

STRIVE

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Identification, Mapping, Assessment and Quantification of the Effects of Disturbance on the Peat Soil Carbon Stock in Ireland

STRIVE

Environmental Protection
Agency Programme

2007-2013

Environmental Protection Agency

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EPA STRIVE Programme 2007-2013

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The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Table of Contents

Acknowledgements	ii
Disclaimer	ii
Details of Project Partners	iii
Executive Summary	vii
1 General Introduction	1
1.1 Background	1
1.2 The Global Carbon Cycle	1
1.3 Controls on the Peatland Carbon Stock	2
1.4 Definition of Peatland	3
1.5 Peatland Formation	3
1.6 Peatland Distribution in Ireland	4
1.7 Irish Peatland Carbon Stock	4
1.8 Classification of Peatland Disturbance	5
1.9 Peatland Disturbance	6
1.10 Potential Impact of Disturbance on the Carbon Flux and Peat Soil Organic Carbon	9
1.11 Remote Sensing and Peatland Disturbance	10
1.12 Overall Project Aims	11
2 Classifying Peatland Disturbance	13
2.1 Introduction	13
2.2 Methods	13
2.3 Results and Discussion	16
2.4 Conclusions	19
3 Object-oriented Classification of Disturbance in Irish Peatlands using Medium- and High-resolution Satellite Imagery	20
3.1 Introduction	20
3.2 Methodology	22
3.3 Results	29
3.4 Discussion	34
3.5 Conclusion	41

4	Detecting Drainage using an Object-oriented Method and High-resolution Satellite Imagery	42
4.1	Methodology	42
4.2	Results	44
4.3	Discussion	44
4.4	Conclusion	44
5	Overall Conclusions and Recommendations	45
5.1	Conclusions	45
5.2	Recommendations	46
5.3	Key Recommendations	47
	Acronyms and Annotations	48
	References	49

Executive Summary

Until recently, soil organic carbon (SOC) was an often over-looked part of the global carbon cycle. However, EU level legislation – for example, the EU's Thematic Strategy on the Protection of Soil (and its accompanying proposal for a Soil Framework Directive) requires that SOC stocks are monitored for degradation that has occurred or is likely to occur through land-use change, erosion or landslides and climate change.

In Ireland peatlands are extensive, covering between 17% and 20% of the national land area. The most recent estimate of the peatland SOC stock is 1566 Mt C or 75% of the national SOC stock. In the natural system, carbon (C) sequestration and emission is balanced. However, where peatlands are disturbed, this balance is upset and C emission can exceed C sequestration. Disturbance can be caused by both natural and anthropogenic processes. A key element when accounting for disturbance of peatlands is the definition of what disturbance is and how to describe or classify it. Peatland disturbance is defined, in this study, as *'any natural or anthropogenic event that interrupts the natural trajectory of growth of the peatland'*. In Ireland the rate of disturbance has accelerated over the last seventy years.

A framework for classification was developed to characterise the type and severity of the disturbance. Disturbance in peatlands can affect hydrology, vegetation and C stock to differing degrees. These components form the basis of the classification which is a gradient of absolute disturbance. A disturbance cube was developed to help visualise the type and severity of different types of disturbance and to enable an observer to quickly establish the category of disturbance. The disturbance cube offers a robust, rapid and reproducible method of classifying peatland disturbance. The subjective nature of assessing peatland disturbance was assessed through a comparison of opinions solicited from independent experts and by then comparing these opinions with the disturbance classification derived using the disturbance cube framework. This analysis provided confidence that the disturbance cube is a reliable and meaningful method for determining peatland disturbance.

An object-oriented method was used to examine very high-resolution satellite images (1 m to 4 m spatial resolution) of raised peatland sites throughout the midlands of Ireland. Peatland disturbance is relatively easy to identify on the ground, but it is difficult to quantify and challenging to define a systematic method of isolating where disturbance has occurred. The extent of raised bogs was delineated from the Derived Irish Peat Map version 2 (DIPMV2). An object-oriented approach was used to produce maps of disturbance type from medium- (India Remote Sensing) and high-resolution (*Geoeye-1* and *Ikonos*) imagery. The main disturbance types identified were conversion to pasture, afforestation, draining, cutover and cutaway peatlands. The medium-resolution imagery was useful for examining peatland disturbance over large areas, but there was added value in developing maps using high-resolution imagery. The overall accuracy assessment for the disturbance maps was between 62% and 90%. The methodology allows the extent and severity of disturbance to be identified, which is a critical issue for quantification and security of the peatland C stock.

Due to the lack of high-resolution imagery on a nationwide basis the object-oriented method was applied to medium-resolution imagery (23 m spatial resolution). This enabled just three classes to be identified from the landscape: forestry, pasture and peatland. The extent of peat was delineated from the DIPMV2 and therefore the forestry and pasture classes were defined as disturbance. However, the resolution was not good enough to determine disturbance on the peatland classes. Much of the disturbance is caused by the planting of forestry on peatlands. This is particularly extensive on upland areas in the midlands, west Kerry and in the border region. The national scale map of disturbance shows the extent of pasture, forest and industrial classes as well as peat classes and is a first attempt to show the spatial extent of disturbance. However, the spatial resolution of the satellite imagery means that it is difficult to discriminate different types of disturbance on the peatland areas.

This research goes some way to addressing the BOGLAND recommendation for the management of peatlands for biodiversity: MPB4 – *the development of an inventory of the condition of all peatlands*. However, more work is needed to further discriminate the levels and extent of disturbance on all of Ireland's peatlands. This research shows that the use of high-resolution imagery at several sites improved both the identification of disturbance types and the accuracy of detecting that disturbance (high-resolution imagery is up to 23% more accurate), thus producing much more accurate disturbance maps when compared to medium-resolution imagery. Therefore, the determination of the full extent of disturbance on Irish peatlands would benefit from a nationwide database of geo- and ortho- rectified high-resolution imagery. This data would be examined with object-oriented methods to produce accurate maps of peatland disturbance.

Further research is also needed to quantify the effect of different disturbance types on the peatland SOC stock; this includes the placement of eddy covariance flux towers or gas flux chambers to monitor C fluxes at various disturbance sites as well as an extensive ground survey to record bulk density, C content and peat depth. The data from such a project would enhance our knowledge of the total peatland SOC stock, identify emission or uptake hotspots and also enable land managers to make informed decisions with regard to

conservation and restoration of peatlands as well as developing procedures to deal with future disturbances such as climate change.

Key Recommendations

- Acquisition of high and very high-resolution imagery of peatlands nationwide in order to create a highly accurate assessment of peatland disturbance using object-oriented methods.
- An extensive ground survey of peatlands to collect data relating to C density and peat depth.
- The disturbance cube classification framework has been demonstrated to be a reliable assessment of peatland degradation. It is recommended that the method be adopted more widely by those engaged in peatlands assessment.
- Establish a network of eddy covariance flux towers or gas flux chambers on both disturbed and undisturbed peatlands nationwide to acquire data on the impact of different disturbance types on the peatland C stock.
- Educate the public and peatland users about the impact of peatland disturbance on the peatland C stock. This should be based on a policy that informs from the bottom-up rather than a top-down approach.

1 General Introduction

1.1 Background

Until recently, soil organic carbon (SOC) was an oft over-looked part of the global carbon (C) cycle (Leifeld et al., 2005). However, recent EU level legislation, for example the EU's Thematic Strategy on the Protection of Soil (and its accompanying proposal for a Soil Framework directive) require that SOC stocks are monitored for degradation that has occurred or is likely to occur through land-use change, erosion or landslides and climate change. In climate change studies, peatland SOC is being recognised as a potential source or sink of CO₂. When disturbed, peatlands can emit large amounts of CO₂ and undisturbed peatland may act as a CO₂ sink. European Union (EU) and national policies now aim to protect the soil organic matter (SOM) and thus protect peatland SOC stock.

1.1.1 Thematic Strategy for Soil Protection

The aim of the Thematic Strategy for Soil Protection is 'to ensure that Europe's soils remain healthy and capable of supporting human activities and ecosystems' (EU, 2006). The legislative proposal for a Soil Framework Directive accompanying the strategy will oblige Ireland to tackle threats such as landslides, contamination, soil erosion, the loss of SOM, compaction, salinisation and sealing wherever they occur, or threaten to occur (Schils et al., 2008). Many of these threats are relevant to peatlands; landslides and bog bursts have been recorded at several locations around Ireland. Notable occurrences were at Cuilcagh Mountain, Co. Fermanagh and at Pollatomish, Co. Mayo (Dykes et al., 2008; Long and Jennings, 2006) as well as at Derrybrien, Co. Galway (Warburton et al., 2004a). Soil erosion and the loss of SOM are particularly pertinent with regard to peatlands. Bradshaw and McGee (1988) stated that upland blanket peat soil erosion is widespread throughout Ireland and that recent human activity, including overstocking, afforestation, turf-cutting and infrastructure (Douglas et al., 2008) has intensified erosion. Erosion in peatlands by its nature results in the loss of SOM. Increased levels of human activity in upland blanket bogs combined with climate

change projections make it essential to record threats and their current and possible future location (Sweeney et al., 2008).

1.1.2 Habitats Directive

Most of Ireland's biodiversity policy is influenced by the Habitats Directive (EU, 2007). The main aim of this directive is to achieve favourable conservation status for habitats, including active raised and blanket bogs and degraded blanket bogs (EPA, 2008). A recent National Parks and Wildlife Service (NPWS) report on their condition shows that Irish peatlands have a bad overall conservation status (NPWS, 2008). In Ireland, the Environmental Protection Agency (EPA) is responsible for monitoring and assessing activities associated with environmental protection. The EPA has identified four priority challenges that are in line with Ireland's national and international obligations (Coll et al., 2009):

- 1 Limiting and adapting to climate change;
- 2 Reversing environmental degradation;
- 3 Mainstreaming environmental considerations;
- 4 Complying with environmental legislation and agreements.

1.2 The Global Carbon Cycle

In the natural system, C removal and sequestration from the atmosphere and emission to the atmosphere are in equilibrium on an annual or multiple annual timescale. In the global terrestrial system, C is removed from the atmosphere through photosynthesis and Gross Primary Productivity (GPP) at a rate of 120 GtC y⁻¹ (IPCC, 2001), 50% of this carbon is re-emitted through plant respiration resulting in Net Primary Productivity (NPP) value of 60 GtC y⁻¹. The remaining C is returned to the atmosphere, through processes like fire and (animal) organism respiration as they consume the plant matter (Schils et al., 2008). These natural CO₂ effluxes are an order of magnitude bigger than the human effluxes, but they are in equilibrium with the amount of CO₂ removed from the atmosphere by the plant growth. Anthropogenic effluxes of CO₂ act as a perturbation to the

natural equilibrium. During the 1990s, human activities such as land-use change, fossil-fuel combustion and cement production were estimated to have emitted an extra 7–8 GtC yr⁻¹ to the atmosphere. The natural world responds to the additional CO₂ availability in the atmosphere through increased uptake; nevertheless, it has been shown that all the additional CO₂ is not removed by photosynthesis or GPP (Ballantyne et al., 2012). This has led to an increase in an atmospheric burden of CO₂ in the atmosphere of the order of 3 GtC yr⁻¹ (Schils et al., 2008).

Even though the global SOC stock is estimated to be 1500 GtC, this accounts for only the SOC found in the top 1 m of soil. Soil organic carbon stocks contain twice as much C as that found in the atmosphere (760 GtC) and triple the amount found in vegetation (500 GtC) (Davidson and Janssens, 2006). In the C cycle, peatlands are unique in that they sequester and store C over relatively long periods of time – effectively removing it from the system.

1.2.1 Peatland component of the global carbon cycle

Peatlands are an important and dynamic global C pool (Gorham, 1991). They can make significant contributions to national C fluxes (Clymo et al., 1998; McGettigan et al., 2010; Tolonen and Turunen, 1996). When peat is actively forming, it sequesters CO₂ from the atmosphere to create a potentially long-term C store (House et al., 2010) within the peatland ecosystem. If this ecosystem is disturbed, the stored C is at high risk of being mobilised and emitted into the atmosphere.

The peatland SOC stock is important because it also contains up to ten times more C per unit area than mineral soils (Dise, 2009); therefore, relatively small peatland areas can contain large amounts of carbon. Peatlands cover about 3% of the earth's surface. (Gorham, 1991; Worrall et al., 2009; Worrall et al., 2003; Roulet, 2009), yet they contain about one-third of all terrestrial SOC. Peatlands are estimated to store about 612 GtC (Yu et al., 2010b), most of which is found in northern peatlands (estimated to be between 455 and 547 Gt of carbon), tropical and southern peatlands contain 40 and 15 GtC, respectively (Gorham, 1991; Turunen et al., 2002; Yu et al., 2010a). These C stocks are the largest near-surface reserves of terrestrial organic C and therefore their stability has important implications for climate change (Page et al., 2002).

1.3 Controls on the Peatland Carbon Stock

The SOC stock in peatlands is controlled by the balance between the inputs and outputs of C in the below-ground environment. This balance can be influenced by numerous factors, including climate change. The main input to the system is plant detritus and outputs are dominated by the efflux of CO₂ from the root respiration and the microbial aerobic decomposition of organic matter in the soil, and decomposition in anaerobic conditions, which produces methane (CH₄).

Hydrologic leaching of particulate and dissolved C can also be important (Dinsmore et al., 2011; Davidson and Janssens, 2006). These processes are regulated by both temperature and hydrology (Xiang and Freeman, 2009). Low temperature inhibits chemical and biochemical reactions in the soil and root respiration while microbial decomposition is subject to water limitation (Davidson and Janssens, 2006). Hydrology controls the balance between aerobic and anaerobic conditions with high water tables enabling peatlands to maintain anaerobic conditions. It is these anaerobic conditions that inhibit the production of biodegradative hydrolase enzymes and allow C to accumulate (Anderson et al., 2009; Brown et al., 2007; Davidson and Janssens, 2006; Evans et al., 1999; Freeman et al., 2001b). Therefore, the peatland C stock accumulated over centuries is only stable as long as anaerobic conditions are sustained (Charman, 2002; Davidson and Janssens, 2006).

Nevertheless, the regional impact of climate change may change the balance of inputs and output. The average global surface temperature has increased by 0.76°C from 1850–1899 to 2001–2005 (IPCC, 2007). The projections for future climate change state that the global average surface temperature is likely to increase by approximately 1.8°C to 4.0°C over the present century relative to the 1980–1999 period (Sweeney et al., 2008). Precipitation increases are likely by the middle of this century in the mid to high latitudes, with large year-to-year variations (Giorgi and Bi, 2005; Sweeney et al., 2008).

Most C uptake processes are sensitive to climate change (Luo, 2007), and peatland emissions of CO₂ are dependent on temperature and water table levels (Luo et al., 2004). However, there is considerable uncertainty as to the effect of climate change on soils and particular in peat soils.

Bridgman et al. (2008a) report that peatlands can gain or lose large amounts of soil C within a few years. Peatlands located in the higher latitudes are expected to receive increased winter and decreased summer precipitation.

1.4 Definition of Peatland

Many studies use the terms 'peat' and 'peatland' interchangeably. In this study the terms 'peat', 'peat soil' and 'peatland' are based on the definitions set out in Connolly and Holden (2009) and Renou-Wilson et al. (2011):

- **Peat:** a sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material;
- **Peat soil:** organic soil materials which have accumulated sedentarily and have at least 30% (dry mass) organic matter over a depth of at least 45 cm on undrained land and 30 cm deep on drained land; the depth requirement does not apply in the event that the peat layer is over bedrock;
- **Peatland:** a geographical area where peat soil occurs, and, for mapping purposes, a peatland should cover a minimum spatial extent of 1 ha.

These definitions will be adopted for this study, but it should be noted that the definition of a peatland has to be conceptually extended to include the complete ecosystem that is integrated with the peat soil.

1.5 Peatland Formation

Peatlands are classified as either 'ombrotrophic' or 'minerotrophic'. Minerotrophic peatlands receive water from subsuperficial waters (Chesworth, 2008) while ombrotrophic peatlands receive their water and nutrient supply solely from the atmosphere (Charman, 2002). In Ireland, the dominant peatland type is ombrotrophic and this is sub-divided into blanket or raised bog. Some minerotrophic peatlands do exist but they are small in number and area. The main factors that contributed to raised and blanket bog development were an oceanic, warm and wet climate, combined with anthropogenic influences such as the clearing of woodland by early settlers (Charman, 2002; Hammond, 1979; Huang, 2002; Mitchell and Ryan, 1997; O'Connell, 1990). Irish peatlands began to develop during the Holocene after the retreat of the Midlandian glaciers approximately 17,000 to 13,000 14C years BP (Before Present)

(Knight, 2003; Warren et al., 2002). The retreat of the glaciers left behind an undulating landscape studded with lakes and large water-filled basins. Slowly these lakes were in-filled by partially decomposed organic matter to create low-nutrient fens (Aalen et al., 1997; Bennett and Glasser, 1996; Feehan and O'Donovan, 1996; Tallis, 1998). The formation of raised bogs, often developing over fens, began early in the Holocene at approximately 7,000 to 5,000 14C years BP. These bogs are mainly confined to areas where the annual rainfall is between 750 and 1000 mm (Schouten, 2002).

Hammond (1981) subdivided raised bogs based on vegetation type, with the most common being Midland and Transitional. Raised bogs have a distinctive dome shape that can be elevated to a height of several metres above ground water influence. They also have a clearly defined perimeter called a 'rand' (Moore, 2002). Over the past 7,000 years raised bogs in Ireland have attained a maximum depth of between 9 and 12 m, but the average is about 7 m (undisturbed) (Coll et al., 2009; Feehan and O'Donovan, 1996; Hammond, 1979).

Blanket bogs in Ireland are subdivided into 'Low-level Atlantic' and 'Montane', based on elevation (Feehan and O'Donovan, 1996; Hammond, 1979; Schouten, 2002). The climate for blanket bog formation in upland and lowland areas is typified by very high annual precipitation levels (>1250 mm) and over 200 days of rainfall (Hammond, 1979; O'Connell, 1990; Schouten, 2002). All of Ireland's Low-level Atlantic blanket bogs and much of its Montane blanket bogs are located along the Western seaboard. However, Montane blanket bogs can also be found in counties Antrim, Down, Offaly, Tipperary, Tyrone, Waterford and Wicklow.

Blanket-bog formation began locally in some regions as early as 9,400 years BP. Blanket bog initially develops in discrete locations and ultimately fuses into a widespread peatland ranging in depth from 2 to 8 m, with an average depth of 3 m on lowlands and 1.5 m in mountainous regions (Feehan and O'Donovan, 1996). The most active stage of growth was between 5,100 and 3,100 years BP (Tallis, 1998). Throp and Glanville (2003) dated charcoal in the basal layer of blanket bog in the Liffey catchment to 6,800 to 6,630 years BP.

Hammond (1979) showed that different peatland types have different vegetation and that specific communities depend on microtopography and conditions of growth.

Microtopography, on both raised and blanket bogs, ranges from natural features such as pools, hollows, lawns, flats and hummocks (Schouten, 2002) to anthropogenic features, including turf banks and drainage ditches (Feehan and O'Donovan, 1996). Each microtopographical feature has a distinct vegetation type associated with it, depending on the nutrient and water requirements of the plants (Bryant and Baird, 2003). Pools for example contain aquatic plant species such as *Sphagnum cuspidatum* and *Cladopodiella fluitans*. Hummocks, on the other hand, are much drier and usually contain *Calluna* species (Schouten, 2002). Both vascular (*Calluna*) and non-vascular (*Sphagnum*) plants are present. *Calluna vulgaris* (Heather) has been a particularly successful vascular plant and can be found on all types of peatlands in Ireland (Mehner et al., 2004). It will flourish in drier locations where the groundwater table is not at the surface, such as along river courses and drainage channels and behind the cutover areas in old 'turbary' (see Section 1.9.2) areas (Feehan and O'Donovan, 1996; Schouten, 2002). Sphagnum is found extensively in Irish peatlands and is one of the most important peat-forming plants (Bubier et al., 1997; Feehan and O'Donovan, 1996; Mehner et al., 2004). It is extremely sensitive to changes in hydrology and individual species have adapted to different microtopographical features.

1.6 Peatland Distribution in Ireland

In Ireland peatlands are spatially extensive and cover between 17% and 20% of the national land area (Connolly and Holden, 2009; Hammond, 1979) as raised and blanket bog, or fen, but pristine peatland ecosystems are very rare. The distribution of peat soils varies greatly by region and county, and the exact area of these soils is difficult to quantify.

The extent of peatlands has been mapped over the past forty years. In the 'Peatland Map of Ireland', Hammond (1979) estimated that ombrotrophic peatlands extended over about 1.17 M ha. The 'General Soil Map', which was published around the same time as Hammond's map estimated that peatlands covered an area of 1.10 M ha (Gardiner and Radford, 1980a; Gardiner and Radford, 1980b). The differences in these two maps reflect the use of soil associations in the 'General Soil Map' legend. Compiled in 1990, the 'CORINE Land-cover Map' estimated that peat bogs covered 0.90 M ha

(O'Sullivan, 1994). The most recent CORINE (2006) estimated peat bog area as 1.09 M ha. This is most likely an underestimation of the extent of peat soils as CORINE is a land-cover map. Because many peat soil areas may be covered by forestry or pastures, they are not then classified as peatland in this context. CORINE also has a minimum mapping unit of 25 ha, so smaller peatlands areas do not appear. Connolly et al. (2007) and Connolly and Holden (2009) have been working on reducing the uncertainty surrounding peatland extent.

The Derived Irish Peat Map (DIPM) is a maximum likelihood map derived from the above three sources. The DIPM estimated peatland extent at 0.95 M ha (Connolly et al., 2007). However, industrial peatlands and fens were excluded from that study because of a lack of peat depth data. The DIPMV2 (Connolly and Holden, 2009) updated the DIPM, using the 'Peatland Map of Ireland' (Hammond, 1979) and new data from 'CORINE 2000' (Bossard et al., 2000) and the 'Indicative Soil Map of Ireland' (Daly and Fealy, 2007). The 'Indicative Soil Map of Ireland' has a mapping unit of 1 ha which is smaller than CORINE and other maps and therefore many previously unmapped peatlands, especially in the Drumlin Belt, across the north of Ireland (Clark and Meehan, 2001), were included in the DIPMV2. The area of peat estimated was 1.47 M ha.

The DIPMV2 represents the areal extent of peatlands that will be assessed in terms of degradation in this study. As with all maps, the issues surrounding scale and mapping units can lead to derived products containing systematic over- or under-estimations of a resource.

1.7 Irish Peatland Carbon Stock

The estimation of total peatland C stock can be calculated as a product of peatland area, peat depth, peat dry bulk density and proportion of C (Chapman et al., 2009; Tomlinson, 2005). Several studies have recently estimated peatland C stocks in Ireland and the UK using this method (Chapman et al., 2009; Eaton et al., 2008; Tomlinson, 2005; Tomlinson and Milne, 2006). In Ireland, owing to a lack of extensive peatland surveys of peat depth and bulk density there is uncertainty surrounding these parameters. However, recent calculations estimate the peatland stock to be in a range of between 1071 and 1570 Mt C. These figures could be improved if better data were available.

Tomlinson (2005) estimated that the peatland SOC stock was 1071 Mt C or 53% of the national stock. Eaton et al. (2008) calculated a national peatland SOC stock of 1503 Mt C or 62%. These figures were calculated using various peatland areas; 1.21 M ha (Eaton et al., 2008) and 1.19 M ha (Tomlinson, 2005). However, in Ireland, and particularly on blanket bogs, there is considerable uncertainty surrounding the spatial heterogeneity of peat depth, peat C densities and C content due to a lack of observations. The average peat C content ranges from 900 to 1247 t C ha⁻¹ but can be as much as 3025 t C ha⁻¹ in deep intact raised bogs (Tomlinson, 2005).

Renou-Wilson et al. (2011) estimated that peatlands contained 1566 Mt C or 75% of the national stock based on extrapolating the result for the SOC stock of blanket bogs in the Wicklow Mountains (Holden and Connolly, 2011). Holden and Connolly (2011) have suggested that, because of the undulating glacial landscape that underlies blanket bogs, modelled peat depths may create more accurate estimates of peat SOC stock. They estimated Irish blanket bog SOC stock to be approximately 1073 Mt C (similar to Tomlinson's estimate for the entire peat C stock). This value compares to a figure of 573 Mt C that was derived from work compiled by Tomlinson (2006) and may indicate that the total peatland SOC stock is higher than earlier estimates. However, the work by Holden and Connolly (2011) does not integrate disturbance data derived for this report.

1.8 Classification of Peatland Disturbance

In a normally functioning peatland ecosystem there is a balance between various cycles that occur in the peatland flora and fauna (Schulze and Mooney, 1994). Major disturbance incidences contribute to changes to the form and function of the peatland and lead to ecological change, particularly where the anaerobic condition is altered or the on-going accumulation of organic matter (and thus SOC) is reduced, stopped or even reversed (Benscoter and Vitt, 2008; Charman, 2002).

It is clear from the history of surveys of Irish peatlands and from global perspectives of peatland disturbance that there is a need to accurately describe peatland disturbance in order to have meaningful long-term monitoring of peatland C stores. Intact peatlands

store large amounts of C in an anaerobic environment which inhibits decomposition. This stored C becomes more vulnerable to loss to the atmosphere when these peatlands are disturbed. The peat above the water table becomes aerobic and begins to decompose several times faster than peat in the anaerobic zone (Freeman et al., 2001b). The drained peat is also dryer and potentially more vulnerable to fires. Deep peat fires, such as those that occur in Indonesia (Page et al., 2002) are not a problem in Ireland at present. However, in scenarios where summer warming is predicted they could become an issue (Sweeney et al., 2008).

Examining and classifying peatland disturbance is the first step to creating a meaningful way of measuring the extent and severity of disturbance. Cross (1990) developed a scoring system to evaluate the condition of Irish raised bogs from low (A) to high (D) supported by individual attributes of the sites, including damage to hydrology, habitat diversity and presence of rare species (Charman, 2002). Lindsay and Immirzi (1996) distinguished three types of disturbance in lowland raised bog environments:

- 1 Primary, which still contain an intact peat deposit but might be drained or burned;
- 2 Secondary where peat removal by hand and industrial cutting with some regeneration has occurred; and
- 3 Archaic where land has been claimed for agricultural purposes.

These categories can also be applied to blanket bog (Lindsay, 1995). Parkyn et al. (1997) used modifiers such as drainage, vegetation and erosion to aid in bog classification. Peat condition can be affected by natural processes and can be classified as indistinct, scarred, dissected by gullies or densely dissected (Wishart and Warburton, 2001). Charman (2002) discussed the classification of disturbance along a gradient from natural to artificial processes in relation to conservation and restoration; he states that the use of this type of system for examining peatlands is useful in specific areas but may lead to inconsistent responses in management scenarios. Keyworth et al. (2009) developed a classification system to assess the extent and severity of erosion on upland organic soils in Scotland. They assigned a descriptor and erosion risk to each vegetation class and land-cover type.

1.9 Peatland Disturbance

Peatlands and their C stock are vulnerable to ecosystem disturbance (Barber, 1993; Bridgham et al., 1999; Page et al., 2010; Robroek et al., 2010). Disturbance can be caused by both natural and anthropogenic processes (Wieder et al., 2008). Natural disturbance includes processes such as climate change, erosion, wildfire that may affect peatland vegetation and the C stock. Catastrophic disturbances such as bog bursts and landslides lead to the rapid removal or displacement of the C stock and destruction of the peatland hydrology, however, they affect relatively small areas (Albertson et al., 2009; Boylan et al., 2008; Bradshaw and McGee, 1988; Bragg and Tallis, 2001; Dykes et al., 2008; Turetsky et al., 2002).

While piping systems within the peat also leads to the removal of dissolved organic C (Holden, 2005), these are difficult to classify over large areas. These disturbances may be exacerbated by anthropogenic activities.

Historically, peatland disturbance in Ireland has been predominantly influenced by anthropogenic activity such as drainage for peat extraction, fire and land-use change, so that efforts were made to convert them for agriculture and forestry or to extract peat for horticulture or fuel extraction (Wilson et al., 2011). These activities affect the peatland ecosystem function, reduce its ability to uptake C and are detrimental to the storage of C. All disturbance can also have a large impact on microbial, plant and animal community structures, and pH (Camill, 1999).

In some cases, such as on industrial, commercially planted and burned peatlands, it is relatively easy to distinguish and classify the type of disturbance. However, in many cases, the disturbance pattern is complex. Disturbed sites may contain a mosaic of historical and contemporary disturbance that is difficult to classify accurately. Disturbance can affect the hydrology, vegetation and C stock of a peatland. It is very likely that disturbance to one leads to disturbance of the other two, e.g. a hydrological disturbance lowers the water table leading to changes in vegetation and perhaps C dynamics. Disturbance to the vegetation such as fire can, depending on its severity, lead to a loss of C in the system. Disturbance to the C stock in the form of extraction or bog bursts affects both the hydrology and the vegetation.

Therefore, understanding the disturbance of peatlands in Ireland is a complex spatial and temporal problem. Peatland disturbance is relatively easy to identify on the ground, but it is difficult to quantify and challenging to define a systematic method of isolating where disturbance has occurred. The root of the complexity is the combination of contemporary and historical activities that have influenced and affected the bogs. Historically, peatlands were regarded as wet wastelands (Feehan and O'Donovan, 1996) and as recently as the 1960s were seen as a land-use problem in Ireland (Dwyer, 1962).

Recent studies show that most of peatlands in Ireland have been disturbed and have bad conservation status (Douglas et al., 2008; NPWS, 2008; Renou-Wilson and Farrell, 2009). Ireland's peatlands have a long history of being subjected to anthropogenic activities, such as drainage, peat extraction, conversion to pasture and afforestation along with other pressures such as overgrazing, fire and infrastructural developments (Hammond, 1979; NPWS, 2008; Renou-Wilson and Farrell, 2009). Worrall et al. (2009) highlight that land-use practices and climate warming, may, in the future, reduce the SOC stock in peatlands.

According to the published surveys of blanket and raised bogs in Ireland, peatlands are disturbed to a high degree and by several factors (Cross, 1990; Hammond, 1979; NPWS, 2008). Several studies of peatland extent and disturbance have been conducted in the last forty years and the general trend of disturbance to peatlands has increased over both time and space in Ireland.

Hammond (1979) estimated that 44% of peatlands in Ireland were 'disturbed', using the term 'man modified' to describe disturbance as well as machine peat, milled peat and moss peat. Hammond (1979) described man modified as 'areas where the bogland surface has been physically disturbed and the natural vegetation altered'. Later studies show a landscape where peatland disturbance has become much more extensive. In 1990, Cross determined that 83% of raised bogs were disturbed with only 23,000 ha remaining intact. Foss (1998) showed that 92% of raised bogs and 82% of blanket bogs had been man modified. Both of these later studies depict a large increase in the extent of disturbance on Irish peatlands. Most of this disturbance was the result of

cutting (Connolly et al., 2007; Cross, 1990; Douglas et al., 2008; Hammond, 1979; NPWS, 2008; Renou-Wilson and Farrell, 2009).

The *CORINE* land-cover map attempted to map disturbance on both raised and blanket peatlands. The 2000 map depicted that 84% of raised bogs and 38% of blanket bogs were exploited. However, there is an anomaly in the *CORINE* data as it suggests that 35,000 ha were intact. On closer examination of the *CORINE* data in ArcGIS and Google it seems that their definition of intact is very different from both Cross (1990) and Foss (1998) as well as the definition used in this study. Peatlands that have very obvious historical disturbance are included in the intact classification. *CORINE* has one category for peatland: peatbogs (Level 412 in the *CORINE* nomenclature). Within this class are descriptions of what can be included and excluded (Brossard, 2000). This includes peat-extracting areas, such as those developed by Bord na Móna (BnM) but excludes cutover peatlands or raised bogs with cutting around the edges which have been included in the intact classification in *CORINE*. In the above surveys these would have been classed as not intact; therefore, the *CORINE* data does not give an accurate representation of the amount of peatland that is intact.

As a result, because of this, and because *CORINE 2000* is a land-cover map, peatlands that lie beneath forestry or have been converted to pasture are not included, so actual rates of disturbance will, most likely, be higher. Connolly et al. (2007) produced the DIPM, which showed that at 74% of ground-truth sites ($n = \sim 300$) disturbance was evident. In the recent NPWS report on the status of EU-protected habitats and species in Ireland the overall assessment of the habitat conservation status was 'bad' for blanket bogs and 'unfavourable-bad' for raised bogs (NPWS, 2008). The range and area of the habitat within its range of occurrence is also unstable and/or decreasing (IPCC, 2010).

The main anthropogenic activities affecting Irish blanket and raised bogs are afforestation, drainage and mining for fuel (both small-scale and industrial), agricultural conversion, livestock management in general and overstocking in particular, burning, and wind farm development (Dise, 2009, NPWS, 2008). These threats and their effects on peatlands may be exacerbated by climate change and expanding human activities (Smith et al., 2009; Strack et al., 2008b). Most peatlands in

Ireland have experienced centuries of anthropogenic impacts, including cutting and conversion to pasture and more recently, afforestation (Foss, 1998). The rate of disturbance of peatlands has increased over the last seventy years (Foss, 1998). However, Tomlinson (2010) found that in Northern Ireland C losses because of peat extraction had fallen to 30–40% of 1990–1991 estimates. This reduction was mainly due to a fall-off in the demand for peat as a fuel. In Ireland, emissions from coal and peat in the residential sector decreased by 61.8% between 1990 and 2010 (Duffy et al., 2012). Assuming that a decrease in emissions is reflected in a decrease in peat extraction as in Northern Ireland, this would indicate that peat extraction for the residential sector in Ireland has also decreased. However, without a more detailed breakdown of the ratio of coal and peat decreases it is difficult to say if a decrease in extraction (based on the above assumption) has occurred.

1.9.1 Drainage and hydrology

Drainage occurs in most countries where peat is found. It is the precursor to extraction, afforestation and conversion to pasture and it directly and immediately disturbs the hydrology of the peatland (Cagampan and Waddington, 2008; Dwyer, 1962; Poulin et al., 2005; Price, 2003; Waddington et al., 2008). However, early drainage efforts in Ireland were aimed at reducing flooding (Holden et al., 2004). Currently peatlands in both the southern and northern hemispheres have been drained (Chapman et al., 2003; Fargione et al., 2008; Holden et al., 2004). Peat extraction occurs in many countries, including Canada, the Netherlands, Finland, Russia, Poland, the UK and Ireland (Dabrowska-Zielinska et al., 2009; Farrell and Doyle, 2003; Hammond, 1979; Holden et al., 2004; Vasander et al., 2003; Waddington et al., 2008). However, drainage has a negative effect of the peatland. Open-cut drains increase the drainage density and lead to lower water tables on the peatlands (Holden et al., 2007). They can also lead to drying and subsidence in the surrounding peat. Wilson et al. (2010) found that at a study site in Wales drains cut into upland blanket bog led to the creation of a localised dry zone within 2 m of the drain, that surface water is less common and that within 5 m of a drain water tables are lower.

Decay does occur in the catotelm, albeit very slowly (Charman, 2002). However, as the permanently water-logged catotelm drains, the balance between aerobic

and anaerobic conditions in this peat zone change, exposing anaerobic zones to oxygen and increased oxidisation and decay (Strack et al., 2008a). Peatland drains may also act as conduits allowing dissolved organic carbon (DOC) and particulate organic carbon (POC) to be released into the natural drainage network (Wallage et al., 2006; Gibson et al., 2009; Holden et al., 2007; Evans and Warburton, 2010). The C stock is stable only as long as water-logged anaerobic conditions are maintained (Charman, 2002; Davidson and Janssens, 2006).

1.9.2 Peat extraction

In Ireland, peat extraction occurs at both large-scale industrial and small-scale non-industrial sites. While there is little or no information on the extent of domestic mechanised extraction, there is some anecdotal evidence that it occurs on a wide scale. Small-scale peat extraction has occurred throughout history (Cruickshank et al., 1995; Moore, 2002; Price, 2003). In Ireland 'turbary rights' developed over time the right to enter onto another person's land to dig and take away turf (peat for fuel) (Cruickshank et al., 1995). This system continues to exist on many peatlands (Charman, 2002). These rights were granted to residents in a particular parish, community or landlord estate and they had customary right of turbary on a particular bog (Feehan and O'Donovan, 1996). Therefore, on bogs where turbary rights existed, many people worked small plots. Small-scale, hand-won extraction was extensive and by the eighteenth century peat fuel was used by city as well as country dwellers (Feehan and O'Donovan, 1996). For example, about 200 persons or bodies have a title interest in Clara bog, a raised bog occupying an area of about 7 km² in Co. Offaly (Feehan and O'Donovan, 1996).

Modern techniques, which are highly destructive in contrast to traditional methods, are now used to extract peat for domestic fuel (David Wilson, and Caitriona Douglas, pers. comm.). These techniques include compact harvesters, commonly known as 'sausage machines' and 'field-press' machines, where peat is dug from a peat face by a JCB and loaded into a hopper (Cruickshank et al., 1995). However, since 1990, there has been a consistent decline in the use of peat in the residential sector (O'Leary et al., 2008; Duffy et al., 2012). This trend is also seen in

Northern Ireland, where peat extraction declined by about 30–40% compared to the 1990–1991 period, as noted above. This marked fall has been driven by the introduction of new restrictions on peat-cutting in 2005 (Tomlinson, 2010).

At a completely different scale, the semi-state companies BnM and Coillte Teo have exploited the peatland resource for electricity generation and forestry (Renou et al., 2006). Bord na Móna was formed in 1946 and acquired 53,000 ha which it began to develop between 1946 and 1973 (Feehan and O'Donovan, 1996). At present there are 85,000 ha of industrialised peatlands. Bord na Móna actively extracts peat, predominantly for electricity production, on about 50% of its land holdings and about 16,000 ha are already exhausted for industrial peat extraction (Renou et al., 2006). The vast majority of industrialised peatlands (91%) are located on raised bogs, although some 8,000 ha (9%) are located on blanket bog in Co. Mayo (Farrell and Doyle, 2003). On Industrial peatlands, the ecosystem function is badly disturbed as vegetation is stripped, drainage put in place and peat soil is physically removed (Tuittila et al., 2000). In the aerobic zones the rate of decomposition is much faster than in the anaerobic zones (Belyea and Clymo, 1999; Froking, 2001). Peat extraction also leads to a decrease in the SOC stock at a site and removes the potential for revival by making plant establishment difficult (Cagampan and Waddington, 2008; Dawson and Smith, 2007; Turetsky et al., 2002; Wieder et al., 2009).

1.9.3 Afforestation

Ireland's National Forest Inventory (NFI) has estimated that 301,000 ha of peatland (predominantly blanket bog [216,000 or 72%]) has been afforested. This accounts for one-third of the national forest estate (NFI, 2008). Most afforestation activity took place during the 1960s and 1970s (Byrne and Milne, 2006). The primary impact of forestry is drainage of peatlands to allow the roots of the trees access to an aerated zone (Finer and Laine, 1998). Peatland afforestation also leads to a reduction in natural bog vegetation due to drainage and shading. This effectively changes the rate of organic matter accumulation of the top of the profile (Anderson, 1997; Charman, 2002; Finer and Laine, 1998; Wallace et al., 1992). Whether this causes a net change in SOC stock remains unclear. Recent studies of afforested peatlands

have shown that over the longer term (30–60 years) these sites may be either sources or sinks for SOC (Hargreaves et al., 2003; Lohila et al., 2007).

1.9.4 Wildfire

There are no datasets on the effect of peatland fires in Ireland. Fire can have a major impact on peatlands, as was seen on the North Yorkshire Moors in 1976 and in Indonesia in 1997 where some peatland surfaces were reduced by between 25 cm and 85 cm (Maltby et al., 1990; Page et al., 2002; Schimel and Baker, 2002). The fires in Indonesia released about 1000 M t of C into the atmosphere (Holden, 2005). Fire affects the structure and productivity of the burnt area and can lead to reduced land cover and C sequestration potential (Bragg and Tallis, 2001; Garnett et al., 2000; Zoltai et al., 1998). Even though fires reduce C accumulation in bogs, pre-fire conditions generally return within decades of the burning (Kuhry, 1994). However, this is preceded by invasive graminoid species, which are not C accumulators.

There is little data on fire and its effect on the Irish peatland C stock: however, the NPWS has recorded fires on several peatlands. Much of the work on the effects of fire on peatlands has been done in Canada and in the studies of the 1997 fire in Indonesia (Page et al., 2002; Turetsky et al., 2002; Wieder et al., 2009). Climate change poses a potential risk because the frequency of fires, both natural and anthropogenic, may increase because of predicted warmer drier summers (Albertson et al., 2009). This work in the UK has indicated that there will be little change in wildfire incidence in the near future but this is to change from 2070 as climate change intensifies (Albertson et al., 2010). Therefore, a predicted shift to dryer summers in Ireland may have the effect of increasing wildfires causing serious damage to the peatland C stock and ecosystem function (Cross, 1990; Maltby et al., 1990; Page et al., 2002; Schimel and Baker, 2002).

1.9.5 Natural disturbance

Natural disturbance includes bog bursts, peat slides and erosion, all of which can be exacerbated by human involvement (Boylan et al., 2008; Warburton et al., 2004b). Landslides are particularly obvious (Boylan et al., 2008; Dykes et al., 2008). Bog bursts are characteristic rapid mass movements of peatland areas

and their occurrence is natural but can be influenced by human activity (Warburton et al., 2004b). When a bog burst occurs, the surface of the peat may rupture and liquefied basal peat may be expelled at the margin of the peat mass or through surface tears (Warburton et al., 2004b). This disruption of the peat mass leads to a modification of hydrology and of plant communities (Milton et al., 2005; Yeloff et al., 2006). In Ireland, the Derrybrien bog slide is a recent severe example, involving an estimated 450,000 m³ of peat (Renou-Wilson and Farrell, 2009). Erosion is a widespread disturbance that severely affects peatlands and especially mountain blanket bogs. Bradshaw and McGee (1988) conducted a study into the possible causes of erosion on mountain blanket bogs in Wicklow and Donegal. They concluded that the original causes of the erosion was likely to be natural and occurred when a critical depth or a combination of peat types became unstable on sloping ground (Bradshaw and McGee, 1988; Tallis, 1998).

All of these contemporary and historical activities have led to the development of a peatland landscape that is characterised by a spatially complex mosaic of disturbance, ranging in scale from c. 10 m² to c. 10 km².

1.10 Potential Impact of Disturbance on the Carbon Flux and Peat Soil Organic Carbon

Peatlands in Ireland are estimated to emit about 2.64 Mt C per year while only sequestering ~57,402 t C per year (Renou-Wilson et al., 2011). These figures from Canada and Ireland indicate that disturbance has a large impact on the ability of a peatland to function as a C sink. Turetsky et al. (2002) completed the first regional-scale analyses of the effects of disturbance on peatland ecosystems under current environmental regimes in Canada. They noted that C uptake was reduced by 85% in comparison to a non-disturbed scenario. During periods of no disturbance, they suggested that Canadian peatlands accumulate 24.5 gC/m²/yr, but under contemporary levels of disturbance this was reduced to 3.6 gC/m²/yr. Irish peatlands have suffered extensive disturbance – much of the peatland has undergone substantial changes because of peat extraction, drainage, burning and

forestry plantations (Eaton et al., 2008; NPWS, 2008; Turetsky et al., 2002). Peatland surface structure is an important factor controlling the rate of C sequestration (Belyea and Malmer, 2004; Koehler et al., 2011). In Ireland, peatland C uptake data are sparse. Carbon uptake has been recorded at two sites: the relatively undisturbed Atlantic blanket bog at Glencar, Co. Kerry and Clara bog, a stressed raised bog. At Glencar, the annual measured net ecosystem CO₂ exchange was measured over a five-year period from 2002 to 2007 and ranged from -16.5 ± 5.1 and -95 ± 23.2 g C-CO₂ m⁻² (indicating a C sink) (Sottocornola and Kiely, 2010). However, Koehler et al. (2011) note that although the Glencar site was a sink for CO₂, it was a net source of C when the sum of CH₄ and DOC were taken into account. At Clara measurements were taken at both intact and disturbed locations. Carbon uptake on the intact site at Clara bog was about 33 g C/m²/yr. This was several times greater than the C uptake at the damaged site (David Wilson, pers. comm.).

Sweeney et al. (2008) worked on downscaling Global Climate Model (GCM) output to create climate projections for Ireland. By the 2050s their modelling indicates year-round warming with an increase of between 1.4 to 1.8 °C with changes as high as 3°C possible (Sweeney et al., 2008). An increase in winter and a decrease in summer precipitation is also predicted, but there are large regional variations, with the Midlands and east coast receiving increased rainfall in the winter. The predicted changes in climate have the potential to impact on Irish peatlands. Many of these peatlands are already degraded and disturbed. Sottocornola and Kiely (2010) concluded that the CO₂ sequestration capacity of Irish blanket bogs is likely to be particularly affected by climate change because the ecosystem appears to be extremely sensitive to hydro-meteorological variations. The drying of bogs will probably cause large losses of soil C (Bridgham et al., 2008b). These changes, according to Albertson et al. (2010) will lead to increased incidence of wildfire by 2070. A recent study by Kiely et al. (2009) found that Irish peatlands may be very susceptible to changing climate conditions and may become net sources of C with only modest change in climate.

1.11 Remote Sensing and Peatland Disturbance

Despite earlier programmes to drain peatlands, these activities are now regarded as being a threat to the preservation of the ecosystem and its C stock (Wallage et al., 2006), especially on blanket bogs which are now recognised as habitats of high global conservation importance (Bellamy et al., 2012). Given the potential impact that drains and disturbance have on peatlands, there is a need to identify disturbance for conservation assessment (Crowe et al., 2008). Peatland drains have been mapped using ground surveys and aerial photography interpretation (Armstrong et al., 2010; Mladinich, 2010). Holden et al. (2007) surveyed peatland drains in several upland blanket peat catchments in northern Britain. The extent of drainage can clearly be seen on aerial photographs (Lindsay et al., 1988) and could potentially be digitised. However, surveys are expensive and often can be limited in size (Mladinich, 2010). Anthropogenic disturbance of natural landscapes typically introduces regular geometric shapes that appear very different to natural features. For example, drainage ditches are straight, compared to streams that meander, forest boundaries are straight with angular interfaces, compared to curved boundaries of natural woodlands and industrial peatlands are typified by parallel lines of surface drainage ditches that are rarely, if ever, found in nature. It also has created complex, fine-resolution spatial patterns over the extent of the bog. Therefore, determining peatland disturbance and drainage systems is often a difficult and expensive task (Holden et al., 2007).

Remote sensing offers the ability to examine peatlands at a *landscape* level (Evrendilek et al., 2011). For instance, Dissanska et al. (2009) used very high-resolution (VHR) imagery and a semi-automatic object-based approach to map the extent of peatlands in James Bay, Quebec. Evrendilek et al. (2011) also used high-resolution *Geoeye-1* satellite imagery to quantify changes in a peatland between 1944 and 2009, although they encountered difficulties in spectrally separating water bodies and ditches. Several studies have used object-based image analysis to extract narrow linear features. He et al. (2011) used VHR

Quickbird and medium-resolution SPOT (Système Pour l'Observation de la Terre) imagery to detect narrow linear forest disturbances. Jin et al. (2009) used object-based image analysis (OBIA) to extract road details. However, Anderson et al. (2010) state that object-oriented classification is a subjective approach in which a user defines the criteria for classification, which may lead to error. Despite this issue, single features in VHR imagery are represented by multiple pixels and thus traditional pixel-based image-processing techniques are not as effective as with low- and medium-resolution data (Mladinich, 2010). Anthropogenic disturbance can alter both the spectral characteristics of a peatland and the texture (patterns of spectral reflectance) (Harris, 2008): therefore, an object-oriented approach to feature detection, using OBIA and VHR satellite imagery, has the potential to identify and isolate disturbance features in a remote-sensing image.

Object-oriented software has been used to determine if high accuracy levels can be determined from high-resolution data. Cleve et al. (2008) found that an object-based approach resulted in a 42% and a 14% greater accuracy for built area and surface vegetation categories respectively. Evrendilek et al. (2011) used this approach to quantify land-use land cover changes in a Turkish peatland between 1944 and 2009. Chubey et al. (2006) also used this approach to inventory forest and found that it worked well.

There are several object-oriented software packages available: Definiens eCognition, Erdas Objective and Vision Learn Systems' (VLS) *Feature Analyst* (FA) for ArcGIS (which was chosen for use in this work). This uses an inductive-learning based approach to object recognition and feature extraction where the inductive learner learns from a set of labelled examples (Blundell and Opitz, 2006). The user trains the system with a sample of extracted features from an image. The system develops a classification based on a combination of user-selected parameters such as feature type, spectral bands or size and internal software algorithms (a blackbox approach) that correlates known data, that is spectral or spatial signatures with the trained areas.

Connolly and Holden (2011a), who define peatland disturbance as '*any natural or anthropogenic event that interrupts the natural trajectory of growth of the peatland*', have devised a method for classifying and helping users deploy an object-oriented analysis of peatland

disturbance. The system is based on a 'disturbance cube' (Fig. 2.2), where each dimension (x, y and z) is related to the severity of disturbance in peatland C stock, hydrology and vegetation. The severity of disturbance is measured, subjectively, on a scale of 1–3. The result of this is a table of 27 potential classes of disturbance (not all are peat) and an extra class for pristine peat (Table 2.1). The system is subjective but the subjectivity of the author (denoted later as 'Observer') was tested against other peatland Experts to determine how different or similar their measure was.

1.12 Overall Project Aims

The goals of this project were twofold:

- 1 Identify, categorise, quantify and map peatland disturbance to enable a more accurate estimation of peatland C stock and
- 2 Assess how that stock is affected by disturbance at present and into the future.

The overall project aims included:

- Creating a definition of peatland disturbance in Ireland;
- Creating baseline knowledge in relation to the effects of disturbance on peatland C stock that will support future developments with regard to implementing the Soil Framework Directive;
- Identifying, assessing and quantifying the threat of disturbance to the C stock in Irish peatlands in order to monitor the quality of peatlands and predict how climate change may affect the C stock;
- Using Geographical Information Systems (GIS) and remote-sensing technology to record the quality of the environment by developing a map of peatlands disturbance;
- Developing new techniques involving the use of remote-sensing technology, GIS and C analysers to assess the C stock;
- Developing accurate information to form baseline data with regard to effects of disturbance of the C stock in order to inform policy-makers about the impacts of various mainstream activities on the C stock, for example wind farms and afforestation. These baseline data can be used to examine future effects of climate change on peat soil C dynamics in Irish peatlands;

- Disseminating research findings via conference presentations and publication in peer-reviewed journals;
- Enhancing the capability of Irish researchers to be at the forefront of cutting-edge environmental research within the knowledge economy.

The objectives of the sections that follow are to: (i) classify peatland disturbance (Section 2); (ii) use object-oriented image analysis to identify disturbance features in high-resolution satellite imagery (Section 3) and (iii) use object-oriented method and high-resolution imagery to detect drainage (Section 4).

2 Classifying Peatland Disturbance

2.1 Introduction

A key element when accounting for disturbance of peatlands is the definition of what disturbance is and how to describe or classify it. White and Jentsch (2001) presented a consideration of the definitions for relative and absolute disturbance. 'Relative' disturbance considers events that are outside of the normal range of dynamics within an ecosystem. Therefore, an event like a falling tree in old-growth forests is not considered disturbance. Absolute disturbance is any event that causes physical and measurable changes in all variables, whether those changes are recurrent, expected or normal. White and Pickett (1985) defined absolute disturbance as 'a discrete event in time that disrupts the ecosystem, community or population structure and changes the resources, substrate availability or physical environment'. This definition is similar to that used by Hammond (1979) for peatlands: 'areas where the bogland surface has been physically disturbed and the natural vegetation altered'. The temporal and spatial scale of disturbance should also be considered as this may affect how disturbance is observed (Hofgaard et al., 2010) and classified. In this study disturbance was defined as: 'any natural or anthropogenic event that interrupts the natural trajectory of growth of the peatland'.

2.2 Methods

2.2.1 Study sites

The study sites were selected in the:

- Wicklow Mountains (53°8'16.00'N, 6°18'43.44'W);
- Slieve Bloom Mountains (53°5'33.21'N, 7°34'27.63'W);
- Clara/Turraun bog (53°19'15.82'N, 7°37'25.09'W);
- Tullaghanrock bog (53°54'35.22'N, 8°29'57.96'W);
- Lough Hoe and Ox mountains (54°5'36.05'N, 8°57'0.63'W);
- Bangor/Bellacorrick bog (54°9'4.25'N, 9°41'10.42'W);
- Connemara (53°25'17.07'N, 9°36'54.42'W).

Representing an east-west transect across Ireland (Fig. 2.1), the sites vary in terms of weather conditions, elevation, and peat depth. Annual precipitation at the Low-level Atlantic and High-level Montane blanket bog sites in the west and in the upland areas, above 152 m in the middle and east of Ireland is greater than 1200 mm.



Figure 2.1. Location of general study sites.

The raised bogs in the middle of the country have a precipitation range predominantly between 800 and 1200 mm, although in some areas the maximum is 1600 mm. Deep peat is found in both blanket and raised bogs. The deepest peat is found in raised bogs in the Midlands of Ireland and on low-lying blanket bogs in the West of Ireland in Donegal, Galway and Mayo (Hammond, 1979).

All of the sites contain a complex mosaic of disturbed and non-disturbed areas. The disturbed areas have, in many cases, experienced disturbance both recently and historically – predominantly through drainage, forestry, natural and anthropogenic erosion, extraction and in

some cases fire. The undisturbed areas are usually located some distance from roads or areas of human influence. This classification of peatland disturbance involves several steps. Step 1 looks at the development of a definition and a classification framework. Step 2 is vital for examining the subjective nature of several different Experts' opinions, and it allows the Observer to have confidence in the disturbance assessment using the disturbance cube classification framework. Step 3 deals with the application of the disturbance cube framework.

2.2.2 Step 1. Development of conceptual classification framework

A framework for classification was developed to convey the categorisation and severity of disturbance. Disturbance in peatlands can affect hydrology, vegetation and C stock to differing degrees. These components form the basis of the classification, which is a gradient of absolute disturbance. A disturbance cube was developed to visualise the type and severity of different types of disturbance and to enable an observer to quickly establish the category of disturbance (Fig. 2.2).

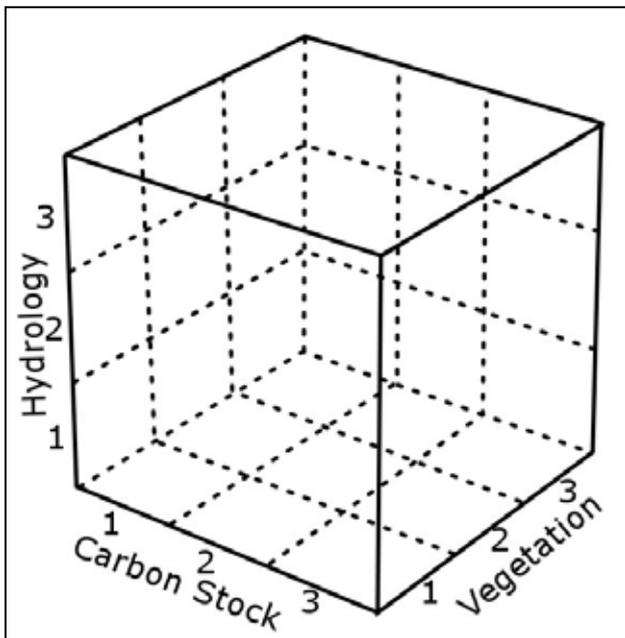


Figure 2.2. The Disturbance cube.

Pristine peat is located at the origin in the cube and more disturbed peat falls some distance away along one or more of the x, y and z axes. Each axis was divided into three sections similar to that of the NPWS system where 1 is 'favourable/good', 2 is 'poor/ok' and 3 is 'bad/bad' (NPWS, 2008). This scale is indicative of the condition of the peatland. Good (1) means that the hydrology of the site is dominated by natural processes, the vegetation consists of abundant peatland vegetation and the C stock is intact. Ok (2) means that the hydrology is affected by drainage, the vegetation composition is changing or is less abundant with some bare patches and the C stock is being or has been removed, either naturally or through human intervention. Bad (3) means extensive drainage or gullyng causing completely modified hydrology, the peatland vegetation has been removed through natural or human processes and the C stock is severely depleted or has been removed.

This system yields 27 potential classes (Table 2.1), each of which was assigned a descriptive label based on its value in each dimension. An extra class was added to the table to represent pristine peatlands where the hydrology, vegetation and C stock are given a '0' disturbance value. The classification framework was used by the primary Observer to record disturbance at 115 sample points across the field sites used for evaluation.

2.2.3 Step 2. Evaluation of operator assignment of classes

The development of the classification framework and its application in the field is an informed yet subjective process. Different experts may disagree about the severity and sometimes the type of disturbance. A survey to examine disturbance in photographs was devised to examine whether or not several peatland Experts' opinions of disturbance differed from (i) the primary Observer (Observer, i.e. the corresponding author) and (ii) from each other. The survey was conducted using Google Docs (now called Google Drive) and Google Earth. The Observer assembled 120 photographs which were captured with a Canon ixus™ camera at the various field sites across Ireland. The

Table 2.1. Peatland disturbance classification determined from the disturbance cube.

	Vegetation	Carbon	Hydrology	Disturbance descriptor*
1	0	0	0	Untouched/Pristine
2	1	1	1	Very little disturbance, retaining ecosystem function
3	1	1	2	Some drainage
4	1	1	3	Extensive drainage
5	1	2	1	Old disturbance
6	1	2	2	Old disturbance/erosion
7	1	2	3	Severe erosion
8	1	3	1	Industrial (cutaway) restoring
9	1	3	2	Industrial (cutaway) some recovery
10	1	3	3	Not peat
11	2	1	1	Fire recovery
12	2	1	2	Fire recovery and drainage/felled sites
13	2	1	3	Fire recovery and severe drainage
14	2	2	1	Restored peatlands
15	2	2	2	Forested peatlands and recovery forested peatlands
16	2	2	3	Industrial with changing vegetation
17	2	3	1	Industrial peatland restoration
18	2	3	2	Industrial peatland
19	2	3	3	Not peat
20	3	1	1	Fire on non-drained bog
21	3	1	2	Industrial/felled forest
22	3	1	3	Industrial/felled forest/converted to pasture
23	3	2	1	flooded industrial (restoration)
24	3	2	2	Industrial/old cutaway
25	3	2	3	Industrial/converted to pasture/old cutover
26	3	3	1	Not peat
27	3	3	2	Not peat
28	3	3	3	Not peat

*These descriptors are non-exclusive i.e, other descriptors may be suitable in different situations

assembled photographs were not representative of the disturbance classes in [Table 2.1](#). The main aim of the survey was to allow the Observer to have confidence in the disturbance cube classification framework (Step 1). This was done by examining how the Observer’s subjective opinion of disturbance in the survey differed from that of several peatland experts (Expert).

Four experts from BNM, University College Dublin (UCD) and the NPWS agreed to take part in the survey. Each expert has considerable knowledge of classifying

peatland condition and therefore was asked to examine the photographs and assess the level of disturbance at each site and to rank it from 1–10 (where 1 = undisturbed and 10 = very disturbed).

In [Table 2.2](#) a simple test was performed based on the percentage of agreement between the Experts and the Observer in regard to whether a site was disturbed or undisturbed. It is assumed that the Observer’s response is more accurate in terms of true characterisation of the sites, as the Observer has *in situ* experience.

Table 2.2. Table of agreement between Observer and Experts.

		% Agreement			
	Observer	Expert 1	Expert 2	Expert 3	Expert 4
Observer		0.85	0.9	0.75	0.77
Expert 1	0.85		0.78	0.73	0.75
Expert 2	0.9	0.78		0.74	0.61
Expert 3	0.75	0.73	0.74		0.66
Expert 4	0.77	0.75	0.61	0.66	

2.2.4 Step 3: Application of the disturbance cube framework

The function of Step 2 was to examine the subjective nature of several different Experts' opinions and if there was a significant difference in those opinions in relation to disturbance and the scale of disturbance. Once this was assessed, the Observer could determine disturbance at a particular site using the disturbance cube classification framework. Each site was assigned a code based on the extent and type of disturbance in each of the three dimensions in the disturbance cube i.e. 111 (Vegetation = 1, Carbon = 1, Hydrology = 1) means there is little disturbance in all three variables, 231 (Vegetation = 2, Carbon = 3, Hydrology = 1) could be a restored industrial peatland where much of the C (peat) has been removed but the drains are blocked and vegetation is returning. The sites can then be described, in general terms, using the descriptors in [Table 2.1](#). Therefore, a disturbance code and a descriptor were assigned to each of the 115 sites used in Step 2 for the evaluation. In [Table 2.4](#), these Observer-assigned disturbance codes and descriptors were compared to the Expert average score to examine how they related to each other. The disturbance cube framework was then used to visit and classify disturbance at 172 sites over the study area.

2.3 Results and Discussion

The first stage in the implementation of the disturbance cube classification framework was to examine how the subjective assessment of the Observer related to that of the Experts. In a test of agreement of whether or not a site was disturbed, the range of agreement between the Observer and the Expert was from 75% to 90% with an average of 82% ([Table 2.2](#)). The subjective opinion of all the Experts, in relation

to the photographic evidence, was also examined to determine how well the Observer's classification of the severity of disturbance differed from the Experts (on a scale of 1–10). [Table 2.3](#) shows the rank correlation test that compares the Observer's severity classification to each Expert severity classification. It also compares each Expert to one another. There was no significant difference between the Observer's classification of the severity of disturbance and the Experts' (Expert 1 and Expert 2, $P < 0.000001$, Expert 3, $P = 0.000003$ and Expert 4, $P = 0.049965$) ([Table 2.3](#)). The high level of agreement on what is considered disturbed between the Observer and the Experts and the lack of a significant statistical difference between the Observer and the Experts on the severity of disturbance shows that the Observer's classification disturbance and severity of disturbance is consistent with the Experts.

When the data were subdivided into less disturbed and more disturbed values and tested using the rank order correlation test, there was no significant difference between the Observer and Expert 1 or Expert 2 (Expert 3 and Expert 4's n-value was too low to determine a relationship). There was, however, a significant difference between Observer and Expert 2 (1–8 n = 28 [$P = 0.338968$]), Expert 3 (1–8 n = 17 [$P = 0.069803$]) and Expert 4 (1–8 n = 14 [$P = 0.267101$]). This means that although there is not a significant difference between the Observer's opinion and Expert 2, 3 and 4's opinion on whether or not a peatland is disturbed, there is a difference in the classification of the severity of disturbance. However, this may be explained by the extra contextual (*in situ*) knowledge, gained by the Observer from visiting each. Each of the Experts did not have this extra information as they had access only to a photograph of each site. These

Table 2.3. Rank correlation test of agreement of severity of disturbance between Observer and Experts.

		n	rs	t	p (one tailed)	df	p (two-tailed)
Observer	Expert 1	115	0.761	12.47	<.000001	113	<.000001
Expert 1	Expert 3	28	0.551	3.37	0.001178	26	0.002356
Observer	Expert 2	52	0.771	8.55	<.000001	50	<.000001
Expert 1	Expert 4	18	0.476	2.16	0.023146	16	0.046292
Expert 2	Expert 1	52	0.659	6.19	0.000001	50	0.000001
Expert 2	Expert 4	19	0.405	1.83	0.042421	17	0.084841
Observer	Expert 3	28	0.748	5.75	0.000003	26	0.000005
Expert 4	Expert 3	19	0.398	1.79	0.045641	17	0.091281
Expert 2	Expert 3	27	0.581	3.57	0.000741	25	0.001481
Observer	Expert 4	19	0.389	1.74	0.049965	17	0.099929

Table 2.4. Classification frequency of peatland disturbance for the 172 sampling sites. The table also indicates the mean disturbance score for the sub-set of 115 sample sites used for operator evaluation.

Average disturbance score by Experts	Classification	N	Descriptor
3.7	111	8	Very little disturbance
5.0	112	8	Some drainage
5.8	113	6	Extensive drainage
n/a	121	1	Old disturbance
5.5	122	12	Old disturbance/erosion
n/a	123	1	Severe erosion
4.8	212	10	Fire recovery and drainage/felled sites
n/a	213	1	Fire recovery and severe drainage
6.3	222	16	Forested peatlands and recovery forested peatlands
8.0	223	33	Industrial with changing vegetation
9.8	313	2	Industrial/felled forest/converted to pasture
9.8	322	3	Industrial
9.1	323	66	Industrial/converted to pasture
10.0	333	5	Not peat
Total		172	

data show that the peatland experts agreed on what is and is not disturbed; however there can be differences in opinion when it comes to assessing the severity of disturbance, especially in less disturbed areas¹.

¹ More detail can be found in: Connolly, J. and Holden, N.M. (2011). Classification of peatland disturbance. *Land degradation and development*. DOI: 10.1002/ldr.1149

When both the Observer and Experts' observations are plotted against the average observation at each site (Fig. 2.3), the Observer data lies in the upper range of the disturbance scale. Despite this, the Observer is still within the data cloud and the difference could be related to having *in-situ* knowledge and therefore having more information available on the disturbance at each site than the Experts as they only viewed a photograph

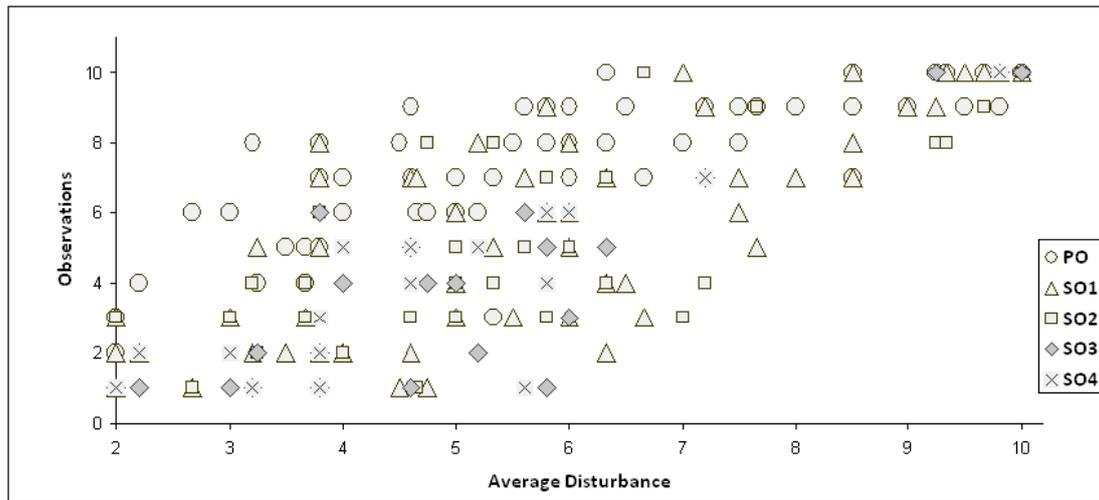


Figure 2.3. Observer (PO) and Expert (SO) observations plotted against the average observations at each site.

of the site. The analysis is important as it shows that most of the Experts' opinion of what is disturbed is similar but that differences do exist between them with regard to the severity of disturbance. It also shows that despite the Observer's subjective opinion being slightly more pessimistic than the Experts, it is not statistically different.

2.3.1 Application of the disturbance cube classification framework

The disturbance cube combined with [Table 2.1](#) offers a simple, quick and robust method for determining the severity of disturbance at a site on the ground or in satellite image. By assigning either the numbers 1, 2 or 3 to each of the three components, an overview of the peatland site may be achieved quickly. When the method was applied to the 172 sites disturbance was evident at the vast majority of them. Most of these sites were located within walking distance of a road and therefore disturbance was highly likely at these points given the high level of anthropogenic access and historical factors.

Only eight sites were classed as 111 and five of these were located in the Slieve Bloom Mountains. Much of the middle categories 121, 122, 123 were related to older cutover areas predominantly in the Wicklow and Ox mountains. Most of the sites visited exhibited severe disturbance ranging from active cutting, forestry, conversions to pasture and old cutover. Several classes, such as 112, 122, 212, 222, 323, had distinct

disturbance profiles where drainage, old cutover, burning, forestry and drainage to pasture respectively were the obvious disturbance types. Other classes, including 223, contained a mosaic of disturbance types that included scrub, forest, active and old cutting as well as drained to pasture. The more severely disturbed sites dominated this survey, with 80% of sites falling into these categories.

2.3.2 Relating the Observer's opinion to the conceptual classification cube framework

The average Expert disturbance value was used as there was no significant difference between the Observers' evaluations. There was very good agreement in the trend of Expert disturbance score and the disturbance indicated using the cube method classification ([Table 2.4](#)). The sites classified as 111, 112, 113, 122 and 212 have on average lower Expert scores (3.7, 5.0, 5.8, 5.5, and 4.8 respectively). These represent sites with some disturbance. The more disturbed sites classified as 222, 223, 313, 322, 323, 333 had, on average, higher Expert scores (6.3, 8.0, 9.8, 9.8, 9.1 and 10 respectively). The results indicate that the Observer has a similar concept of disturbance to the Experts ([Table 2.3](#), [Table 2.4](#)) and that the Observer-allocated disturbance cube classes reflect the same trend of opinion of disturbance that the Experts had. This process shows that the disturbance cube classifications recorded by the Observer to classify disturbance quickly and efficiently in the field are consistent with expert opinion.

2.4 Conclusions

This section presents a disturbance cube that offers a robust, rapid and reproducible method of classifying peatland disturbance. The subjective nature of assessing peatland disturbance was analysed by comparing expert opinion and then comparing this with the severity of disturbance derived using the disturbance cube framework. Therefore, despite the complexities associated with peatland disturbance, the disturbance cube classification framework allows disturbance to be examined in three 'dimensions'. This allows an operator to focus on specific site attributes to assess local complexity and derive a meaningful classification

that summarises the disturbance status of a given site. The framework provides a new way for describing disturbance that allows (i) accurate communication between experts whether they are field or remote-sensing experts; (ii) non-experts to judge disturbance at a site knowing it can be communicated to others and (iii) the comparison of sites with different types/causes of disturbance in terms of mid-point impacts i.e. potential types of consequences such as loss of C rather than end-point consequences, such as ecosystem death due to climate change. This process provides confidence that the disturbance cube is a reliable and meaningful method for determining peatland disturbance.

3 Object-oriented Classification of Disturbance in Irish Peatlands using Medium- and High-resolution Satellite Imagery

3.1 Introduction

Landscapes can be dominated by natural processes or human management (Uuemaa et al., 2008). Peatlands in Ireland have been extensively disturbed through human management (or mismanagement). Up to the early twentieth century peatlands were relatively undisturbed (Watts, 1990). Since the 1940s, they have been exploited for fuel, electricity production, agriculture, forestry and horticultural products, which has left a landscape characterised by geometric patterns, straight lines and right angles (Cooper and Loftus, 1998; Farrell and Boyle, 1990). Understanding disturbance of peatlands in Ireland is a complex spatial and temporal problem. While it is possible to identify disturbance by field sampling (Cruickshank et al., 1995), due to the extensive, remote and sometimes dangerous nature of peatlands, it may better to use remote-sensing techniques (Brown et al., 2007). These can include:

- 1 Qualitative interpretation of aerial photographs;
- 2 Qualitative interpretation of satellite images;
- 3 Quantitative interpretation of aerial photographs;
- 4 Quantitative interpretation of satellite images.

In this section a combination of remote-sensing and object-oriented classification is used to identify disturbance on peatlands – firstly on raised bogs in the Irish midlands using medium- and high-resolution imagery satellite imagery and secondly nationwide using medium-resolution satellite imagery.

The traditional approach taken to examining satellite imagery is to classify the image on a ‘per-pixel’ basis. However as visual interpretation of images is time consuming and not consistently repeatable, an alternative is needed, such as object-oriented classification (Elmqvist et al., 2008; Kim et al., 2008). Connolly and Holden (2011b) showed that both high- and medium-resolution imagery are useful for examining disturbance on peatlands. Satellite platforms

such as *Ikonos* and *Quickbird* have led to increased availability of high-resolution imagery (<5 m resolution). High-resolution imagery enhances the visual ability to differentiate features in heterogeneous environments (Elmqvist et al., 2008; Miller et al., 2009). High-resolution data also leads to much higher accuracies compared to medium-resolution imagery. However, the data are expensive to acquire. In this study the acquisition of high-resolution data was constrained by funding and by the lack of coverage over Ireland of high-resolution imagery. Medium-resolution satellite imagery is, however, available for Ireland and includes *Landsat TM*, *SPOT* and *India Remote Sensing (IRS)* (see Fig. 3.1). The IRS data was chosen because of the large tile size which reduces pre-processing. Connolly and Holden (2011b) noted that while the accuracy of medium-resolution imagery is lower than high-resolution imagery, the accuracy assessments are still relatively good, particularly with object-oriented approaches.

Object-oriented classification works on objects in an image instead of single pixels (Gao and Mas, 2008). It is a two-step approach involving image segmentation and image classification (Kim et al., 2008). The segmentation step is useful for areas where no boundaries are readily available, such as peatlands. Image segmentation involves an image being divided into segments which contain homogenous, continuous, contiguous objects that represent meaningful objects on the landscape (Elmqvist et al., 2008; Gao and Mas, 2008; Geneletti and Gorte, 2003). It is important to be aware that the quality of the object-based classification is highly dependent on the image segmentation (Kim et al., 2008). As noted above, this research used FA software, released by VLS (Miller et al., 2009). This software bridges the gap between image segmentation and object-extraction approaches. *Feature Analyst* uses a pixel-based computerised learning classification. As each pixel is classified, the output is converted from raster to vector

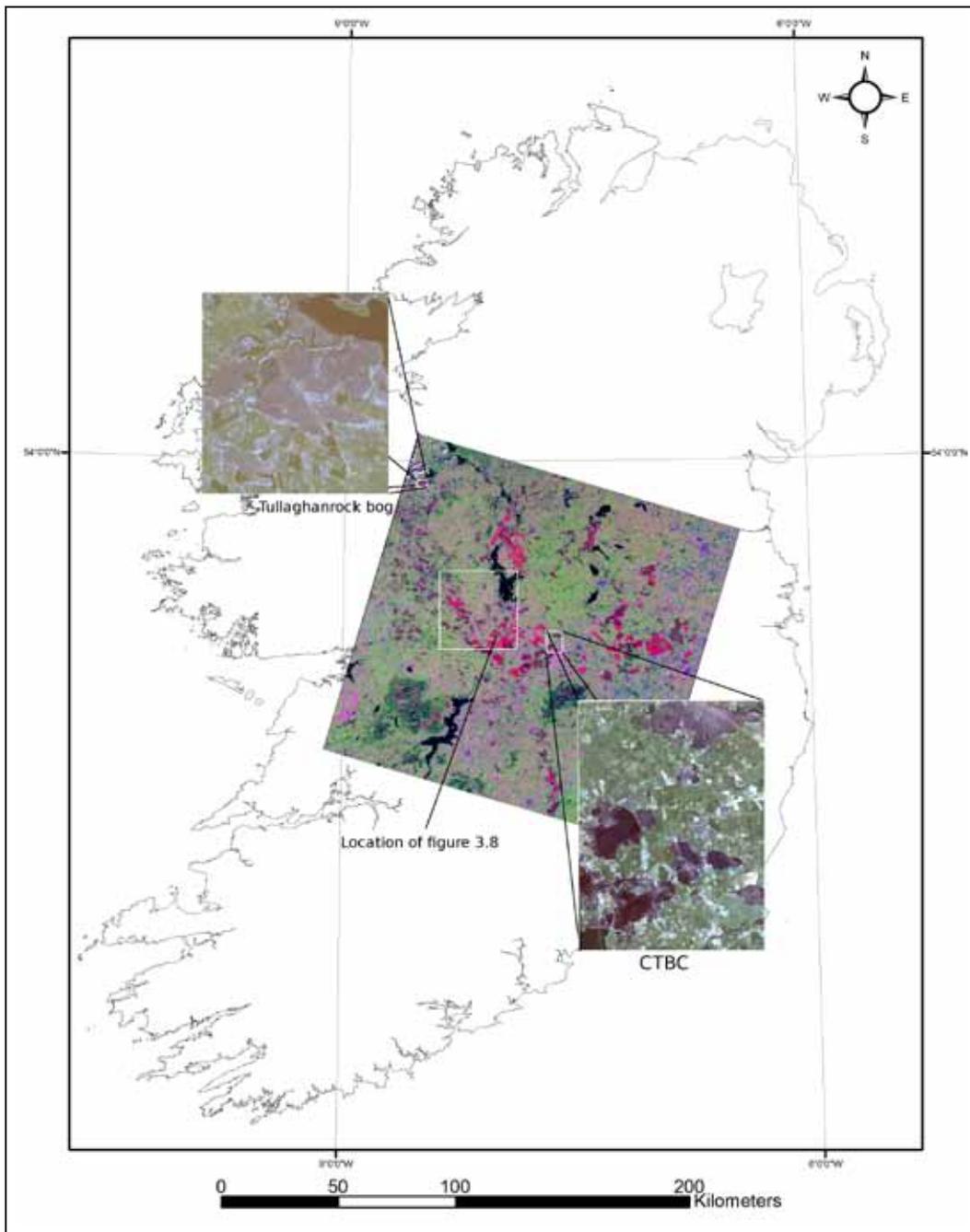


Figure 3.1. Location map of India Remote Sensing (IRS) medium and *Geoeye-1/ikonos* high-resolution study sites (Tullaghanrock and Clara/Turraun Bog complex [CTBC] raised bog areas are not to scale).

and neighbouring pixels with the same classification are aggregated, thus creating similar objects (Miller et al., 2009). One strength of the FA approach is that it does not require extensive training and the process can be iterative in order to get the best results. It is available in the ERSI ArcGIS environment and

therefore outputs can be readily imported into a geodatabase (Raines et al., 2008). Yuan (2008) used an FA object-based classifier to extract accurate land-cover features from high-resolution aerial photography and *Quickbird* satellite imagery and concluded that a hierarchical learning approach in FA was very useful.

3.2 Methodology

In this research, the DIPMV2 (Connolly and Holden, 2009) was used to indicate the presence of peat soils. The object-oriented feature extraction approach was used to examine DIPMV2-defined raised bogs at two particular sites where both high- and medium-resolution imagery was available. It was also tested across a swath of the Irish Midlands and later applied to all of Ireland (cloud free). Peatland disturbance was examined at the two sites using *Geoeye-1* and *Ikonos* high-resolution imagery, and across larger areas using IRS medium-resolution imagery. The accuracy of each map was examined and the overall accuracy was determined: overall accuracy = correctly classified pixels/total number of pixels.

3.2.1 Study sites

The two sites chosen for high-resolution imaging were Tullaghanrock bog (Fig. 3.2), and the Clara/Turraun bog complex (CTBC) (Fig. 3.3). Tullaghanrock bog is located in Co. Roscommon to the north-east of Ballaghaderreen (53°54'49.33'N 8°30'30.61'W).

According to Hammond (1979), it is a transitional raised bog. Its elevation is about 70 m and annual precipitation is between 1000 and 1200 mm. The bog is dissected by a road running north-west to south-east and there is a major drain running the length of the bog to the east of the road. The central part of this bog is classified as intact. However, the edges of the bog have also been extensively cutover and there is a small area of forestry and pasture in the south-east corner. These disturbances

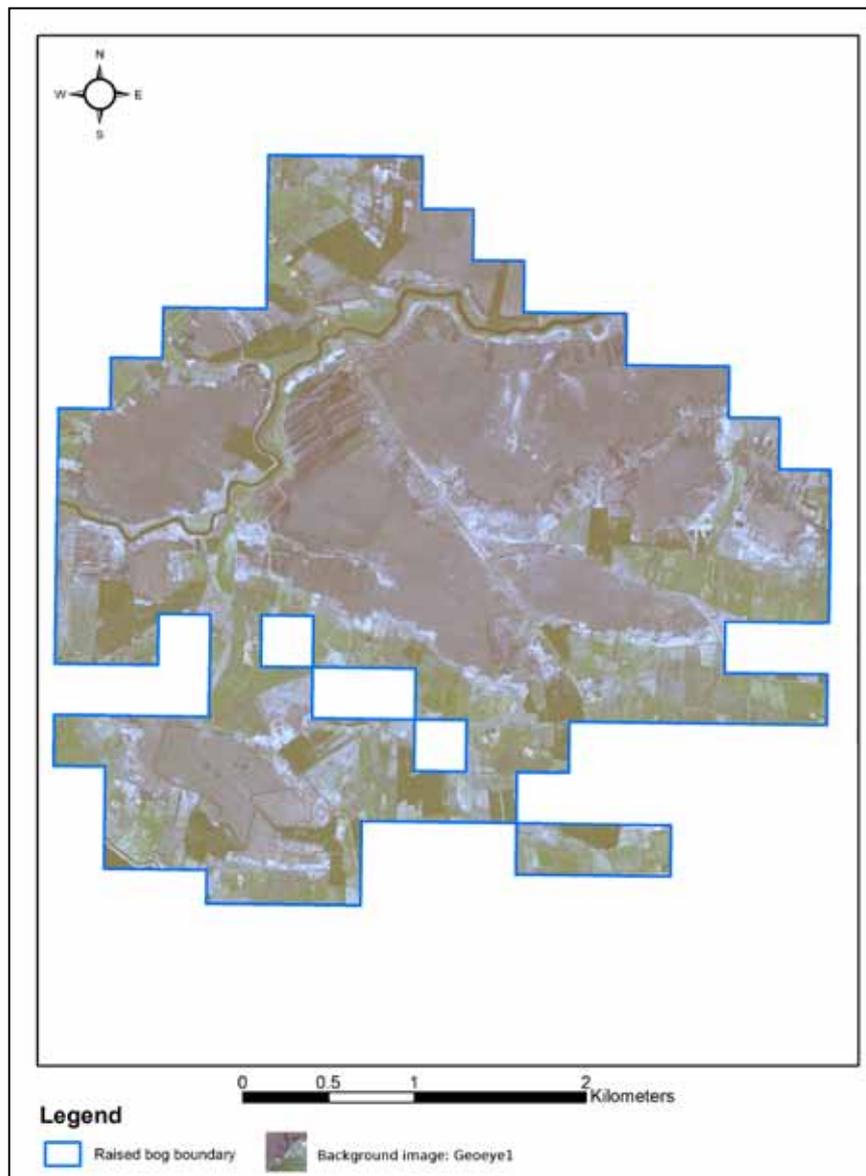


Figure 3.2. High-resolution (0.5 m) *Geoeye-1* image of Tullaghanrock bog raised bog area.

are typical on raised bogs in Ireland. Much of the centre of the bog is relatively undisturbed.

The CTBC, which is located to south of Clara in Co. Offaly, consists of a relatively intact raised bog, Clara bog (53°19'22.44'N 7°37'34.02'W) and several cutaway peatlands, including Oughter bog (53°14'56.63'N 7°40'24.63'W). Clara's elevation is about 53 m and Oughter bog's is about 50 m. The annual precipitation in this area is between 800 and 1000 mm. Clara bog is bisected by a road running more or less north to south. The bog was originally much larger than it is today but it has experienced extensive modification (Crushell et al., 2008). Here, the whole bog is classified as intact. However, Crushell et al. (2008) note that the contemporary bog at Clara has experienced extensive disturbance, especially on the eastern side. The

eastern bog was drained intensively and these drains were subsequently blocked and the bog is now being restored. The western side is in much better condition although there is evidence of drainage and cutting along the road. The southern side of the bog continues to be cut for domestic fuel. There is also a large forestry plantation at the southern edge of the bog along the road. Oughter bog is a BnM Industrial/cutaway bog. The area of the bog is about 4.6 km². A habitat map was created by BnM's ecology team in 2010 based on the ground-truth 2004 OSI aerial photos (C. Farrell, pers. comm.). The map depicts the spatial extent of various land-cover classes on the bog. The habitat map is dominated by extensive area of bare peat (possibly still in production when the *Geoeye-1* imagery was taken), a large area of pioneer poor fen community and Birch scrub. There

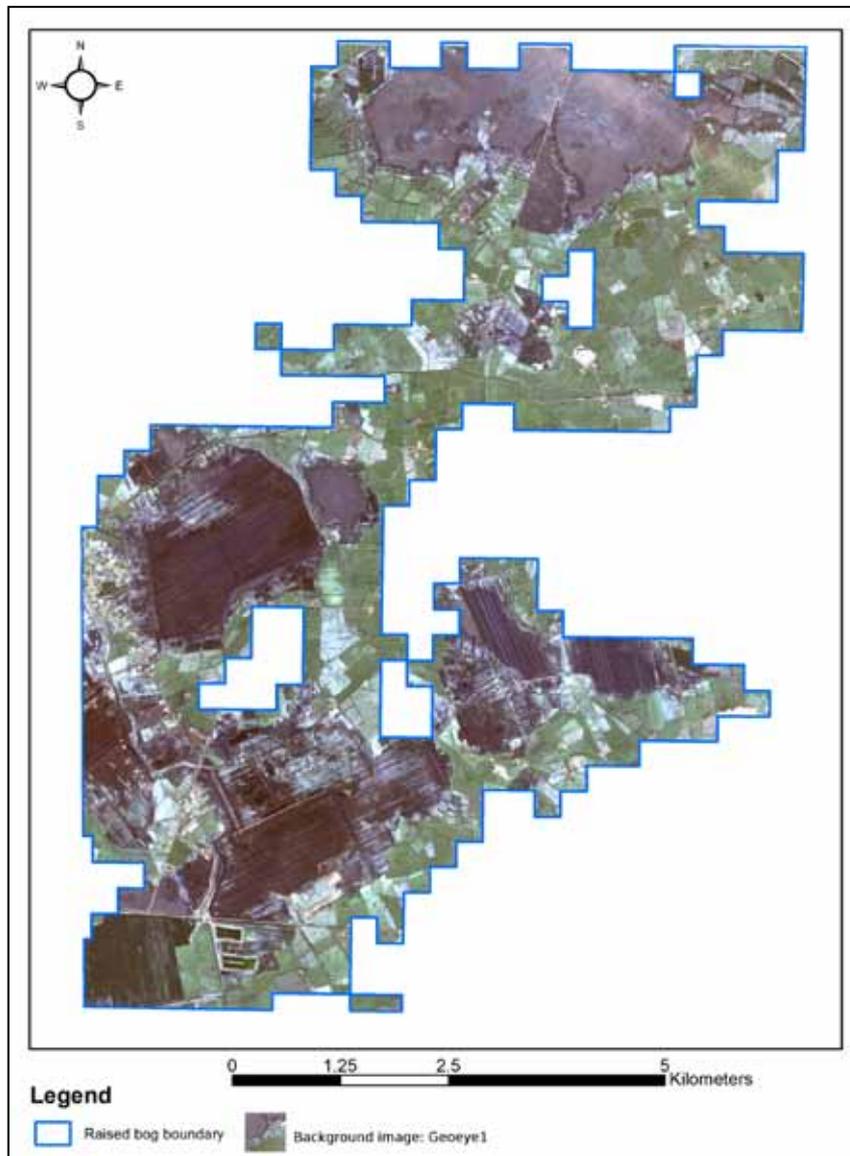


Figure 3.3. High-resolution (1.0 m) *Ikonos* image of the Clara/Turraun Bog complex (CTBC) raised bog area.

are some smaller areas of cutover peatland, raised bog, bog woodland, improved grassland and a mosaic of bare peat and wet/dry grassland.

One area was chosen to test the ability of the feature extraction method to identify peatland disturbance. The extent of the satellite image for this area is 20,350 km² of Ireland, centred near Athlone, Co. Westmeath (Fig. 3.1). This area predominantly consists of raised bogs, many of which have been exploited by BnM; however, there are areas of Montane blanket bog but these were excluded from this study. The maximum elevation for raised bogs in Ireland is about 152 m (Hammond, 1979). The average annual precipitation for raised bogs in the swath area is between 800 and 1200 mm. Many of the industrial bogs have been exhausted and natural colonisation by coniferous forest, woodland scrub and grasses is taking place. The raised bogs in the western side of the image have not been exploited for industrial mining; however, they have been extensively cutover around their edges.

The final stage of this process was to examine the extent of peat soils delineated by the DIPMV2 to determine disturbance on Irish peatlands. According to the DIPMV2, peat soils extend over about 20% of the national land area (Connolly and Holden, 2009). It is known from previous surveys that large areas have been disturbed through forestry and conversion to pastureland. This stage covers all peatland types present in Ireland. However, cloud cover was an issue in West Cork, North West Mayo, West Donegal and the Inishowen Peninsula.

3.2.2 *High-resolution and medium satellite imagery*

Two high-resolution multispectral images (*Ikonos* and *Geoeye-1*) were acquired for Tullaghanrock and Clara bog on the 13/04/2010 and 18/03/2009, respectively. Each of the images covers an area of 73 km² and 50 km², respectively, consisting of peatland areas around the study sites. The *Geoeye-1* product contained Blue, Green, Red and Near-Infrared bands at 2 m resolution and a panchromatic band at 0.5 m resolution. The *Ikonos* imagery contained Blue, Green, Red and Near-Infrared bands at 4 m resolution and a panchromatic band at 1 m resolution. Each image was geo- and ortho-rectified and both were pan-sharpened using the

High Pass Filter (HPF) technique in the Erdas Imagine software.

The IRS medium-resolution satellite images were acquired from the IRS *P6 LISS 3* satellite at 20 m resolution between 2005 and 2006. The data consist of three visible and one near infra-red band. The swath width is 141 km. The images were geo-rectified using the geo-rectification tool in ArcGIS. The DIPMV2 defined the peat soil extent and this was used as an Area of Interest (AOI) on the IRS images. SPOT satellite imagery is also available for Ireland: however, SPOT satellite scenes are much smaller and therefore require much more pre-processing time.

3.2.3 *Object-oriented feature extraction*

The DIPMV2 was used to isolate areas of peatland in both the high and medium imagery. The FA software was manually trained to identify different land-cover types such as high bog, forestry, industrial peatlands, cutover areas, pasture and rough grazing areas on the high-resolution images (Figs 3.4 and 3.6). In Figs 3.9 to 3.16, the IRS medium-resolution imagery was used as it was available and covered the country in several satellite scenes. Even though the IRS imagery offered good spatial coverage, there was a lot of cloud cover along the western seaboard which prevented classification of these areas. Cloud masks were created to remove these areas from the imagery. Within the object-oriented software several parameters are adjustable. These were varied for the high- and medium-resolution imagery in order to capture the best representation of the disturbance state of the raised bogs. These parameters included spatial resolution, input bands, input representation and learning options. Several combinations and iterations were processed resulting in a maps of disturbance for Irish peatlands (Figs 3.4–3.17). The first iteration of the process outputs a vector file in the ArcGIS shapefile format, which is examined and evaluated to permit a cycle of improvement of training data to maximise the accuracy of the map. Several disturbance maps were produced at high and medium resolutions. The disturbance cube was used as a guide to the severity of disturbance and a 'traffic light' system similar to NPWS (2008) was used to highlight disturbance. Green areas represent

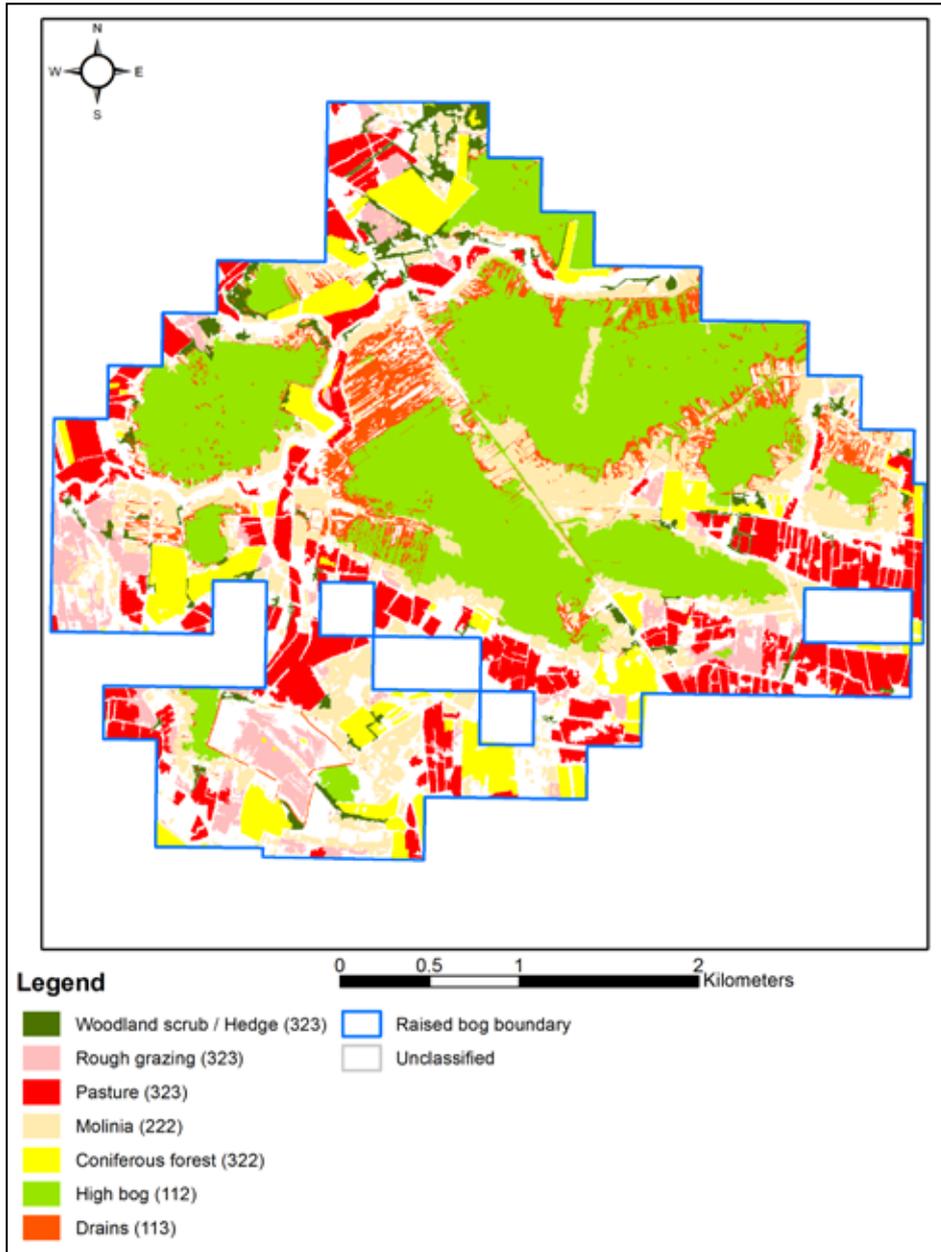


Figure 3.4. Geoeye-1 high-resolution disturbance map, Tullaghanrock bog using National Parks and Wildlife Service (NPWS) traffic light system i.e. red = disturbed, yellow = forest, orange = medium disturbance, green = relatively undisturbed (all maps here follow this convention).

peatlands that are relatively undisturbed (Clara bog, [Fig. 3.6](#)), shades of orange and yellow reflect medium disturbance (peripheral areas of Tullaghanrock bog, [Fig. 3.4](#)) and red indicates a high level of disturbance to the peatland, that is conversion to pasture or industrial peat. These maps were ground-truthed and assessed for accuracy.

3.2.4 Ground-truthing

Buchanan et al. (2008a) assessed the accuracy of forest versus non-forest using a reference dataset produced from visual interpretation of high-resolution *Quickbird* images in GE. The spatial extent of high-resolution imagery for Ireland in GE has increased considerably in 2010/11. The high-resolution areas were demarcated

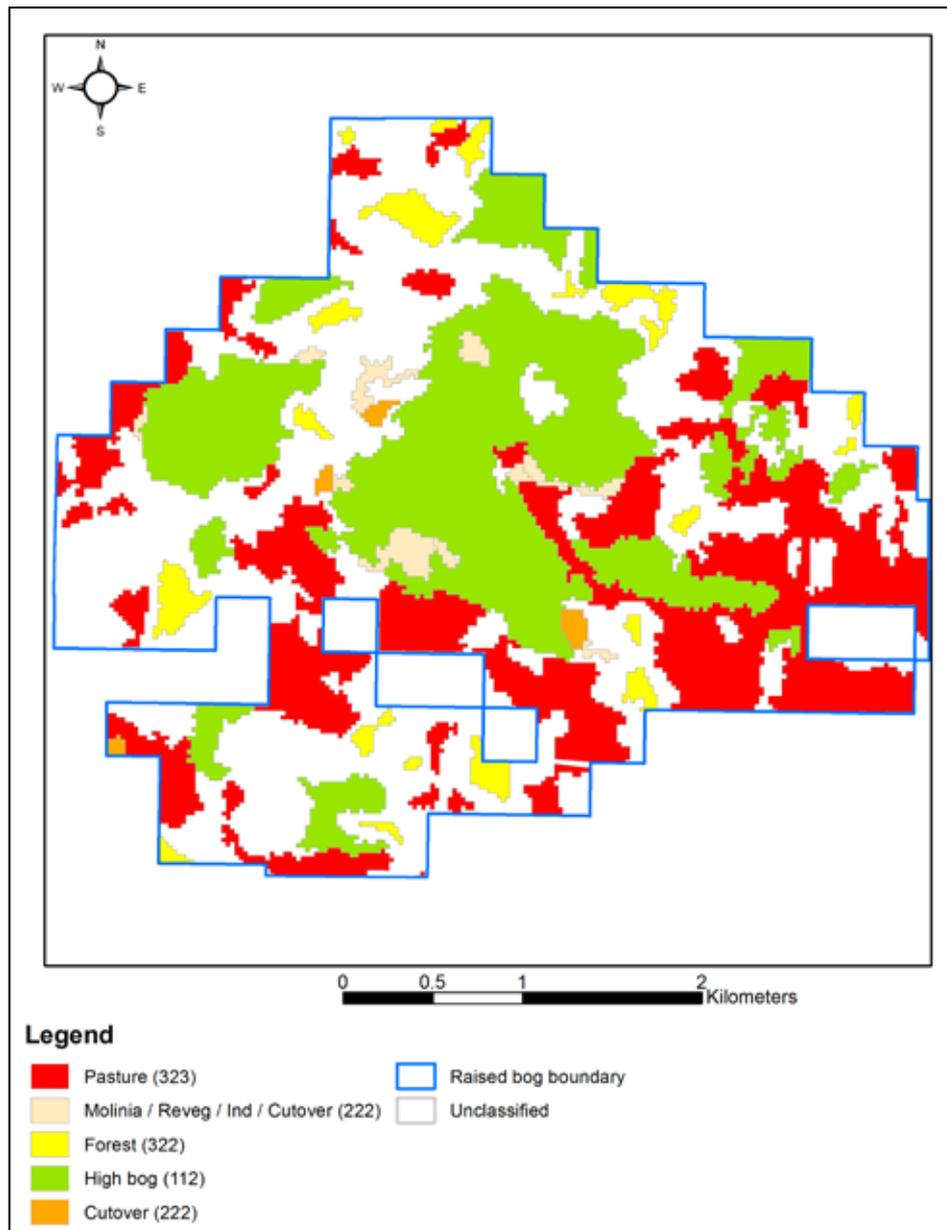


FIGURE 3.5 India Remote Sense (IRS) medium-resolution disturbance map at Tullaganrock bog.

in GE and imported to ArcGIS as a shapefile. The Hawth's tool software programme (Beyer, 2004) was used to create random sample points which were then exported back to GE to be used in conjunction with ArcGIS to visually extract a database of accurate ground-truth points. Three ground-truth point datasets were created so that one was used to examine the accuracy of the medium-resolution data and the others

to examine the accuracy of the high-resolution data. A fourth set of data points was created using a BnM habitat map, for Oughter bog in the Clara/Turraun bog complex, as ground-truth data. These datasets were subsequently intersected with the three disturbance maps to form a confusion matrix to assess the accuracy of the shapefiles produced in the object-oriented feature extraction process.

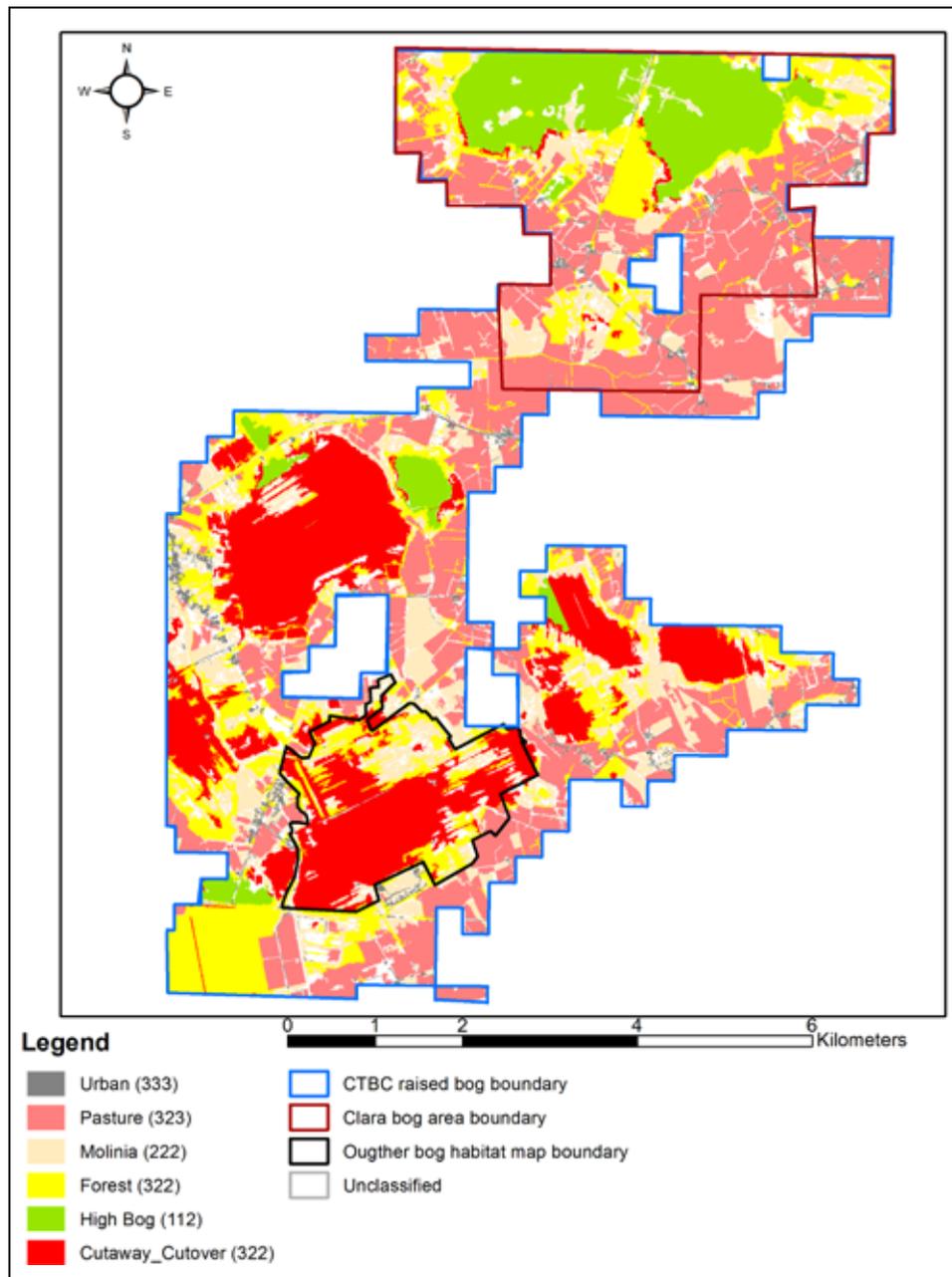


Figure 3.6. Ikonos high-resolution disturbance map, Clara/Turraun Bog complex (CTBC).

3.2.5 Accuracy assessment

The overall accuracy was calculated for each map:²

- 1 3.4. High-resolution Tullaghanrock bog;
- 2 3.5. Medium-resolution Tullaghanrock bog;

- 3 3.6. High-resolution CTBC;
- 4 3.7. Medium-resolution CTBC;
- 5 3.8 Medium-resolution midlands;
- 6 3.9–3.16 National-scale maps;
- 7 3.17 National-scale map.

2 For a more detailed accuracy assessment and error matrices please see: Connolly, J. and Holden, N. M. (2011) Object-oriented classification of disturbance on raised bogs in the Irish Midlands using medium- and high-resolution satellite imagery. *Irish Geography*, 44:1, 111–35.

The purpose of calculating the accuracy assessment of the object-oriented feature extraction for both medium and high-resolution images was three-fold: (i) to examine the process when used with the high-

resolution images, (ii) to examine it when used with the medium-resolution images and (iii) to compare the

medium- and high-resolution disturbance maps with each other.

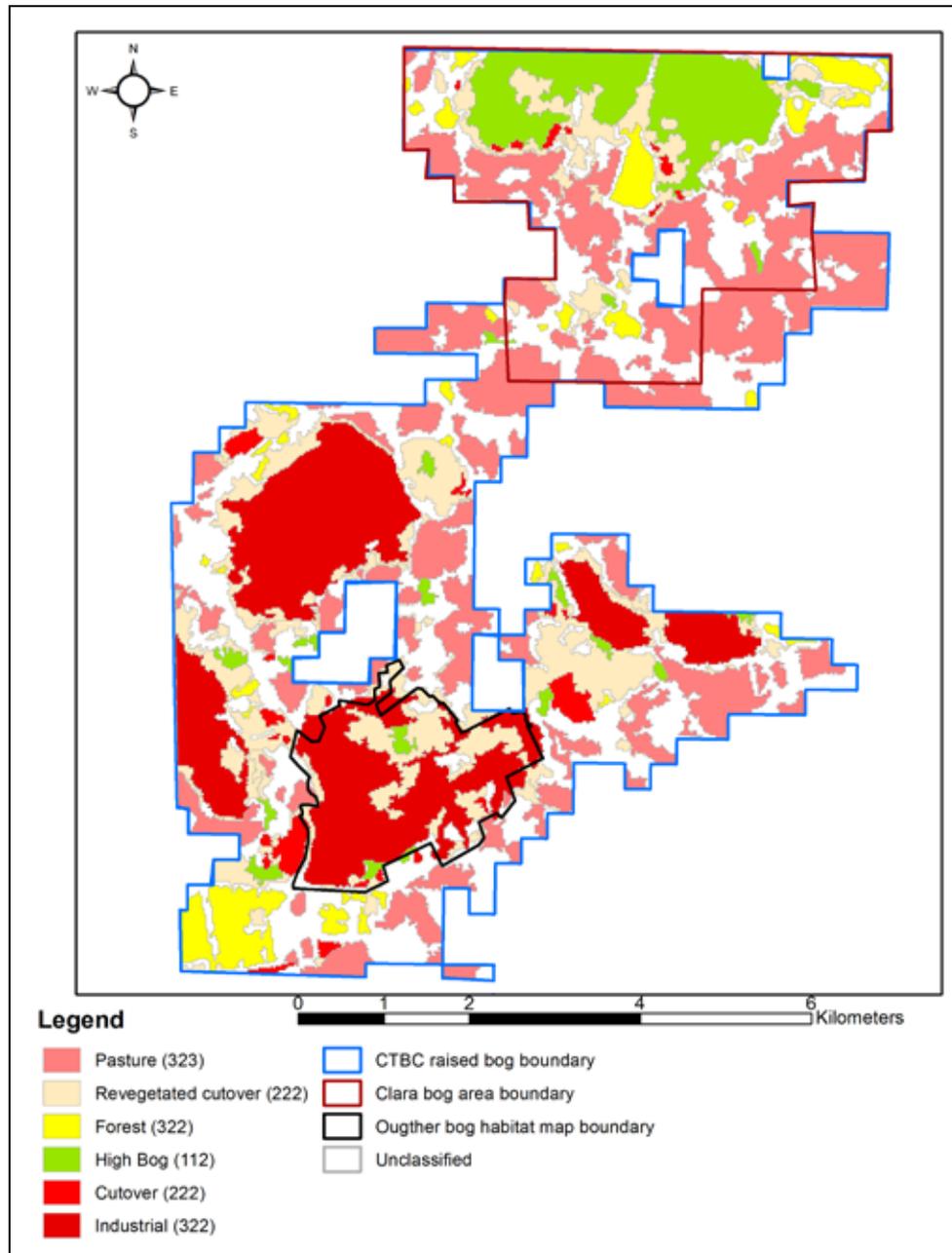


Figure 3.7. India Remote Sensor (IRS) medium-resolution disturbance map, Clara/Turraun Bog complex (CTBC) raised bog area.

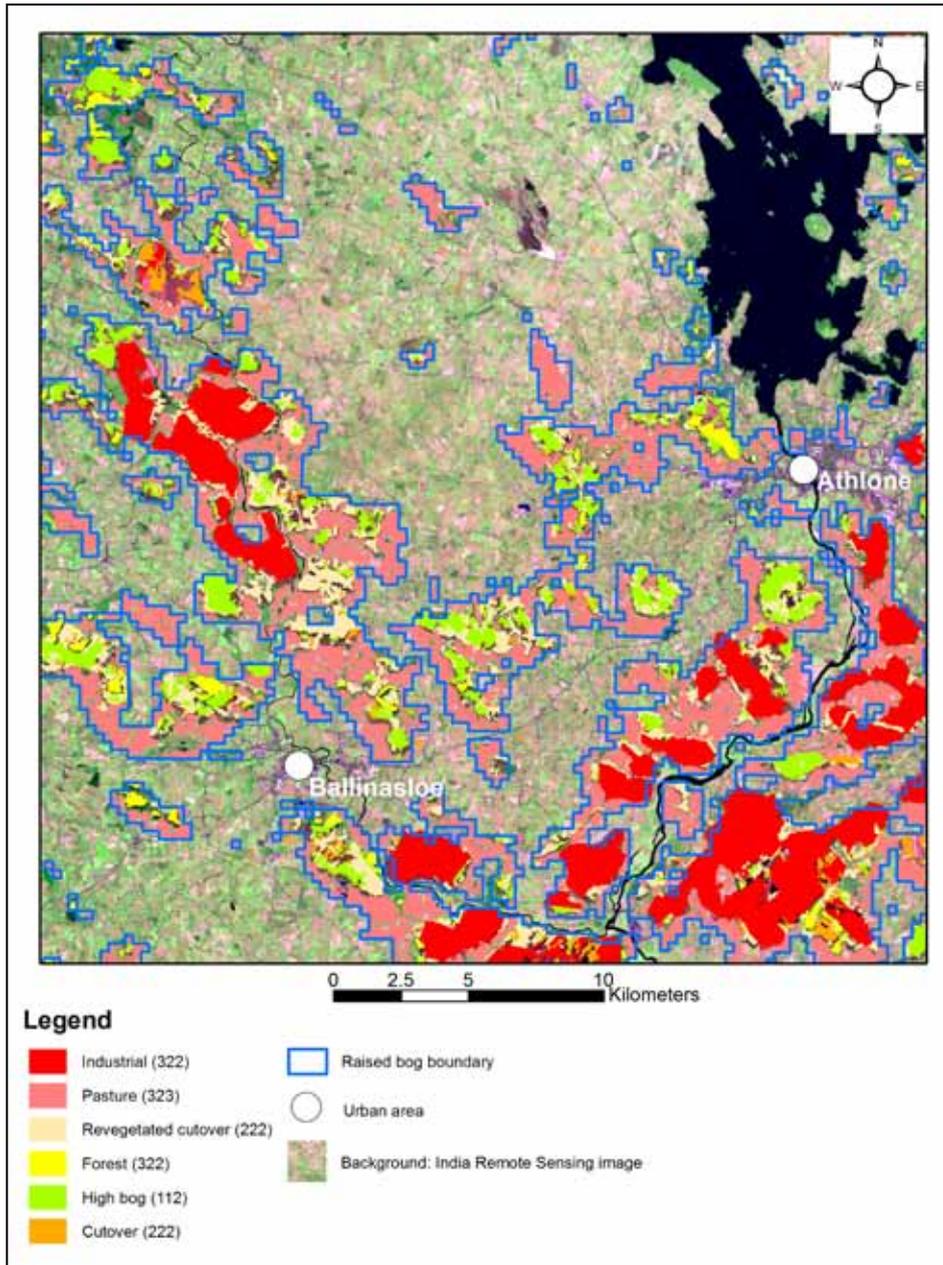


Figure 3.8. Subset of India Remote Sensor (IRS) medium-resolution disturbance map for Midland raised bogs in Ireland.

3.3 Results

3.3.1 High-resolution imagery

The object-oriented classifications on the high- and medium-resolution images resulted in the production of several disturbance maps. Five of these were located at the study sites: two high-resolution site-specific maps at Tullaghanrock bog and at the CTBC (Figs 3.4 and 3.6) and three medium-resolution maps of raised bogs; at Tullaghanrock bog and at the CTBC (Figs 3.5 and 3.7) and on raised bogs the Midlands of Ireland (Fig. 3.8). The overall accuracy was calculated for each map (Table 3.1).

Table 3.1. Overall accuracy assessment at each study site.

Figure	Study site	Imagery	Overall accuracy (%)
3.4	Tullaghanrock bog	GeosEye-1	85
3.5	Tullaghanrock bog	IRS	72
3.6	CTBC (Oughter)	Ikonos	66
3.7	CTBC (Oughter)	IRS	62
3.6	CTBC (Clara)	Ikonos	90
3.7	CTBC (Clara)	IRS	73
3.8	Midlands	IRS	74

Several landcover classes were selected as suitable for training in the FA object-oriented classification of the IRS medium-resolution image. These included industrial peatlands, cutover peatlands, high bog, pasture, revegetated cutaway, revegetated cutover and forest. It was necessary to aggregate some of these classes in both the IRS and ground-truth data to allow a more accurate comparison of the data. For example, in the medium-resolution IRS raised-bog disturbance map, the ground-truth classes of revegetated cutover and cutover were aggregated to match the IRS map classes of cutover, revegetated cutover and grassy peat (Molina). The classes high bog and high bog with drains, and felled forest and forest were also aggregated. The reason for combining the revegetated and cutover classes was that, despite their difference on the ground, in the IRS map, it was difficult to discriminate between them because they have similar spectra. Similarly, the high bog and high-bog drain classes could be discriminated clearly in the high-resolution images but this was not feasible in the IRS image. The classes of felled forest and forest were aggregated for temporal reason rather than the spectral or spatial. Many of the felled forest ground-truth points in the GE dataset (2009/10) were forest in the 2006 IRS image. The accuracy of each of these classes³ was examined against a ground-truth dataset consisting of several classes and 337 random data points. The accuracy of the IRS disturbance maps is relatively good for most classes, with the overall accuracy ranging from 62% to 74%.

At Tullaghanrock, a more detailed approach was taken. The extent of the bog was used to clip both the medium and high-resolution disturbance maps in ArcGIS. Each of these were then examined in more detail using a Google Earth-derived ground-truth dataset consisting of 959 and 807, respectively, randomly sampled data points. The IRS disturbance map performed reasonably well with an overall accuracy of 72%, which is very similar to the larger national-scale map. The high-

resolution *Geoeye-1* disturbance map performed much better with an overall accuracy of 85%.

A similar procedure was carried out for the CTBC (Figs 3.6 and 3.7). Clara and Oughter bog were examined as examples of contrasting peatlands, Clara being relatively intact and Oughter an exhausted industrial peatland. While both peatlands are depicted in the same image in Figs 3.6 and 3.7, their accuracy assessment was conducted separately. The overall accuracy of the medium-resolution IRS disturbance map for Clara was 73% similar and similar that at Tullaghanrock. Again, the high-resolution data performed much better. The overall accuracy for the *Ikonos* disturbance map for Clara was 90%. The ground-truth data for the Oughter bog was derived from randomly sampling a BnM habitat map. The habitat was created in 2009 using 2004 Ordnance Survey aerial imagery. Both the IRS and *Ikonos* disturbance maps performed poorly here with overall accuracy at 62% and 66%. On the Oughter bog habitat map there is very little raised bog and what was present in 2004 would likely have been disturbed by 2009. This therefore raised difficulties with regard to the accuracy in the map. There was also confusion in the forest class, and revegetated cutaway was misclassified as forest.

3.3.2 Medium-resolution imagery

Each IRS-derived image was analysed individually, using the FA object-oriented techniques described above resulting in the creation of eight regional disturbance maps (Figs 3.9–3.16) and one combined national map (Fig. 3.17). In all these maps three categories were detected in the imagery: (i) forest, (ii) pasture and (iii) open peatland. There was one exception to this in Fig. 3.16 where extensive heather areas in the imagery made it necessary for a peat sub-category – peatland heather – to be initiated as these heather peatlands were not sufficiently captured. A fourth category, industrial peatlands, was implemented in images where industrial peatlands are present. Google Earth was used as a ground-truthing tool for all of the images (Buchanan et al., 2008b).

There were some issues regarding imagery availability and cloud cover. There are two sections in Donegal that did not have IRS satellite imagery available for them: north-east Donegal and the Inishowen Peninsula.

3 More detail on these classes can be found in: Connolly, J. and Holden, N. M. (2011) Object-oriented classification of disturbance on raised bogs in the Irish Midlands using medium- and high-resolution satellite imagery. *Irish Geography*, 44:1, 111–135.

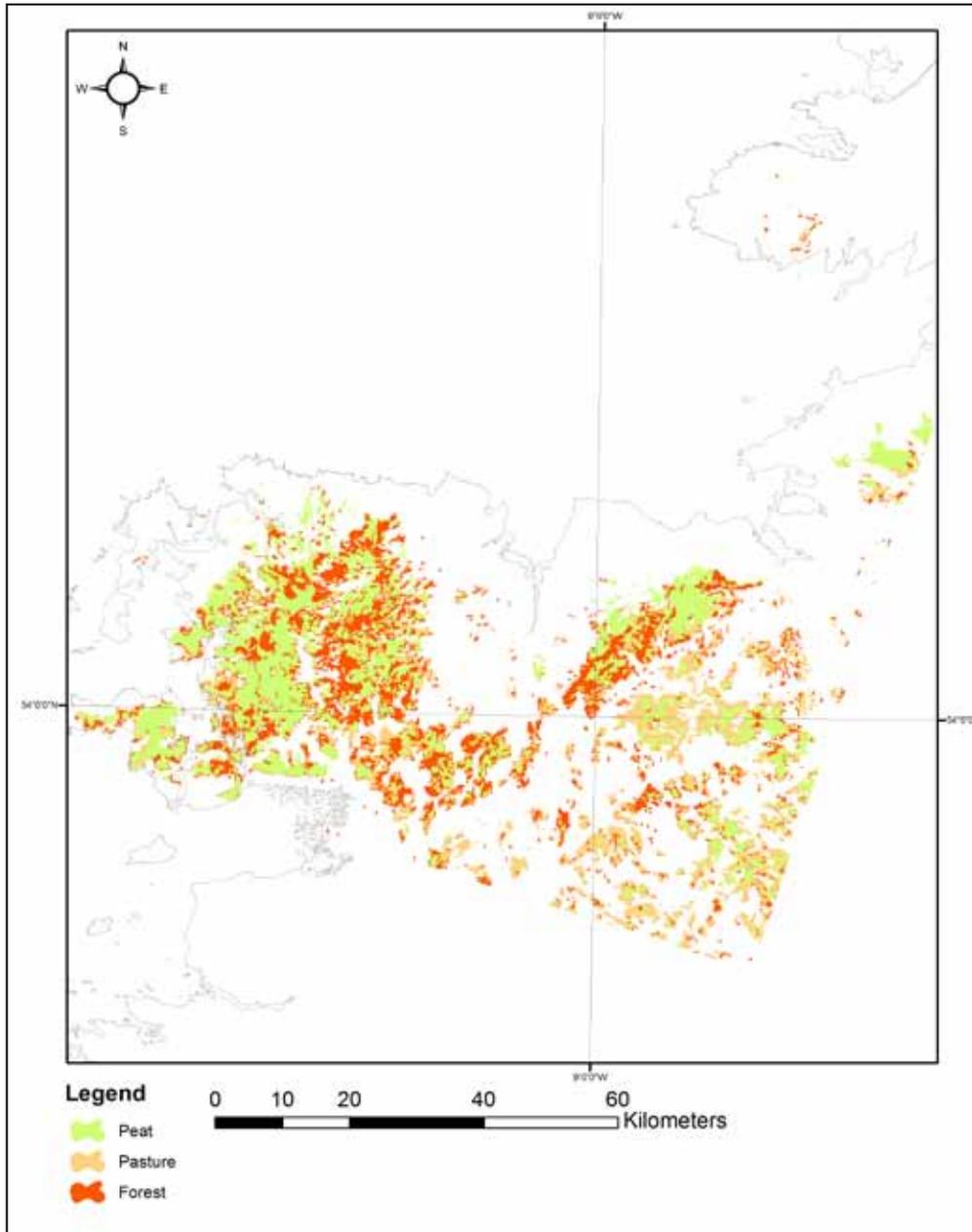


Figure 3.9 Disturbance classification for Mayo region.

These two areas consist of about 3.7% of the DIPMV2 area. This is why they are excluded from the map in [Fig. 3.10](#). In terms of cloud-free data, 74% of the available imagery was cloud free. Cloud was an issue in North Mayo, Donegal, small areas in Connemara and in Munster.

In the cloud-free areas, the results showed that forestry plantations are extensive throughout Ireland and with large areas of the DIPMV2 covered along the border counties, in west Kerry and in upland areas in the

midland. Much of the peatlands in the Limerick/Kerry/Cork region as well as those in the midlands have been converted to pasture. On a national basis about 66% or 967,870 ha of the DIPMV2 area have either been converted to pasture, planted or undergone industrial extraction. The south of Ireland and along the east coast (namely the Wicklow Mountains) and the Connemara/Clare region have the largest areas of open peatland within the DIPMV2. However, the type of disturbance that occurs in these areas is not detectable in the IRS

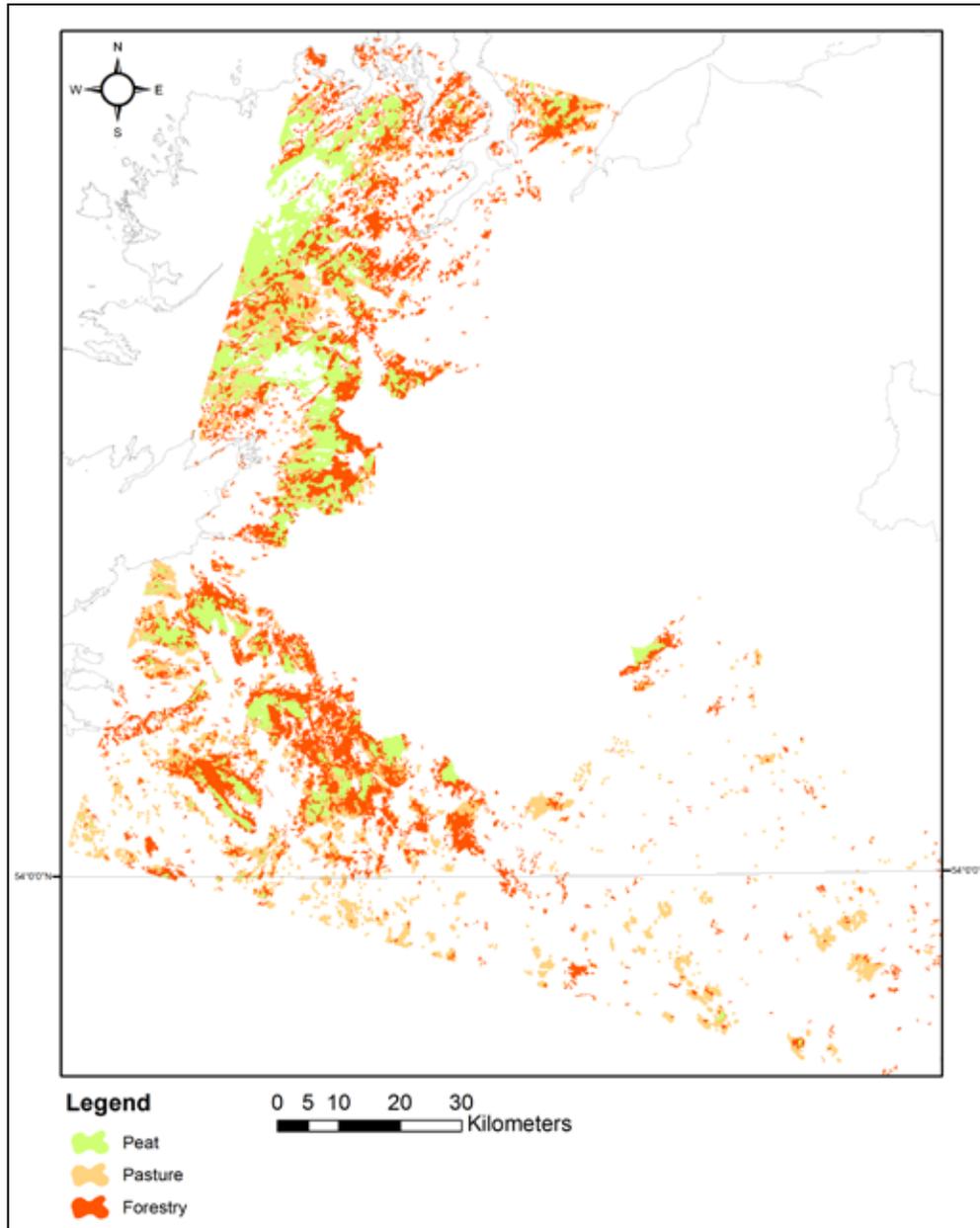


Figure 3.10. Disturbance classification for Border region

Table 3.2. The % area of each of the three (and industrial) categories.

Figure	Area	Accuracy %		% of DIPMV2 area			
		Overall	Kappa*	Peat (%)	Forest (%)	Pasture (%)	Industrial (%)
3.9	Mayo	70	0.54	42	33	24	
3.10	Border	79	0.67	21	54	25	
3.11	Connemara/Clare	77	0.63	52	10	38	
3.12	Midlands	77	0.68	34	15	39	11
3.13	Limerick/Kerry/Cork	86	0.78	26	25	49	
3.14	West Kerry	77	0.62	32	57	11	
3.15	South	76	0.65	77	18	6	
3.16	East Coast	84	0.77	72	20	8	
3.17	National	77	0.66	34	27	35	4

*Observed unweighted kappa

satellite imagery. [Table 3.2](#) shows the accuracy of each map and the percentage of the DIPMV2 that was classified as peat, forest, pasture or industrial in each area by the object-oriented method.

The overall accuracy for the regional disturbance maps ranged from 70% to 86%. Overall accuracy for the national map was 77%. The 'kappa' value is useful for examining how accurate maps are over and above accuracy simply by chance. The kappa statistic corrects for this chance agreement. Low kappa values mean that there is a low degree of agreement beyond chance, so that a kappa value of 0, 0 -0.2 or 0.2 to 0.4 gives no, slight or fair agreement beyond chance

while a kappa value of 0.4–0.6, 0.6–0.8 or 0.8–1.0 give moderate, substantial and almost perfect agreement beyond chance (McGinn et al., 2004). In this study the Kappa value ranges from 0.54 to 0.78 ([Table 3.2](#)) and is mostly in the 0.6 to 0.8 range. This indicates that there is a substantial degree of agreement beyond chance for most of the disturbance maps and a fair to moderate agreement for map with 0.54 Kappa values (McGinn et al., 2004). The Kappa value for the nationwide disturbance map was 0.66, again indicating that there is a substantial degree of agreement beyond chance between the ground-truth and object-oriented classification maps.

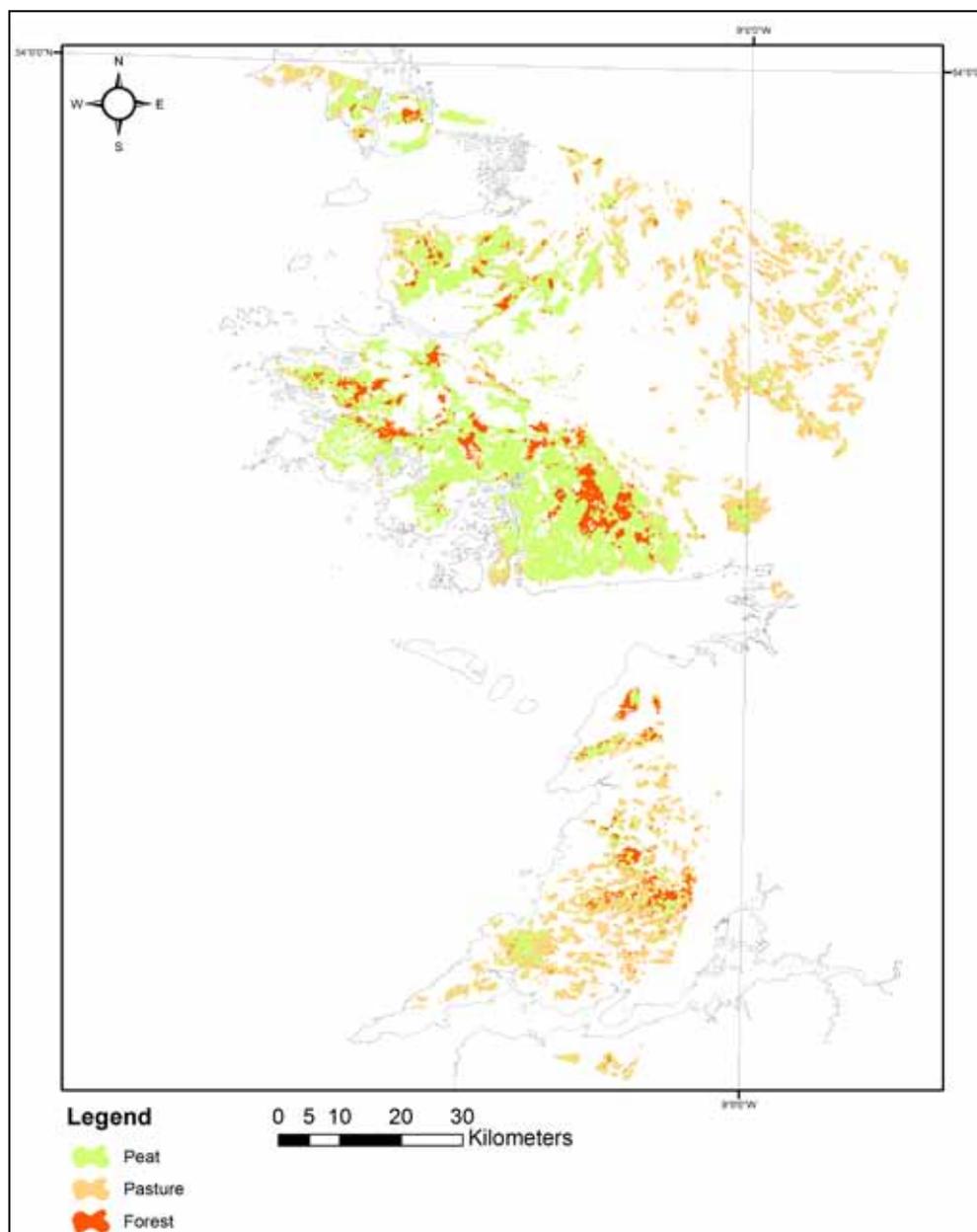


Figure 3.11. Disturbance classification for Galway/Clare region.

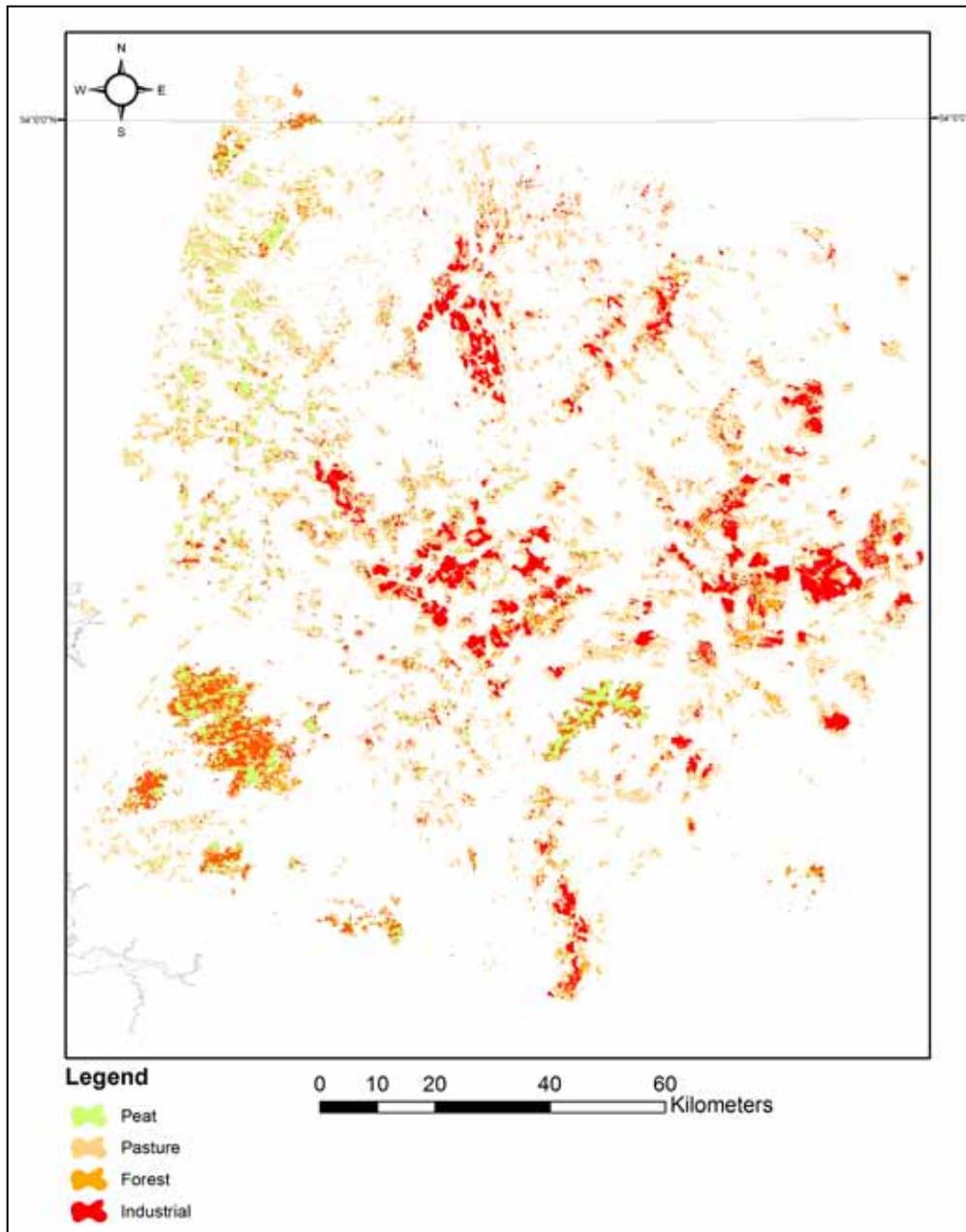


Figure 3.12. Disturbance classification for Midlands region.

These maps give an improved indication of the spatial extent of disturbance and on its location, on areas that have been defined as peat soil according to the DIPMV2 map. However, the spatial resolution of the IRS imagery (20 m) means that finer disturbance, such as domestic extraction, fire or drainage, that may be currently present on peatlands are not detected. Higher resolution imagery is essential to detect these types of disturbance in these areas.

3.4 Discussion

Peatland disturbance in Ireland is a complex spatial and temporal problem. Several studies have already shown that the extent of disturbance in Irish peatlands is severe (Connolly et al., 2007; Cross, 1990; Douglas et al., 2008; Hammond, 1979; NPWS, 2008; Renou-Wilson and Farrell, 2009). However, this work gives a spatial dimension to surveys of peatland disturbance. The maps produced in the current research are the first

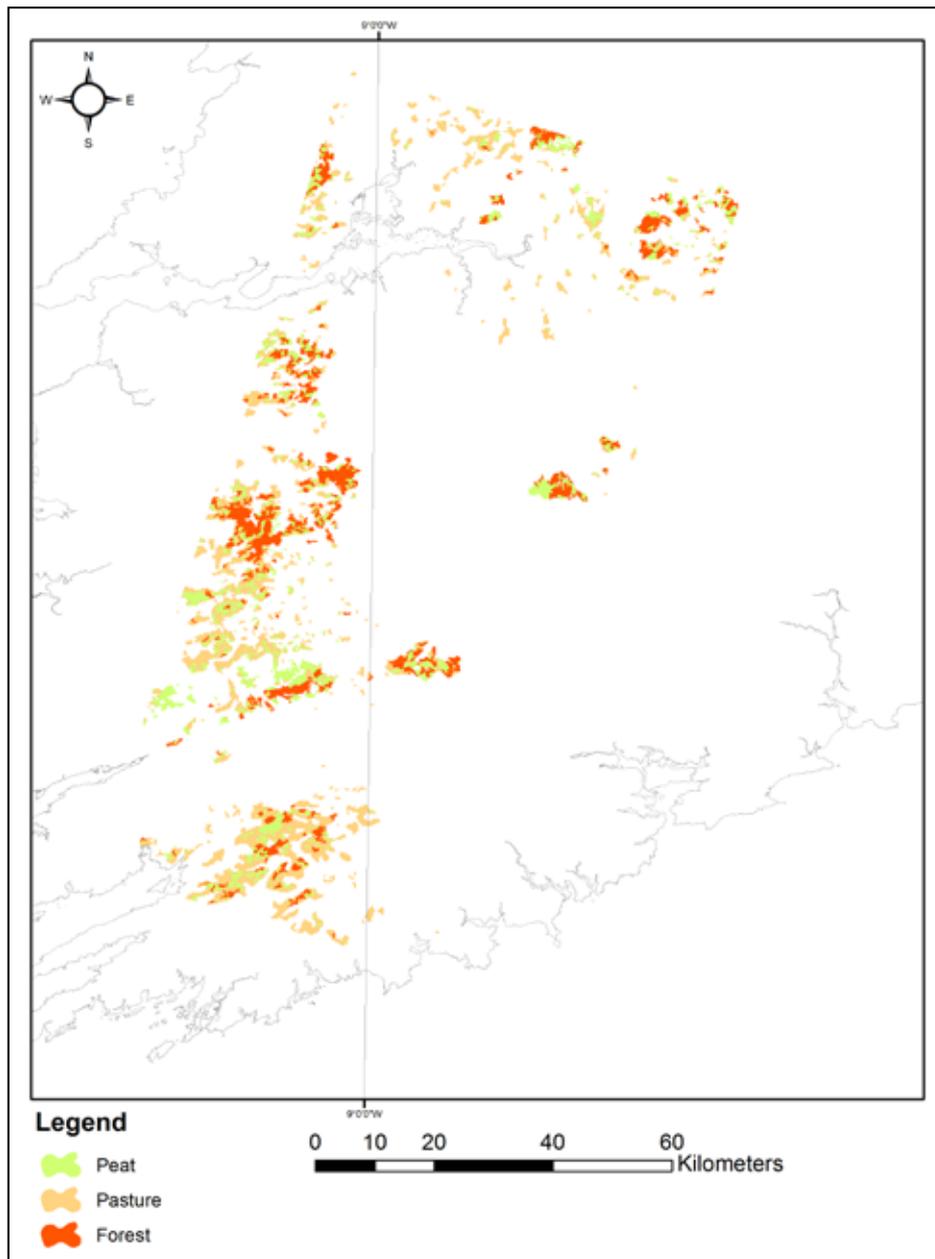


Figure 3.13. Disturbance classification for Limerick/Kerry/Cork region.

attempt at mapping the spatial extent of disturbance on peatlands on a national level using medium- and high-resolution satellite imagery.

Detecting peatland disturbance is a complex spatial issue. Peatland disturbance occurs at various spatial scales, ranging from fine-scale disturbances such as drainage to large-scale disturbance such as land reclamation and forestry. High-resolution imagery with resolutions of 0.5 m to 1.0 m are ideal for detecting fine-scale disturbance; however, there are a number of

constraints, including the cost of imagery and the lack of an archive of high-resolution imagery over Ireland. Therefore, it is necessary to use medium, and coarse, resolution satellite imagery which does not have the same financial and coverage constraints, to examine peatland disturbance on a nationwide basis. However, the drawback is that the ability to detect finer-scale disturbance is lost. Despite this, medium-resolution imagery, such as IRS, can detect large-area land-use units such as forestry plantations and pasture and, when used in conjunction with ancillary data such as

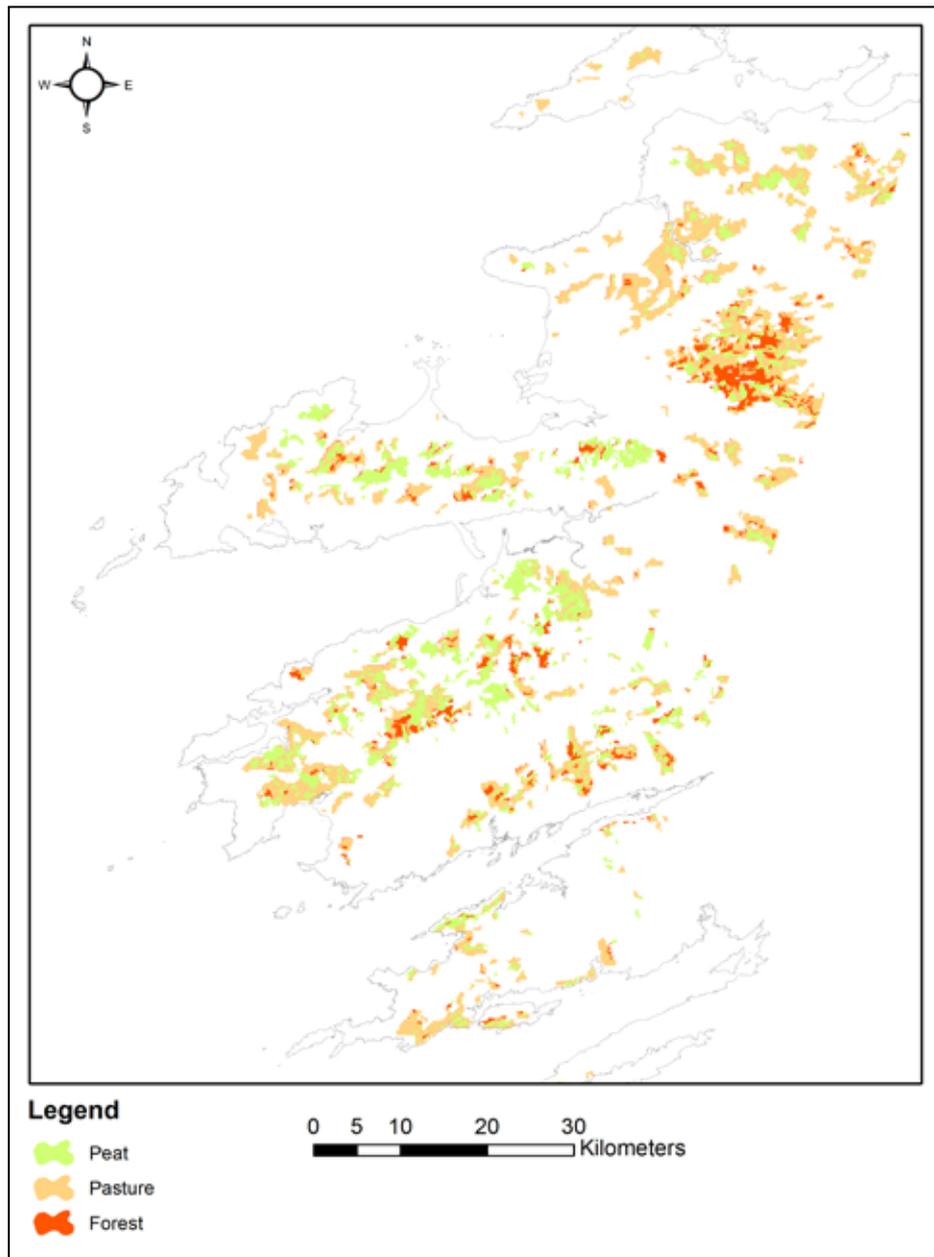


Figure 3.14. Disturbance classification for Kerry/West Cork region.

the DIPMV2, can yield useful information on the spatial extent of disturbance.

In both the regional and national disturbance maps (Figs 3.9–3.17) it is clear that disturbance is spatially extensive. In these maps the NPWS traffic light system is used to identify disturbance: red (forest), orange (pasture) and pink (industrial). In the green ‘peat’ areas, no large-scale disturbance was detected at this resolution. However, this does not mean that disturbance does not exist at these sites. Fine-scale disturbance is extensively present in these areas but

cannot be detected because of the limitations of the satellite sensor. This is seen clearly when Figs 3.4 and 3.5 are compared. Forestry plantations and agricultural conversions from peatland to pasture are spatially extensive. Much of the disturbance caused by forestry is relatively recent, that is in the last forty or fifty years. The conversion of peatlands to pasture has occurred over the last two hundred years. The results also show that open peatland areas are still relatively extensive, particularly in mountainous areas along the east coast and along the western seaboard. However, it must be

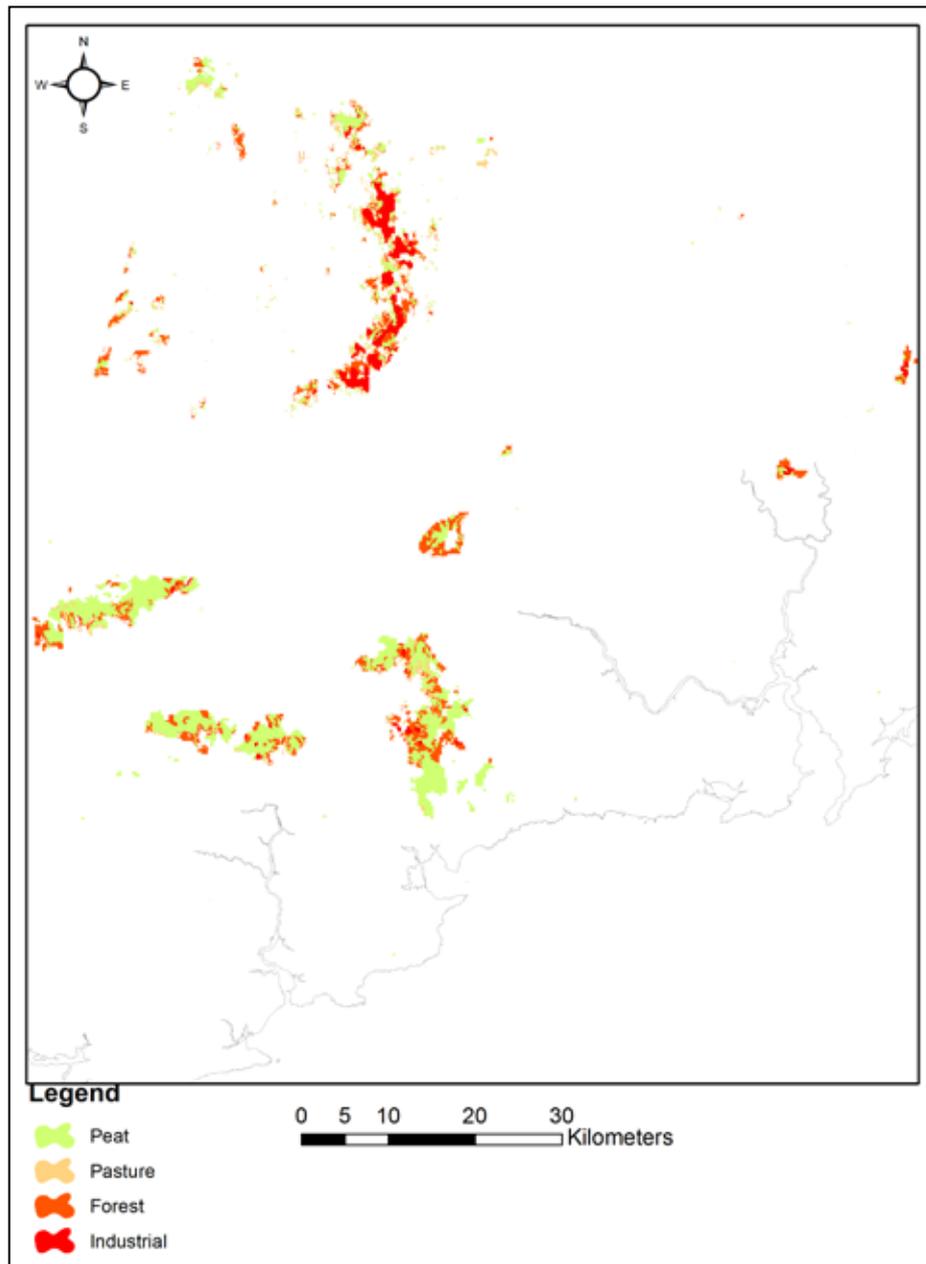


Figure 3.15. Disturbance classification for South region.

noted that disturbance probably is extensive in these areas, as can be seen in the Wicklow Mountains (Connolly et al., 2011).

In this work the disturbance cube methodology was developed and used as a guide to identify and determine the severity of disturbance during the object-oriented training process. The methodology was based partly on the definition of peatland disturbance created here: 'Any natural or anthropogenic event that interrupts the natural trajectory of growth of the peatland'. For example, when the imagery was acquired (both high and medium

resolution) the disturbance cube classes 112 (high bog), 323 (pasture) and 222 (cutover) were useful for both the training and identification process. The classes are also useful for understanding the type and area of disturbance that is extracted from an image. In this research, the peat soil areas (from the DIPMV2) examined contain many land-cover types, which – when viewed in the context of the disturbance definition – represent areas of disturbance. Therefore, the extracted objects such as forest, cutover, pasture, drainage, industrial and rough grazing represent different states of peatland

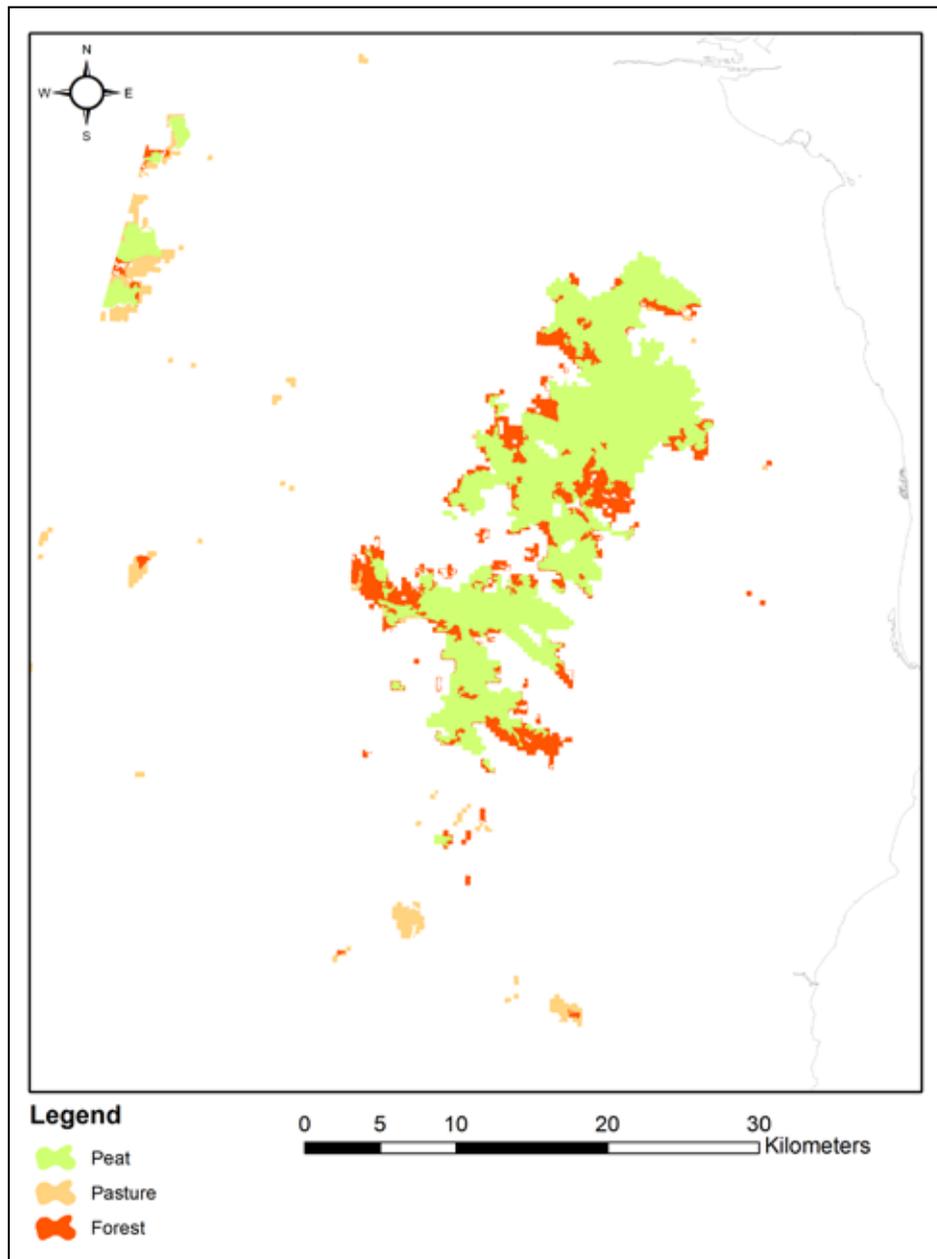


Figure 3.16. Disturbance classification for the Wicklow region.

disturbance. The disturbance cube classifications can be linked to object or disturbance areas that can be extracted from the images, more so in high-resolution rather than in medium-resolution images. Despite this, there is an imperfect alignment between the object-oriented classes and the cube classes, particularly in the IRS imagery. The high-resolution imagery test studies at Tullaghanrock bog, Clara and at Oughter bog depict maps of disturbance that are more detailed and accurate in general and have classes that can be related to and informed by the disturbance cube.

In this research overall accuracy for medium and high-resolution derived maps ranged between 62% and 90%, with the higher-accuracy values related to the high-resolution imagery. The medium-resolution imagery permitted relatively accurate maps to be produced, given the constraints, but only large area disturbances such as forestry or pasture conversions could be extracted. There was clearly added value in using the process with high-resolution imagery. The IRS (medium-resolution) disturbance map (Fig. 3.8) covers 3,919 km² of raised bog in Ireland as delineated by the DIPMV2 (Connolly

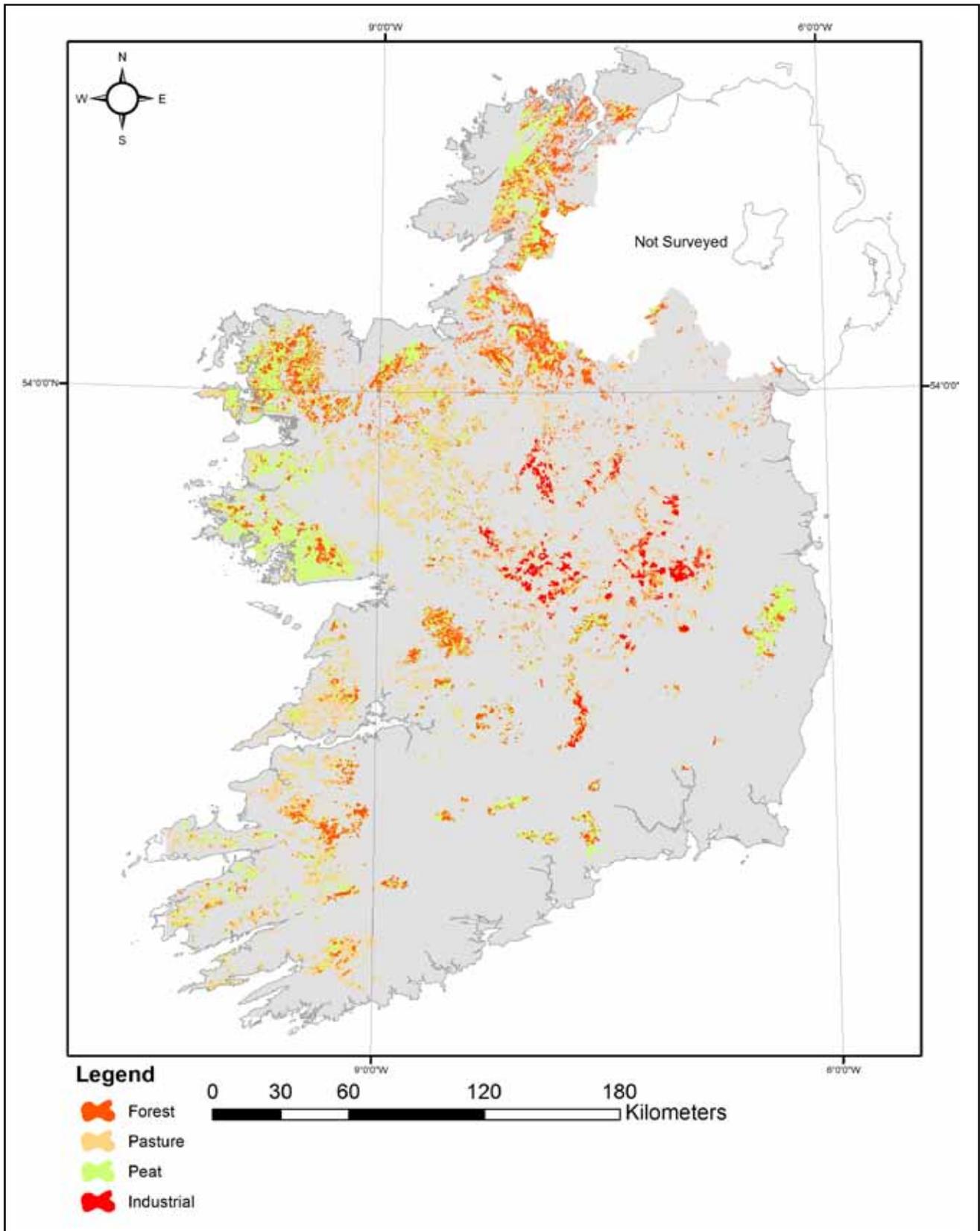


Figure 3.17. Nationwide disturbance classification (using medium-resolution (20 m) imagery).

and Holden, 2009) and covers the majority of raised bogs in central Ireland. The overall accuracy of the map, produced using the object-oriented method, was 74%. Detailed accuracy assessments were high with values ranging from 80% and over 90%.⁴ This reflects the fact that these classes are spatially and in many cases spectrally distinct on the landscape. Sulla-Menashe et al. (2011) found it difficult to discretely map various shrub-dominated ecosystems with MODIS data. They found that the tundra biome contains heterogeneous ecosystems containing perennial shrubs, grasses, sedges, mosses and lichens. In Ireland, cutover and revegetating cutover and Molina peatland areas contain a fine-scale heterogeneous landscape consisting of a mix of grasses, shrubs, bare peat, sedges and mosses that are difficult to discriminate from one another at this resolution and thus difficult to map. Therefore, on these spatially complex heterogeneous areas similar types such as cutover, revegetated cutover and contained Molina, were aggregated to simplify the process. However, the accuracy of these areas was much lower, most likely because surface conditions are similar to other classes examined, such as rough grazing and revegetated industrial peatlands and are therefore difficult to discriminate from one another – especially in the medium-resolution imagery. Despite this, [Fig. 3.8](#) gives an indication as to the state of disturbance on Ireland's raised bogs.

Many peatlands are located in remote inaccessible areas. Therefore, collecting ground-truth data in remote landscape can be difficult and dangerous. By using Google Earth high-resolution imagery ground-truth data can be 'accessed' quickly. However, this method has both advantages and disadvantages. Expert knowledge of a landscape as well as some ground-truth data is essential for gathering this data especially in ambiguous classes. The downside of this method is that there is a higher likelihood of misclassifying the ground-truth data, especially in peat soil areas where the land cover is different to what it might be if disturbance had not taken place i.e. it is difficult to assess whether or not

peat is present at a certain location if the land use is pasture. Therefore, the DIPMV2 map (Connolly and Holden, 2009) was used to delineate peatland area and to aid the GE ground-truth data-acquisition process. This integration of ancillary data was essential for this project and was particularly useful in areas such as pasture area located to the south of the Clara high bog. These pastures were converted from peatland over the last 200 years (Crushell et al., 2008).

Moving from a regional scale to that of an individual bog the difference between high and medium-resolution imagery was clear. Tullaghanrock and Clara bogs represent raised bogs that have experienced anthropogenic disturbance, and include Oughter bog where the raised bog ecosystem has predominantly been destroyed by mining. In Tullaghanrock, the high-resolution *Geoeye-1* disturbance map performed much better than the low-resolution IRS maps ([Table 3.3](#)).

A similar trend was found at Clara bog where the overall accuracy of the high-resolution *Ikonos* imagery is 90% compared to 73% for the IRS imagery. However, in the detailed accuracy assessments there are some differences. The IRS forest class achieved a better accuracy of 87% compared to 83%. *Ikonos* predominantly misclassified cutover areas as 'forest'; however, the ground-truth dataset aggregates woodland shrub and forest and – on closer inspection of the imagery – low amounts of shrub vegetation may be present on some of the cutover areas.

The discrimination of land-cover classes in highly heterogeneous landscapes is the major issue. This occurs throughout the maps where classes that are relatively homogeneous, both spectrally and spatially, work well with the object-orient approach while those that are more heterogeneous have disturbance objects that are difficult to discriminate for the object-oriented software and therefore are less accurate in the medium-resolution imagery.

On an industrial mined peatland, Oughter bog, the ground conditions were very different from those at Tullaghanrock and Clara bogs owing to severely reduced vegetation cover. In both the medium and high-resolution disturbance maps the overall accuracy was only 62% and 66% respectively. In the IRS map the high bog class performed particularly poorly at 8%. In the

4 Further details can be found in: Connolly, J. and Holden, N. M. (2011) Object-oriented classification of disturbance on raised bogs in the Irish Midlands using medium- and high-resolution satellite imagery. *Irish Geography*, 44: 1, 111–135.

Table 3.3. Difference between accuracy on maps derived from high- and medium-resolution imagery.

Resolution	Class				
	Pasture (%)	Molina (%)	Forest (%)	High bog (%)	Cutover (%)
High (Geoeye-1)	84	66	91	90	84
Low (IRS)	66	55	82	78	7

high bog class 83% of the sample points were located on revegetated cutaway. On visual inspection of the IRS image this class looks very similar to high bog, which could explain the misclassification in the disturbance map. In the *Ikonos* (high-resolution) map no high bog classes were identified and some areas described as raised bogs in the Oughter habitat map are cutover in the image. In this map the forest class also performed very poorly.

It might have been expected that the cutaway/industrial peatland classes in both disturbance maps would have performed better. As it is, they have a relatively low user accuracy of 64% (IRS) and 80% (*Ikonos*). A possible explanation is that the habitat map used as a ground-truth tool was itself ground-truthed in 2004 and the IRS and *Ikonos* disturbance maps were derived from images from 2006 and 2009, respectively. It could be argued that the vegetation on these areas has altered over the intervening two- to five-year period. The heterogeneous areas produce low accuracies and this is in line with observations at other local sites and on the regional scale. Nonetheless, the pasture class in both maps and the Molina class in the *Ikonos* map performed very well. (The pasture is an area of improved grassland in the south-east of the site.)

Despite the low accuracy assessment for the heterogeneous cutover and grass sites, the approach worked well. Discrete disturbance such as industrial, forest and conversion to pasture can be accurately extracted from both the medium and high-resolution images. Cutover bog disturbance is much harder to classify given the fine-scale heterogeneous landscape. The low accuracy is related to the revegetated/cutover and Molina classes. These classes may be spectrally similar in that revegetating cutover may be similar to a high bog drain with Molina or a revegetating cutaway bog. This is where the issue of a fine-scale heterogeneous

landscape affects the object-oriented method. Despite this, overall accuracy ranged from 62% to 90%.

3.5 Conclusion

Both raised and blanket bogs in Ireland are extensively disturbed. This disturbance has been documented by Cross (1990), Foss (1998) and more recently by the NPWS (2008). Hammond (1979) in *The Peatland Map of Ireland* and Bossard (2000) in *CORINE 2000* made attempts to map peatland disturbance: however, it was at a relatively low scale of 1:575,000 and 25 ha, respectively. In this research medium- (20 m) and high- (0.5 m and 1 m) resolution images from IRS and *Geoeye-1/Ikonos* were used to map disturbance using an object-oriented approach. The resulting disturbance maps achieved good overall accuracies ranging from 62% and 90%. These maps are a useful addition to the literature on disturbance in Ireland as they depict disturbance spatially and show that disturbance of the area denoted as peat soil in the DIPMV2 map is widespread. The medium-resolution imagery is useful for examining peatland disturbance over large areas and could be classed as indicative disturbance maps. These maps depict the areas where landscape level disturbance has occurred but they are very weak in identifying fine-scale disturbances. However, as fine-scale disturbance can be identified clearly in high-resolution imagery, there is clearly added value in developing disturbance maps derived from high-resolution imagery as they are more accurate. The medium-resolution imagery can be used to identify peatland areas where there is fine-scale disturbance and allow target acquisition of high-resolution imagery. This reduces costs, especially as national-scale acquisition of high-resolution imagery may be prohibitive and also designates particular areas for more targeted studies.

4 Detecting Drainage using an Object-oriented Method and High-resolution Satellite Imagery

4.1 Methodology

4.1.1 Study area

The study area is located in an area of Low-level Atlantic blanket bog in north-west Mayo, Ireland ($54^{\circ} 7'41''\text{N}$, $9^{\circ}48'44''\text{W}$) (Fig. 4.1). The elevation ranges from sea level to ~ 70 m. The mean annual precipitation from 1961 to 1990 was between 1200 and 1600 mm (Met Éireann, 2011). Modelled peat depth ranges from 40 to 583. Peat depth has been measured at the nearby Glenamoy bog-complex and is up to 6 metres in depth in low-lying areas (NPWS, 2006). The blanket bog in

this area has been extensively drained and cut away to provide fuel for the nearby defunct Bellacorrick power station (Dwyer, 1962). About 25% of the 8000 ha of industrial blanket was exhausted and taken out of production (Farrell and Doyle, 2003). Intact blanket bog in the area has been designated EU Priority Habitat status under the Habitats Directive 92/43/EEC (Farrell and Doyle, 2003). This area was chosen because it has a mix of intact and drained peatlands and may have the hydrological conditions to promote the re-establishment of peatland vegetation.

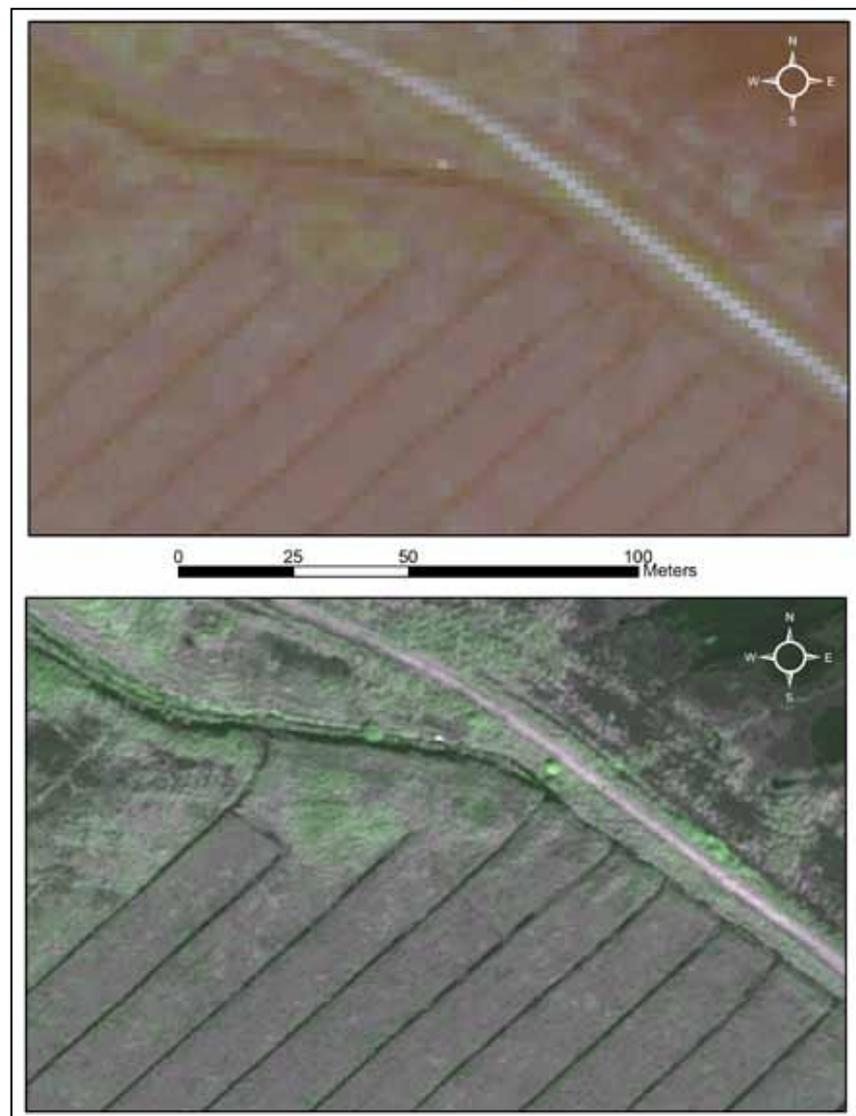


Figure 4.1. Pan-sharpened image from 4.0 m resolution on the top to 0.5 m on the bottom.

4.1.2 Remote-sensing data and pre-processing

A *Geoeye-1* geo- and orthorectified multi-spectral image (2 m) including a panchromatic band (0.5 m) was acquired on 26 August 2010 for the study area. It covers an area of ~67 km² of low-level Atlantic blanket bog. The 2-meter multi-spectral image was pan-sharpened to 0.5 m using the HPF method in *Erdas Imagine* to create a VHR image. The image was subsequently imported into ArcGIS for use with VLS FA, the object-oriented image analysis software extension (Fig. 4.1).

4.1.3 Object-oriented image analysis

As noted above, FA is an extension for ArcGIS (O'Brien, 2003): it uses machine-learning techniques and user-defined spectral, spatial, temporal and ancillary information to model the feature-extraction process (O'Brien, 2003; Mladinich, 2010). The software uses a neural network extraction model to detect features that have both spectral and spatial characteristics that are similar to the training examples and uses these to classify the remaining image (O'Brien, 2003; Kaiser et al., 2004). The training samples can be different shapes, including points, lines and polygons. In the current research, the line function was used to train the software to recognise narrow linear features, that is peatland drains, of less than 10 m in width.

4.1.4 Reference dataset

Ideally, the reference dataset would be created by visiting the site and walking along the drains with a GPS. This can be a dangerous activity given the wet

nature of peatlands and it is impossible to walk along the centre of the drains. To overcome this issue the reference data was created by digitising the middle of each of these drains in the pan-sharpened *Geoeye-1* image. Over 100 segments and the middle of each of the drainage ditches were digitised (Fig. 4.2).

4.1.5 Accuracy assessment

It is necessary to determine the accuracy of the peatland drains if the data are going to be useful for land managers. However, traditional accuracy assessment methods using discrete sample points do not work well with linear object features (Lathrop et al., 2010). Lathrop et al. (2010) used an independent reference image manually interpreted from their image. They buffered their extracted linear features and the reference data were clipped to the buffered extraction. The results were examined using an agreement percentage and a commission error percentage. He et al. (2011) used a buffer of two-image (SPOT) pixels and assumed that only linear features that fell within this buffer could be used to compute errors of commission and omission for their narrow linear features. In this work the extracted data was buffered to 1 m i.e. 2 x 0.5 m or two-image pixels. This was then used to clip the reference data using the clip function in the Analysis toolbox in ArcGIS. This gave the total area of clipped drains (or TAC). The total area of the reference (TAR) drains was calculated and finally the total area of the extracted (TAE) linear features delineated by the reference data was acquired. The percentage agreement and percentage commission



Figure 4.2. Subsection of the reference dataset.

were then calculated using the following equations after Lathrop et al. (2010) (Eqs 4.1 and 4.2):

$$\text{Agreement (\%)} = \text{TAC}/\text{TAR} * 100 \quad (\text{Eq 4.1})$$

$$\text{Commission error (\%)} = ((\text{TAE}-\text{TAC})/\text{TAR}) * 100 \quad (\text{Eq 4.2})$$

4.2 Results

4.2.1 Accuracy assessment

Point-based accuracy assessment was considered for use with the linear features: however, there is difficulty with the approach as it is a site/pixel specific assessment of an object-based feature (Schopfer and Lang, 2006). Instead, the 'epsilon band' method is used (2010). The accuracy assessment of these images is currently ongoing but initial results indicate that the method can extract the location of peatland drains accurately.

4.3 Discussion

Peatland drains have an impact on the ecosystem and its C stock. Drains lower the water table and lead to the oxidisation of the peat. They also act as conduits for the emission of DOC and POC from the system. The mapping of peatland drains is a time-consuming, difficult and potentially dangerous task. However, in peatlands where restoration will take place it is essential to know their location to allow land managers, conservation & restoration officers and policy-makers to block them to prevent or slow down C emission from the peatland ecosystem.

Drains located on a blanket bog in the west of Ireland were accurately extracted from a very high-resolution (0.5) pan-sharpened satellite image. Peatland drainage occurs on peatlands all over the globe from Ireland to Indonesia. The drains on the blanket bog here are very straight and wide and thus the method works very well (Fig. 4.3). This method could be used as a step in scaling up C budget data from specific sites (Rowson et al., 2010) to larger areas thus producing better estimates of how this type of disturbance is potentially effecting peatlands and when combined with models predicting climate change could be very useful in identifying peatland areas that should be conserved. Many peatland drains are very narrow, so it is essential that very high-resolution imagery is used to be able to identify their location and density.

4.4 Conclusion

The method presented here could be a valuable tool for aiding land management (particularly that related to the new Kyoto Protocol activity: Rewetting and drainage). The object-based image analysis (OBIA) approach accurately extracts valuable information on drainage extent and density in a west of Ireland blanket bog ecosystem from very high-resolution satellite imagery. At this site the method performed very well. The method has serious potential for extracting information extent and density of peatland drains over large areas such as the blanket bogs of the West of Ireland.

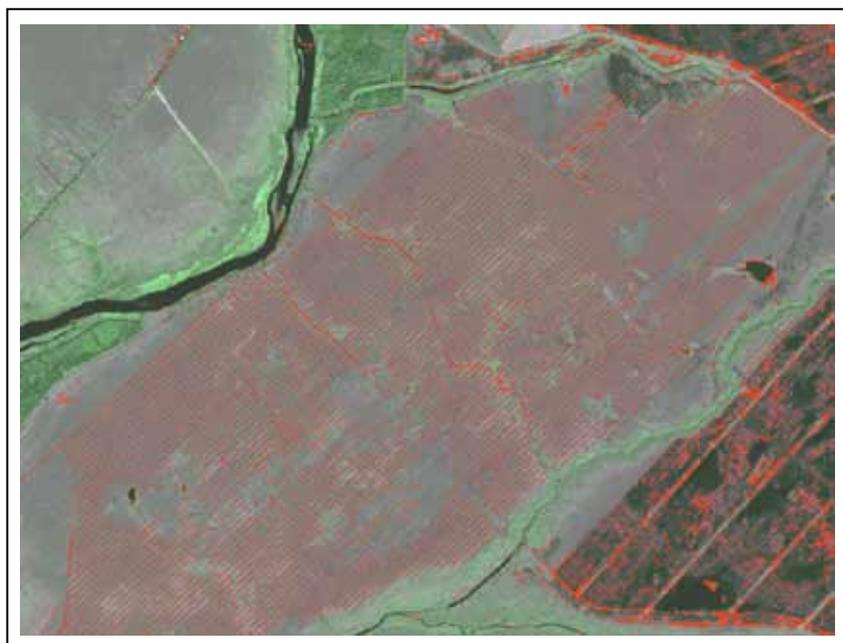


Figure 4.3. A section of the delineated drains image.

5 Overall Conclusions and Recommendations

5.1 Conclusions

Ireland's peatlands are extensively disturbed, experiencing a wide range of disturbances. Both the NPWS review of the conservation status of peatland and the recent BOGLAND report have shown that the past and current management practices have led to peatlands being damaged or becoming deteriorated. Raised bogs are particularly degraded and intact raised bogs, according to BOGLAND, do not exist anymore due to these unsustainable management practices. The NPWS rate degraded raised bogs (i.e. those still capable of regeneration) as poor and blanket bogs (and Active Blanket Bog) also have an overall rating of Bad (NPWS, 2008). The *CORINE 2000* land-cover map should not be used to assess disturbance as it is constrained by its nomenclature which does not adequately describe disturbed peatlands.

The results from this research agree with both the NPWS and BOGLAND synopsis. All types of peatlands in Ireland have experienced extensive disturbance. The regional and national disturbance maps produced in this report depict a situation where peatlands have been disturbed by both large spatial-scale processes such as afforestation and conversion to pasture as well as finer scale disturbances such as drainage (which is extensive), burning, and small-scale peat extraction.

Both the medium- and high-resolution maps are very useful for detecting peatland disturbance. The medium-resolution maps are useful for identifying the areas where large-scale landscape-wide disturbance has occurred, such as forestry planting and reclamation for pasture. However, these medium-resolution maps need to be used with caution. They do not detect the extensive fine-scale disturbance that occurs on many open peatland areas. These maps are useful in that they provide an over- or indicative view of the spatial extent of disturbance and can be used as an indicator to identify areas that need further investigation using high-resolution satellite imagery datasets.

The use of high-resolution imagery in this research to detect peatland disturbance is constrained by both cloud cover and cost of imagery. It is difficult to

acquire up-to-date high-resolution satellite imagery for peatlands. However, where this data is available very accurate disturbance maps can be produced. Not only do these high-resolution maps show the extent of disturbance, it is also possible to determine the severity of that disturbance, i.e. the impact on the C stock and ecological function in the peatland. The high-resolution maps are up to 23% more accurate and in some cases the overall accuracy is up to 90%. As a result, this method is a relatively simple and robust way of determining peatland disturbance on the Irish landscape.

In Ireland, peat soils cover about 20.6% of the national land area and contain up to 75% of the total SOC in Ireland (Renou-Wilson et al., 2011; Connolly and Holden, 2009). The long-term C flux monitoring station at Glencar showed that over a five-year period a relatively undisturbed peatland can uptake between -16.5 ± 5.1 and -95 ± 23.2 g C-CO₂ m⁻² (Sottocornola and Kiely, 2010). Much focus has been on the effect of drainage on the peatland and how this affects the peat C stock. In the last several years, there has been a concerted effort to understand this effect of drainage and drain blocking on the ecosystem and DOC, POC and the C flux (Armstrong et al., 2009; Armstrong et al., 2010; Holden et al., 2004; Holden et al., 2007; Strack et al., 2008a; Wilson et al., 2010; Wilson et al., 2011; Ramchunder et al., 2009). Drainage and subsequent afforestation and peat extraction lead to lower water table levels and increasing volumes of aerobic peat. Freeman et al. (2001a; 2004) found that phenol oxidase experienced a seven-fold increase in activity under more aerated conditions, leading to a significant increase in peatland decomposition. When a peatland is disturbed, C uptake is reduced dramatically and in many cases the SOC is removed from the system either through extraction or decomposition. The long-term and widespread disturbance of peatland hydrology in Ireland may lead to a greater loss of C through decomposition. Because peatland disturbance is so extensive, Ireland's SOC stock is very vulnerable, especially to future disturbance such as climate change (Renou-Wilson et al., 2011).

In March 2010, Iceland added the 'restoration of drained wetlands' to its climate mitigation policy, under Kyoto Protocol Article 3.4 and in December 2010 a new activity called 'peatland re-wetting and drainage' was defined under the Kyoto Protocol (Renou-Wilson et al., 2011). The development of the methods used in this research to detect disturbance and drains density on peatlands – i.e. identifying the spatial extent and severity of peatland disturbance – may be useful in identifying suitable peatlands for further investigation in relation to this Article 3.4 activity. These methods could be very useful for land managers and conservationists. There is large scope for Ireland to add the restoration of drained wetlands/peatlands to its climate mitigation policy. This could create momentum for peatland restoration and conservation which could aid the fulfilment of Ireland's obligations regarding the Kyoto Protocol, the proposed Soil Framework Directive and the Habitats Directive. Restoring disturbed peatlands could potentially sequester large amounts of C.

Ireland's national SOC stocks are threatened by anthropogenic and natural disturbances; this research is a first step to identifying the location, extent and severity of those disturbances. Further research, using high-resolution imagery, will allow detailed maps of the spatial extent of all peatland disturbances to be created. The identification of peatland disturbance is essential for calculating SOC stocks and the vulnerability of peatlands to current and future disturbances, including climate change. It is also useful for the creation of baseline data with regard to peatland re-wetting and drainage. The medium-resolution national scale maps can be used as indicative tools to identify peatland areas that can be targeted with high-resolution imagery for further study and thus reduce acquisition costs. However, the ideal situation would be the acquisition of national-scale high-resolution imagery and the production of a national high-resolution disturbance map in order to develop highly accurate maps of national peatland disturbance.

The research methodologies developed in this research have produced a national-scale map of peatland disturbance, but, with high-resolution imagery, there is the potential to fill in the knowledge gaps with regard to the extent and severity of peatland disturbance throughout Ireland, and to identify those areas that may be at further risk of disturbance and degradation due to anthropogenic influences or climate change. This could

enable policy-makers to use the resulting disturbance maps to identify disturbed peatlands that are suitable for restoration and C sequestration. However, if this were to happen, more ancillary research is needed with regard to C uptake and emissions. A network of flux towers located on disturbed, non-disturbed, and restored peatlands to determine how disturbance affects the C flux is needed. More research is also necessary with regard to constraining the peat area, condition, peat depth and volume mapping as well as the acquisition of bulk density data to ensure accurate calculations of the peatland SOC stock. The method developed here may be useful in other regions for the development of more accurate estimations of peatland disturbance, C stock and for examining the effect of predicted climate change on these vulnerable ecosystems.

5.2 Recommendations

Peatlands are spatially extensive and extensively disturbed. While there is great difficulty associated with detecting peatland disturbance, the use of semi-automatic techniques with multispectral satellite images aid disturbance detection – particularly when high-resolution satellite imagery is used. This current research goes some way to addressing the BOGLAND recommendation for the management of peatlands for biodiversity: MPB4 '*the development of an inventory of the condition of all peatlands*', in that the extent of disturbances such as afforestation and land reclamation are relatively easily identified on medium-resolution imagery. However, the detection of finer-scale disturbances such as mechanised turf extraction is impossible at the medium-resolution scale. High-resolution satellite imagery can detect most types of fine-scale disturbance such as drainage and turf extraction. The current research shows that the use of high-resolution imagery significantly improves the identification of disturbance types which, on SPOT medium resolution imagery, is limited to the two types of disturbance: forestry and reclaimed pasture. The accuracy of the maps derived from the high-resolution imagery was also much higher than that from the medium-resolution imagery.

In order to determine the true extent of disturbance on Irish peatlands it is recommended that a high-resolution database of geo- and orthorectified imagery is created, ideally nationwide. As noted above, high-

resolution imagery is essential in the detection and monitoring of peatland disturbance and its use leads to improvements in accuracy of up to 23% over medium-resolution imagery. However, there are large constraints surrounding the creation of such a database; high-resolution imagery costs between €25 and €35 per km², which means that the imagery alone would cost about between 2.3 and 3.03 million euros. There is also an issue with cloud cover; O'Connell et al. (2013) found that Landsat ETM+ was able to capture only five cloud-free images over the east coast of Ireland in 2001. This may be about to change with the launch of the upcoming European Space Agency (ESA). The ESA *Sentinel-2* satellite will 'routinely deliver high-resolution optical images' at a resolution of 10 m: although this is not as precise as the high-resolution imagery utilised in this research, it is an improvement on the medium-resolution imagery used here. The *Sentinel-2* satellite is due to be launched in 2014. Despite these issues associated with the detection of disturbance in the medium-resolution imagery, the object-oriented method used here is relatively robust and – where good-quality imagery is available – can yield excellent results for identifying the extent and severity of disturbance on peatlands.

Further research is also needed to quantify the effect of different disturbance types on the peatland SOC stock. In order to create accurate estimates of the effect of past and current management practices on the peatland C stock it is recommended that an extensive ground survey of C content and peat depth be carried out. The

data yielded from such a project would enhance our knowledge of the total peatland SOC stock and enable land managers to make informed decisions with regard to conservation and restoration of peatlands as well as developing procedures to deal with future disturbances such as climate change.

5.3 Key Recommendations

- Acquisition of high and very high-resolution imagery of peatlands nationwide in order to create a highly accurate assessment of peatland disturbance, implemented using the above object-oriented methods.
- An extensive ground survey of peatlands to collect data relating to C density and peat depth.
- The disturbance cube classification framework has been demonstrated to be a reliable assessment of peatland degradation. It is recommended that the method be adopted more widely by those engaged in peatlands assessment.
- Establish a network of eddy covariance flux towers or gas flux chambers on both disturbed and undisturbed peatlands nationwide to acquire data on the impact of different disturbance types on the peatland C stock.
- Educate the public and peatland users about the impact of peatland disturbance on the peatland C stock. This should be based on a policy that informs from the bottom-up rather than a top-down approach.

Acronyms and Annotations

AOI	Area of Interest
BNM	Bord na Móna
BP	Before Present
C	Carbon
CH ₄	Methane
CO ₂	Carbon dioxide
CORINE	Cordination of Information on the Environment
CTBC	Clara/Turraun bog complex
DIPM	Derived Irish Peat Map
DIPMV2	Derived Irish Peat Map Version 2
EPA	Environmental Protection Agency
EU	European Union
FA	Feature Analyst
GCM	Global Climate Model
GE	Google Earth
GPP	Gross Primary Productivity
GPS	Global Positioning System
GtC	Giga tonnes of carbon
IRS	India Remote Sensing
M ha	Million hectare
MODIS	Moderate Resolution Imaging Spectroradiometer
MPB4	Management of Peatlands for Biodiversity – Action 4
Mt C	Mega Tonne of Carbon
NPWS	National Parks and Wildlife Service
OBIA	Object-Based Image Analysis
OM	Organic Matter
SOC	Soil organic carbon
SOM	Soil organic matter
SPOT	Système Pour l’Observation de la Terre
TAC	Total area of clipped drains
TAE	Total area of the extracted linear features delineated by the reference data
TAR	Total area of the reference drains
UCD	University College Dublin
UNFCCC	United Nations Framework Convention on Climate Change
VHR	Very high resolution
VLS	Visual Learning Systems

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An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaoil do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomhnithe a bhfuilimid gníomhach leo ná comhshaoil na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil, Pobal agus Rialtais Áitiúil.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaoil i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistriúcháin dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreal;
- scardadh dramhuisce.

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí chomhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaoil mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOIL

- Monatóireacht ar chaighdeán aer agus caighdeán aibhneacha, locha, uisce taoide agus uisce talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntiú a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdeán aer agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaoil na hÉireann (cosúil le plananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaoil a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózón.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaoil na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstíúrthóir agus ceithre Stíúrthóir.

Tá obair na Ghníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Chomhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.



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