the classification of the whole bog for management purposes as they show the variation in classes according to the general categories of undisturbed bog, disturbed bog and Carr woodland.

8.7 Probability images

As in the Wedholme section of this report (section 6.8.4), the rule images that are an automated by-product of the maximum likelihood classification are presented here (Figures 39 to 44). They show the probability that each pixel belongs to a particular class (with the brightest white being the highest probability) rather than just a final allocation to a class.

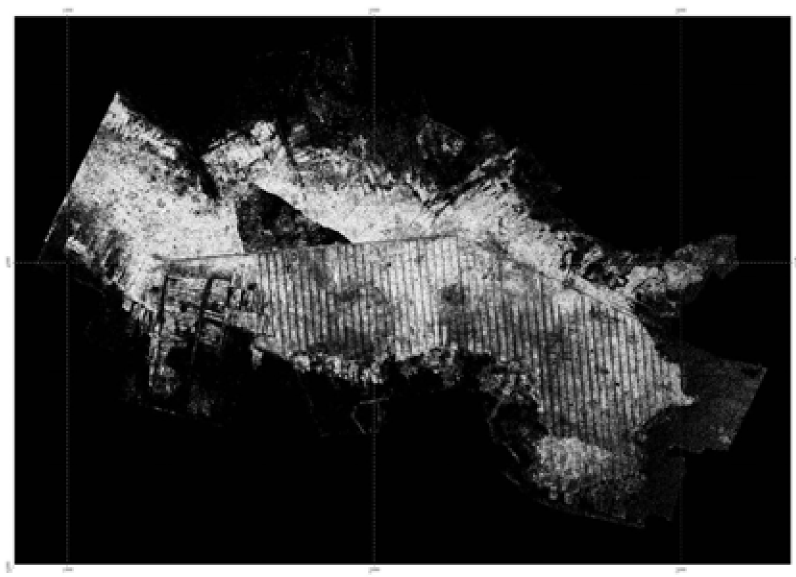

Figure 39. Rule image of the Primary bog (P1) class

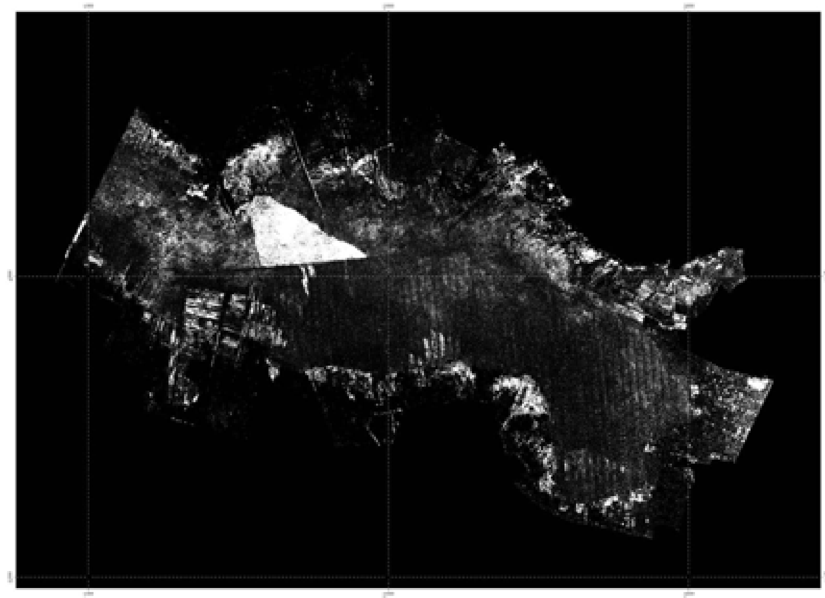

Figure 40. Rule image of the Primary bog (P2 burnt) class

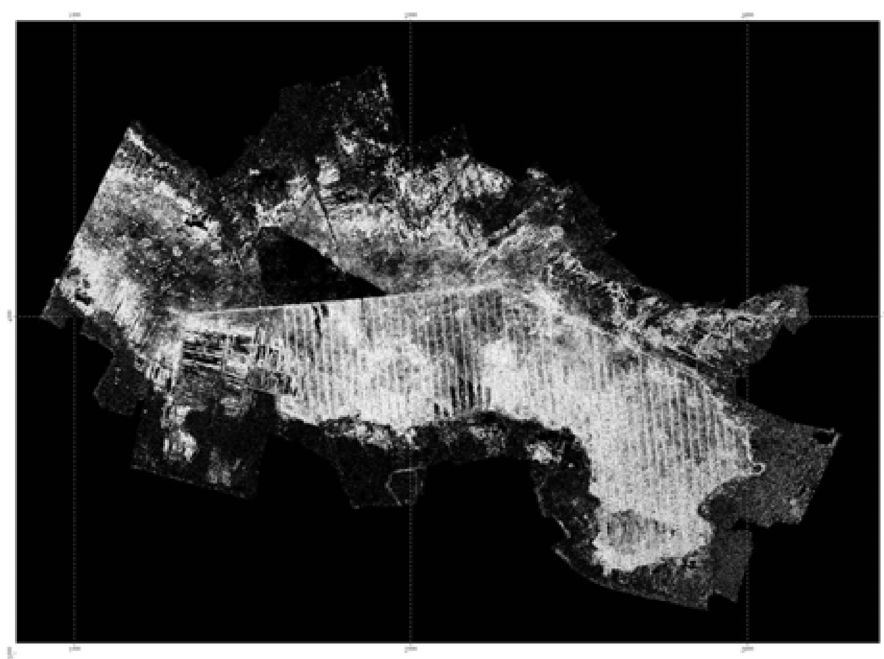

Figure 41. Rule image of the Primary bog (P3) class

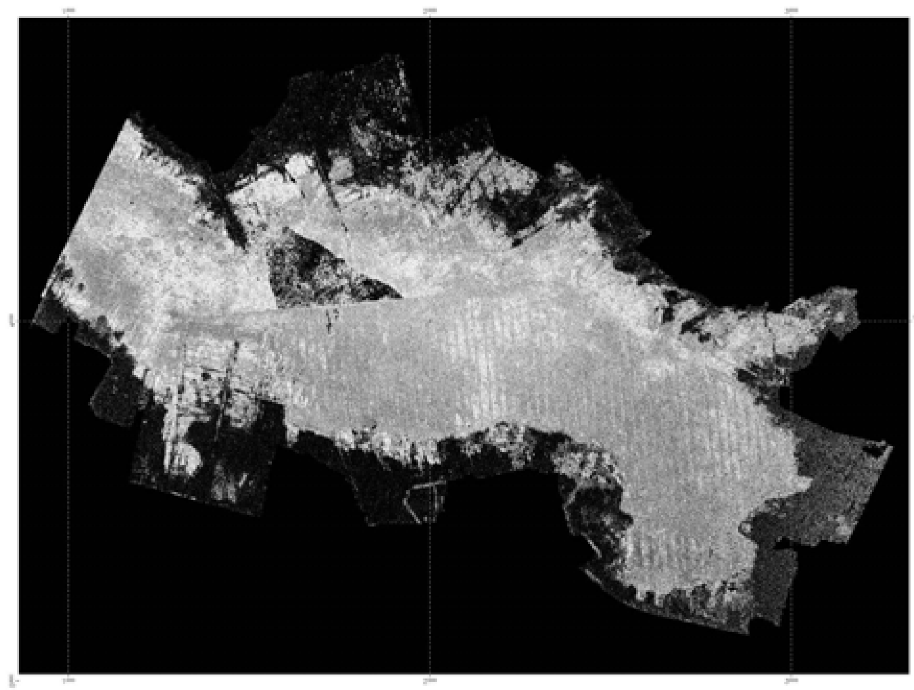

Figure 42. Rule image of the Secondary bog (S1 cut) class

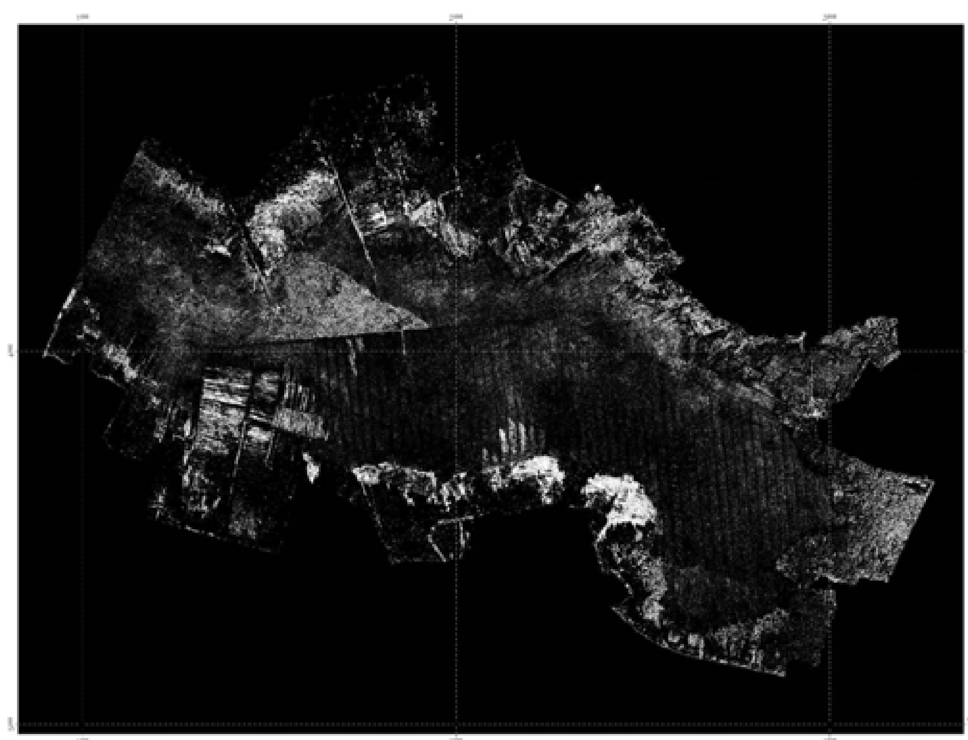

Figure 43. Rule image of the Secondary bog (S2 cut) class

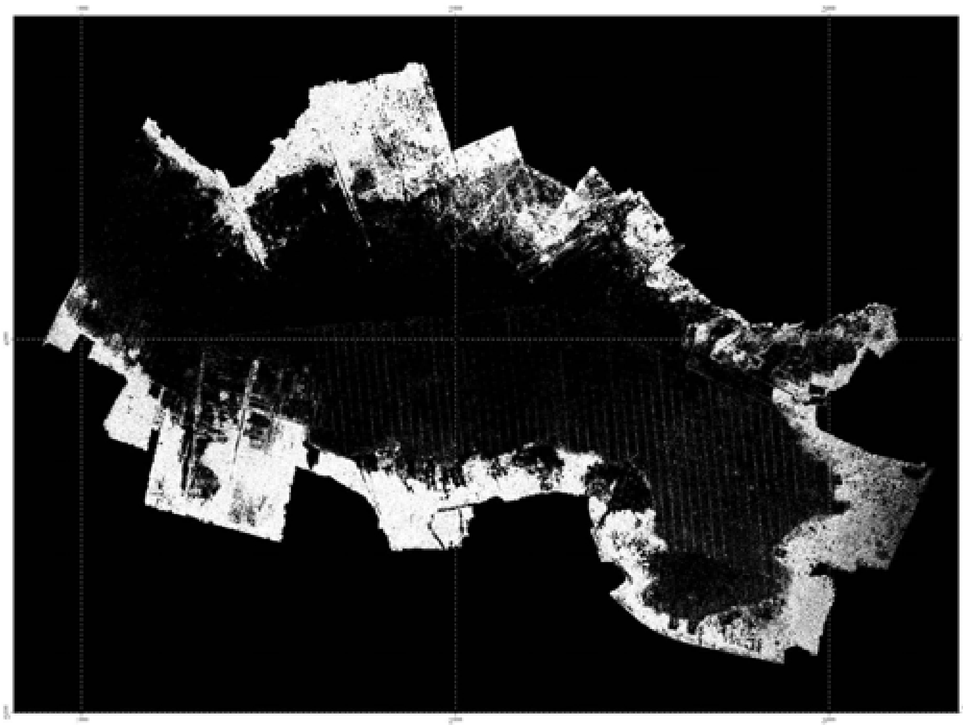

Figure 44. Rule image of Carr woodland class

Not surprisingly, the classes that have clusters of pixels with a very high probability of belonging to them are the classes that were highlighted as having the highest classification accuracies (namely the primary closed carr and the burnt areas). The mixing that was discussed earlier between ‘B-P1’, ‘B-P3’ and ‘B-S1 cut1’ is evident again here. There is a high frequency of white pixels in each of these probability images and there is not always a sharp difference in brightness between the areas separated as different condition classes in Figure 34. This means that although the classifier has separated the area of interest into ‘distinct’ condition classes there is also a high probability that some of these pixels share characteristics with another class. The spectral similarity within a condition class (such as ‘B-P2 burnt’ and ‘B-P2 lead contamination’) can sometimes be less than the spectral similarity between condition classes (for instance ‘B-P1’ and ‘B-P3’).

In conclusion, the most successful classification of Ballynahone Bog was achieved by an initial categorisation of the condition of the surface based upon a visual interpretation of the scanned aerial photograph, followed by a more objective spectrally-based classification of the digital data in red, green and blue wavelengths. Although the overall results were comparable in accuracy with those derived from analysis of the Ikonos image of Wedholme Flow, the aerial photographs were much more problematic to work with and better suited to a conventional visual interpretation.

9. Assessment of the remote sensing classification results and proposal for a revised LRBI classification system

9.1 Rationale for a revised LRBI classification system

Lowland raised bogs may be classified using a system based on functional hydrology. Ivanov (1981) described a fourfold system in which a mire complex possibly containing several different mire types is termed a macrotope. The macrotope is regarded as a self contained unit in terms of hydrology and vegetation (Lindsay, et al., 1988). A single raised peat bog dome is termed a mesotope. This unit is sometimes subdivided into the gently-domed central area, termed the mire expanse and the steeply sloping edge to the dome known as the mire margin or rand. Surrounding an intact raised peat bog there are fringing minerotrophic fen or carr communities drained by streams. This hydrologically distinct unit, known as lagg, is regarded as a separate mesotope. The surface of the mesotopes may support patterned features formed from sets of pools and hummocks, known as microtopes. Finally, distinct levels may be recognised within in the hummock / hollow complex and these features are termed microforms or nanotopes (Lindsay & Campagna Popolo 1998).

The classification system designed by Lindsay and Immirzi (1996) for the LRBI was principally concerned with characterising the mire expanse sub-unit, and provided only limited categorisation of conditions on cut-over areas or peat soils now lacking bog vegetation. The various refinements introduced by the Scottish Lowland Raised Bog Inventory - e.g. vegetation modifiers - give more detail across the whole spectrum of bog peat environments. However, neither this nor the original LRBI provided an explicit category for the lagg fen zone.

The classification system designed by Lindsay and Immirzi (1996) for the LRBI was principally concerned with the mire expanse sub-unit. By contrast the current study is concerned with all of the units that form a single raised peat bog. For this reason new classes must be added to the original set of LRBI categories to accommodate certain aspects of the mire margin sub-unit and the lagg mesotope. The modified scheme is presented in Table 17 and Table 18.

9.2 Explanation of the revised condition classes

The first modification to the LRBI system designed by Lindsay and Immirzi (1996) involves the addition of a ‘mesotope prefix’ to distinguish between the raised bog dome and the lagg communities. The prefix B- denotes bog, whereas L- indicates lagg. The letters P and S remain and stand for ‘Primary Mire’ and ‘Secondary Mire’. The term ‘mire’ is used here since it encompasses bogs, fens and swamps. The modified classification is explained below

9.2.1 Modified Condition Classes

B-P1 to B-P5: Primary Near-natural / Primary degraded / Primary drained / Open canopy wooded and closed canopy wooded raised bog

The first five condition classes of the modified scheme are directly equivalent to the primary classes P1 to P5 in the original scheme devised by Lindsay and Immirzi (1996). Definitions for these classes remain unaltered.

B-P6: Rand (raised bog margin)

Structurally intact raised bogs have a slightly domed to near-flat expanse bordered by steeply sloping margins termed 'rand'. This mire margin (*sensu* Sjörs, 1948) is hydrologically distinct, being defined by faster lateral seepage rates than the main mire dome. The marginal areas are supplied by seepages, which originate from the mire expanse (endotelmic, Lindsay *et al*., 1988). The improved surface drainage across the mire margin zone tends to give rise to a characteristic vegetation zone often dominated by a somewhat drier vegetation type. In typical UK bogs, where the lagg zone has been completely drained, this marginal zone becomes particularly dry towards the edge of the upstanding dome, and is often characterised by a dominance of *Calluna vulgaris* or *Molinia caerulea*. These vegetation types are relatively easy to recognise in remotely sensed images and therefore the rand warrants a separate class in the modified scheme. The different vegetation types found on the rand may be represented in the scheme by the vegetation modifiers 'L' for *Calluna* and 'H' for *Molinia* (see Table 18).

Most British raised bogs have been damaged by large-scale peat extraction or peripheral domestic peat cutting to the extent that the rand is rarely located in its original position. Nevertheless a rand slope forms at the edge of the cut peat dome and the vegetation that establishes on the primary, steeply sloping surface is somewhat similar to that of an undisturbed rand.

B-S1 and B-S2: Secondary re-vegetated active bog and peat extraction

These classes are directly equivalent to S1 and S2 in the original scheme and their definitions remain unaltered.

B-S3: Secondary re-vegetated degraded bog

Analyses of the field survey results from Wedholme Flow and Cors Caron indicate the need for an additional 'Secondary' class. The original LRBI scheme accommodates two situations, (1) cuttings that are active and re-vegetating / re-vegetated and (2) cuttings that are not vegetated. Wedholme Flow in particular, has dry re-vegetated peat cuttings that are not actively accumulating peat. To cover this situation the category B-S3 was added to the scheme. The vegetation cover may contain dwarf shrubs, *Cladonia* spp. and *Molinia caerulea*. Again the SRBLCS vegetation modifiers (Parkyn & Stoneman 1997) can be used to distinguish the different vegetation types.

L-P1: Primary near natural lagg fen

The lagg fen surrounding most raised bogs has been severely damaged by a wide range of land use pressures and now very few remnants of near-natural lagg fen remain. The east margin of Cors Caron supports a narrow band of lagg fen, adjacent to the Teifi river channel. Air photographs and CASI imagery suggest that the mire surface here is structurally intact and recent coring work (Hughes, 2002) and vegetation mapping (Schulz, in prep.) support this interpretation. The vegetation contains a range of fen bryophytes and herbs together with various *Carex* species. L-P1 may be defined as intact, open lagg that has an ability to accumulate peat and supports a typical range of fen species.

L-P3: Primary degraded lagg

This condition class refers to uncut lagg fen communities that have been substantially altered by disturbances such as peat cutting and drainage works. The peat surface may be vegetated but ‘dry’ in character, supporting few or no typical lagg fen species.

L-P/S4: Primary/secondary open fen carr

Raised bogs are commonly surrounded by a wooded fringe consisting of arboreal species tolerant of at least some waterlogging. Communities consisting of *Salix* and *Alnus* (possibly with some *Quercus*) usually indicate eutrophic to mesotrophic fen carr conditions where they are found growing on peat. In open canopy woodland it may be possible to detect a secondary peat surface using Lidar but the tree canopy may disguise cuttings in some areas. Consequently, the condition class category used in the present study does not distinguish between primary and secondary peat surfaces.

Where the fringing woodland is principally composed of *Betula* with an oligotrophic ground layer it is categorised as either B-P4 or B-P5 (see above). Ground data may be required to distinguish between the bog and lagg woodland categories since remotely sensed imagery contains insufficient data to separate different tree species within the woodland category.

Carr woodland may be designated on the basis of airborne data where it occurs immediately adjacent to sharply rising mineral ground. In this context the woodland is likely to be fen carr because the peat surface will receive a significant amount of slope runoff. This criterion was used in the present project and checked against field data.

L-P/S5: Primary / Secondary closed fen carr

Closed carr woodland may be dominated by *Salix* or *Alnus* with some *Quercus*. The canopy forms an almost complete cover. In this case the primary status of the peat surface may be impossible to establish from airborne data.

L-S: Secondary lagg fen

Secondary lagg fen refers to open lagg communities that are actively regenerating over old peat cuttings. The lagg contains a mix of typical fen species and it is capable of peat accumulation.

A1 Archaic (agriculture), A2 Built development, U Not determined

These classes remain unaltered in the modified classification scheme.

Combinations of classes

The condition of some parts of Cors Caron and Wedholme Flow appear to fall half way between two condition classes. In these cases classes were combined to provide a more accurate description of the surface condition. Two hybrid classes were used; B-P1/2 and B-S1/3.

Hybrid class B-P1/2

This class is defined as primary active bog with a moderately degraded or altered vegetation community. The northern uncut section of Wedholme Flow was included in the B-P1/2 category because the entire surface had been significantly affected by the surrounding cutting and it supported a somewhat reduced *Sphagnum* cover with an abundance of *Cladonia* spp. The vegetation surface could not be considered to be 'near-natural' (B-P1) but equally it was not degraded to the point of being 'inactive' (B-P2).

The original LRBI condition class scheme has no vegetation modifier for a Lichen-dominated community; therefore the new modifier 'LCH', standing for 'lichen-dominated', was added to the list.

Hybrid class B-S1/3

A hybrid 'Secondary' class was also required for the project because some of the regenerating peat cuttings were clearly re-vegetating and contained a small amount of *Sphagnum* but they did not appear to be peat forming. The cuttings therefore fell half way between B-S1 and BS3.

Table 17. Modified scheme for remotely-sensed classification of raised bog and lagg fen mesotopes

Class	Name	Description
B-P1*	Primary natural / near-natural raised bog	A primary peat dome with an extensive cover of colourful Sphagna, with the ability to accumulate peat.
B-P2*	Primary degraded raised bog	Primary surface where the vegetation has been modified by factors other than drainage (e.g. burning / grazing).
B-P3*	Primary drained raised bog	Primary drained bog in which a regular drainage pattern exists.
B-P4	Primary open canopy wooded raised bog	Primary bog supporting open canopy woodland or scrub.
B-P5	Primary closed canopy wooded raised bog	Bogs supporting closed canopy woodland. Trees may have 'self-seeded' but often they are present because of deliberate planting. Self-seeding is often a symptom of damage. Tree cover enhances oxidation and drying of the peat surface.
P16†	Raised bog margin	Rand slope of the raised bog, usually supporting *Calluna vulgaris* and / or *Molinia caerulea.*
B-S1*	Secondary re-vegetating active bog	Actively regenerating raised peat cuttings (peat forming).
B-S2	Secondary, commercial / domestic peat extraction	Large expanses of bare peat for modern industrial-scale raised peat extraction or recently abandoned raised peat cuttings.
B-S3	Secondary re-vegetated degraded bog	Dry, re-vegetated raised bog cuttings (non-peat forming).
L-P1*	Primary near-natural lagg fen	A primary open lagg fen surface dominated by sedges and fen herbs with the ability to accumulate peat.
L-P3	Primary degraded lagg fen	Primary lagg fen surface where the vegetation has been modified (e.g. by drainage).
L-P4	Primary open carr	Open carr woodland dominated by *Salix* or *Alnus* with *Quercus.*
L-P5	Primary closed carr	Closed carr woodland dominated by *Salix* or *Alnus* with *Quercus.*
L-S*	Secondary lagg fen	Regenerated or regenerating lagg fen.
A1	Archaic (agriculture)	Bogs drained for agriculture. The peat is oxidised with a lowered surface. Eventually fen peats will be exposed.
A2	Built development	Peatland covered by structures such as buildings, roads or railway lines.
U	Not determined	Condition not yet classified.

* denotes condition classes that are considered to be 'active' under Annex I of the EC Habitats Directive.

† This condition class is not usually found in its former natural position

Table 18. Vegetation modifiers used in land cover classification

Drainage Modifiers	**Vegetation Modifiers**	**Erosion Modifiers**
I irregular	BP broadleaf plantation	MIC micro-broken
N narrow	CP coniferous plantation	Y gully erosion
M moderate	MP mixed plantation	
W wide	PF plantation felled	
A absent	PFR plantation felled and replanted	
U unknown	BS broadleaf self-sown	
	CS coniferous self-sown	
	MS mixed self-sown	
	GS gorse, bramble etc	
	O or C open or closed canopy	
	L low shrub dominated	
	H herb dominated	
	SPH *Sphagnum* dominated	
	BRY bryophyte dominated	
	BAR bare peat dominated	
	BBA bryophyte / bare peat co-dominant	
	BAS bare peat / *Sphagnum* co-dominant	
	LCH Lichen-dominated	

9.3 Summary

The use of lidar can distinguish between hand-cut and milled bog and fen surfaces and uncut mire. This instrument may be used to determine the major classifications of "Primary" and "Secondary" peat bog. Further classification of bog condition may require a number of data sources including air photographs and multispectral imagery. The study of a complete raised bog macrotope requires the extension of the existing condition class system, produced by Lindsay and Immirzi (1996), to include mire margin (*sensu* Sjőrs, 1948) and lagg fen. The existing Lowland Raised Bog Inventory (LRBI) condition class categories are principally designed for the mire expanse mesotope. Ground-based surveys of the mire vegetation at Cors Caron and Wedholme Flow showed that new primary and secondary bog categories were required as well as additional lagg categories. Furthermore the modified condition class categories can be refined further with the use of hybrid categories (e.g. B-P1/2), which indicate that the mire condition lies between two categories, and with the use of a new a larger range of vegetation modifiers.

10. Relative costs of different RS approaches

One of the primary attractions of using remotely sensed data is the reduced cost compared to traditional surveying techniques. There are, however, still a number of factors that need to be considered in order to ensure that the data used are the best value and the most suitable for the task at hand.

When comparing prices from different sources it is important to note factors such as the minimum amount of data that have to be purchased at any one time. For instance, Ikonos data is only £11/km^2 but a minimum of 100km^2 has to be ordered regardless of the size of the area of interest. This would make it relatively cheaper to buy data for larger areas – if more than 100km^2 is required then this is not a limitation. Similarly, if aerial photography is the preferred data source it is necessary to consider the distance the aeroplane has to fly to the site in order to collect the data as this will impact on the overall cost.

Another factor that will affect cost is whether or not there is (recent) archived data available. It will generally be significantly cheaper to purchase archived data than to fund the acquisition of a new data set (see Table 19). Of particular note is the cost of lidar data which has proved to be fundamental to this project. If available it costs £300/km^2 (data are sold in tiles, if there is not a complete tile available only the proportion that is covered is charged for). The basic acquisition cost for these data, however, is £10 000 which would have considerable affects on the feasibility of purchasing it for most applications. It is due to the high cost of commissioning a survey to acquire lidar data that only patchy cover was used in this report for Wedholme Flow (this was all that was available from the archive). The high cost meant that it was not purchased at all for the Cors Caron study (no archived data were available). However, the archive of available lidar data is continually being added to (see Figure 45 for a graphical representation of the current archived lidar data) and even partial coverage of an area has proved to be extremely useful. Although expensive, Lidar is a valuable source of information that can add considerable detail to spectral information and be used to distinguish between features in its own right (as it allows a much more in-depth study of variables such as relief, pattern and context). Thus, while cost comparison of different data sources is important, the relative usefulness of them must also be considered.

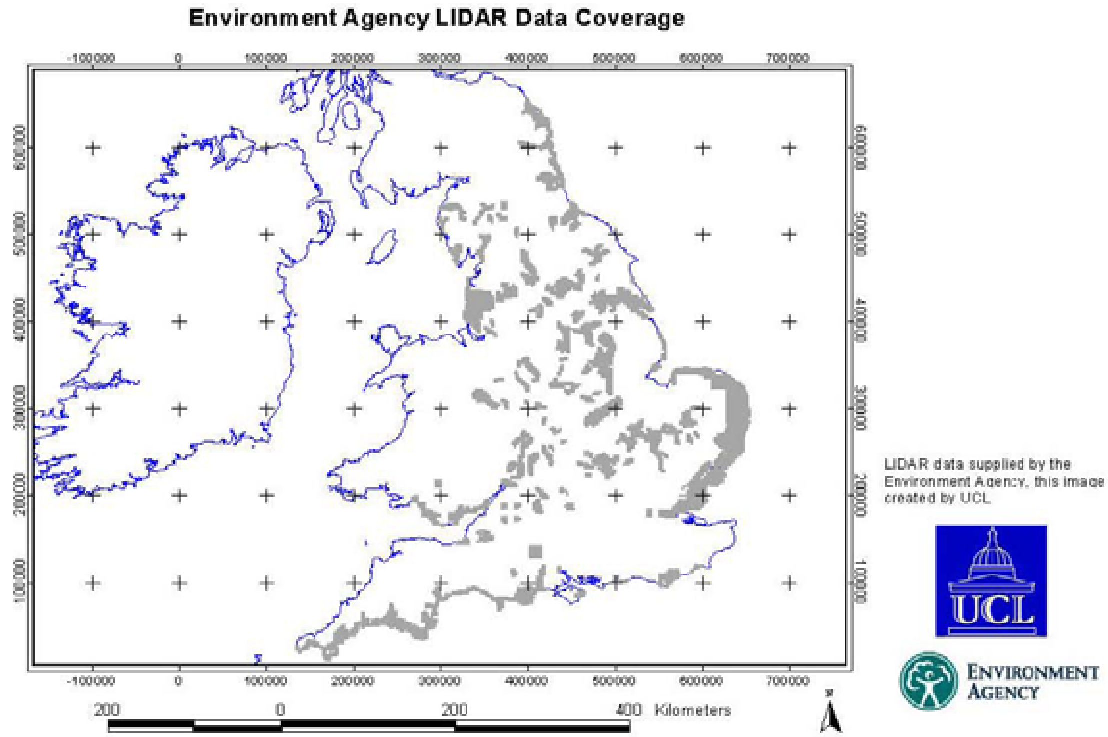

Figure 45. Current Environment Agency lidar coverage of the UK (source : www.landmap.ac.uk/lidar/lidar.html, 14/2/03)

It is important to note that the prices presented in Table 19 are all estimates of the actual costs of purchasing data. This is especially true where data are being newly acquired. For instance, in the case of aerial photography the flying distance to the area of interest may impact significantly on the overall cost. Also, with CASI data from the EA, details of processing costs will be added on application.

NERC has currently been unable to provide a figure for the acquisition of CASI and ATM data (note that archived ATM data were used for the Cors Caron section of this report). However, from previous experience with this organisation it would be expected that their prices would be competitive with any alternative sources. The method used by NERC is such that there is often a possibility of combining data collection with other survey work. Thus if data are being collected for another purpose in an area close to a site that is of interest, there is potential for the overall acquisition cost (of £10,000) to be reduced.

The amount of data that would be necessary to conduct a nationwide survey of lowland raised peat bogs would be large. It would be advisable to use archived data wherever possible and to carefully plan data acquisition. For example, surveying a number of areas close together on one day would minimise flying distances between sites. This would be more cost-effective than paying for the aircraft to visit the same area repeatedly.

Table 19. Summary of data costs

Data type	Data Type	Source/ provided By	Archived Cost	Acquisition Cost
Satellite	IKONOS (Figure 46 and Figure 47)	Infoterra	**£12/km^2** (min. 100km^2) = **£1,125**	**£12/km^2** (min. 100km^2) = **£1,125**
	Quickbird	GIM/ Digital Globe	**£16/km^2** (Min 25km^2)	**£16/km^2** (Min 64km^2)
Aerial Photography	CASI (Figure 48)	EA	**£200/km^2**	**£10,000**
	CASI (Figure 48)	NERC	**£52/** line km	?
	ATM (Figure 48)	NERC	**£52**/ line km	?
	LIDAR (Figure 45)	EA	**£300/ km^2**	**£10,000**
	X-band SAR (Figure 50)	Global Terrain (NEXTMap Britain)	Digital Surface Model (0.5m RMSE) £25/km^2 (min. 100km^2) = **£2500**	N/A
			Digital Surface Model (0.5m RMSE) £30/km^2 (min. 100km^2) = **£3000**	N/A
	Aerial Photography	Getmapping	1/2km^2 **£25** 1km^2 **£48**	N/A
Map Data	Digimap (standard)	Edina	Urban: 500m x 500m: **£39**	N/A
			Rural: 1km x 1km: **£18**	N/A
			Moorland: 5km x 5km: **£37**	N/A

If archived data are not available then it will be necessary to determine the acquisition costs of different sources and to establish which would be the most suitable for a particular area. While Table 19 provides a brief summary of acquisition costs for various sources it may be useful to compare the costs of purchasing data for a particular study area. For this purpose Hatfield Moors in Southern Yorkshire (Grid reference 470500E 406500N) was considered. It has been proposed to the European Commission (through Natura 2000) that in recognition of its ecological importance the site should be protected under the European Habitats Directive (http://www.ipcc.ie). While peat extraction has ceased on two other lowland raised bogs (Thorne Moor and Wedholme Flow) that were also recognised as areas of international importance for conservation, extraction will only be phased out on Hatfield Moor by 2004 (http://www.forests.org). This is likely to raise some interesting management issues and it is probably an area that will be surveyed in the future. As such it has been chosen as the site on which to base a scenario for data acquisition. The cost of acquiring data for Hatfield Moor for both a 1km^2 area (or a 1km flightline where appropriate) and 5km^2 (or a 5km flightline) is shown in Table 20. While it would be necessary to purchase 5km^2 of data to gain complete coverage of the area, a 1km^2 subsection may also provide useful information (it may be worth considering purchasing data of parts of the areas of interest rather than whole areas as a means of reducing the overall cost of data).

Table 20. Costs of various scenarios

Data Type	**If available from archive**		**If acquired specifically**	
	1km^2	5km^2	1km^2	5km^2
IKONOS	£1,125	£1,125	£1,125	£1,125
IKONOS and Lidar	£1,125	£2,625	£11,125	£11,125
IKONOS and (a) X-band SAR	£3,625	£3,625	£3,625	£3,625
CASI (at full EA cost)	£200	£1,000	£10,000	£10,000

Within the scope of this project there is the possibility of combining different available data sources from which most information can be extracted. This flexibility means that if there are data already available for a particular area of interest, it is likely that this could be usefully incorporated into the study.

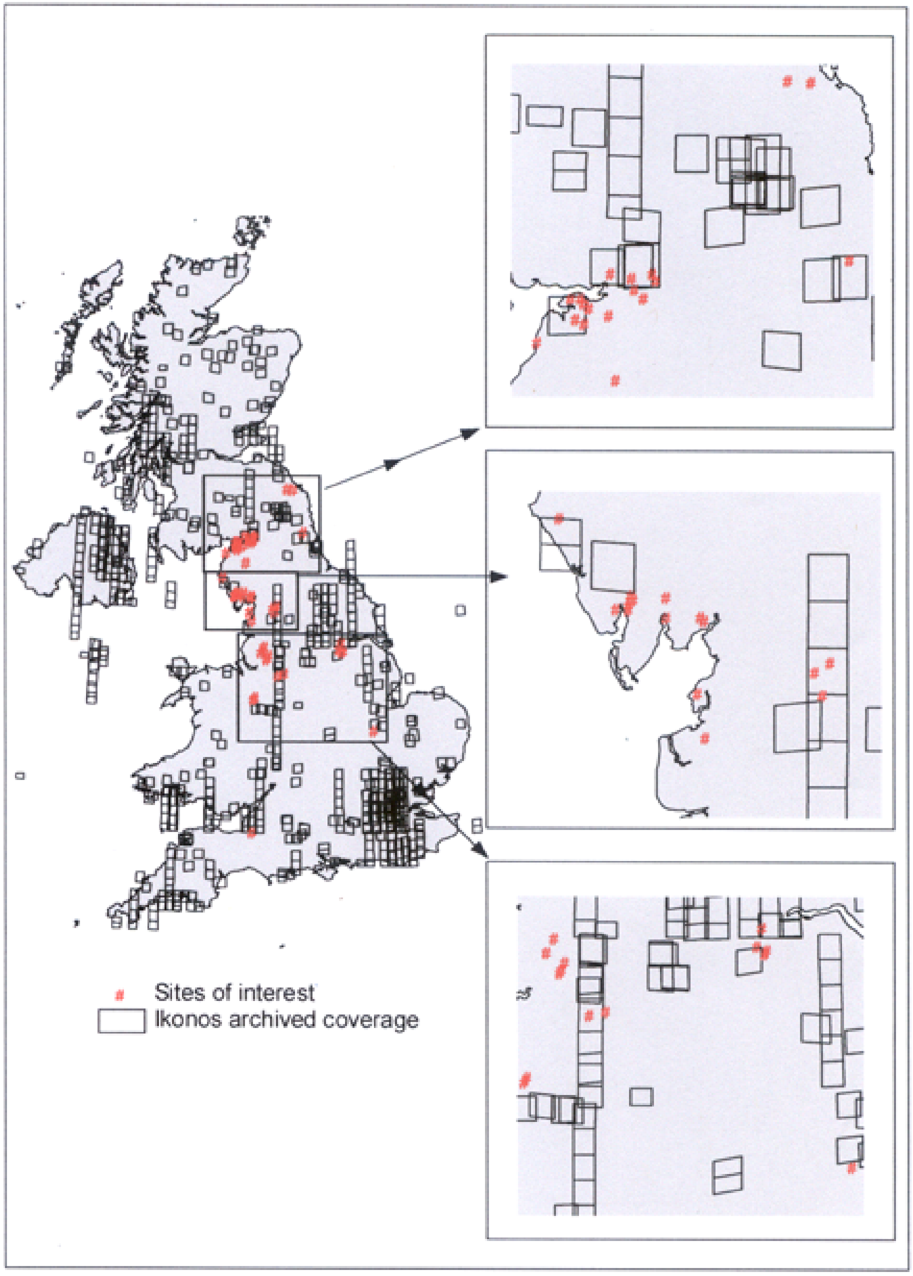

Figure 46. Current UK coverage of Ikonos data with the raised bog SSSI sites shown by red hash symbols (source: pers. Comm.., Sheena White, Infoterra, 11/2/03; SSSI sites provided by Dr. Roger Meade, May 2003)

Table 21. Ikonos Coverage of Lowland Raised Bog SSSI in England

Site Name	Ikonos Coverage
Austwick and Lawkland Mosses	Y
Black Moss (Egremont)	Y
Black Snib	Y
Bolton Fell Moss	Y
Bowness Common	Y
Glasson Moss	Y
Gleads Moss	Y
Hesley Moss	Y
Prestwick Carr	Y
Solway Moss	Y
Swarth Moor	Y
Thorne, Crowle and Goole Moors	Y
Walton Moss	Y
Wedholme Flow	Y
Westhay Moor	P

Site Name	Ikonos Coverage
Danes Moss (inc. Moss Head Farm Outlier)	N/E
Drumburgh Moss	N/E
Hatfield Moors	N/E
Oulton Moss	N/E

- This information is based on the central points of the sites of interest.
- Information on Ikonos availability was provided by Infoterra and is for acquisitions with less than 20% cloud.

Y=Coverage
P=Partial coverage
N=No coverage
N/E=No coverage but on the edge of a data collection site

Table 22. Sites for which no Ikonos data are currently available

Arnaby / Shaw Moss	Lower Duddon Mosses
Astley and Bedford Mosses	Meathop Moss
Bowscale Moss	Nichols Moss
Epworth Turbary	Orton Moss
Fenns, Whixall & Bettisfield Mosses	Red Moss
Ford Moss	Risley Moss
Haxey Turbary	Roudsea Moss
Heathwaite Moss	Rusland Valley Mosses
Heysham Moss	Salta Moss
Holburn Moss	Scaleby Moss
Holcroft Moss (remnant)	Wem Moss (inc. Cadney Moss)
Holme Fen	White Moss, Crosbymoor
Ince Moss	White Moss, Duddon
Latter Rigg Moss	Winmarleigh Moss (remnant)
Little Bampton Moss	Wreaks Moss

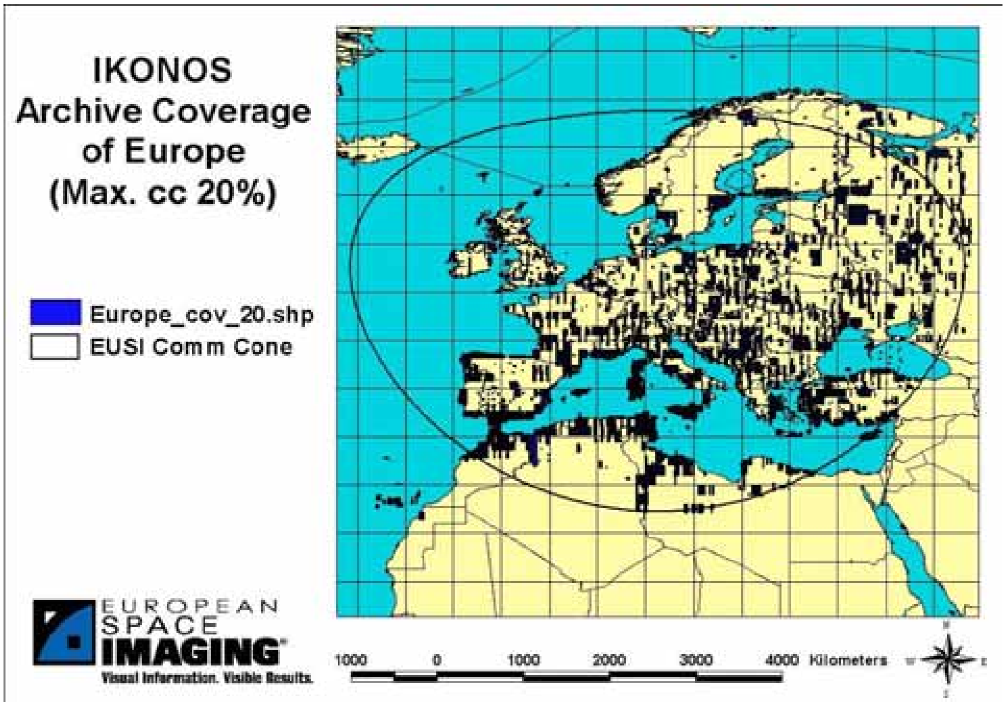

Figure 47. EU coverage of Ikonos data (source pers. comm., Sheena White, Infoterra, 11/2/03)

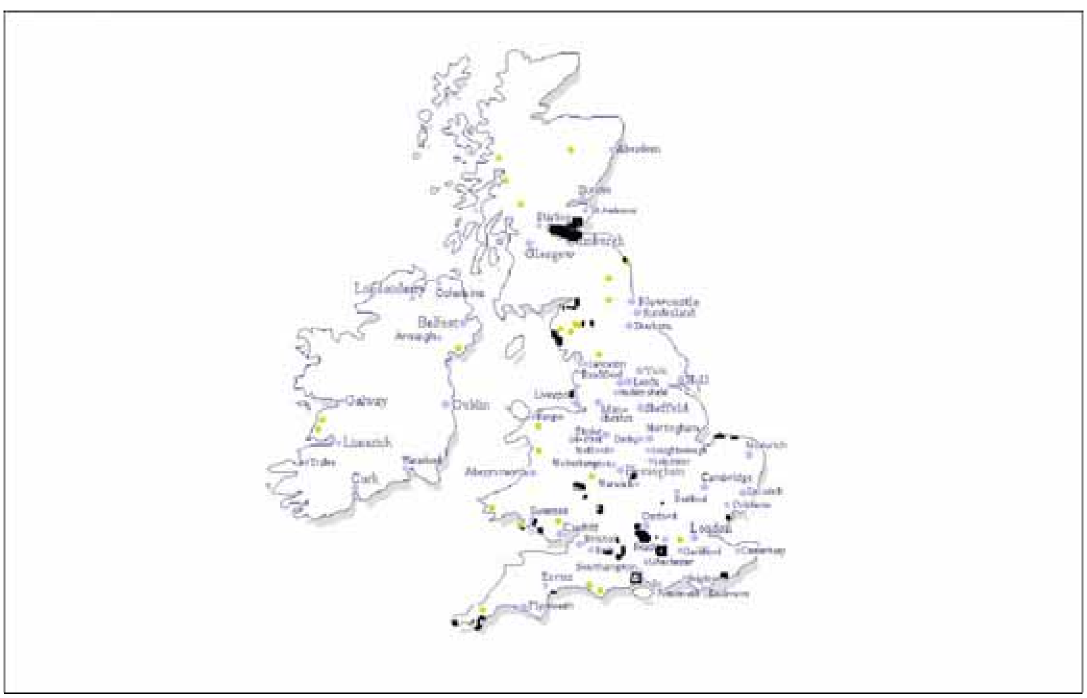

Figure 48. Environment Agency UK CASI coverage (source : pers. comm. Kyle Brown, Environment Agency, 9/1/03)

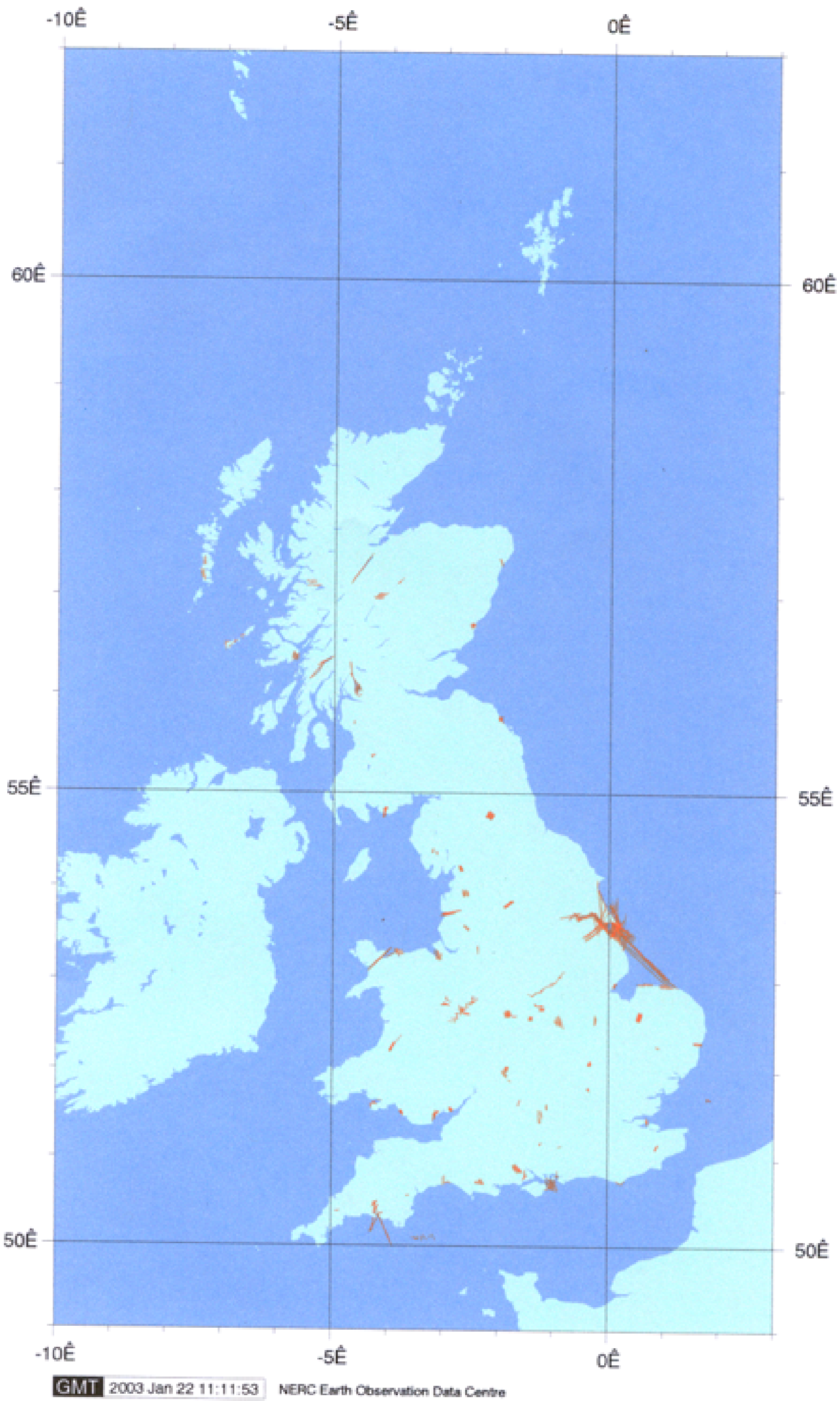

Figure 49. UK coverage of NERC airborne data (source pers. comm. Matt Pritchard, NERC EO Data Centre, 22/1/03)

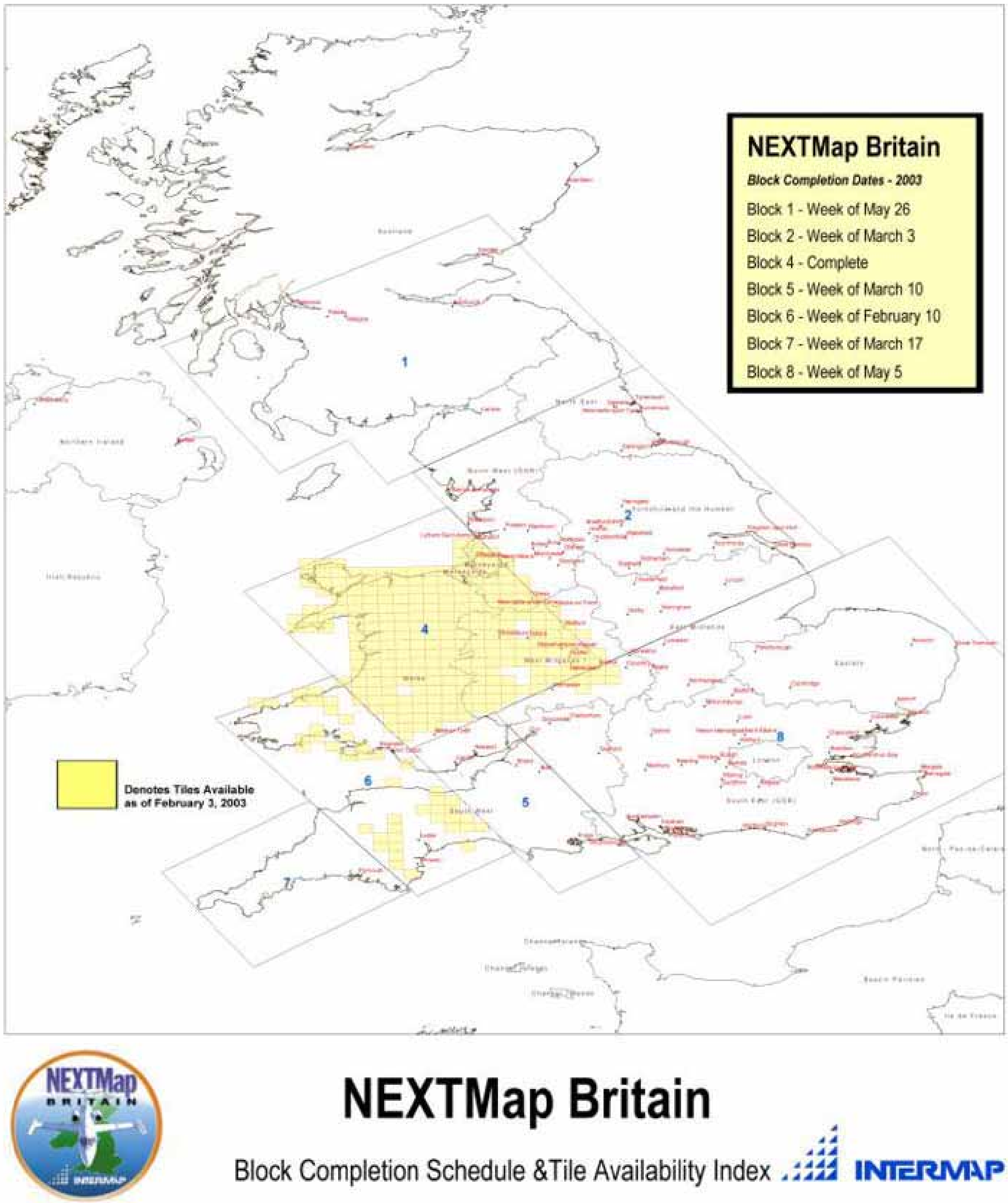

Figure 50. UK coverage of the NEXTMap X-band interferometric SAR
(source : http://www.globalterrain.com/NEXTMAP/, 14/2/03)

11. Conclusion

Three very different lowland raised bogs were studied, using a wide range of remotely sensed data and analytical methods. The main conclusion we have drawn from this study is that the identification of bog condition categories using remote sensing is best achieved using the following data sources:

1. High spatial resolution remotely sensed data (4 metre pixel size proved ideal for the bogs we studied)
2. Multispectral data. Unlike most vegetation communities, we found that data in the near infra-red were relatively less important than those in the visible wavelengths. However, we found clear evidence of additional information on bog condition in the short-wave infra-red region (1.55 – 1.75_m).
3. Information on bog surface microrelief. We found that the most effective way to include these data was visual interpretation of digitally processed lidar images. Fully automated analysis of the lidar data was less effective, possibly because the human interpreter can more easily discriminate between irrelevant detail and those patterns characteristic of disturbance and human interference. Where lidar data were unavailable, as at Ballynahone and Cors Caron, visual interpretation of colour aerial photographs provided an adequate substitute, especially if stereo interpretation was used.

The major drawbacks of aerial photographs were the need to mosaic individual images to achieve the spatial coverage necessary and the lack of radiometric calibration. Scanning the photographs and balancing the colour and contrast sufficiently to allow the classification to proceed was a lengthy process which could be avoided by using Ikonos data and airborne lidar. Although we found it necessary to geometrically correct the Ikonos data, the distortion was much less severe than the aerial photography, and the lidar data were provided in 2km tiles already registered to the OS National Grid.

The final conclusion concerns the creation of the final bog condition classification map. The many subtle combinations of classes present and the different views held by those involved in mapping and managing such communities means that any particular categorisation is rarely final. Digital image processing offers a way to present data in an objective manner which can then be interpreted according to the current understanding and needs of the user. In particular, the rule images produced as a by-product of the maximum likelihood procedure are an ideal starting point for an expert system approach to bog condition classification. They encapsulate the degree to which each pixel is similar in spectral terms to one of several ‘end-member’ communities, which may be precisely defined in spectral terms or may be defined by the user to represent ‘ideal’ classes. The allocation of pixels in the image to a single class could be most intelligently achieved using information from the rule images, constrained by the evidence on surface micro relief provided by the lidar data.

12. Acknowledgements

The authors would like to acknowledge the assistance given by the landowners, tenants and site managers at each of the three sisters visited in the field: Frank Mawby and Alan Todhunter at Wedholme Flow; Paul Culyer and Andy Tolky at Cors Caron; and Dermot Hughes, Director of Programmes, Ulster Wildlife Trust at Ballynahone. Additionally, we thank Peter Jones for assistance in the field at Cors Caron. NERC provided the Airborne Thematic Mapper data of the Cors Caron site, the Environment Agency the lidar data, and Infoterra PLC the Ikonos data for Wedholme Flow.

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14. Appendix

Table 23. Vegetation quadrats from Wedholme Flow

	WHF-1	WHF-2	WHF-3	WHF-4	WHF-5	WHF-6	WHF-7	WHF-8	WHF-9	WHF-10	WHF-11	WHF-12	WHF-13	WHF-14	WHF-15	WHF-16	WHF-17	WHF-18	WHF-19	WHF-20
Calluna vulgaris	20	4	1		90	<1			<1	<1	<1		2	90	65		5	70		28
Erica tetralix	25	30	5						4			<1	3				2		7	4
Andromeda polyfolia	2	2	3						2			<1	2						3	2
Oxycoccus palustria												18	6						5	4
Eriophorum. angustifolium	2	2	<1	+				20	2					+		+			10	<1
Erio. vaginatum	4	3	25	25	<1	25	70	<1	7			6	6		15	30	25	15	10	20
Rhynchospora alba	2	25	5		<1				25											
Molinia caerulea					<1	25				25	25	25	30	R	1	2	1			
S. subnitens	43		2										14							
S. capillifolium		3	9																25	30
S. cuspidatum			2	75			25	80	35								25			
S. papillosum	5	6	5						9			8						1		7
S. fallax												4								
S. magellanicum	10	<1	1						1					<1					20	20
S. tenellum	8	20	15																5	15
S. gimbriatum												1								
Sphagnum, total	65	28	30																50	70
Odontoschisma sphagni	10	12	10																15	15
Hypnum cupressiforme						2														
Myrica gale										50	45									
Cladonia unicalis																				
Calypogeia											<1									
Dryopteris spec											<									
Potentilla erecta										2	3									
Betula pubescens	+																			

Leucobryum glaucum																				
Cladonia fimbriata																				
Drosera rotundifolia	2	1	<1						<1					1	1			<1	1	1
D. anglica									R											
Open Waterpools							5									70	40			
bare peat														10						
Dicranum												1								
Dicranum ähnl. Moos																				
Vaccinium myrtillus										<1										
Polytrichum strictum												3								
P. commune																				
Aulacommnium palustre											<1	1								
GPS - position	NY 21780 BNG 54571	NY 21504 BNG 5431^7	NY 21224 BNG 54192	NY 21302 BNG 54097	NY 21302 BNG 54097	NY 21700 BNG 54313	NY 21709 BNG 54316	NY 21733 BNG 54256	NY 21690 BNG 54331	NY 21350 BNG 53188	NY 21344 BNG 53157	NY 21358 BNG 53224	NY 21363 BNG 53240	NY 21778 BNG 53263	NY 21613 BNG 53221	NY 21613 BNG 53221	NY 21468 BNG 53226	NY 21468 BNG 53226	NY 21291 BNG 52785	NY 21284 BNG 52779

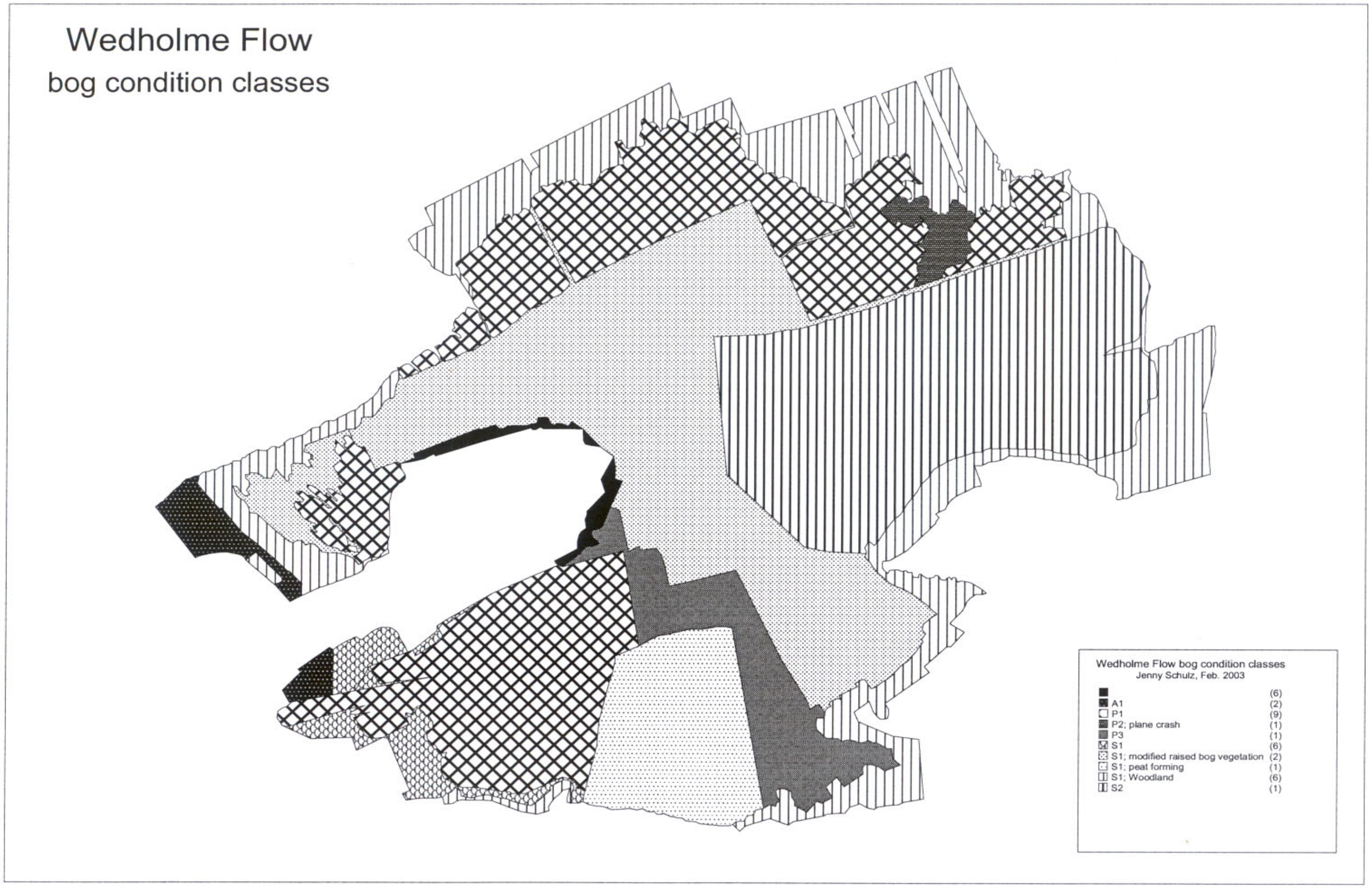

Wedholme Flow
bog condition classes
Wedholme Flow bog condition classes
Jenny Schulz, Feb. 2003
(6)
A1 (2)
P1 (9)
P2; plane crash (1)
P3 (1)
S1 (6)
S1; modified raised bog vegetation (2)
S1; peat forming (1)
S1; Woodland (6)
S2 (1)

Table 24. Vegetation quadrats from Cors Caron

	SE-1	SE-2	SE-3	NE-1	NE-2	NE-3	NE-4	NE-5	NE-6	W-1-2	W-1-8	W-1-18	W-F-6	W-F-10	W-F-16	W-J-2	W-J-12	W-J-14
Calluna vulgaris	4	2	3	2	1			4	10		12	10	10	30	10	30	7	1
Erica tetralix	15	17	17	20	2	<1			12		4	4	8	8	3	6	6	6
Empetrum nigrum											2	2	1	3	1			
Andromeda polyfolia	4	6	6	3	2	2			2		3	2	3	4	3	3	4	2
Oxycoccus palustris						3					2	5	3	3	4	2	6	1
Eriophorum angustifolium	<1	<1	<1	1	<1	<1			<1		+	<1	<1		+	<1		
E. vaginatum	8	8	10	6	1	30			8		18	12	15	20	15	10	5	5
Rhynchospora alba	5	6	3	<1	<1				10		1	<1	1	<1	1	1		
Scirpus cespitosus	3	6	4	5	2				3		2	2	1		4	4		1
Narthecium ossifragum				<1	<1							1	1	<1	<1			
Molinia caerulea	3	R	1	<1	1	<1	1	80		75							30	30
Sphagnum subnitens				3							<1		1	3				
S. capillifolium					6							4				<1	5	
S. cuspidatum	10	2	1	1	8				2		1		1			1		<1
S. papillosum	12	6	1		6	3			5		3	1	12	2	5	<1		
S. fallax																		
S. angustifolium						65												
S. magellanicum																		
S. tenellum	1	2	4		2				10			4	6	1	1	3		
S. pulchrum												6	3	1	2	28		
S. fimbriatum																		
***Sphagnum*, total**	**23**	**10**	**6**	**4**	**22**	**68**			**17**			**15**	**23**	**7**	**8**			
Odontoschisma sphagni	10	10	10	8	<1	<1			6		5	4	6	3	5	6		2
Hypnum cupressiforme	4	5		6	<1	<1		3		3	5	6	4	8	10	10	12	8
Pleurozium schreberi				<1	<1	<1											<1	
Myrica gale																		
Cladonia portentosa	6	6	4	15				1	12		20	9	7	7	15	5	10	20
C. unicalis		<1	<1						<1			1		3				
C. cenotea		<1	<1								<1					1		
C. ciliate			1	3					3			1	1					

Potentilla erecta																		
Betula pubescens																		
Leucobryum glaucum				<1									2	<1		1	2	<1
Cladonia fimbriata		<1	<1								<1			<1				<1
Drosera rotundifolia	<1	<1		<1	1	<1			<1			<1	<1	<1	<1	<1		
D. intermedia													<1					
Open Waterpools																		
Dicranum c scoparium			<1	2	1													
Vaccinium myrtillus																	1	
Polytrichum strictum						3								<1				
P. commune																		
Aulacomnium palustre																		
Salix cinerea							80											
Agrostis canina							40											
Carex canescens							1											
C. lasiocarpa							1											
C. nigra																		
Holcus lanatus							<1											
Juncus effusus							18											
Rhytidiadelphus triquetrus							2											
Eurhynchium praelongum							3											
Rumex spec.							<1											
Rumex acetosa																		
Comarum palustre							<1											

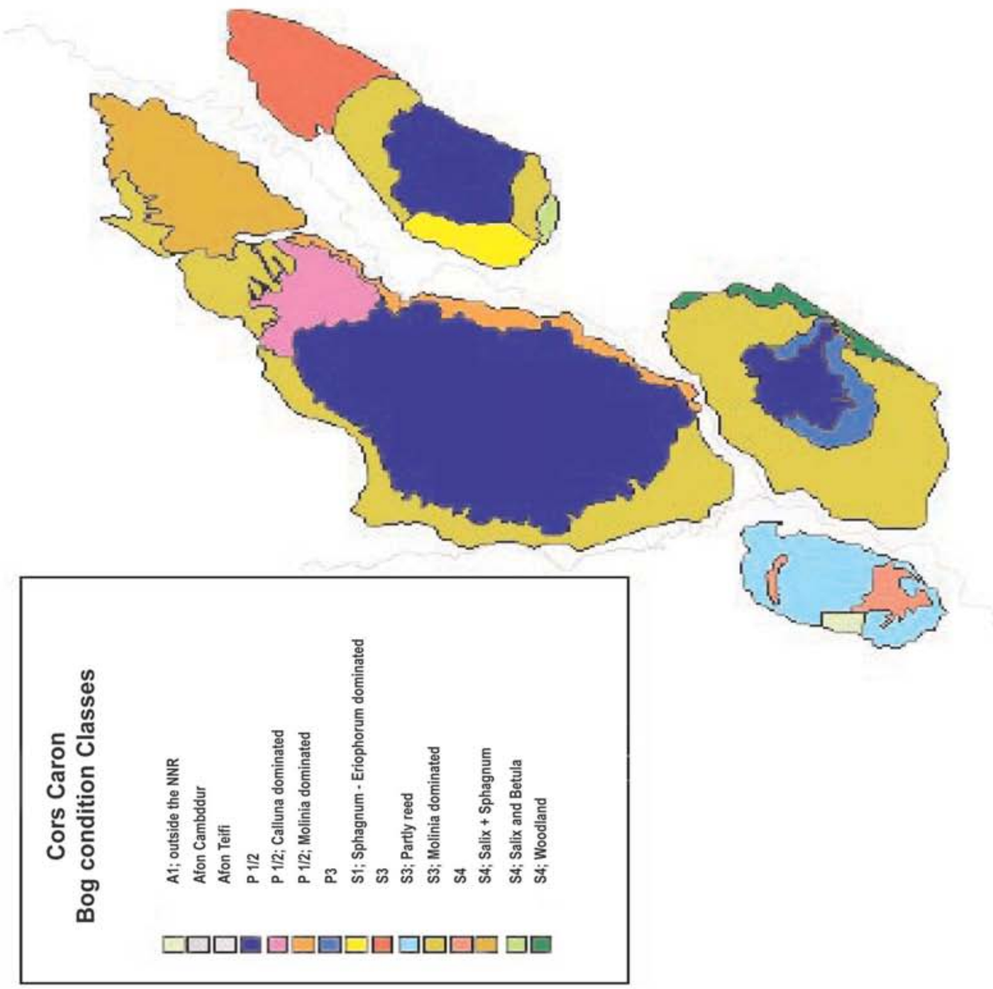
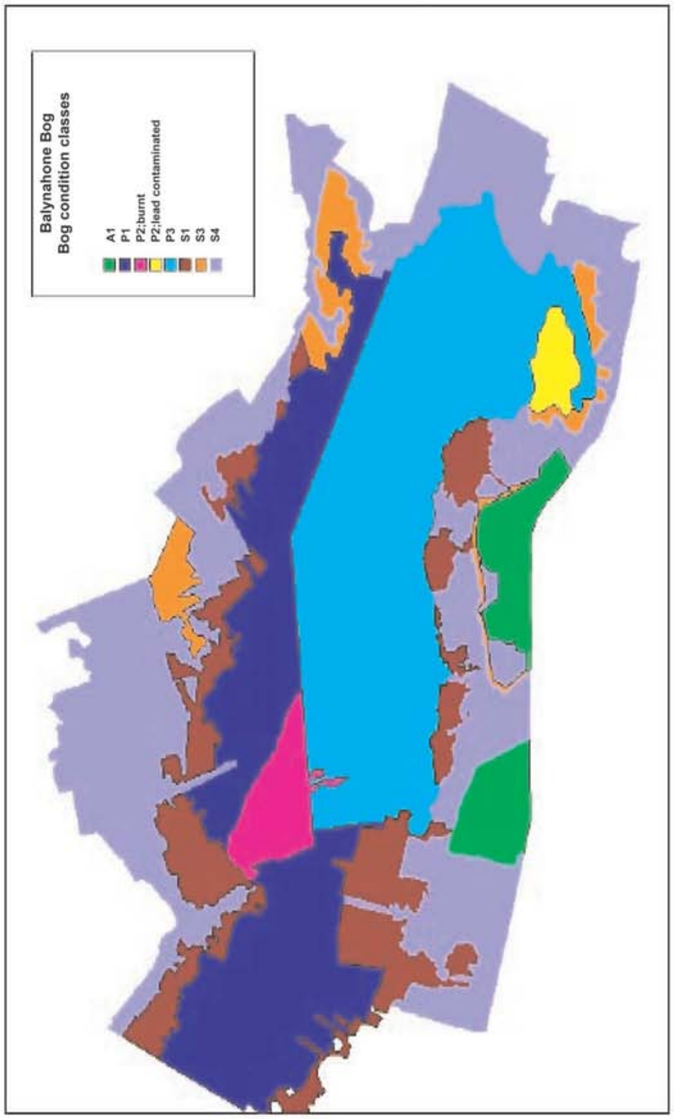

Cors Caron
Bog condition Classes
A1; outside the NNR
Afon Cambddur
Afon Teifi
P 1/2
P 1/2; Calluna dominated
P 1/2; Molinia dominated
P3
S1; Sphagnum - Eriophorum dominated
S3
S3; Partly reed
S3; Molinia dominated
S4
S4; Salix + Sphagnum
S4; Salix and Betula
S4; Woodland

Table 25. Vegetation quadrats from Ballynahone Bog

	BYH-1	BYH-2	BYH-3	BYH-4	BYH-5	BYH-6	BYH-7	BYH-8	BYH-9	BYH-10	BYH-11	BYH-12	BYH-13	BYH-14	BYH-15	BYH-16	BYH-17	BYH-18	BYH-19	BYH-20	BYH-21	BYH-22
Date					15/10/2002											16/10/2002						
Betula pubescens, tree layer																						50 (tree layer)
Betula pubescens, field layer							<1													1	<1	
Myrica gale								10	<1	<1												
Calluna vulgaris		<1	45	12	70	45	75	65	40	40	30	1	10	5	12	6	50	35	50	30	90	
Erica tetralix		1	10	10	10	10	4		8	8	8		6	20	15	10	6	8	8	3	1	
Vaccinium oxycoccos								4	4	4	1											
Drosera anglica									r													
Drosera rotundifolia				<1		<1					<1					<1	<1		<1			
Eriophorum angustifolium	2	1	<1	<1	3	<1	<1		<1	<1	1	3	<1	1	1	<1	<1	<1	<1	2	<1	<1
Eriophorum vaginatum		1	5	30		5		8	12	10	3	8	5		1		3	2	<1	6	1	1
Juncus effusus																						1
Narthecium ossifragum		<1		1		1		1		<1	<1			3	4	4	1	<1				
Rhynchospora alba						3					<1		3	3	1	2	2	<1	1			
Scirpus cespitosus			1	3	<1	3	1			2	2		10		2	3	<1	1	1			
Total *Sphagnum*			**8**	**14**	**6**	**20**	**<1**	**34**	**41**	**61**	**40**	**78**	**36**	**10**	**18**	**10**	**22**	**30**	**31**	**8**		**56**
Sphagnum capillifolium			1	4		6		30	20	40	10		15	1	2	1	2	8	8			1
S. fimbriatum																				1		30
S. subnitens			4	2		1		1			2	50	3	3	6	4	3	8	5	2		
S. magellanicum			<1	<1	1	4		2	1	1	10		2	1	2	1	1		1			
S. palustre																						25
S. papillosum			<1	2	1	4		1			10	18	10	3	6	2	11	8	10			
S. angustifolium								<1														
S. cuspidatum												10					1			5		
S. pulchrum																			5			
S. tenellum			3	6	4	5	<1		20	20	8		6	2	2	2	4	6	2			
Aulacomnium palustre									<1													
Campylopus flexuosus		1							<1					3				<1				
Dicranum scoparium													<1				5					
Hypnum cupressiforme			4		4	2	6	3	4	6	2		4	1	<1	4	<1	2	1		8	6

Leucobryum glaucum																1						
Odontoschisma sphagni				10	15	10			6	6	10		12	8	8	6	1	2	5			
Polytrichum commune																				15		30
Polytrichum strictum					<1			<1														
Cladonia cenotea													<1	1				1				
Cladonia fimbriata		>1				<1										<1						
Cladonia portentosa			6	<1				<1	2									2	5		<1	
Zygogonium ericetorum	25	6	<1	<1	<1	<1	<1						1	<1		<1						
Open Water																				3		
Grid Reference	IH 86475 ITH 97455	IH 86461 ITH 97449	IH 86474 ITH 97611	IH 86430 ITH 97734	IH 86444 ITH 97787	IH 86361 ITH 97812	IH 86244 ITH 97720	IH 86479 ITH 98021	IH 86381 ITH 98049	IH 86299 ITH 98072	IH 86261 ITH 97871	IH 85302 ITH 97890	IH 85401 ITH 98143	IH 85477 ITH 98165	IH 85532 ITH 98179	IH 85542 ITH 98114	IH 85020 ITH 98310	IH 85111 ITH 98231	IH 85218 ITH 98113	IH 85364 ITH 97952	IH 85364 ITH 97952	IH 85297 ITH 97681
Comments	lead contaminated	lead contaminated										cut		burnt	burnt	burnt					cut	cut


Balynahone Bog
Bog condition classes
A1
P1
P2;burnt
P2;lead contaminated
P3
S1
S3
S4