# Nocturnal Lepidoptera of Midland Raised Bogs

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# Table of Contents

# List of Tables

# List of Figures

# Declaration of Authorship

I certify that the work presented herein is, to the best of my knowledge, original, resulting from research performed by me, except where acknowledged otherwise. This work has not been submitted in whole, or in part, at this or any other university.

Signed:

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Ciara Flynn Date

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Finally, I wish to dedicate this thesis to my mother, Margaret.

# Abstract

Raised bogs started to form in Ireland at least 7000 years ago when peat started to accumulate in water-filled depressions left after the last glacial period. Due to centuries of damaging human activities, only 1% of the living, growing active raised bog habitat remains and this is rapidly being lost. Raised bogs are important reservoirs of biodiversity, hosting many uniquely adapted plant and animal species and are of high conservation concern internationally.

The aims of this study were to objectively assess the potential of macro-moths as active raised bog biodiversity indicators, to collate baseline information on the distribution of this fauna on threatened midland raised bog habitat and to identify species with restricted distributions which may be of conservation concern.

Macro-moths were sampled using light-traps on twelve midland raised bogs from early July to the end of October in 2011. Six high conservation value bogs designated as Special Areas of Conservations (SACs) and six undesignated and degraded bogs were surveyed.

A total of 1,816 adult individuals of 93 moth species were recorded, representing 16% of the Irish moth fauna. Four species new to County Offaly were recorded. Only two potential indicator species of active raised bog were found, with only one species (*Acronicta menyanthidis* (Esper, 1789)) significantly correlated with the wettest areas of active raised bog *($P = 0.01$).*

Raised bog associated nocturnal macro-moth assemblages showed a significantly nested structure ($P < 0.01$), common in fragmented habitats, whereby species-poor sites form a nested subset of species-rich sites.

The difference between designated and undesignated raised bog associated moth assemblages was significant (A = 0.044; $P = 0.038$), but within group homogeneity was low.

As designated and undesignated bogs contain assemblages which are broadly similar, the findings of this study would suggest that even degraded undesignated raised bog remnants, may be of significant conservation value for macro-moth species.

# 1. Introduction

## 1.1 Formation of raised bogs

Raised bogs are dome-shaped bodies of peat, which started to develop at least 7,000 years BP (Mitchell, 1990), chiefly in basins or shallow lakes formed due to impeded drainage, after the last glaciation (Hammond, 1968, Cross, 1989, Cross, 1990, Kelly, 1993). Net primary production has exceeded decomposition over thousands of years and as a result peat (organic carbon-rich matter) has accumulated over time (Vitt, 2006). The water table remains close to the surface throughout the year as much of the rainfall is held by the sponge-like action of the living *Sphagnum* moss layer (the acrotelm) which carpets the bog. The presence of an acrotelm is of paramount importance to the bog, as it is here that peat formation continues to occur (Kelly, 1993, Joosten and Clarke, 2002). Bog habitat with a peat-forming acrotelm is called ‘active raised bog’, whereas habitat which has ceased to form peat is known as ‘degraded raised bog’. Acrotelm thickness (the height of the acrotelm surface above the water table) varies on bogs, resulting in a distinctly patterned microtopography of pools, hollows, lawns and hummocks (Belyea and Clymo, 2001).

## 1.2 Abiotic and Biotic Features of Raised Bogs

Bogs are cool habitats relative to the surrounding terrain (Schumann and Joosten, 2008). The blanket of *Sphagnum* moss and the accumulated peat insulate the habitat and the high water table is resistant to rapid warming due to the high specific heat capacity of water. Raised bogs are hydrologically isolated and rely primarily on precipitation as a water and nutrient input source (Lafleur *et al.*, 2005). Bogs may therefore be considered to be ombrotrophic because their vegetation thrives under heavy precipitation, thereby making them acidic (pH < 4) and are said to be oligotrophic because the nutrient supply and amounts of calcium and magnesium are low (Renou-Wilson *et al.*, 2011). While they are characterised by low species richness, they are nonetheless important reservoirs of biodiversity as they contain uniquely adapted plant and animal species not found elsewhere (Duelli and Obrist, 1998).

## 1.3 Midland raised bog complexes

The heart of the central limestone plain of Ireland is characterized by large raised bog complexes of the true midland subtype (Cross, 1990), which have been exploited as a source of fuel for centuries (Foss *et al.*, 2001). Some areas of raised bog have now been cut-away entirely and have been reclaimed, in the main, as agricultural grassland (Foss *et al.*, 2001). Midland raised bogs, in particular, have a long history of industrial exploitation (McNally, 1997). The surface of a number of bog complexes has been extensively cutover for commercial peat moss and fuel production. Such bogs, where the surface has been stripped and is either bare or partly revegetating, are classified as secondary degraded bog (Fernandez *et al.*, in prep.) (Figure 1.1). Intact bogs have not been cutover and are classified as either active (peat forming) or degraded (not peat forming).

Today, areas of the intact bog are mainly very small remnants of once much larger bog complexes. Of the previous national estimate (310,000 ha) (Hammond, 1979), only 50,000 ha of intact raised bog remains today (DAHG, 2014). This is a loss of 84%. The conservation status of active raised bog habitat has recently been assessed as “bad” and the overall trend of this habitat is declining. This assessment is based on historic losses and on-going declines due to peat extraction and continued drying, shrinking and slumping of the bog structure (NPWS, 2013a). There has been a 99% loss of this habitat type (DAHG, 2014). It is estimated that active raised bog habitat has decreased by 20-30% for the 2001-2012 period (NPWS, 2013b) and that, in 2012, only an estimated 1,639 ha of this habitat remained nationally (DAHG, 2014).

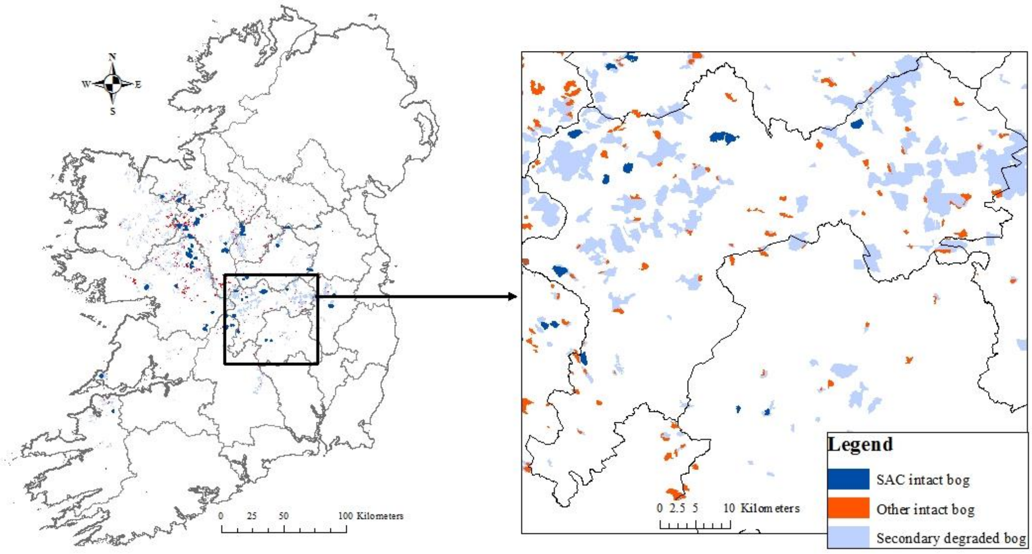


**Figure 1.1 Distribution of Irish raised bogs (study area inset).**
Adapted from Fernandez *et al.*, in prep. SAC refers to Special Area of Conservation

## 1.4 Conservation and Management Challenges

Raised bogs face some key challenges in maintaining their biodiversity into the future due to continuing habitat deterioration and loss, particularly through peat extraction (Kelly *et al.*, 1995a; Fernandez *et al.*, 2005a, 2006a, 2012) and drainage (Joosten and Clarke, 2002, Schouten, 2002), including arterial drainage (Kelly *et al.*, 1995a). Vegetation burning (Fernandez *et al.*, 2005a), invasive and problematic native species (Fernandez *et al.*, in prep.), aerial nitrogen pollution (Tomassen *et al.*, 2004) and climate change (Renou-Wilson *et al.*, 2011, Ronkainen *et al.*, 2013) have also been proffered as current and future threats. Climate change, in particular, is likely to become a key threat to biodiversity as a 38% decrease in the suitable climate area for raised bogs has been predicted to occur by 2075 (Jones *et al.*, 2006). Stenotopic species (i.e. species tolerant of only a narrow range of environmental factors) such as the large heath butterfly, *Coenonympha tullia* (L.), are predicted to lose climate space (Berry *et al.*, 2003).

As raised bog habitat is lost, habitat fragmentation and consequent isolation may decrease the local species pool availability, thereby reducing the number of species available to colonise bog sites (Dzwonko and Loster, 1992, Pärtel *et al.*, 1996, Zobel *et* *al.*, 1998), leaving species vulnerable to stochastic extinction (Dennis and Eales, 1999). The Habitat – Heterogeneity Hypothesis proposes that large areas have more kinds of habitats and therefore more species than small areas (Williams, 1964). The vast majority of intact raised bogs are small and may be unable to maintain population sizes necessary for long-term viability, leading to extinction debt (Berglund and Jonsson, 2005, Báldi and Vörös, 2006), or delay between fragmentation and species extinction representing a debt or future ecological cost for current habitat destruction (Tilman *et al.,* 1994).

## 1.5 Conservation Policy

In Ireland, 53 intact raised bogs have been designated as Special Areas of Conservation (SACs) (DAHG, 2014) part of the Natura 2000 network, a collection of protected areas stretching across Europe (Evans, 2006, Council of Europe, 1992). Natura 2000 forms the backbone of European biodiversity conservation policy implementation (Maiorano *et al.*, 2007, Chiarucci *et al.*, 2008, Gaston *et al.*, 2008, Pullin *et al.*, 2009).

As with the majority of Natura 2000 sites, designation of raised bog SACs was based on phytosociological associations within habitats and did not directly consider the conservation of their invertebrate fauna (Hernandez-Manrique *et al.*, 2012). This was due to limited taxonomic and distribution knowledge of these groups (Leather *et al.*, 2008, Diniz-Filho *et al.*, 2010, Zamin *et al.*, 2010).

The aim of SACs selected by habitat is to protect species occupying those habitats. This is termed a 'coarse filter' approach whereby conserving representative examples of biological communities and ecosystems that occur within a region, the majority of species within the region will be conserved (Noss and Cooperrider, 1994, Hunter, 2005). Studies have investigated the effectiveness of the Natura 2000 network in achieving its objective of halting the loss of biodiversity in Europe. They have found that this objective is not being met in relation to a number of different taxa including plants (Dimitrakipoulos *et al.*, 2004), vertebrates (Maiorano *et al.*, 2007, Jantke *et al.*, 2011) and lichens (Rubio-Salcedo *et al.*, 2013). Studies on the effectiveness of the network in conserving invertebrates are mixed with Verovnik *et al.* (2011) concluding that a planned extension to the network in Slovenia will conserve butterfly biodiversity, while Davies *et al.* (2007) expressed concern that the management objectives of protected areas take little account of factors important to insects such as structural diversity and small-scale plant-community heterogeneity. In a study of carabids of Irish wetland habitats, Williams *et al.* (2014) found that, while species richness was higher on designated sites, Red Data Book species richness was higher on undesignated sites.

## 1.6 Peatland invertebrate conservation

There is a growing recognition of the need to include invertebrates in planning and assessment of peatland conservation measures (van Duinen *et al.*, 2003, JNCC, 2008, Whitehouse *et al.*, 2008, Hannigan *et al.*, 2011, Hannigan and Kelly-Quinn, 2012). To effectively conserve regional biodiversity and allocate resources among sites, the geographical distribution of diversity within the region must be known (Jost *et al.*, 2010). It is also important to establish a baseline reference fauna in relatively pristine bogs to measure the success of bog restoration projects in terms of reinstating a characteristic invertebrate fauna (Brinson and Rheinhardt, 1996, Gorham and Rochefort, 2003, Mazerolle *et al.*, 2006, Hannigan and Kelly-Quinn, 2012). At present, raised bog restoration measures in Europe are mostly measured by the development of a *Sphagnum*-dominated vegetation and the presence of characteristic *Sphagnum* and vascular plant species (van Duinen *et al.*, 2003).

Given the threatened state of peatland biodiversity, loss of characteristic invertebrate species could also be used as an indication of habitat degradation (Hannigan *et al.*, 2011). In addition, because only a small number of near-pristine raised bogs are left in the country, particularly of the midland type (Cross, 1990), the few characteristic specialised species representing a ‘good bog’ are of very high national or global biodiversity importance in their own right, contributing specially adapted organisms unable to survive elsewhere in the landscape (Duelli and Obrist, 2003, Bezděk *et al.*, 2006).

## 1.7 Peatland invertebrate biodiversity

Invertebrates form a major component of peatland biodiversity (Speight and Blackith, 1983). However, compared to the Irish peatland flora (Praeger, 1934, Tansley, 1939, Osvald, 1949, Moore, 1954, 1962, 1968, Bellamy and Bellamy, 1966, White and Doyle, 1982, Leach and Corbett, 1987, Doyle and Doyle, 1990, Kelly, 1993, Kelly and Schouten, 2002), the peatland invertebrate fauna has remained largely unexplored until recent decades (Good, 1984, Higgins, 1984, Reynolds, 1984a,1984b,1985, Speight, 1990, Crushell, 2008). While invertebrate species new to Ireland are still being discovered in bogs and fens across the country (Higgins, 1984, Ashe, 1987, O'Connor and Speight, 1987, Bond, 1989, Nolan, 2007, Hannigan and Kelly-Quinn, 2012), it can be assumed that the contribution of Irish peatlands to biodiversity is not yet fully understood (Renou-Wilson *et al.*, 2011).

## 1.8 Invertebrates as biodiversity indicators

Monitoring, and even in the short-term basic inventory, of the total invertebrate fauna may be impractical due to limited financial and taxonomic resources (Sauberer *et al.*, 2004) even in species-poor habitats such as active and degraded raised bog (Duelli and Obrist, 2003). Therefore, surrogate species or biodiversity indicators (McGeoch, 1998) are needed to act as proxies for other less well-known taxa (Duelli and Obrist, 2003, Favreau *et al.*, 2006, Lewandowski *et al.*, 2010). A number of invertebrate species or assemblages have been used or proposed as peatland biodiversity indicators, including carnivorous ground beetles (Coleoptera: Carabidae)(Bezděk *et al.*, 2006, Williams and Gormally, 2010, Williams *et al.*, 2014), hoverflies (Syrphidae) (Speight *et al.*, 2002) and aquatic macroinvertebrate communities (Hannigan and Kelly-Quinn, 2012).

Shaw & Wind (1997), in an evaluation of European nature indicator groups found that moths were probably very useful indicators of raised bog biodiversity. On lowland heaths and moorland in Great Britain, spiders, homopteran bugs and moths are relatively more important than other invertebrate groups (Drake *et al.*, 2007). Unlike butterflies, a number of stenotopic moth species occur on peatlands (Bond, 1984, Spitzer and Danks, 2006), while similar to butterflies, they are conspicuous, their taxonomy (Bond *et al.*, 2006) and life history traits are well-known (Bond and Gittings, 2008) and of late they have been extensively recorded by amateur naturalists in Ireland (Tyner, 2014a).

## 1.9 Aims of the project

The aim of this project was to establish whether there is a distinct macro-moth fauna associated with the wettest areas of designated sites (active raised bog) by comparing the assemblages found in this area of the study sites to those found on undesignated sites where this wet habitat has been lost (Intact degraded or secondary degraded raised bog) in order to assess their potential as biodiversity indicators. A further aim was to collate baseline information on the distribution of moth fauna on midland raised bogs and to identify species with restricted distributions which may be under threat from loss of midland raised bog habitat.

# 2 Materials and Methods

## 2.1 Introduction

Night-flying phototactic macro-moths (hereafter referred to as moths) were sampled using light-traps on twelve midland raised bogs from the beginning of July (2nd and 3rd July) to the end of October in 2011. Six high conservation value designated bogs (SACs) and six undesignated and degraded bogs were surveyed. Preliminary sampling was carried out on designated sites in 2009 and 2010. When sample size is limited (< 10 nights), it has been shown by Jonason *et al.*, 2014, to be slightly better to concentrate on the warmest summer nights (June – August). Sampling in early June 2011 would have increased the number of species recorded but this was not possible due to time constraints. However, seventy-seven percent of raised bog associated species (20 out of 26) recorded during preliminary sampling in mid and late June 2009 and 2010 (Appendix B), were recorded in 2011. Of the six species not recorded in 2011, five were recorded as either singletons or doubletons in June 2009 and 2010 samples combined, so the statistical impact of their absence is minor. The sixth species, *Spilosoma lutea* (Hufn.), (seven specimens recorded in 2009 and 2010), is considered widespread and common and sampling in 2011 took place within its maximum flight period (Tyner, 2014a) and so its absence suggests that raised bog may not be its preferred habitat.

## 2.2 Study site selection

All bogs surveyed are located in County Offaly, with the exception of Clonaltra, an undesignated, degraded bog, part of which lies in County Westmeath (Figure 2.1). The designated raised bog sites chosen constitute six out of the seven (85%) SAC bogs in County Offaly and are intact bogs which still support typical high bog vegetation, and contain varying amounts of active raised bog habitat (Table 2.1).

The nearest six highly modified but vegetated, undesignated, degraded raised bogs to each designated bog was selected after consulting with aerial photography (Figure 2.2). Both intact degraded and secondary degraded bogs were chosen. Intact (degraded) indicates that the bog has been surface drained or otherwise modified and contains no Active Raised Bog habitat. The secondary degraded bogs were highly drained and had been subject to surface stripping and cutting and were partly revegetating. Distance between sites ranged from 2.02km (Ferbane to Moyclare) to 49.48km (Sharavogue to Raheenmore). Full site descriptions may be found in Appendix A.

### 2.2.1 Designated sites

Active raised bog habitat consists of both central and sub-central ecotopes. An ecotope is defined as the abiotic environment of a particular biotic system (Küchler, 1967, Whittaker *et al.*, 1973). Central ecotope has a very soft and often quaking surface. The microtopography usually ranges from pools to tall, well developed hummocks and pools are usually frequent to dominant. Generally, sub-central ecotope is lawn dominated with only a few hummocks. The surface is soft and sometimes quaking, occasionally hard (Fernandez *et al.*, 2005a).

Designated site ecotope mapping was consulted (Fernandez *et al.*, 2005b) and the largest area of central ecotope on each designated bog was selected as a sampling point. On Sharavogue bog, an area of sub-central ecotope was selected as this bog contains no central ecotope. This sampling site was reclassified as sub-marginal ecotope in 2011, due to more comprehensive surveying (Fernandez *et al.*, 2012b).

**1**

**2**

**3**

**4**

**Figure 2.1 Study habitats.**
1: Intact (active) raised bog (Clara Bog), 2: Intact (active) raised bog (Moyclare Bog), 3: Intact (degraded) raised bog (Kilballyskea Bog) 4: Secondary degraded raised bog (Clonaltra Bog).

On Ferbane Bog, placement of the trap within the central ecotope was not possible due to its extreme quaking nature. It was therefore placed in marginal ecotope as close to central ecotope as possible. Marginal ecotope is considered to be degraded raised bog habitat. The water level is low and the surface is generally hard (Fernandez *et al.*, 2005a).

### 2.2.2 Undesignated sites

On undesignated, degraded bogs, central locations on the high bog remnants were selected as sampling points so that there was a maximum distance to the edge from the sampling point, thereby decreasing the number of vagrant species (Webb, 1989).

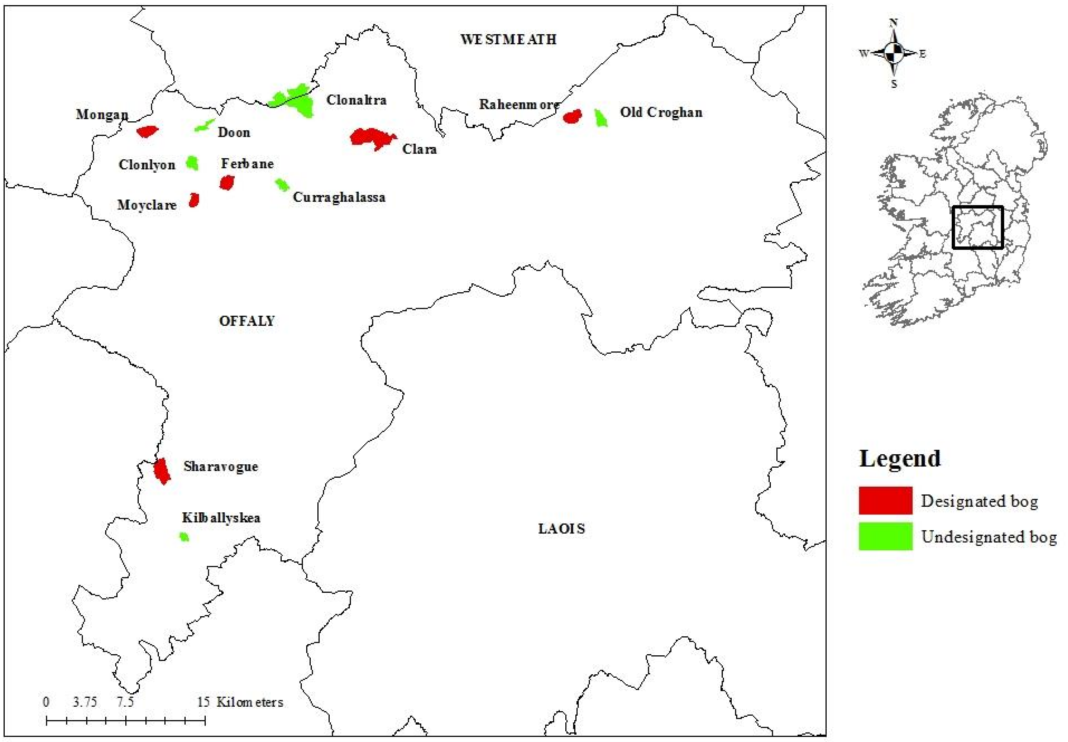


**Figure 2.2 Location of study sites.**

**Table 2.1 Summary of midland raised bog study sites.**

| Site number | Site name | Site Code | Sampling point (Irish grid) | Designation status | Type |
|---|---|---|---|---|---|
| 1 | Sharavogue | Sha | S204912 198228 | Designated | Intact (active) |
| 2 | Mongan | Mon | N203404 230784 | Designated | Intact (active) |
| 3 | Ferbane | Fer | N210683 226225 | Designated | Intact (active) |
| 4 | Moyclare | Moy | N207727 224052 | Designated | Intact (active) |
| 5 | Clara | Cla | N224263 230288 | Designated | Intact (active) |
| 6 | Raheenmore | Rah | N243784 232132 | Designated | Intact (active) |
| 7 | Old Croghan | Old | N246366 231987 | Undesignated | Secondary degraded |
| 8 | Clonaltra | Clon | N215546 233335 | Undesignated | Secondary degraded |
| 9 | Curraghalassa | Cur | N215893 225939 | Undesignated | Intact (degraded) |
| 10 | Doon | Doon | N208503 231046 | Undesignated | Intact (degraded) |
| 11 | Clonlyon | Clonly | N207680 227929 | Undesignated | Intact (degraded) |
| 12 | Kilballyskea | Kilbal | S206879 192290 | Undesignated | Intact (degraded) |

## 2.3 Light traps

Moths were sampled using portable light traps (Heath-type actinic 15 W; Anglian Lepidopterist Supplies, UK) (Heath, 1965) (Figure 2.3). Despite an incomplete understanding of the mechanism by which moths are attracted to light (Mazkhin-Porshnyakov, 1960, Hsiao, 1972, Baker and Sadovy, 1978), this sampling method has been the most widely used by both professional and amateur naturalists to survey moths for many years (Weissling and Knight, 1994, Beavis, 1995, Fry and Waring, 2001, Young, 2005). Light trapping yields a large number of specimens with minimum effort (Young, 1997, Fry and Waring, 2001). It has been recommended as the best method for surveying macro-moths by Natural England (Drake *et al.*, 2007), who describe light-trapping as the only practical and rapid method for sampling arboreal assemblages, since few surveyors can identify larval stages.

### 2.3.1 Light trapping and selective sampling

Unlike passive methods of invertebrate sampling (i.e. pitfall traps, malaise traps, transect walks), light traps sample moth communities selectively (Beck and Linsenmair, 2006). The physiology and behaviour of individual moth species determines their response to light, which can give rise to biases in trapping rates for different species which must be considered when analysing results (Bowden, 1982, McGeachie, 1989, van Langevelde *et al.*, 2011). Weather conditions and moon phase can result in significant differences in abundance and richness of moth catches. Temperature has been found to be the most important meteorological factor influencing total number and species richness of catches (Persson, 1976, Gaydecki, 1984, McGeachie, 1987, Dent and Pawar, 1988, Holyoak *et al.*, 1997, Butler *et al.*, 1999, Hirao *et al.*, 2008). Williams (1940) reported a doubling of numbers of individuals caught for each 2.8˚C rise in temperature. Numbers of individuals caught in light traps decrease around the time of a full moon (Williams, 1936, Persson, 1976, McGeachie, 1989, Yela and Holyoak, 1997). Trap catches have also been found to be low around the new moon, when at no time can moths orientate by it (Nowinszky and Puskas, 2011).

The comparison of beta-diversity of ensembles does not pose any significant problems, because the distortion is expected to be dependent on the physiology and behaviour of the species rather than on different habitats (Brehm, 2002). However, because of the influence of temperature on numbers of species caught, sampling on multiple sites must be temporally standardised. Also, since the number of species found is positively correlated with sampling effort, this effort has to be exactly quantified in any inventory (Duelli *et al.*, 1999). Light trapping has been proven to produce readily interpretable and ecologically meaningful results in studies on the biodiversity of Lepidoptera (Schulze and Fiedler, 2003, Fiedler and Schulze, 2004).

### 2.3.2 Advantages of light trapping

Due to the very fragile nature of lowland raised bog habitats, light trapping may be more appropriate than regular fixed transect walks (Borcard and Matthey, 1995). The low wattage needed allows the traps to be powered by a sealed portable 12-volt battery. This, combined with their size and light weight make them suitable for use in remote and sensitive sites accessed by foot (Heath, 1965, Magurran, 1985, O'Halloran *et al.*, 2011). Although this battery-run trap type does not result in samples as large as those from generator-run traps, the advantage is that a larger number of identical traps can be deployed simultaneously, which is preferable when comparing sites. Their small attraction range results in a good representation of local abundance (Slade *et al.*, 2013).

### 2.3.3 Operation of light traps

Light traps operate on the 'lobster-pot principle', whereby individuals are drawn to the light from the actinic tube secured vertically between baffles, fall unharmed down a funnel, and rest inside the trap (Merckx *et al.*, 2009a). The purpose of the baffles is to cause the moths to stall in flight and drop into the narrow entrance and into the box below. The box is lined with egg trays, which allow moths to rest in their own compartments, without disturbing the rest of the catch. Moths trapped in a lighted environment will eventually settle down to roost, moving to the unlit undersides of the egg boxes, and will sit in this state undamaged until the trap is examined the following morning. The traps incorporate a light sensor which enables them to turn on and off automatically at sunset and sunrise. Such traps do not require the presence of the researcher during trapping (Holloway *et al.*, 2001, Fiedler and Schulze, 2004).

## 2.4 Sampling methodology

Preliminary sampling was carried out in 2009 and 2010 on the six designated bogs in order devise and refine sampling methodology. Dates of sampling in this period may be found in Appendix B.

Each bog was sampled on five nights between $2^{nd}$ July and $2^{nd}$ October 2011 only (60 trap nights) (Appendix C). Bogs were sampled over a two night period usually with six bogs sampled on each consecutive night. The division of bogs was based on spatial location to facilitate the logistics of trap deployment and collection, however in the main geographic pairs of designated and undesignated sites were sampled on the same night to ensure that variation in weather between trapping nights did not affect between-group comparisons.

Garmin hand-held global positioning system (GPS) receivers (Garmin International, Olathe, KS) were used in the field to record and find the location of each sample site (Irish Grid 10-figure).

Sampling was carried out with the assistance of trained NPWS field staff, who had participated in preliminary sampling in 2009 and 2010. Staff assisted in deploying the traps on the bogs before sunset and collected them the following morning after sunrise. The staff members were provided with field sheets with the grid reference of each sample site and recorded time of trap deployment and collection. Sampling took place only under suitable weather conditions (i.e. minimum night temperature: 10°C; maximum wind speed: 20km/hour; no persistent or heavy rain forecast) (Merckx *et al.*, 2009a). Traps were filled with nine standard-sized egg trays which were identically arranged in each trap to avoid bias (Fry and Waring, 2001). Rain guards were not used in order to simplify trap set-up, as they are easily lost, misplaced or forgotten and were felt unnecessary as actinic tubes are cold and are therefore not damaged by rain.

Traps were placed in the centre of a circle of tubing measuring 1 metre in diameter, which remained onsite for the duration of the study (Figure 2.3). A timed five-minute active search of the habitat and trap surface within the circle took place to ensure there was no bias towards more conspicuous species. All moths from outside the trap were placed in specimen tubes for later identification.

**Figure 2.3 Heath trap in 1 metre diameter circle.**

Trap openings were sealed and traps were placed in labelled, large black plastic sacks which were then sealed. Traps were opened, species identified and recorded indoors in a controlled environment by the author at a National Parks and Wildlife Service office located centrally in County Offaly to avoid excessive travel period.  Traps and batteries were arbitrarily reassigned to sites each night to remove any bias of lamp brightness or battery strength.

Moths were identified to species level according to Waring and Townsend (2009), Skinner (2009) and Manley (2008). Any scarce or rare species were photographed. Ninety-one out of 93 taxa were identified to species level. The four *Amphipoea* species can only be reliably distinguished by examination of genitalia where they occur together (Waring and Townsend, 2009) and therefore these species were was pooled into a species complex *Amphipoea* agg. and analysed as such. This complex was included with the raised bog associated species as one of the species in the complex *(Amphipoea lucens* (Freyer)) is a tyrphobiont and dissection of two specimens confirmed its presence. The species pair *Mesapamea secalis/didyma*, which also requires genetalia preparation to separate, was pooled into a species complex *Mesapamea secalis* agg. and analysed as such. Both species in this pair are considered tyrphobionts and so the species pair was also. Moth scientific names followed the European system (Karsholt & Nieukerken, 2013) and are followed by the abbreviated name of the authority in brackets. Full authority names may be found in Appendix D.  Vascular plant species nomenclature followed Parnell and Curtis, 2012.

## 2.5 Environmental variables

Environmental variables for each study site were derived from the 2004/2005 series of aerial photographs and geospatial information using ArcGIS 10.2.1 (ESRI, 2008).

The following variables were calculated:

(1) minimum distance from sampling point to bog edge
(2) bog perimeter
(3) high bog area
(4) area/perimeter
(5) total drain length on high bog
(6) drain density (D)
(7) elevation at sampling point
(8) bog fragment shape (R)
(9) Isolation (I)

Drain density (D) was calculated by dividing the total length of drains on the high bog by the area of the high bog. Elevational data was derived from Ordnance Survey Ireland 50-metre digital terrain model (DTM).

Fragment shape was measured by the dimensionless parameter (R). Values of R increase as the bog becomes more elongate. The measure was used in a similar study by Usher and Keiller (1998) and defined by Game (1980) as:

$$R = 0.282P/\sqrt{A}$$

Where:

- P is the perimeter of the bog
- A is the area
- 0.282 is a factor which ensures that R = 1 for circular sites.

Percentage habitat cover is a landscape isolation measure especially suitable for a landscape with a high cover of the focal habitat (Winfree *et al.*, 2005, Cozzi *et al.*, 2008, Bruckmann *et al.*, 2010). Isolation was expressed as the area of bog, including the study patch, as a percentage of the area of other habitat within a radius of 2 km of the sampling point. The 2km radius was chosen as it approximates an upper limit to dispersal distances of more mobile non-migratory moth species (Webb, 1989, Nieminen *et al.*, 1999, Moilanen and Nieminen, 2002).

## 2.6 Species variables

Each species was classified using Emmet (1991), Waring and Townsend (2009) and Bond and Gittings (2008) for the following traits; (1) larval feeding guild and (2) larval diet breath (monophagous / oligophagous or polyphagous). Moths were grouped together into the following feeding guilds; heather feeders, tree feeders, lichen feeders, grass feeders, broad-leaved plant feeders, scrub/tree feeders, sedge feeders, deciduous tree feeders and conifer feeders.

### 2.6.1 Non-target species and ecological noise

Flight traps sample both the autochthonous fauna and species simply passing by on dispersal flights (Duelli *et al.*, 1999). These vagrants may be hard to distinguish from resident species and can be a source of 'ecological noise' (New, 1997), posing a serious problem in analyses (Magurran and Henderson, 2003, Truxa and Fiedler, 2012b). Other species may have originated within the raised bog study area due to the presence of invasive and non-typical species such as *Pinus contorta* (Douglas ex Loudon), *P. sylvestris* (L.), *Salix* and *Betula* species or due to other habitats such as mineral rich soak systems and flushes being present.

### 2.6.2 Light trap attraction and sampling ranges

To understand how non-resident moth species are sampled using light traps, it is important to distinguish between the attraction range and the sample range of the trap. Attraction range is defined as the maximum distance from which moths show directed movement towards the light trap and sampling range is the maximum distance from which an insect can physically reach a trap in a given time interval (Shelly and Edu, 2010) (Figure 2.4). Therefore, sampling range includes both the attraction range and any area traversed by the moth, in a given time period, (in this case during one night) before entering the attraction range (Shelly and Edu, 2010).

The literature on the attraction range of moths to light is divided but recent studies suggest the attraction range to a weak light source such as used in the present study, is low, even below 10 metres (Baker and Sadovy, 1978, Sotthibandu, 1978, McGeachie, 1988, Muirhead-Thompson, 1991, Beck and Linsenmair, 2006, Truxa and Fiedler, 2012a, Merckx and Slade, 2014). Maximum attraction range in the present study was less than the least distance from a trap to the edge of a bog, to ensure attraction range lay within the habitat under investigation. As for sampling range, the mobility of the majority of moth species is largely unknown, but is species dependant and could vary from metres to kilometres within a single night (Slade *et al.*, 2013).

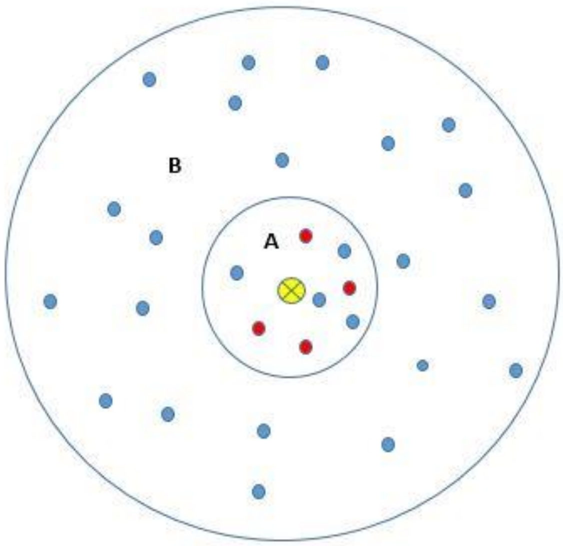


**Figure 2.4 Diagram depicting attraction range (A) and sampling range (B).** Red dots denote individuals resident within the attraction range and which would be expected to display direction flight towards the light trap. Blue dots represent individuals which originate outside the attraction range and pass through the attraction range by chance and then display directional flight towards the light trap (Adapted from Hirao *et al.*, 2008).

### 2.6.3 Raised bog associated species

As this study is focused on moths associated with raised bog habitat, a subset of raised bog moths was extracted from the general moth dataset, in order to reduce the confounding effect of moths recorded originating from within the sampling range but which were not associated with raised bog habitat. In midland raised bogs, where plant communities have been so well documented and vegetation is not very diverse, describing resident phytophagous moth fauna is comparatively easy. Moths associated with raised bog habitat were separated from other species based on information about their habitat and larval foodplant preferences in Emmet (1991), Waring and Townsend

(2009) and Bond and Gittings (2008) (Appendix E). Similar exclusion has been carried out in woodland moth species studies (Webb and Hopkins, 1984, Usher and Keiller, 1998, Fuentes-Montemayor *et al.*, 2012, Oxbrough *et al.*, 2012, Truxa and Fiedler, 2012b).

### 2.6.4 Species of conservation concern

While a Red List of Ireland's butterflies was compiled in 2010 (Regan *et al.*, 2010), there has been no conservation assessment of moths in the Republic of Ireland to date. Therefore, to assess conservation status of raised bog associated moth species, any species classified as endangered (greater than 50% 10 $yr^{-1}$ decline) or vulnerable (greater than 30% 10 $yr^{-1}$ decline) by Conrad *et al.* (2006) using IUCN criteria (IUCN, 2001) were considered to be of conservation concern (Table 2.2).

This classification is based on Rothamsted Insect Survey data (Woiwod and Harrington, 1994) using abundance trends for selected sites in Great Britain. Conrad *et al.* (2006) only analysed data for 337 common and widespread species, represented by more than 500 individuals captured over a 35 year sampling period and so uncommon species were not given a conservation status rating.

Geographically restricted butterfly species have been found to be biotope specialists and tend to be species warranting conservation measures (Thomas and Mallorie, 1985). Species for which conservation status was not available were assigned a distribution status, based on distribution data on the online database MothsIreland (Tyner, 2014a) and any scarce (not encountered often or restricted in range, e.g. the Burren) or rare species were considered vulnerable by virtue of their limited distribution.

Tyrphobionts, species specifically associated with raised bogs (Bond, 1989, Dapkus, 2000, Dapkus, 2004a, Dapkus, 2004b, Dapkus, 2004c, Spitzer and Danks, 2006), were also considered to be of conservation concern due loss of raised bog habitat.

*Thumatha senex* (Hb.), was previously classified as a tyrphobiont by Bond (1989). However its foodplant preference (lichens) (Waring and Townsend, 2009), conservation status (increasing) (Conrad *et al.*, 2006) and widespread distribution (Tyner, 2014a) indicate that this is not the case and therefore this species was excluded from the list.

**Table 2.2 Raised bog associated species of conservation concern**

| Species | Conservation Status |
|---|---|
| *Eugnorisma (Eugnorisma) glareosa* (Esp.) | Endangered |
| *Tholera cespitis* (D. & S.) | Endangered |
| *Xanthorhoe ferrugata* (Cl.) | Endangered |
| *Arctia caja* (L.) | Vulnerable |
| *Celaena haworthii* (Cur.) | Vulnerable/Tyrphobiont |
| *Ceramica pisi* (L.) | Vulnerable |
| *Mniotype adusta* (Esp.) | Vulnerable |
| *Orthonama vittata* (Borkh.) | Vulnerable |
| *Spilosoma lubricipeda* (L.) | Vulnerable |
| *Spilosoma lutea* (Hufn.) | Vulnerable |
| *Xestia (Xestia) agathina* (Dup.) | Vulnerable |
| *Acronicta menyanthidis* (Esp.) | Rare/Tyrphobiont |
| *Dicallomera fascelina* (L.) | Rare |
| *Anarta myrtilli* (L.) | Scarce/Tyrphobiont |
| *Dyscia fagaria* (Thun.) | Scarce |
| *Mythimna pudorina* (D. & S) | Scarce |
| *Papestra biren* (Goeze) | Scarce |
| *Selidosema brunnearia* (Vill.) | Scarce |
| *Syngrapha interrogationis* (L.) | Scarce |
| *Amphipoea lucens* (Freyer) | Tyrphobiont |

## 2.7 The Database of Irish Lepidoptera

The Database of Irish Lepidoptera (Bond and Gittings, 2008) contains species accounts of all resident Irish butterflies and Noctuid moths, describing their habitat preferences, traits and distribution status. The database contains three spreadsheets in which the macrohabitat, microsite preferences and traits of each species are coded using a four-point fuzzy coding system (0-3). It can be used to predict species which should be present in a particular habitat. The presence of species coded "3" would be expected / predicted to occur, while the presence of species coded "2" would also be predicted to occur. A habitat with a high number of predicted species is considered to have a good biodiversity maintenance function for Noctuid moths and indicates it is in good condition. Such databases permit non-specialist site managers to tap into the information hidden behind a list of otherwise meaningless insect species names and are known as ‘expert systems’ (Speight, 2004).

A list of species coded “2” or “3” for association with raised bog was extracted (seven species coded “3” and eight species coded “2”, see Appendix F). This list was then cross referenced with species which are known to occur in the region sampled. In Ireland, counties are units of appropriate scale to function as regional species lists (Speight, 2008). However, given the low moth record density in the counties Offaly and Westmeath (Tyner, 2014b) as well as the addition of two species, coded ‘3’ for raised bog, to the Offaly county list during this study, it was decided to use Ireland as the regional list. This predicted list was then compared with the fauna actually recorded on all bogs in 2009, 2010 and 2011 and an attempt was made to explain predicted species absence.

## 2.8 Statistical analyses

Where appropriate, statistical analyses were carried out with and without non-associated species. For some analysis, species not associated with raised bog were excluded to ensure they did not obscure the results and to allow direct comparison between intact and degraded bog on the basis of raised bog habitat associated fauna only.

### 2.8.1 Comparing species relative abundance

As abundant species are expected to carry most of the information with regard to community patterns (Peck, 2010), the Mann-Whitney U test, the non-parametric equivalent of the independent samples t-test, was used to test if relative abundance of these species differed significantly according to designation status. This test does not make assumptions about the homogeneity of variances or normal distributions (Dytham, 2011). For these analyses relative abundances (relative to total abundance of 93 species) of those 11 species that were represented by at least 1% of individuals among all species sampled in 2011 were compared. Analyses were performed using SPSS (Version 22.0) (IBM Corp., 2013).

### 2.8.2 Species of conservation concern

In order to investigate whether there was a difference in terms of raised bog species of conservation concern, relative abundances of such species were also compared using the Mann-Whitney U test. One species, *Xestia (Xestia) agathina* (Dup.), was omitted as it was clear that its flight season had not been covered by sampling in 2011. In addition, three species (*Celaena haworthii* (Cur.), *Mniotype adusta* (Esp.) and *Mythimna pudorina* (D. & S.) represented by only one individual were also omitted.

### 2.8.3 The Chao 2 species richness estimation method

In invertebrate biodiversity studies, observed number of species is frequently considerably lower than true species richness due to inadequate sampling (May, 1975, Colwell and Coddington, 1994, Beck and Schwanghart, 2010). In such cases, species diversity among habitats cannot be reliably measured by directly comparing observed species richness.

In the case of the macro-moth fauna, sampling using light traps does not guarantee a full suite of species will be sampled, due to individual species varying responses to light stimuli (see Section 2.3.1) as well as capture of individuals who enter the sampling range by chance during the sampling period (see Section 2.6.2). In addition, further species would have been added if sample size had been larger and covered a more extended period, particularly March to June (Jonason *et al*., 2014). As the complete assemblage was not sampled in the present study, the program EstimateS (Colwell, 2013) was used to estimate true species richness. This program has a number of nonparametric methods for estimation of species richness and has been used in similar comparative studies of insect assemblages (Savage *et al.*, 2011, Jonason *et al.*, 2013).

Non-parametric species richness estimators such as Chao 1 and Chao 2 assume homogeneity among samples and should not be applied to datasets where there are large compositional differences, such as along ecological gradients. They can be applied to any sample size (Colwell, 2013), however, they provide a minimum estimate of species richness and will underestimate species richness if the sample size is too low (Magurran, 2004).

The species richness estimation method Chao 2 (Chao, 1984, 1987, Colwell, 2013) was used to estimate the number of species on all undesignated and designated bogs. For each site, the trapping events were collated and species incidence data for each site was then treated as a replicated sample unit. As a rough guide to "sufficient" sample size, the estimated sample completeness should be at least 50%, For Chao 2 this means the proportion of uniques should be less than 50% (Colwell, 2013). This was the case for all samples tested using Chao 2. The method was repeated for designated and undesignated sites separately with six sample replicates in each (classic EstimateS input, using 100 sample randomisations).

In addition, a species richness estimate of the total population was made using Chao 2 with all twelve sample sites used as replicates. The procedure was repeated using just raised bog associated species to estimate the raised bog associated species richness total on all sites. The classic formula as opposed to the bias corrected version was used to calculate Chao 2 as the coefficient of variation of incidence distribution was greater than 0.5 for the undesignated bogs (0.528) and this was, therefore, considered to be the better estimate for incidence-based richness.

The Chao 2 estimator equation is:

$$\hat{S}_{Chao2} = S_{obs} + \left(\frac{m-1}{m}\right)\frac{Q_1^2}{2Q_2}$$

Where:

- $S_{obs}$ = Total number of species observed in all samples pooled
- m = Total number of samples
- $Q_1$ = frequency of uniques (number of species which occur in one sample)
- $Q_2$ = the frequency of duplicates (number of species which occur in two samples)

The log-linear 95% confidence intervals (lower and upper) were calculated. A log-transformation was used so that the lower bound of the resulting interval was at least the number of observed species (Chao and Shen, 2010). The standard deviations were calculated by Chao's 1987 formulas as reproduced in Colwell (2013).

### 2.8.4 Species-Accumulation Curve

A species-accumulation curve was constructed using the software PC-ORD Version 6.0 (McCune and Mefford, 2011) and used to extrapolate an estimate of total species richness of the raised bog associated moth assemblage and thereby assess the accuracy of the Chao 2 species richness estimator. The species-accumulation curve was also used to assess sample size adequacy (McCune and Grace, 2002.)

Calculations were made using raised bog associated species (n=62) and presence-absence data over three years of sampling data. Species incidence data was deemed most suitable in this case due to the confounding effect of environmental conditions on abundance measurements when considering individual trap events over a three-year period.

Each trapping event was considered a sample resulting in 102 samples. All raised bog samples, including undesignated bogs in 2011 were analysed. The procedure was randomised to produce a smooth curve. The sample was subsampled to determine the average number of species as a function of size of the subsample. Subsampling was repeated 500 times for each subsample size.

### 2.8.5 Diversity Indices

Diversity indices are used to capture the species richness and evenness characteristics of an assemblage (Magurran, 2004). The following diversity indices were calculated for undesignated and designated sites and used to compare assemblages of each: Shannon's entropy (Ĥ), exponential Shannon's entropy (exp (Ĥ)), Simpson's Index (D), Simpson's Diversity Index (1/D) and Fisher's Alpha Index. Indices were calculated using the software SPADE (Chao and Shen, 2010), as the bias-corrected version of the exponential Shannon entropy, used in the present analysis, is not available in the EstimateS software. The maximum likelihood estimator (MLE) (Magurran, 2004) was used to avoid bias.

Species abundance data per trap event were aggregated for each bog and diversity indices were calculated for each bog. Diversity scores per bog were then grouped into designated and undesignated sites and statistical difference between groups was compared using the Mann-Whitney U Test. The mean of each diversity index was then found for both designated and undesignated sites.

Diversity indices were calculated for all species and raised bog associated species. One raised bog associated species (the heather-feeding species, *L. porphyria*) was the most abundant species in both designated and undesignated bog groups. Therefore, indices were recalculated excluding this species, in order to reveal any underlying diversity differences. Furthermore, species diversity measures were calculated for heather feeding and non-heather feeding species using literature on food plant preferences in order to reveal any diversity difference being masked by heather feeders as it was considered that the presence of heather feeding species on all sites may have masked underlying diversity differences.

**Shannon's entropy (Ĥ) and exponential Shannon entropy (exp (Ĥ) )**

Shannon's entropy has its origins in information theory (Ulanowicz, 2001) but it is flawed as the addition of each species, even in cases where species are equally even, leads to a smaller increase in the value of the measure (Jost *et al.*, 2010). This behaviour is corrected by using the exponential of Shannon entropy (exp (Ĥ*))* (MacArthur, 1965). This metric also known as 'the effective number of species' (Chao and Shen, 2003, Jost, 2006). Estimated standard error is based on a bootstrap method. Ĥ was calculated using the following equation (Chao and Shen, 2003):

$$\hat{H} = - \sum_{1-k}^{n} f_k \frac{(k(1-f_1/n)/n) log[k(1-f_1/n)/n]}{1-[1-k(1-f_1/n)/n]^n}$$

Where :

- $f_k$= number of species that are represented exactly k times in the sample, k = 0, 1, ...,n

- $k$ = the cut-off point which separates species into "frequent" and "infrequent" groups for incidence data
- $n$ = total number of individuals
- $f_1$ = number of species that are represented once in the sample

**Simpson's Index (D) and Simpson's Diversity Index (1/D*)***

Simpson's index (D) provides a good estimate of diversity at relatively small sample sizes and will rank assemblages consistently, even when species accumulation curves intersect (Magurran, 2004). The index was obtained from the equation (Chao and Shen, 2010):

$$D = \sum_{k=1}^{n} f_k \left(\frac{k}{n}\right)^2$$

Where :

- $k$ = the cut-off point which separates species into "frequent" and "infrequent" groups for incidence data
- $n$ = total number of individuals
- $f_k$= number of species that are represented exactly k times in the sample, k = 0, 1, ...,n

As D increases, diversity decreases so the reciprocal 1/D or Simpson's Diversity Index was also calculated. The value of 1/D will rise as the assemblages become more even. 1/D is also the effective number of species (the number of equally common species which would result in such a value of H or D) and allows direct comparison between observed species richness, estimated species richness and effective number of species (both exp (Ĥ) and 1/D). A drop in value from the former to the later indicates a high degree of dominance in the assemblage (Jost, 2006).

**Fisher's Alpha Index**

Fisher's alpha (Fisher *et al.*, 1943) is a parameter of the log series species abundance model but can be used, even when the log series distribution is not the best description of the underlying species abundance pattern and has been often recommended as the most reliable assessment of alpha diversity (Hayek and Buzas, 1997, Southwood and Henderson, 2000, Magurran, 2004). Moreover, Fisher's alpha has been found to produce relatively stable values at low sample completeness (Taylor, 1978) and may be a good measure if completeness is low (Beck and Schwanghart, 2010). The index was obtained from the equation (Chao and Shen, 2010):

$$\hat{\alpha} = \frac{n(1-\hat{\emptyset})}{\hat{\emptyset}} \quad \text{where } \hat{\emptyset} \text{ is solved by iteration of } \frac{S}{n} = \frac{1-\emptyset}{\emptyset}\left[-\ln(1-\emptyset)\right]$$

Where:

- $\hat{\emptyset}$ = an estimator of $\emptyset$ from the data
- $n$ = total number of individuals
- $S$ = total number of species

### 2.8.6 Data Preparation

Raw species richness counts can only be validly compared when taxon accumulation curves have reached a clear asymptote. Species-area or accumulation curves were used to assess sample size adequacy (McCune and Grace, 2002). The species accumulation curve reached asymptote after singletons had been removed which reduced the number of species (raised bog associated) from 47 to 38. Analysis was carried out using PC-ORD (v. 6.0) (McCune and Mefford, 2011).

### 2.8.7 Cluster analysis

Cluster analysis allows sample units to be assigned to groups on the basis of the similarity of redundant patterns of their responses. Analysis was carried out using the PC-ORD using raised bog associated species only (n=38). Hierarchical agglomerative cluster analysis (McCune and Mefford, 2011) was carried out on the 2011 samples from 12 raised bogs (6 designated and 6 undesignated) using the Sørensen distance measure. The data were log transformed, to reduce the effect of the few dominant species. To logtransform this data which containing zeros, 1 was added to all values before applying the transformation (McCune and Grace, 2002). The flexible beta method was used as the group linkage method with a β value of -0.25. This method avoids distortion, while using the method with a β value of -0.25 reduces the likelihood of chaining (McCune and Grace, 2002). Analysis was carried out using PC-ORD.

### 2.8.8 Multi-response permutation procedure (MRPP)

MRPP is a nonparametric procedure for testing the hypothesis of no difference between two or more groups (McCune and Grace, 2002). Using the results of cluster analysis, statistically significant difference among groups was investigated. A Sørensen distance measure was used as proportional city-block distance measures (e.g. Sørensen distance) are increasingly used in published studies with MRPP and community data (McCune and Grace, 2002). Raw species data was used after removal of singletons and non-raised bog habitat associated species. MRPP was also used to test difference among groups with designated site used as a grouping variable and using presence-absence data for all species and not removing singletons. Analysis was carried out using PC-ORD.

### 2.8.9 Indicator Species analysis

Indicator species analysis allows assessment of the degree to which a species indicates a group based on its constancy and distribution of abundance. It was carried out using the Tichý and Chytrý (2006) analysis which operates on binary data. Analysis was carried out using PC-ORD.

### 2.8.10 Ordination

Whereas classification assigns sample units to discrete groups, ordination orders sampled units along a continuum (Peck, 2010). Ordination was performed in PC-ORD. Species responses were graphed individually as discrete variables using a Poisson distribution to check whether the assumption of multivariate normality was met. The majority of species abundance responses were found to have strong skewness to the left, therefore, statistical methods which assume normality had to be excluded.

Non-metric Multidimensional Scaling analysis (NMS) is an ordination technique suited to non-normal datasets (McCune and Grace, 2002). NMS was used to test for differences in species assemblages or beta diversity patterns. Due to the overriding influence of sample date on the 2011 species abundance data, species presence-absence data was used. The species matrix consisted of 37 species and 12 sites. The Sørensen statistic was used as a distance measure.

NMS was run in Autopilot mode five times using presence-absence data and a stress test was carried out each time to determine dimensionality by graphing an NMS scree plot. All five scree plots suggested a three dimensional solution. NMS was run again five times using the parameter setup as follows: 12 sites, 37 species, presence-absence data, Sørensen distance measure; number of axes = 3; 500 runs with real data; stability criterion = 0.0000001; iterations to evaluate stability = 15; maximum number of iterations = 500; random starting coordinates = time of day (computer clock), number of runs 250; rotation = orthogonal principal axes (this is an eigenanalysis procedure designed to make the axes orthogonal (i.e. independent of one another (perpendicular)). It is a rigid rotation that happens to also have the result that the axes are frequently ordered in decreasing order of importance (Peck, 2010).
Results were inspected and graphed. Solutions were very similar and a final result was chosen after inspection of the plot of iteration vs stress.

#### 2.8.11 Nestedness analysis

Nestedness is a measure of the degree to which species-poor sites are a subset of more species-rich sites and is used to investigate species distribution patterns in ecological networks. In a perfectly nested distribution, species occurring at the site of interest are always present in a more species-rich site, whereas species absent from the site of interest never occur in a less species-rich site (Atmar and Patterson, 1993). Several studies have demonstrated that nestedness contributes in various ways to the stability of mutualistic ecological networks by minimizing competition and lowering species vulnerability to extinction (Bastolla *et al.*, 2009).

It has been shown to be a stable measure even at relatively low sample sizes such as in this case (Nielsen and Bascompte, 2007). Several measures have been proposed to measure the degree of nestedness (Atmar and Patterson, 1993, Brualdi and Shen, 1999, Almeida-Neto and Ulrich, 2010, Staniczenko *et al.*, 2013). The metric used in the present study is NODF (Nestedness metric based on Overlap and Decreasing Fill) (Almeida-Neto and Ulrich, 2010). It has been suggested as particularly robust against variations in matrix size (Almeida-Neto *et al.*, 2008, Ulrich and Almeida-Neto, 2012) and has recently been the most popular and widely used nestedness measure (Strona and Fattorini, 2014). NODF is the percentage of presences in inferior rows and in right columns that are in the same position (column or row) of the presences in, respectively, upper rows and left columns with higher marginal totals for all pairs of columns and rows (Almeida-Neto *et al.*, 2008, Ulrich *et al.*, 2009).

Nestedness data for raised bog species was organised in a binary, presence-absence matrix, where each row was a species (n=47) and each column a site (n=12). The online software 'NeD' was used to calculate nestedness value (Strona *et al.*, 2014). For the NODF metric, Z values > 1.64 indicate significance at $P = 0.05$. To test the significance of the nested pattern, the matrix Z value was compared with null model 2 (CE) (mean "temperature" of 500 randomly generalised matrices) (Strona *et al.*, 2014). CE (proportional row and column totals) assigns to each matrix cell a probability to be occupied proportional to the corresponding row and column totals and has been used in several studies (Bascompte *et al.*, 2003, Bascompte *et al.*, 2007).

As absolute nestedness value depends on matrix size and fill, to facilitate future comparison of degree of nestedness among other datasets, the metric 'relative nestedness (RN)' was calculated. Relative nestedness is defined as $RN = (N-N_R)/N_{R1,}$ where N is the nestedness of the actual matrix and $N_R$ is the average nestedness of random replicates generated from the null model (Bascompte *et al.*, 2003).

To test which environmental variables support the nested pattern, the ranking order of sites in the final packed matrix was correlated with the rank order of sites after rearranging the sites by environmental variable using Spearman Rank Correlation ($r_{s)}$ in SPSS. A significant correspondence suggests that the community is in a predictive order owing to the influence of a given factor.

A polynomial regression was fitted to a graph of raised bog species richness (dependant variable) plotted against drain density in order to explain the nested species richness pattern also using SPSS.

# 3 Results

## 3.1 Moth Abundance & Diversity

In 2011, a total of 1,816 adult individuals of 93 taxa were recorded, representing 16% of the Irish moth fauna (582) (Bond *et al.*, 2006). Ten families were recorded, with two families (Noctuidae and Geometridae) (Figure 3.1.) together accounting for 77% of species and 90% of individuals.

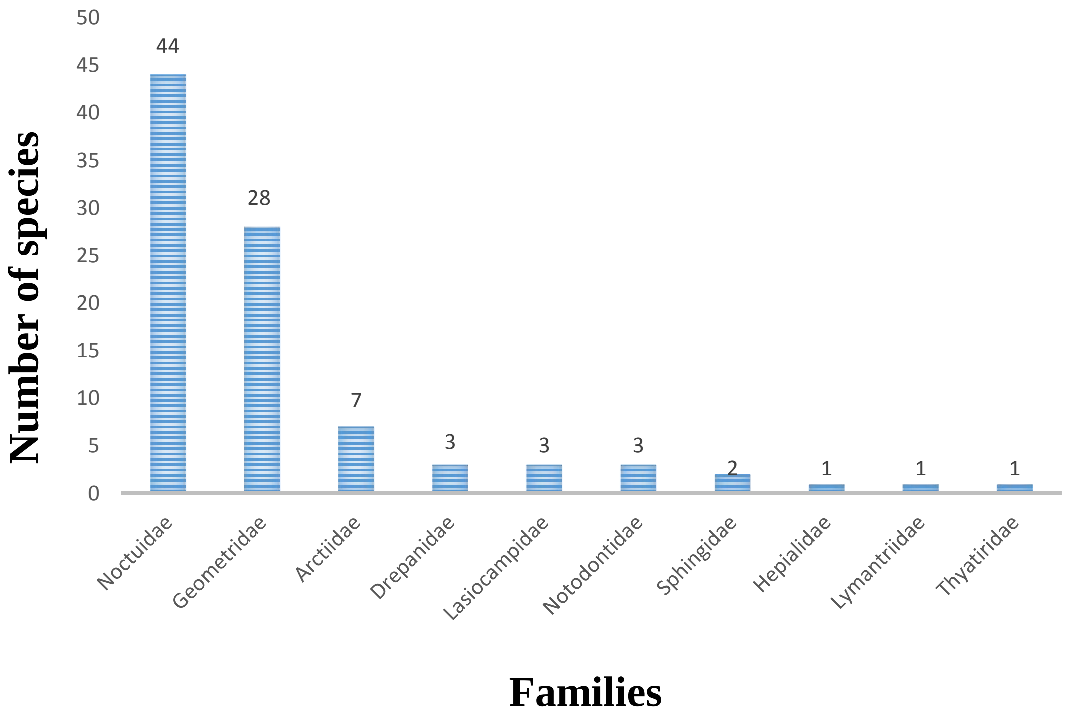


**Figure 3.1 Number of species according to family**

Forty-seven taxa (1650 individuals) were classified as being associated with raised bog habitat (Figure 3.2).



1 2 3



4 5 6



7 8 9



10 11 12



13 14 15

**Figure 3.2 Selected raised bog associated nocturnal Lepidoptera recorded .**
1: *Lycophotia porphyrea* (D.& S.), 2: *Apamea monoglypha* (Hufn.), 3: *Ceramica pisi* (L.), 4: *Eupithecia nanata* (Prout), 5: *Dyscia fagaria* (Thunb.), 6: *Amphipoea* agg., 7: *Selidosema brunnearia* (Vill.), 8: *Xestia (Xestia) agathina* (Dup.), *9: Dicallomera fascelina* (L.). 10: *Eilema lurideola* (Zinck.), 11: *Macrothylacia rubi* (L.), 12: *Acronicta menyanthidis* (Esp.), 13: *Arctia caja* (L.). 14: *Noctua pronuba* (L.), *15: Syngrapha interrogationis* (L.)

The rank-abundance curve revealed that four species dominated the dataset; *Lycophotia porphyrea* (D.& S.), *Apamea monoglypha* (Hufn.), *Noctua pronuba* (L.), *Dyscia fagaria* (Thunb.) *Lycophotia porphyrea* (D.& S.), was the most abundant species on all sites representing just over 50% of individuals (n= 947). The dominance of *L. porphyrea* is represented graphically in Figure 3.3, which also distinguishes between raised bog species (filled diamonds) and other non-associated species (open diamonds). Many species were rare, with 47%, or 44 of the 93 moth species, represented by only one or two individuals. Appendix G shows a rank-abundance curve of moth species collected over 3 years and has a similar shape.

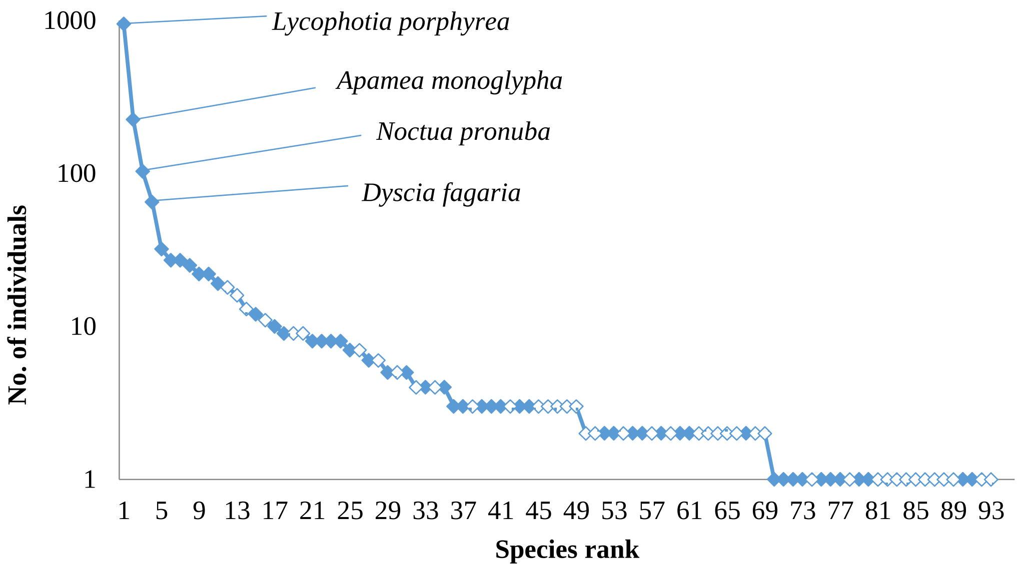


**Figure 3.3 Rank abundance curve 2011 dataset**.
Log-transformed (y' = $\log_{10}$(y)) scale on the y axis. The named species are those comprising more than 2% of the total abundance. Filled diamond = raised bog associated species, Open diamond = other species

The abundance of 11 species was equal to or greater than 1% of total abundance (Table 3.1). *Xestia (Xestia) agathina* (Dup.) featured among the three most abundant species in preliminary sampling but did not feature prominently in 2011 as sampling did not take place during the main part of its flight season (late August – mid September) (Tyner, 2014a)(Appendix G). No abundant species occurred only on designated or undesignated sites and comparison of relative abundance of species revealed no significant difference between designated and undesignated bogs. The only species where the difference approached significance ($P$ = 0.065) was *Eupithecia nanata* (Hb.) (Table 3.1).

**Table 3.1 Abundance of species equal to or greater than 1% of total abundance.** P-value refers to Mann-Whitney U test results.

| Species | Total abundance | Total % abundance | Designated % abundance | Undesignated % abundance | P-value |
|---|---|---|---|---|---|
| *Lycophotia porphyrea* (D. & S.) | 947 | 52.15 | 52.58 | 51.68 | 0.937 |
| *Apamea monoglypha* (Hufn.) | 225 | 12.39 | 15.46 | 9.02 | 0.310 |
| *Noctua pronuba* (L.) | 103 | 5.67 | 6.83 | 4.39 | 0.180 |
| *Dyscia fagaria* (Thunb.) | 65 | 3.58 | 2.94 | 4.28 | 0.485 |
| *Selidosema brunnearia* (Vill.) | 32 | 1.76 | 1.79 | 1.73 | 0.394 |
| *Amphipoea* agg. | 27 | 1.49 | 1.05 | 1.96 | 0.699 |
| *Dicallomera fascelina* (L.) | 27 | 1.49 | 2 | 0.92 | 0.132 |
| *Eilema lurideola* (Zinck.) | 25 | 1.38 | 1.16 | 1.62 | 0.699 |
| *Arctia caja* (L.) | 22 | 1.21 | 1.47 | 0.92 | 0.240 |
| *Phlogophora meticulosa* (L.) | 22 | 1.21 | 1.26 | 1.16 | 1.0 |
| *Eupithecia nanata* (Hb.) | 19 | 1.05 | 0.42 | 1.73 | 0.065 |

Summary statistics for all sites (n=12) sampled in 2011 are shown in Table 3.2. Species richness and the number of individuals trapped varied considerably among bogs, ranging from 18 to 37 species and 55 to 257 individuals, respectively. As the sampling effort was the same for each bog irrespective of area, comparisons are for within habitat diversity (alpha diversity sensu Whittaker (1975)). On designated bogs (n = 6), a total of 951 individuals of 67 species were identified. A similar result was obtained from undesignated bogs (n = 6), where a total of 865 individuals of 73 species were recorded. On designated sites, 33 species (883 individuals) and on undesignated sites, 39 species (767 individuals) were recorded as being associated with raised bogs.

**Table 3.2  Species number and abundance by bog type**

| Bog type/name | All moths | | Raised bog moths | |
|---|---|---|---|---|
| | Species | Individuals | Species | Individuals |
| **Designated** | | | | |
| Sharavogue | 25 | 113 | 15 | 60 |
| Mongan | 22 | 185 | 17 | 92 |
| Ferbane | 33 | 238 | 21 | 139 |
| Moyclare | 18 | 168 | 14 | 80 |
| Clara | 25 | 98 | 16 | 46 |
| Raheenmore | 22 | 149 | 14 | 83 |
| Mean | 24.17 | 158.5 | 16.17 | 83.33 |
| **Undesignated** | | | | |
| Old Croghan | 29 | 176 | 20 | 108 |
| Clonaltra | 24 | 147 | 12 | 72 |
| Curraghalassa | 37 | 114 | 23 | 32 |
| Doon | 33 | 257 | 22 | 155 |
| Clonlyon | 19 | 116 | 15 | 58 |
| Kilballyskea | 19 | 55 | 10 | 22 |
| Mean | 26.83 | 144.17 | 17 | 74.5 |
| **Overall Mean** | 25.5 | 151.3 | 16.6 | 78.92 |
| **Overall Total** | 93 | 1816 | 47 | 1650 |

Excluding singletons, six species were only found on designated raised bogs in 2011 (*Acronicta menyanthidis* (Esp.), *Macrothylacia rubi* (L.), *Eulithis testata* (L.), *Nudaria mundana* (L.), *Deilephila elpenor* (L.)) and *Phragmatobia fuliginosa* (L.), while six species were also only recorded on undesignated raised bog (*Syngrapha interrogationis* (L.), *Xanthorhoe ferrugata* (Cl.), *Perconia strigillaria* (Hb.), *Alcis repandata* (L.), *Gymnoscelis rufifasciata* (Haw.) and *Eugnorisma (Eugnorisma) glareosa* (Esp.) (Figure 3.4). Of the six species found only on undesignated bogs, five had been previously recorded on designated bogs during preliminary sampling in 2009 and 2010, albeit at low abundance. *Syngrapha interrogationis*, *X. ferrugata* and *P. strigillaria* were recorded as singletons on Raheenmore bog, *A. repandata* was recorded as a singleton on Clara Bog while *G. rufifasciata* had previously been recorded as doubletons on Mongan, Clara and Raheenmore Bogs. Only *E. glareosa* was not previously recorded. However preliminary sampling in 2009 and 2010 at the end of August only covered the beginning of its flight season (August to October).

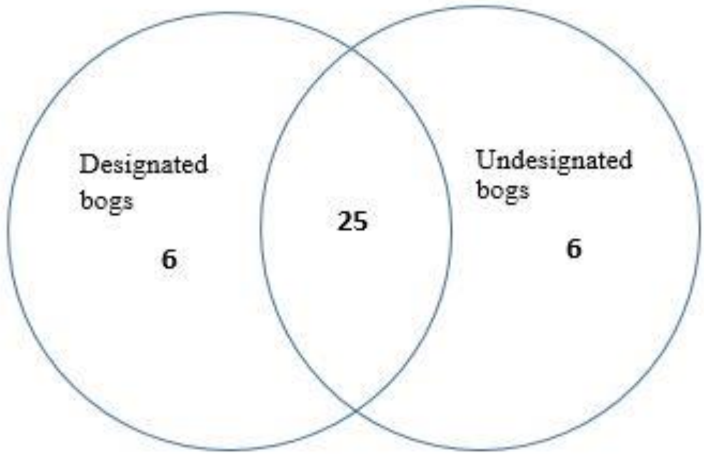


**Figure 3.4 Venn diagram of species distribution among two bog types.**
This analysis includes raised bog associated only and excludes singletons (species found only once during sampling) (n=10), to reduce the influence of poorly sampled species.

## 3.2 Species of Conservation Concern and Species New to Offaly

Of the 47 species associated with raised bog recorded in 2011, 14 species or 30% were found to be of likely conservation concern. Two were classified as endangered, six as vulnerable, two as rare and four as scarce. Two species were classified as tyrphobionts. Difference was tested by comparing relative abundance per site, grouped as designated and undesignated sites, using the Mann-Whitney U test. While a number of species were found at low abundance levels on either one or other bog type, there was no significant difference between the relative abundance of species of conservation concern found on designated and undesignated raised bogs (Table 3.3).

**Table 3.3 Abundance of species of conservation concern in 2011.**
The total recorded in 3 years (2009, 2010 and 2011) is in brackets.
P-value refers to Mann-Whitney U test results for comparison of means.

| Species | Conservation Status | Total No. of Individuals | Designated Sites | Undesignated Sites | P-value |
|---|---|---|---|---|---|
| *Eugnorisma (Eugnorisma)glareosa* (Esp.) | Endangered | 4 (4) | 0 | 4 | 0.394 |
| *Xanthorhoe ferrugata* (Cl.) | Endangered | 2 (2) | 0 | 2 | 0.394 |
| *Arctia caja* (L.) | Vulnerable | 22 (33) | 14 (11) | 8 | 0.240 |
| *Celaena haworthii* (Curt.) | Vulnerable/ Tyrphobiont | 1 (2) | 0 (1) | 1 | 0.699 |
| *Ceramica pisi* (L.) | Vulnerable | 8 (42) | 1(34) | 7 | 0.310 |
| *Mniotype adusta* (Esp.) | Vulnerable | 1 (2) | 0 (1) | 1 | 0.699 |
| *Spilosoma lubricipeda* (L.) | Vulnerable | 6 (13) | 3 (7) | 3 | 0.818 |
| *Xestia (Xestia) agathina* (Dup.) | Vulnerable | 4 (198) | 2 (194) | 2 | 0.818 |
| *Acronicta menyanthidis* (Esp.) | Rare/ Tyrphobiont | 3 (4) | 3 (1) | 0 | 0.394 |
| *Dicallomera fascelina* (L.) | Rare | 27 (43) | 19 (16) | 8 | 0.132 |
| *Dyscia fagaria* (Thunb.) | Scarce | 65 (188) | 28 (123) | 37 | 0.485 |
| *Mythimna pudorina* (D. & S.) | Scarce | 1 (1) | 0 | 1 | 0.699 |
| *Selidosema brunnearia* (Vill.) | Scarce | 32 (33) | 17 (1) | 15 | 0.394 |
| *Syngrapha interrogationis* (L.) | Scarce | 3 (4) | 0 (1) | 3 | 0.180 |

One further endangered species (*Tholera cespitis* (D&S) (n=11), two vulnerable species (*Orthonama vittata* (Borkh.) (n=2) and *Spilosoma lutea* (n=7) and two scarce species (*Anarta myrtilli* (L.) (n=5) and *Papestra biren* (Goeze) (n=5)) were recorded during preliminary sampling on designated raised bogs in 2009 and 2010. Therefore of the 62 raised bog associated species recorded in 2009, 2010 and 2011, 19 species may be considered of conservation concern. Four moth species were added to the Offaly species list during this study; *X. agathina*, *P. biren*, *A. menyanthidis* and *Mniotype adusta* (Esp.).

### 3.3 The Database of Irish Lepidoptera

The Database of Irish Lepidoptera (Bond and Gittings, 2008) was consulted. Of 15 species coded “3” and “2” predicted to occur on raised bog habitat, 11 species (69%) were recorded over the three year period on 12 raised bogs in Offaly (Appendix F). Of these, six species had fewer than ten individuals recorded over three years.

All species coded “3” (n=7) but only 50% (4 out of 8) species coded “2” or species predicted to occur on raised bogs were recorded. The following species coded “2” were not recorded; *Xestia (Xestia) castanea* (Esp.), *Orthosia (Cororthosia) gracilis* (D.& S.), *Apamea crenata* (Hufn.) and *Phytometra viridaria* (Cl.).

*Xestia (Xestia) castanea* (Esp.) is coded “2” but is not on the Offaly species list (Tyner, 2014b) and has a mainly western distribution (Tyner, 2014a).

*Orthosia (Cororthosia) gracilis* (D.& S.) may not have been recorded because its flight season (April/May) was too early to ensure trapping. Another reason may be that the food plant, *Myrica gale* (L.), was not present or that it was present but not close to trapping sites. *Myrica gale* has not been recorded from Ferbane or Raheenmore Bogs (Kelly, 1993, Fernandez *et al.*, in prep.). Bond (1989) recorded *O. gracilis* from the margin of Mongan Bog in an area which had *M. gale* present but did not record this species from the central area of the bog.

*Apamea crenata* (Hufn.) was also not recorded by Bond, 1989 in an extensive multi-annual study of Mongan Bog. Its foodplants are grasses especially *Dactylis glomerata* (L.) (Emmet, 1991), a species not recorded on any of the designated bogs surveyed (Fernandez *et al.*, 2005b, Fernandez and Wilson, 2009, Fernandez *et al.*, 2012b). It is suggested that *A. crenata* may have been incorrectly coded as “2” by Bond and Gittings (2008).

*Phytometra viridaria* (Cl.) is mainly a day-flying moth, only sometimes coming to light (Waring and Townsend, 2009). It was recorded by Bond (1989) from the centre of Mongan Bog. It should also be noted that the foodplants of *P. viridaria* (*Polygala vulgaris* (L.), and *P. serpyllifolia* (Hosé)), have only been recorded from three (Mongan, Moyclare and Clara Bogs) of the six raised bogs (Kelly, 1993, Kelly *et al.*, 1995b, Fernandez *et al.*, 2012b) which could explain its absence from these sites.

In 2011, five species coded "3" for raised bog had fewer than 3 individuals recorded. This low abundance did not allow meaningful comparison between sites in 2011 based on this species subset. This indicates that the sampling regime did not capture these important species and/or they are present on these sites at very low abundances.

It is noteworthy that *A. monoglypha* was recorded on all bogs (263 individuals). It is coded "3" for bog (general) and cutover bog. However, it is suggested that it should be also coded "3" for raised bog.

### 3.4 Observed and Estimated Species Richness Patterns

There was no significant difference in species richness measures between designated and undesignated sites (Table 3.4). The Chao 2 estimator of raised bog species richness on undesignated sites was closest to species richness as estimated from the species-accumulation curve covering 3 years of sampling (62 species) (Figure 3.5), indicating that this is an accurate method for estimating species richness. The species-accumulation curve revealed that approximately 37% of the assemblage was sampled in 2011.

**Table 3.4. Observed and estimated species richness patterns.**
Means ± 1 Standard Deviation and/or 95% Confidence Interval (upper and lower bounds shown in brackets). P-value refers to Mann-Whitney U test results for comparison of means.

| Biodiversity Measure | All Sites | Designated Sites | Undesignated Sites | P-value |
|---|---|---|---|---|
| **All Species** | | | | |
| Mean Observed Species Richness ($S_{obs}$) | 25.5±5.95 | 24.2 ± 5.0 | 26.8 ± 7.4 | 0.589 |
| Observed No. of Individuals | 151.33±55.49 | 158.5 ± 49.5 | 144.2 ± 68.4 | 0.818 |
| Estimated Species Richness | 107.82±7.32 (98.93/ 130.03) | 90.55 ± 11.3 (76.65 / 124.49) | 107.4 ± 16.07 (87.4 / 155.18) | 0.589 |
| **Raised Bog Species** | | | | |
| Mean Observed Species Richness ($S_{obs}$) | 16.6±3.92 | 16.2 ± 2.6 | 17 ± 5.4 | 0.818 |
| Observed No. of individuals | 137.5±55.7 | 147.2 ± 50.9 | 127.8 ± 68.0 | 0.589 |
| Estimated Species Richness | 51.16±3.56 (47.97 / 64.79) | 35.04 ± 2.2 (33.57 / 48.44) | 57.95 ± 13.9 (44.23 / 107.59) | 0.180 |

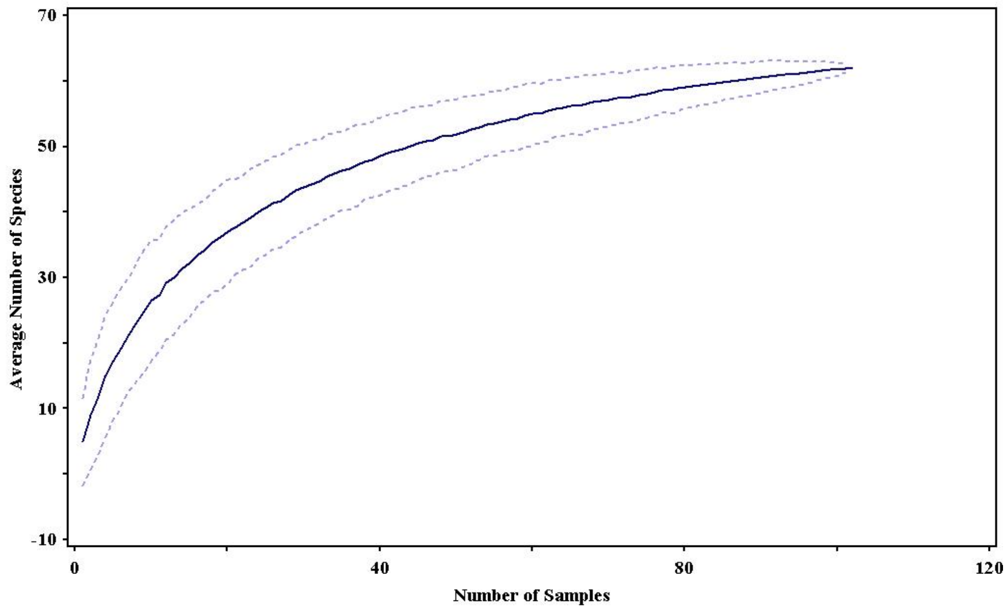


**Figure 3.5 Species-accumulation curve.**
This graph is based on the occurrence of 62 species at 102 light trap samples in 2009, 2010 and 2011. Average species richness based on randomization procedure outlined in McCune and Grace (2002). The hatched line shows the standard deviation from the mean.

## 3.5 Diversity indices

There was no significant difference between diversity indices on designated and undesignated sites (Table 3.5).

**Table 3.5 Comparison of diversity indices.**
Means ± 1 Standard deviation. P-value refers to Mann-Whitney U test results for comparison of means.

| Biodiversity Measure | Designated Sites | Undesignated Sites | P - value |
|---|---|---|---|
| **All Species** | | | |
| Shannon 's Entropy (MLE)* | 1.88±0.2 | 2.09±0.43 | 0.240 |
| Exponential of Shannon Entropy (BC-MLE)** | 7.95±2.37 | 11.33±6.48 | 0.180 |
| Simpson's Index (MLE) | 0.308±0.04 | 0.273±0.1 | 0.589 |
| Simpson's Diversity Index (MLE) | 3.297±0.47 | 4.38±2.34 | 0.589 |
| Fisher's Alpha | 8.32±2.38 | 10.64±4.36 | 0.699 |
| **Raised Bog Species** | | | |
| Shannon's Entropy (MLE) | 1.57±0.14 | 1.6±0.36 | 0.937 |
| Exponential of Shannon Entropy (BC-MLE) | 5.38±0.96 | 6.53±3.21 | 0.699 |
| Simpson's Index (MLE) | 0.36±0.05 | 0.356±0.1 | 0.818 |
| Simpson's Diversity Index (MLE) | 2.8±0.36 | 3.1±1.4 | 0.818 |
| Fisher's Alpha | 4.76±0.87 | 5.7±2.2 | 0.485 |
| **Raised Bog Species without *L. porphyrea*** | | | |
| Shannon's Entropy (MLE) | 2.07±0.289 | 2.25±.33 | 0.485 |
| Exponential of Shannon Entropy (BC-MLE) | 10.34±3.56 | 13.74±4.35 | 0.310 |
| Simpson's Index (MLE) | 0.20±0.08 | 0.15±0.05 | 0.310 |
| Simpson's Diversity Index (MLE) | 5.71±2.54 | 7.26±2.62 | 0.310 |
| Fisher's Alpha | 6.7±1.68 | 8.8±3.06 | 0.180 |
| **Raised Bog heather feeders only** | | | |
| Shannon's Entropy (MLE) | 0.76±.18 | 0.91±0.33 | 0.589 |
| Exponential of Shannon's Entropy (BC-MLE) | 2.32±0.44 | 2.89±1.11 | 0.394 |
| Simpson's Index (MLE) | 0.68±0.09 | 0.61±0.14 | 0.485 |
| Simpson's Diversity Index (MLE) | 1.48±0.19 | 1.73±0.43 | 0.485 |
| Fisher's Alpha | 2.15±0.59 | 2.41±1.02 | 0.818 |
| **Raised bog non-heather feeders only** | | | |
| Shannon's Entropy (MLE) | 1.46±0.33 | 1.62±0.36 | 0.394 |
| Exponential of Shannon's Entropy (BC-MLE) | 5.39±2.04 | 7.07±2.16 | 0.132 |
| Simpson's Index (MLE) | 0.33±0.12 | 0.27±0.1 | 0.485 |
| Simpson's Diversity Index (MLE) | 3.47±1.41 | 4.02±1.23 | 0.485 |
| Fisher's Alpha | 3.15±1.14 | 4.37±1.53 | 0.132 |

*MLE: Maximum likelihood estimator; ** BC-MLE: Bias Corrected Maximum likelihood estimator.

### 3.6 Cluster Analysis

The dendrogram was cut at 25% information remaining. Three groups were formed; Sharavogue, Raheenmore, Old Croghan, Clara and Clonaltra formed one group, Mongan, Moyclare, Ferbane, Doon, Curraghalassa and Clonlyon Glebe formed the second group while Kilballyskea was the sole member of the third group. The bogs were coded for group membership into two groups of six bogs each. Group 1 was sampled mostly on the same date, while Group 2 was sampled on the day before or after. As can be seen in Figure 3.6, bogs separated neatly in these groups, which indicates that date of sampling had an overriding effect on all sampled sites apart from Kilballyskea. These groupings were tested using MRPP and was found to be significant (A = 0.074, $P$ = 0.026). Permanova was carried out using raw species data and grouping the stands (N=12) by the date on which sampling took place. This resulted in an F of 2.7446 and $P$ = 0.0372.

Due to the impact of sample date on the 2011 data, species presence-absence was used in further analysis.

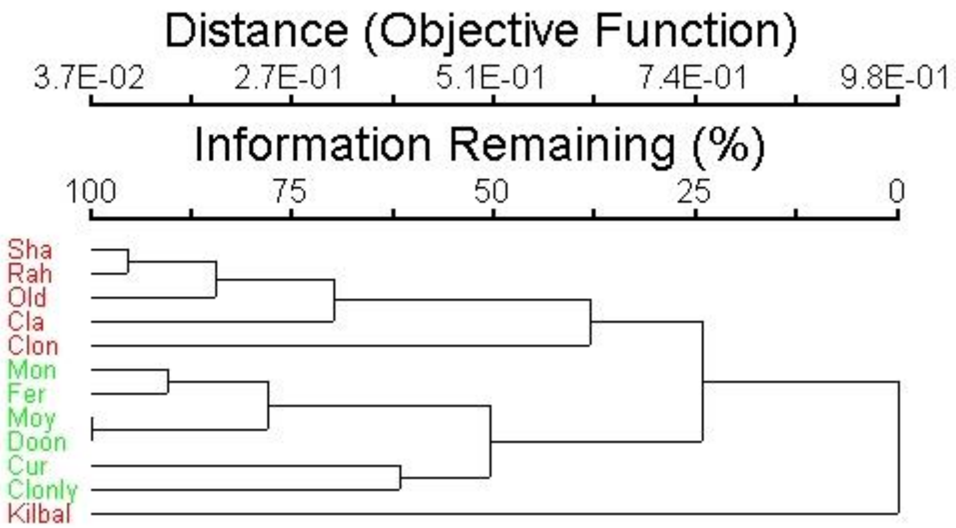


**Figure 3.6 Cluster analysis grouped by sample date.**
Percentage chaining = 27.27% caused by outlier Kilballyskea.

Kiballyskea, an outlier, was removed and cluster analysis was repeated using presence-absence data and coding into two groups (designated and undesignated). Bogs separated into three groups at 25% of information remaining (Figure 3.7) These groupings were tested using MRPP using presence-absence data and was found to be significant (A = 0.153, $P$ = 0.0005).

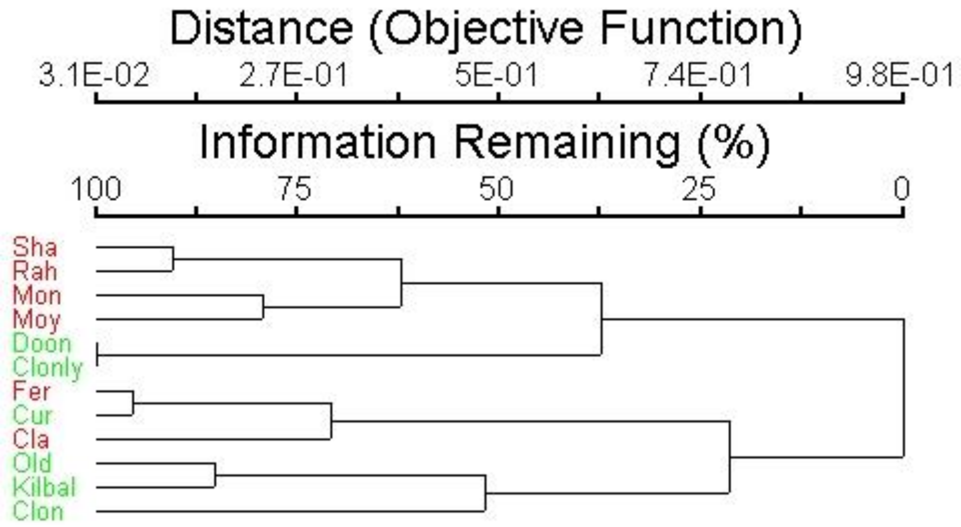


**Figure 3.7 Cluster analysis grouped by bog type.**
Designated bog = red / Undesignated bog = green. Percent chaining = 0.00

Cluster analysis was repeated using presence-absence and coding into two groups (designated and undesignated) without Kilballyskea Bog. Bogs separated into two groups at 30% of information remaining (Figure 3.8). These groupings were tested using MRPP and was found to be significant (A = 0.0889, $P$ = 0.002).

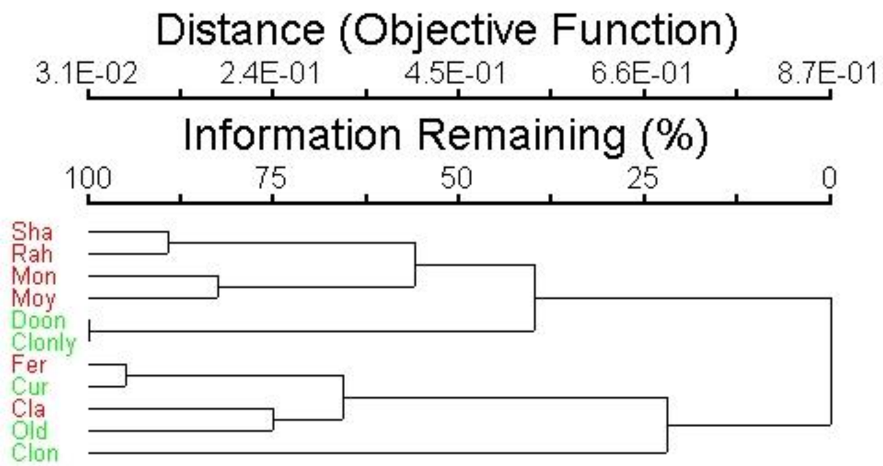


**Figure 3.8 Cluster analysis grouped by bog type without Kilballyskea**
Designated bog = red / Undesignated bog = green. Percent chaining = 3.85

Cluster analysis indicated that Ferbane and Clara grouped with the undesignated bogs, while Doon and Clonlyon grouped with the designated bogs. In order to investigate this further, indicator species analysis was carried out. *Pharmacis fusconebulosa* (DeG.) found to be a significant indicator of Group 2 (observed Indicator Value = 0.845, *P* = 0.0158). This species was found on four of the undesignated bogs and also Ferbane Bog (N=1) and Clara Bog (N=2). Its larval food plant is the roots of bracken, but it has been found on the roots of red fescue and probably also uses the roots of broadleaved herbs (Waring and Townsend, 2009). As it is a significant indicator of Group 2 which mainly contains undesignated sites and it has only been found on designated sites as singletons or doubletons, the species was considered to have been miscatagorised as a raised bog species and was therefore removed and the analysis was repeated.

This did not lead to a major change except that Clonaltra separated out sooner. Bogs separated into three groups at 40% of information remaining (Figure 3.9). These groupings (Group 1 = Sharavogue, Raheenmore, Mongan and Moyclare, Group 2 = Ferbane, Curraghalassa, Clara and Old Croghan, Group 3 = Doon and Clonlyon) were tested using MRPP and was found to be significant (A = 0.182589, *P* = 0.0002).

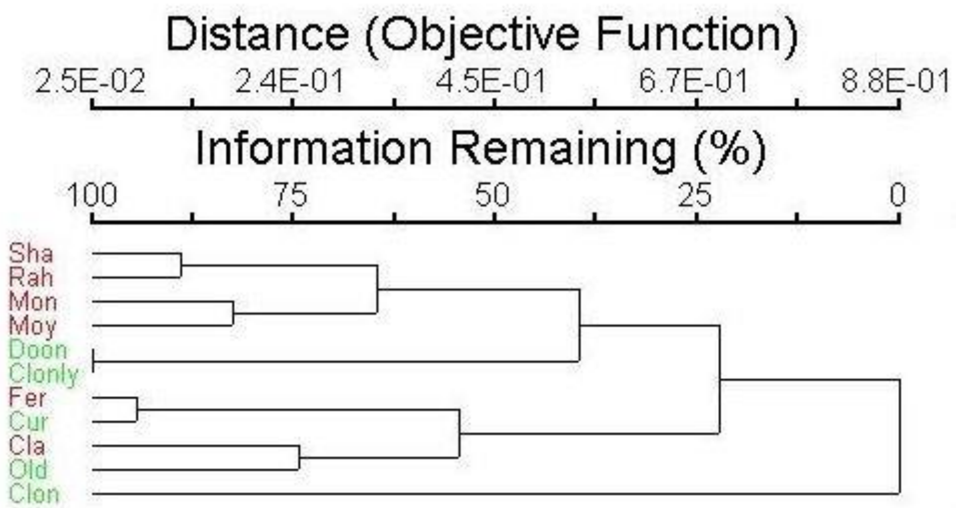


**Figure 3.9 Cluster analysis grouped by bog type after removal of *Pharmacis fusconebulosa* (DeG.).**

## 3.7 Ordination

NMS ordination explained a cumulative 86% ($r^2$ = 0.863) of the variation in the moth species presence-absence data, with three major gradients capturing most of the variances in the communities (Table 3.6); Axis 1 accounting for 42.7% ($r^2$ = 0.427) and Axis 2, 24.3% ($r^2$ = 0.243) and Axis 3, 19.3% ($r^2$ = 0.193).

The designated and undesignated bogs do not cluster together, but rather form a continuum mainly from undesignated to designated bog from the positive to the negative side of Axis 2. However, Old Croghan, an undesignated bog seems more aligned with the designated bogs on this axis while Ferbane bog appears to align with the undesignated bogs as an outlier from the rest of the designated bogs (Figure 3.10). Clonaltra and Kilballyskea seem to be outliers from the rest of the bogs on the negative side of Axis 1.

**Table 3.6 Stress in relation to dimensionality (number of axes).**

| | Stress in real data 250 runs | | | Stress in randomized data Monte Carlo test, 250 runs | | | |
|---|---|---|---|---|---|---|---|
| **Axes** | **Minimum** | **Mean** | **Maximum** | **Minimum** | **Mean** | **Maximum** | **P*** |
| 3 | 6.194 | 7.487 | 24.227 | 6.249 | 10.166 | 23.117 | **0.0040** |

*p = proportion of randomized runs with stress < or = observed stress i.e., If *n* is the number of randomized runs with a final stress less than or equal to the observed minimum stress and N is the number of randomized runs, then p = (1+*n*)/(1+N) or p = (1 + no. permutations <= observed)/(1 + no. permutations)

### Explanatory variables

Of the 25 explanatory variables investigated (Appendix H), only six showed a strong ($r^2$ cutoff value = 0.300) correlation with Axis 1 or 2 (Table 3.7). These were displayed using joint plots (Figure 3.10).

The positive side of Axis 1 ($r^2$ = 0.427) is strongly correlated with lichen feeding species and abundance as well as total abundance. The negative side of Axis 1, is correlated with drain density. Axis 2 separated by drain density, fragment shape and conifer feeding species, even though conifer feeding species were excluded from the matrix on which the ordination was based. Axis 2 separated by distance of the trapping site from the edge of the bog on the negative side of this axis.

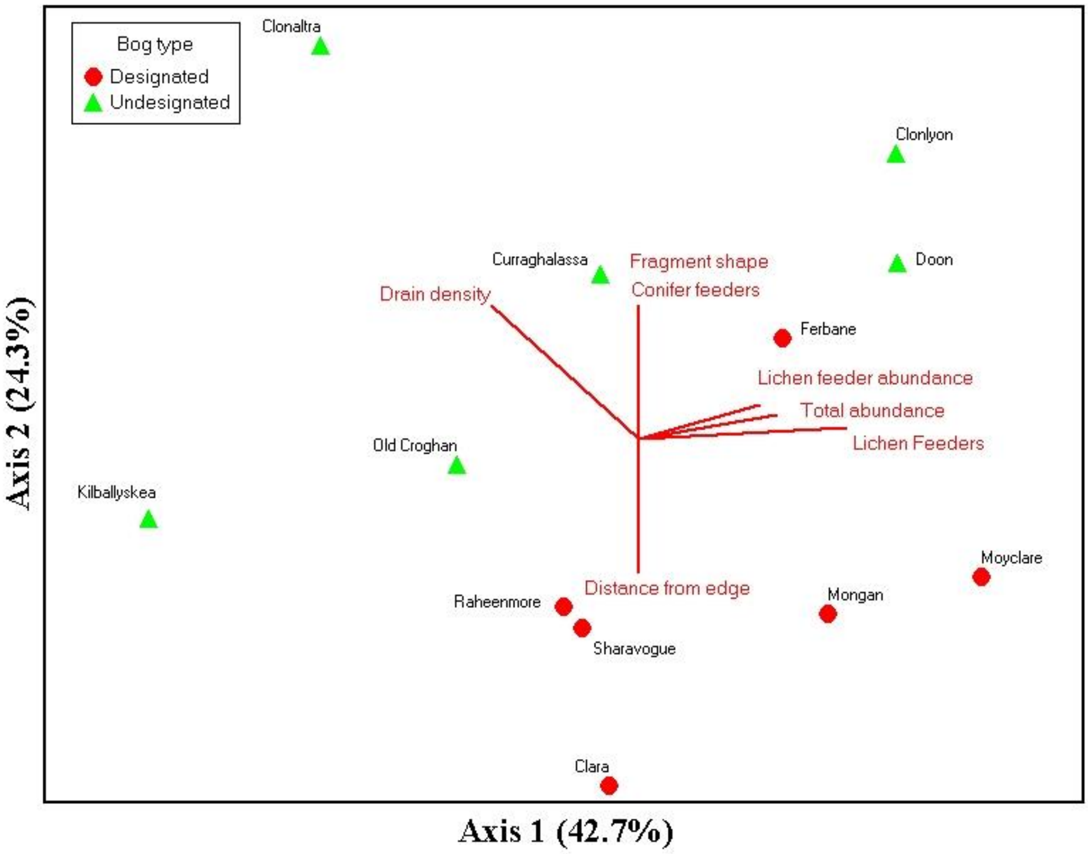


**Figure 3.10 NMS ordination with explanatory variables as vectors.**
Cutoff $r^2$ value = 0.300; Axis 1 $r^2$ = 0.427; Axis 2 $r^2$ = 0.243; Final stress = 6.194; Final instability = 0; Species data = presence-absence; Joint plot showing the relationship of responses to ordination axes. Vector lengths are relative to the correlation coefficients for each variable.

**Table 3.7 Explanatory variables correlation with NMS ordination axes.**
Axis 2 $r^2$ values > 0.2 are in bold

| Axes | 1 | | 2 | |
|---|---|---|---|---|
| Variables | r | $r^2$ | r | $r^2$ |
| Drain density | -0.595 | 0.354 | 0.567 | **0.322** |
| Fragment shape | 0.014 | 0.000 | 0.565 | **0.320** |
| Conifer feeders | 0.031 | 0.001 | 0.562 | **0.315** |
| Lichen feeder abundance | 0.539 | 0.291 | 0.284 | 0.081 |
| Total abundance | 0.576 | 0.332 | 0.243 | 0.059 |
| Lichen feeders | 0.707 | 0.499 | 0.170 | 0.029 |
| Distance from edge | -0.006 | 0.000 | -0.566 | 0.321 |

The Main Matrix (37 species, presence-absence data) was next overlain on the graph of the ordination scores to investigate how each response related to the resulting pattern.

On Axis 1 the four species which had the greatest positive influence were *Eilema lurideola* (Zin.), *A. caja, Mythimna (Mythimna) impura* (Hb.) and *D. fagaria* (Table 3.8, Figure 3.11). The species with the strongest negative influence on Axis 1 scores were *Alcis repandata* (L.) and *Phlogophora meticulosa* (L.). Three species had a strong positive influence on the Axis 2; *S. interrogationis*, *Idaea aversata* (L.), *Eupithecia nanata* (Prout) and *Eugnorisma* (*Eugnorisma) glareosa* (Esp.). Three species had a strong negative influence on Axis 2 scores; *Selidosema brunnearia* (Vill.), *M. rubi* and *A. menyanthidis*. This side of Axis 2 is associated with designated raised bogs and therefore, these species are of interest as potential indicators. However, the orientation of *M. rubi* to this axis may be a sampling artefact as it is considered a widespread species (Tyner, 2014a) and sampling did not cover its peak flight season (May-June). The occurance (presence-absence) of *A. menyanthidis* showed a significant correlation with the largest areas of central ecotope on Mongan and Clara Bogs (*P = 0.01*; Pearson correlation = 0.824) and its orientation towards designated sites with the largest areas of this ecotope agrees with this. *S. brunnearia* did not show any correlation with this ecotope.

**Table 3.8 Species variables correlation with NMS ordination axes.**
Axis 2 $r^2$ values > 0.2 are in bold

| Axes | 1 | | 2 | |
|---|---|---|---|---|
| Variables | r | $r^2$ | r | $r^2$ |
| *Selidosema brunnearia* (Vill.) | 0.313 | 0.098 | -0.686 | **0.470** |
| *Macrothylacia rubi* (L.) | 0.293 | 0.086 | -0.555 | **0.308** |
| *Acronicta menyanthidis* (Esp.) | 0.148 | 0.022 | -0.547 | **0.299** |
| *Phlogophora meticulosa* (L.) | -0.592 | 0.350 | -0.384 | 0.148 |
| *Arctia caja* (L.) | 0.708 | 0.502 | -0.132 | 0.017 |
| *Syngrapha interrogationis* (L.) | -0.079 | 0.006 | 0.762 | **0.580** |
| *Idaea aversata* (L.) | 0.158 | 0.025 | 0.746 | **0.556** |
| *Eupithecia nanata* (Prout) | -0.190 | 0.036 | 0.588 | **0.346** |
| *Eugnorisma (Eugnorisma) glareosa* (Esp.) | -0.332 | 0.110 | 0.586 | **0.343** |
| *Alcis repandata* (L.) | -0.793 | 0.629 | 0.260 | 0.067 |
| *Eilema lurideola* (Zin.) | 0.771 | 0.595 | 0.179 | 0.032 |
| *Mythimna (mythimna) impura* (Hb.) | 0.647 | 0.419 | 0.115 | 0.013 |
| *Dyscia fagaria* (Thun.) | 0.615 | 0.378 | 0.113 | 0.013 |

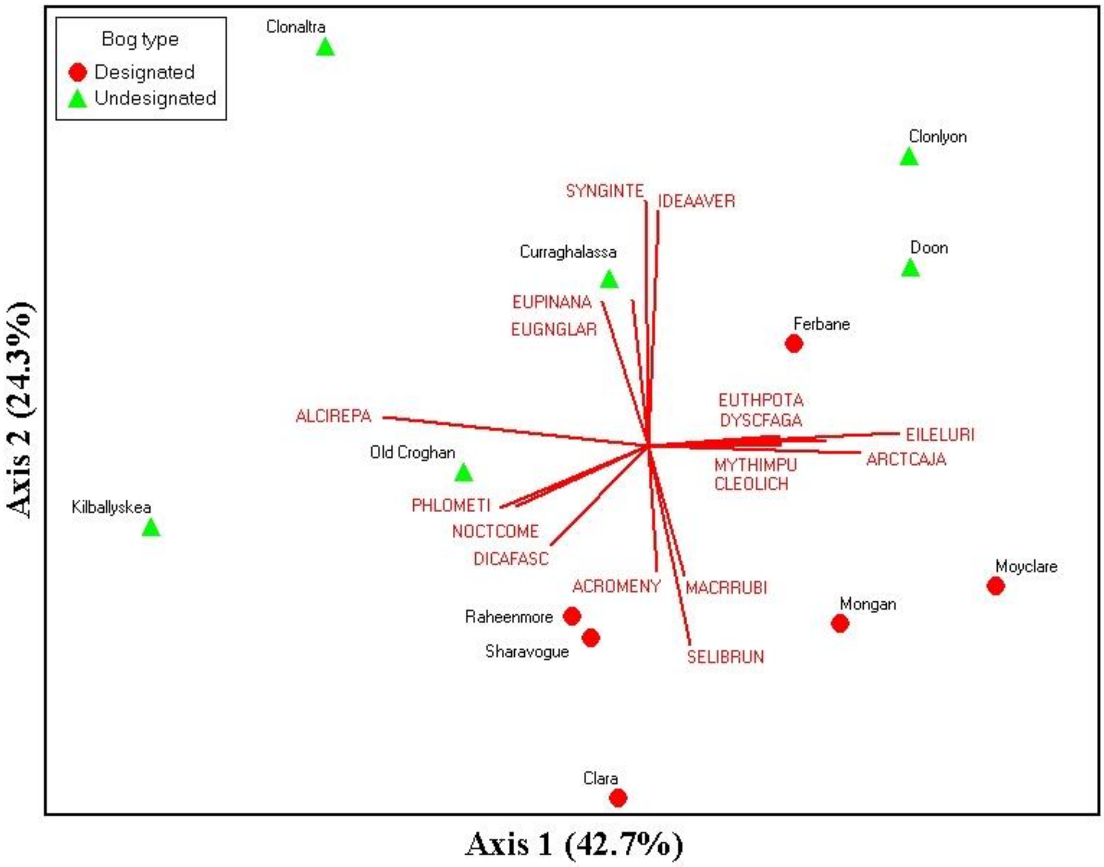


**Figure 3.11 NMS ordination with species presence-absence shown as vectors.** Cutoff $r^2$ value = 0.299; Vector lengths are relative to the correlation coefficients for each variable; Axis 1 $r^2$ = 0.427; Axis 2 $r^2$ = 0.243; Final stress = 6.194; Final instability = 0; Species data = presence-absence. Moth species have been nominated using an abbreviated form of their name. This is formed by taking the first five letters of the genus and the first five of the species names and putting them together. In Appendix 1 a list of these abbreviated forms may be found beside the full name and authority, family and conservation status.

### 3.8 Multi-response Permutation Procedure (MRPP)

Multi-response Permutation Procedure (MRPP) was used to test for difference between groups as defined by designation status with 6 sites in each group and using presence-absence data for 47 species. Chance-corrected within-group agreement, A was 0.04407200, Test statistic T was -1.9371922 and $P$ = 0.038. While the within-group agreement A was low, the difference between observed and expected delta was significant. Therefore, groups were significantly different from each other even though within group homogeneity was low. Indicator species analysis was carried out but no statistically significant indicator species of designated or undesignated bogs were found.

### 3.9 Nestedness

The matrix nestedness value was significantly lower than the mean score for the randomized matrix (Figure 3.12, Table 3.9). Therefore, moth fauna of species-poor raised bogs are statistically significant subsets of more species rich sites (Index value = 50.239, Z score = 2.828, $P < 0.01$). Relative nestedness (RN) is a measure of nestedness corrected for matrix size and fill. RN was 0.17.

Spearman's rank-order correlation was performed to investigate linear correlation between environmental variables and nestedness order. There were no significant correlation between nestedness order and drain density, drain length, habitat connectivity, bog area, bog perimeter length, bog fragment shape or elevation. However, species richness appears to show a quadratic relationship with sites of increasing drain density. This relationship approached significance ($P$ = 0.097) (Fig. 3.13).

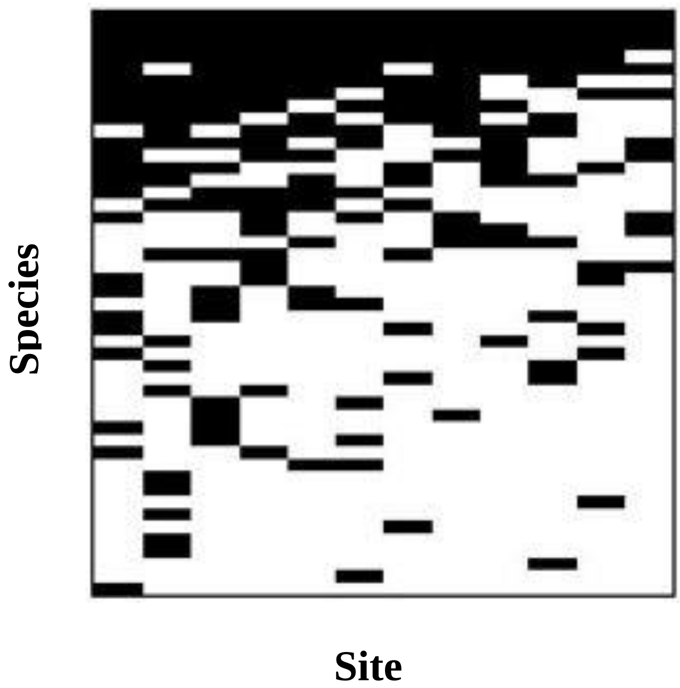


**Figure 3.12 Nestedness matrix of species x sites.**
Rows = 47, Columns = 12, Occurrences = 199, Fill = 0.353, Filled squares represent species presence. The matrix has been sorted to maximize nestedness.

**Table 3.9 Order of sites in packed matrix columns.**
Sites in packed columns in order of decreasing nestedness and raised bog species richness (Original column order = 1-12, where 1-6 = designated sites and 7-12 = undesignated sites). Status; Designated site = 1, Undesignated site = 2.

| **Site** | **9** | **10** | **3** | **7** | **2** | **5** | **11** | **1** | **6** | **4** | **8** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Status** | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 2 |
| **$S_{obs}$** | 23 | 22 | 21 | 20 | 17 | 16 | 15 | 15 | 14 | 14 | 12 | 10 |
| **Code** | Cur | Doon | Fer | Old | Mon | Cla | Clonly | Sha | Rah | Moy | Clon | Kilbal |

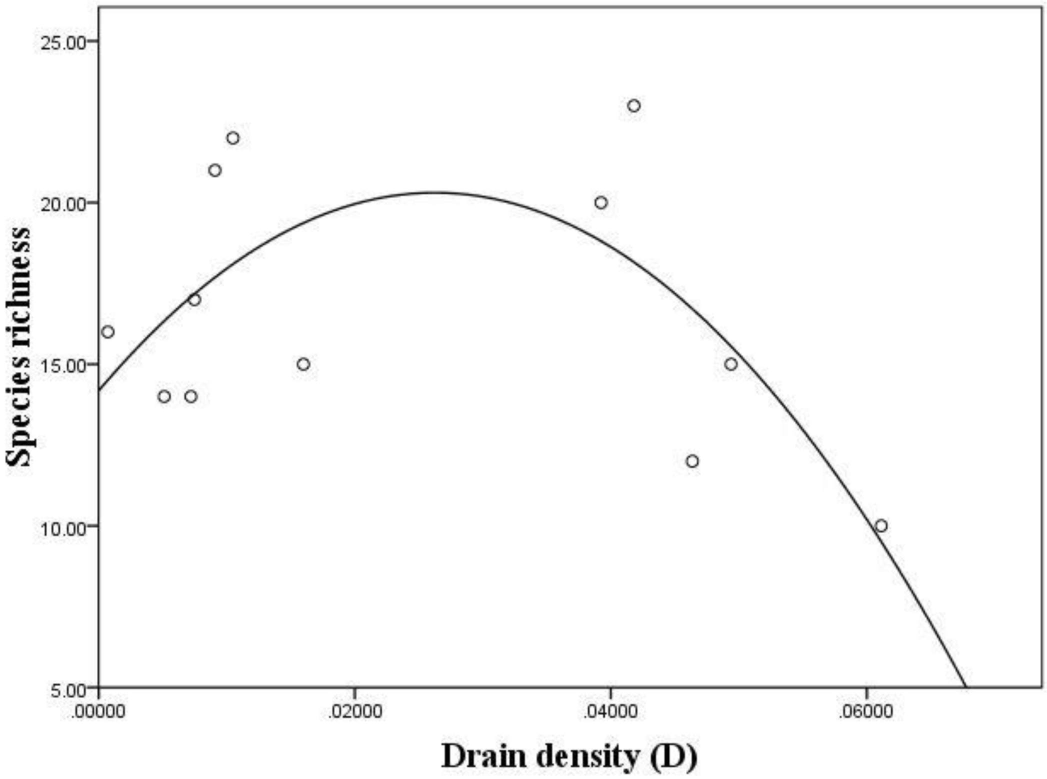


**Figure 3.13 Quadratic relationship between drain density and species richness.**
F = 3.054, $P$ = 0.097, $r^2$ = 0.404, Parameter estimates: constant = 14.184, b1 = 466.36, b2 = -8881.158, Custom equation: Species richness = 14.184 + 466.36*[Drain density] – 8881.158*[Species richness]$^2$.

# 4 Discussion

"*For a comprehensive understanding of biodiversity, including its importance in conservation and ecosystem management, it is important that erroneous assessments are avoided along the whole chain of evidence – from choice of taxon, sampling site and sampling technique, to assurance of quality in taxonomy (Bortolus, 2008), to an unbiased measurement of diversity and a sound interpretation of what can be inferred from it*" (Beck and Schwanghart, 2010).

The present study is the first landscape scale study of its kind conducted in Ireland. It is also the first study to evaluate the biodiversity indicator value of a raised bog associated nocturnal macro-moth assemblage. Ordination showed that two species could have potential as active raised bog biodiversity indicators. One species (*Acronicta menyanthidis* (Esp.)) was significantly correlated with central ecotope ($P$ = 0.01). Biodiversity measures showed that assemblages found on designated and undesignated sites were broadly similar which was supported by nestedness analysis. Difference between groups as defined by designated status was significant ($P$ = 0.038), suggesting that species composition varies, but within group homogeneity was low and no significant group indicator species were found.

The influence of date of sampling on the dataset was discovered through cluster analysis, which highlights a potential weaknesses in the light trapping sampling technique discussed below. Indicator species analysis resulted in a refinement of the raised bog associated species list. The NPWS raised bog habitat monitoring reports and maps (Kelly *et al.*, 1995a,b, Fernandez *et al.*, 2005a,b, Fernandez *et al.*, 2012a,b, Fernandez *et al.,* in prep.) were of great assistance in identifying designated site ecotopes and raised bog flora, which was the basis of the identification of raised bog associated species. Species identification was facilitated through the availability of an excellent field guide (Waring and Townsend, 2009).

While 47 raised bog associated species were recorded in 2011, preliminary sampling, supported by estimated species richness (Chao 2), suggests that there are approximately 62 raised bog associated species. Degraded midland raised bogs harbour an associated moth fauna which is broadly similar to that found in the more pristine areas of designated sites. No significant differences were found when bog types were compared by abundant species, species of conservation concern, observed and estimated species richness or diversity. The only species to be correlated with a bog type was *Eupithecia nanata* (Hb.) which was associated with undesignated bogs at a level approaching significance ($P$ = 0.065). Its larval stages feed on the flowers of *Calluna vulgaris* (Waring and Townsend, 2009). This plant has been noted to flower abundantly under conditions of greater soil aeration in degraded bog areas (Kelly and Schouten, 2002) and provides an explanation for the alignment of this species with degraded sites.

Bogs showed a significant nested structure in terms of raised bog associated moth assemblage, common in fragmented habitats (Fleishman and Murphy, 1999, Schouten *et al.*, 2007), whereby species-poor sites form a nested subset of species-rich sites. Surprisingly, the two most species-rich and species-poor sites in terms of raised bog associated species were undesignated degraded sites. Greater species richness may have been recorded on designated sites if sampling had taken place in drier, usually marginal, areas. Ferbane Bog, where sampling took place in such an area, was the most species-rich of all designated sites. This finding agrees with Bezděk *et al.* (2006), that not all characteristic moth species appear to favour the central areas of raised bogs. Ferbane Bog had fewer associated species than the two most speciose undesignated sites.

It is proposed that the Intermediate Disturbance Hypothesis (IDH) (Connell, 1978) which predicts higher species richness in sites with intermediate levels of heterogeneity and/or disturbance is a possible explanation for this finding. It has been proposed as an explanation of diversity patterns for multiple wetland arthropod taxa (Ward and Stanford, 1983, Townsend *et al.*, 1997, Whiles and Goldowitz, 2001, Sada *et al.*, 2005, Savage *et al.*, 2011). A quadratic relationship between species richness and drain density approached significance ($P$ = 0.097).

Relative abundance of species was not evenly distributed among species. This could be an artefact of sampling as three of the four most abundant species are from the noctuid family which are very strong fliers and may have been over-represented in the sampling range compared to weaker fliers, but also could be a natural trait of raised bog invertebrate communities. Savage *et al.* (2011), in a study of Diptera on temperate Nearctic bogs also found that a small number of species dominated and found bog specialists at very low abundance. More even communities are considered to be more stable in ecology based on the assumption that individuals are more evenly distributed among all the species in a pristine community but disturbed communities are dominated by a few very abundant species. However, in some naturally species-poor habitats such as bogs, a low evenness value may not equate to a 'less natural' system (Drake *et al.*, 2007).

*Lycophotia porphyria* (D&S) was the most abundant moth at all sites sampled. A number of raised bog studies refer to this species being present in very large numbers on raised bogs (Bond, 1989, Dapkus, 2001, Dapkus, 2004a, Dapkus, 2004d). Webb (1986) noted that this species is very abundant on heathland, where catches from a single night's trapping may exceed over a thousand individuals. Its larval food plant is *Calluna vulgaris* and it has been suggested as an indicator species of bog desiccation and succession (Dapkus, 2004a). However, this study shows that this species may dominate even in the wettest areas of the most pristine sites and therefore for Irish raised bogs at least, does not appear to be of value as a negative indicator.

As found in previous peatland studies (Bond, 1984, van Swaay *et al.*, 2006, Williams *et al.*, 2014), the findings of this study would suggest that midland raised bogs may harbour proportionally more moths of conservation concern than other habitats. It is noteworthy that some of the undesignated degraded sites hold species which are considered rare or scarce. Williams *et al.* (2014) related a similar finding to the need for disturbed areas such as basking areas and thermal properties of vegetation structures on undesignated peatland sites. Raised bog, both designated and undesignated, may also be neorefugium (Nekola, 1999, Devictor *et al.*, 2007) for species like *Arctia caja* (L.) which is declining sharply in the wider countryside (Conrad *et al.*, 2002) but which is one of the more abundant species found in this study.

Bog area or isolation were found not to be significantly related to change in assemblage composition across sites as revealed by ordination. Although this is contrary to the expectations of the theory of island biogeography (MacArthur and Wilson, 1967), Savage *et al.* (2011) also found that bog size had no influence on species richness or diversity in a study of Neartic bog dipteran fauna. It has been found in studies on *Coenympha tullia* (L.) that the probability of site occupancy depends as much on the quality of resources within the habitats as on site geography (i.e. habitat area and isolation) (Dennis and Eales, 1997, 1999).

It has been suggested that the species-area relationship is stronger for habitat specialists than for generalists (Harrison and Bruna, 1999). Some stenotopic species were found at such low abundances that this relationship may not have become apparent. Another reason could be that taxa which require large areas of intact bog may already have disappeared from the midlands. For example, *Carsia sororiata* (Hb.), a possible cold-stage relict with an arctic-alpine distribution (Ford, 1954) which feeds on *Vaccinium vitis-idaea* (L.) and *V. myrtillus* (L.) (Waring and Townsend, 2009), was previously recorded on raised bogs in Offaly (Thompson and Nelson, 2008) but was not recorded during this study. Lozan *et al.* (2012) reported the disappearance of the tyrphobiontic butterfly *Colias palaeno* (L.) and noctuid moth *Anarta cordigera* (Thun.) about 20 years ago on Červené Blato Bog (Southern Bohemia, Czech Republic).

Ordination showed the directional shift in assemblage composition associated with the designation status was found to be related (Pearson's r = -0.566) to distance from the edge of the bog. Slade *et al.* (2013) found that 'distance to the edge' was the most important predictor of the abundance of moth species with a strong forest affinity, suggesting that species found to be associated with designated bogs are particularly stenotopic. *Acronicta menyanthidis* (Esp.) (r = -0.547) and *Selidosema brunnearia* (Vill.) (r = -0.686) were correlated with designated raised bogs indicating that these species could be associated with active raised bog habitat. *Acronicta menyanthidis* is considered a tyrphobiont in Europe (Dapkus, 2000, Spitzer and Danks, 2006). One of its larval foodplants is *Menyanthes trifoliata*, a common species of bog pools, whose presence indicates very wet conditions (Kelly and Schouten, 2002). The occurance of *A. menyanthidis* showed a significant correlation with the largest areas of central ecotope (Mongan and Clara Bogs) ($P$ = 0.01; Pearson correlation = 0.824). *Selidosema brunnearia* showed no correlation with central ecotope. That its foodplant is *Calluna vulgaris* (Waring and Townsend, 2009) is suggestive of a wide distribution not found in Northern Ireland, where it shows a restricted distribution despite the availability of large areas of apparently suitable habitat (NIEA, 2010). The reason for the restricted distribution of *S. brunnearia* merits further study, as it shows potential as an active raised bog indicator species.

Directional shifts towards undesignated bogs was related to complex fragment shape (r = 0.565). A number of studies have reported woodland moth species richness as being significantly related to fragment shape with greater species richness found in woodlands with a compact shape than in woodlands with more complex or elongated shapes (Usher and Keiller, 1998, Fuentes-Montemayor *et al.*, 2012). Usher and Keiller (1998) found that only 'woodland' and geometrid species richness was significantly related to woodland shape. This suggests that species associated with undesignated raised bogs which have more complex shapes may be less stenotopic than species found in bogs with more compact shapes.

Drainage density (r = -0.595) was associated with disturbed and less species-rich undesignated bogs. Increased drainage is associated with deterioration and loss of raised bog habitat (Fernandez *et al.*, 2005a). The impact of drainage is likely to be greater on the true midland sub-type, which has less humified and more permeable peat, than on the western sub-type (Cross, 1990). Surface drainage damages and destroys the acrotelm and the peat-forming *Sphagnum*-dominated vegetation. Plant community distribution is primarily determined by hydrological factors (Ivanov, 1981), which in turn is likely to influence phytophagous insect species distribution.

The positive side of Axis 1 was associated with the lichen feeding species richness and abundance. It is tentatively suggested that bogs at this side of the axis may display populations which have not been impacted by fire. On heathlands in Scotland, fire return intervals shorter than 15-20 years have been found to likely lead to a decline in lichen diversity (Davies and Legg, 2008). Lichens have been used as *a priori* indicators of fire history and Fernandez *et al.* (2005b) linked areas of high *Cladonia* cover to the absence of burning. This possible link merits further study.

Light trap catches are known to vary markedly from one night to the next in part due to changes in meteorological and astronomical conditions (Williams, 1937, Nemec, 1971, Morton *et al.*, 1981, Bowden, 1982, Tucker, 1983, Thomas, 1996) and are a form of sampling error in studies of absolute abundance (Holyoak *et al.*, 1997). The present study shows, even when an attempt to trap on consecutive nights with similar weather conditions is made, differences in moth activity can mask underlying true abundance differences and therefore rule out any analysis which relies on abundance counts. It is recommended that in future sampling is exactly temporally aligned.

The use of kill traps and solar charged batteries should be investigated as this would lessen the amount of time necessary to inspect traps every morning and allow traps to be inspected every couple of days, allowing more traps to be deployed at the same time. However, secure storage of moths in the field is problematic as the adult stage cannot be stored in commonly used preservatives. Traps would also have to be secured from animal disturbance.

Sampling moths by light trapping has potential for larger landscape scale investigations but may not be suitable on its own for fine grain studies of ecological gradients (Bezděk *et al.*, 2006) on designated bogs. In such cases, better ecological results are usually obtained if larval stages of selected species are intensively studied at habitat and microhabitat level (Spitzer *et al.*, 2003, Dover and Settele, 2009, Pennekamp *et al.*, 2013). For example, *A. myrtilli*, a species maximally associated with raised bog (Bond and Gittings, 2008) and suggested Irish tyrphobiont (Bond, 1989), is a day-flying species but there is a reference in Lorimer (1979) which quotes Bretherton (1974) that a night flight is recorded occasionally. Its flight season in Britain is from April to October (Bond and Gittings, 2008) and therefore would have been expected to be recorded in the present study. However, in three years of sampling, this species was only recorded on one night (23/06/09) at four designated raised bog sites which ties in with Bretherton's observation. It is clear that alternative methods are needed to sample this important raised bog species.

The present study shows that defining an associated assemblage is possible in botanically uniform, low diversity and well surveyed climax habitat such as raised bog and can successfully overcome the problems associated with trapping vagrants and non-associated species commonly referred to in relation to light trapping (New, 1997). Using an assemblage to reveal differences between sites when sampling using this technique may be more appropriate than focusing on maximally associated species or tyrphobionts which are recorded at low abundance levels.

This study has revealed two potential indicators of active raised bog and one potential indicator of central ecotope. As this habitat is under threat, further investigation of other potential indicator species and groups should be encouraged, focusing on a greater number of sites with large areas of central ecotope.

Persistance of species can be divided into the concepts of resilience and redundancy (Shaffer and Stein, 2000). The number of sites on which a species occur may be seen as a measure of redundancy, thereby saving enough populations so that some could be lost without loss of the species. Given the broad similarity in moth fauna, even small remaining fragments of intact bog may be important to conserve in order to maintain redundancy into the future, particularly in light of the threat of climate change. Even bogs that are botanically and abiotically defined as "degraded" harbour moth species of conservation concern.

An assessment of the biodiversity of intact raised bog fragments and the ecosystem services this wetland ecosystem type provides should be undertaken in line with Ireland's obligation under Action 5 of the EU Biodiversity Strategy (European Commission, 2011, 2013). Analysis of alternative uses such as peat extraction should be included in this assessment (Bullock *et al.*, 2012). The National Raised Bog SAC Management Plan (DAHG, 2014) and the National Peatlands Strategy (NPWS, 2014) are currently being developed to give direction to Ireland's approach to peatland management, including bog conservation and restoration, over the coming decades and is another opportunity to include research, restoration and management measures to benefit the raised bog invertebrate fauna.

The present study has outlined a group of 62 raised bog associated species (Appendix E). It is hoped that this preliminary list will be added to and revised in future years. For example, efforts should be made to establish whether *C. sororiata* has become locally extinct. Along with the Database of Irish Lepidoptera (Bond and Gittings, 2008), it is suggested that the list of raised bog associated species could be used by field workers to assess the biodiversity maintenance function of active and degraded raised bog habitat, with sites hosting many of these species being in better condition than those hosting few. The presence of *A. menyanthidis* and *S. brunnearia* would be of particular significance given their conservation status and also their alignment with active raised bog habitat. High lichen feeding species richness could indicate that the bog has not been burnt for many years.

# 5 Conclusion

Sampling moths using light traps revealed two potential indicators of active raised bog habitat and only one (*A. menyanthidis)* potential indicator of central ecotope.

Therefore, a multi-taxa or 'shopping basket' approach (Di Castri *et al.*, 1992, Hammond, 1994, Vane-Wright *et al.*, 1994, Kotze and Samways, 1999, Ricketts *et al.*, 1999, Dormann *et al.*, 2007, Haslett, 2007) to invertebrate biodiversity indicators of active raised bog biodiversity is recommended. A number of functional groups, incorporating species with an aquatic life stage and an association with *Sphagnum* mosses should be assessed. Undesignated intact raised bog fragments appear to harbour significant moth biodiversity and should be included in any assessment of potential indicator species.

Species show a nested pattern among sites. Species richness appears to peak at intermediate levels of disturbance with drain density suggested as a possible driver. Due to the nested nature of raised bog species richness, independent of designated status and the location of species of conservation concern on undesignated sites, midland raised bog biodiversity conservation policy should be focused at a landscape level as well as on designated sites.

In short, the findings of this study suggest that further research on potential raised bog biodiversity indicator species should take place at a landscape scale and not just focus on designated sites and should include a suite of carefully selected species or groups. Raised bogs which are thought of as botanically degraded may still harbour invertebrates of conservation concern and a relatively high species richness. This should be investigated further and the ecosystem services provided by such sites should be weighed against other uses of these sites such as peat extraction.

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# Appendices

## Appendix A Site Descriptions

### Designated Bogs

<u>Sharavogue (Site Code 000585)</u>

Sharavogue bog (53°02’15”N, 7°55’44”W) is 137.01ha in area and lies 5km south of Birr, County Offaly (Fernandez *et al.,* 2012b). It is situated on the eastern side of narrow river valley of the Little Brosna River. It is classified as a Ridge River B bog type, where the ridges adjacent to the bog consist of low / moderate permeability rock so the water table is higher than in a Ridge River A type bog. The hydraulic gradient from ridge to river across the bog is steeper than A and less affected by regional drainage. There tends to be a stronger upwelling of groundwater along the break in slope at the base of the ridge (Kelly *et al.*, 1995b). Sharavogue bog has an oval shape and a well-developed dome, which is relatively long and narrow.

In 1988, surface drains were constructed across the bog in preparation for commercial peat extraction but these drains were blocked between 1994 and 1999. Over a half of the original bog has been cutaway since the 1840s (Fernandez *et al.*, 2005b). The cutting was concentrated in the past on the east and north of the bog. Only four active plots were being cut in 2003 (Fernandez *et al.*, 2005b) and turf cutting has now ceased. Sharavogue Bog has been regularly burnt in the past. According to Cross (1990), the bog suffered from severe damage from burning. However, no burning has taken place within the last ten years (Fernandez *et al.*, 2012b).

<u>Mongan (Site Code 000580)</u>

Mongan Bog (53°19’40”N, 7°57’11”W) is located 2km east of the Clonmacnoise and the River Shannon in the western part of County Offaly. It is 124.37ha in area and has an approximately elliptical shape (Fernandez et al., 2012b). Although it is considered to be a midland raised bog it has flora more typical of western raised bog (Anonymous, 2005a). This bog has been classified as a Basin bog type since it is surrounded on all sides by low relief bedrock ridges (Kelly *et al.,* 2005b). Two species of micro-moth, *Biselachista serricornis* (Stain.) and *Aristotelia ericinella* (Zell.), were first recorded from Ireland from the bog (Bond, 1989). Turf cutting has now ceased and only two turf plots were reported as being actively cut in the past 10 years. Drains are infilling with regeneration of peat forming vegetation in some. The majority of the blocked drains can be classed as reduced functional.

A fire in 2010 damaged 40% of the high bog area (50ha), but not much evidence of this fire was apparent during the 2011 habitat survey indicating that it was not severe (Fernandez *et al.*, 2012b). The 2004/05 survey noted that in this complex the lichen cover was very high up to 90% in places suggesting that the site had previously not been burnt for some time. An exceptionally rich lichen flora is found on the bog in comparison with other Midland raised bogs (Anonymous, 2005a), with many of these species occurring on old ling heather (McCarthy *et al.*, 1985). Lichen species abundance has been attributed mainly to a prolonged absence of burning over many parts of the bog.

Ferbane (Site Code 000575)

Ferbane bog (53°17’01”N, 7°50’14”W) is located immediately northwest of Ferbane town in north-western Co. Offaly. It is 119.96ha in area and has been classified as a Basin Bog type since it is surrounded on all sides by low relief bedrock ridges (Kelly *et al.,* 1995b, Fernandez *et al.*, in prep.). The bog is shaped like an irregular rectangle with the longest axis orientated north-south (Fernandez *et al.,* 2005b).

This site has suffered extensive drainage and the south and east of the high bog are criss-crossed by drains most of which correspond to lines marked on the 1910 6" sheet. Some old drains have infilled and have become non-functional. Pine is invading from the north-east and south and is thought to be associated with the extensive surface drains in this area. It was noted that marginal drainage effects were significant (Kelly *et al.,* 2005b).

A small portion of this site was burned in 2010. However, there are extensive areas with a very high *Cladonia* spp. cover and significant burning has not occurred since before 1995. Turf cutting has ceased at this site.

Moyclare (Site Code 000581)

Moyclare bog (53°16’08”N, 7°53’07”W) is located approximately 4km west of the town of Ferbane. At 74.26ha, it is a small sized bog and has been classified as a Basin bog type since it is surrounded on all sides by low relief bedrock ridges (Kelly *et al.,* 2005b). A deep drain and old metalled track almost crosses the centre of the site and there is subsidence associated with this. Old drains occur in places around the edge of the bog (Kelly *et al.,* 2005b). Several active and reduced functional as well as blocked drains occur on Moyclare bog. Restoration work has been carried out at the site, resulting in the damming of many of the high bog surface drains.

There is no evidence of any burning events on the high bog since 1994/95. However, at that time recent burning was seen along the western edge into drain bA and in a large area to the south (Kelly *et al.,* 2005b). There have been no burning events in the last ten years. Turf cutting has ceased on this bog.

Clara (SAC Site Code 000572)

Clara Bog (53°19’13”N, 7°37’39”W) is situated two kilometres south of Clara, Co. Offaly. At 443ha in extent, it is one of the largest intact raised bogs in Western Europe and the largest remaining example of the True Midland sub-type (Cross, 1990, Fernandez *et al.,* 2005a, Fernandez and Wilson, 2009). In geomorphological terms, Clara can be classed as a Ridge River A type bog, where the bog formed between an esker, a ridge of glacial sand and gravel material, and the Silver River. The hydraulic gradient from ridge to river is shallow (Kelly, 1993) as the high permeability material in the esker leads to a relatively deep water-table. The bog is famous for its soak systems. A soak is richer in nutrients than the other parts of the bog, as a result of which plants characteristic of fens occur. Clara Bog is roughly oblong-shaped and stretched in an east-west direction. The Clara to Rahan road, constructed sometime between 1778 and 1809 (Crushell *et al.,* 2008), splits the bog into two shallow domes which slope towards this road (Bell, 1991). Since its construction, drainage has taken place on either side in a zone of about 250-300 metres (Schouten *et al.,* 1994) and the bog has subsided more than 8 metres along it (van der Schaaf, 2002). Clara Bog East was surface drained in 1983/84, when Bord na Móna installed approximately 150km of drains c. 0.5m deep and every 15 metres apart as the first stage of industrial peat extraction process (Kelly, 1993, Schouten *et al.,* 1994). In the 1993 and 1994, the drains were blocked with peat dams. However, the active bog on Clara East is fragmented and is still developing and recovering from the drainage system (Fernandez *et al.*, 2005b).

The bog has suffered from burning in places, particularly in the vicinity of the road and adjacent to peat cutting areas in the south-west of the site. Fire events were recorded on Clara Bog west in 2000 and 2008 (C. Malone pers. comm., 2013).

Fernandez (2006b) noted that over half (55.68%) of the original bog area has been cutaway since the 1800s with the most intense cutting having occurred to the south of the present day high bog. Turf cutting has now ceased on the site.

<u>Raheenmore (SAC Site Code 000582)</u>

Raheenmore Bog (53°20’17”N, 7°20’36”W) is situated about 5km north-west of Daingean and 12km north-east of Tullamore, Co. Offaly. It is 130.54ha in area and is a typical basin raised bog where the bog dome is surrounded on all sides by higher mineral ground. The peat reaches maximum depth of 13 metres in the south-west part of the bog (Smyth, 1992, Fernandez *et al.*, 2012b). Raheenmore has an elliptical shape, which is elongated in an east-west direction.

Raheenmore bog is surrounded almost completely by very deep drains (up to 4 metres in places). Some of these were dug as part of a Boyne Arterial Drainage Scheme carried out in 1981 (Fernandez *et al.*, 2005b) and others installed by adjoining landowners also in the early 1980’s. These drains, some of which extend into the gravel layer underlying the peat, are seriously affecting the hydrology of the bog (Kelly, 1993). Conservation works were carried out at Raheenmore Bog in the period 1994-1999 as part of a Raised Bog Restoration Project. These works involved the blocking of drains and the construction of three peat dams. Two of the peat dams at the margin of the high bog failed in 1999 and are not functioning (Anonymous, 2005b).

According to Kelly (1993) very little cutting took place on Raheenmore, except for two marginal areas to the south-east and north-west and turf has not been cut on the site for many years. The north-eastern section of the bog was burnt in the past prior to the 1992 survey (Kelly, 1993) but no burning has been recorded since this time.

## Undesignated Bogs

Kilballyskea

Kilballyskea (52°58’53”N, 7°53’51”W) is a small bog east of the village of Shinrone which lies in an isolated basin. The area of high bog is 70 hectares. It is a small domed bog which has been extensively cut away around the margin in the past but there has been no active cutting for many years. The entire bog was described as having been burned within the last 2-3 years prior to 1983. The bog was plough drained in the late 1980’s and ditch drained in the early 1990’s. The perimeter drain is very deep (4.5 metres wide and 3 metres deep) and was dug in mineral soil. This bog was assessed for designation as a Natural Heritage Area (Derwin *et al.,* 2002) but was not selected as it was found to be 100% drained. The bog is dominated by dry heath vegetation, dominated by tall ling heather (up to 1 metre tall), with a ground layer of typical heathland mosses. It is being colonised by birch and scots pine.

Doon

Doon Bog (53°19’47”N, 7°52’20”W) is located, directly north of Ferbane and east of Clonmacnoise and is a remnant high bog. It is separated from a much larger bog by the R444, which runs east – west along the southern side of the site. The bog south of the R444 has been cutover, however there has been no commercial extraction of peat to the north of the road, only some limited ditching. The east side of the site appears to form part of Doon Demesne and a townland boundary runs through the site. A segment of the Clonmacnoise esker (Mannion’s Hill), lies to the north of the bog (Tubridy and Meehan, 2006). Doon Esker Wood pNHA lies close to the site.

Curraghalassa

Curraghalassa bog (53°18’08”N, 7°53’05”W) is located approximately four kilometres east of Ferbane in Co. Offaly. It is isolated from the main Lemanaghan Bog by Ferbane-Clara Road, which passes along its northern boundary. It mainly consists of ditched high bog, surrounded by cutover bog along the south-eastern boundary and there is encroachment from private cutting around other sections. The drainage has been very effective and there is significant subsidence along the drains creating ridges in the centres of the fields and troughs along the drains. However, it has not been used for production due to an archaeological find (20 gold coins dating from 1279-1301) (Bord na Móna, 2011a). The high bog is very dry and dominated by heather. The main topographical features of this bog are two small mineral islands or mounds that both have several mature Oak and Ash (Bord na Móna, 2011a). The majority of the woodland / scrub has been damaged recently by fire. This fire has also affected the high bog south of the mineral islands and significant areas of heather have been burnt and the ground cover now has a significant portion of bare peat (Bord na Móna, 2011a).

Clonlyon

Clonlyon Bog (53°18’08”N, 7°53’05”W) is a relatively small (88ha) basin bog located north-west of Ferbane, bordering the Blackwater River. It is roughly rectangular in shape (Bord na Móna, 2011b). In 1993, it was selected as a proposed Natural Heritage Area (Site Code 893) but was delisted in 1998. The bog was originally developed for production by Bord na Móna in the late 1980s – 1990s. The bog was ditched with regular drains and some of the vegetation was removed. Other outflow drains were put into the bog. The majority of the bog has deep drains (1 – 2 m deep) while the east side has shallower drains. The majority of the site was screw-levelled, which indicates that the vegetation was cleared off the field (the production area between two drains usually 15m wide) and pushed to centre of field to create camber for drainage. The vegetation typically recolonising the high bog is dominated by heather about 10-20 cm in height. There is a relatively narrow band of undrained high bog around the margin that still has typical raised bog features not found in the central drained areas.

Industrial peat production is due to start in the near future. Domestic turf cutting occurs on peripheral areas to the south and east of the bog. Some of the cutting along the eastern side is quite intensive and there has been sausage peat cut from the surface of the high bog in places (Bord na Móna, 2011b).

Clonaltra

This site (53°18’08”N, 7°53’05”W) is known as Bellair North (Bord na Móna, 2011c). It is situated approximately six kilometres south of Moate in Co. Westmeath along the Westmeath / Offaly county border. The Athlone / Dublin railway line runs to the south of the site. Drains have been installed in the area surveyed and there is likely to have been some industrial moss peat production. It is now revegetating with mostly heather (pioneer dry heath) and some *Molinia caerulea* (L.) dominated vegetation (Bord na Móna, 2011c). Pine are colonising the pioneer dry heath and remnant intact raised bog to the west of the track, in the northern part. The western side of this section also seems to have been burnt in the past 10 years although much of the vegetation is recovering. There is some remnant or intact raised bog along the western margin.

Old Croghan

Also known as Clonearl Bog (53°20’10”N, 7°18’14”W), this is a small raised bog. It lies immediately to the southwest of Croghan Hill, a volcanic plug that constitutes the highest (234m) point in the surrounding landscape. The bog is currently being developed for peat moss extraction. Drainage ditches were inserted some 25 years ago, with drains in the southern part of the bog developed in the mid-1990s. Field drains have been placed at 10m intervals in a north-west – southeast direction, but surface vegetation, dominated now by Calluna vulgaris (L.), remains across much of the southern part of the bog (Plunkett *et al.,* 2009). In 2003, human remains, consisting of the upper torso and arms of an adult male, were discovered by a machine operative in the bucket of a mechanical excavator during the recutting of a drain in the southern part of the bog. The remains were later found to be a preserved bog body dating from the early Iron Age (Plunkett *et al.,* 2009).

## Appendix B Preliminary sampling dates

Table A.1 Preliminary sampling dates (designated sites only)

| **Date** | **Sampling Sequence** |
|---|---|
| 22/06/09 | 1 |
| 27/07/09 | 2 |
| 27/08/09 | 3 |
| 14/05/10 | 1 |
| 16/06/10 | 2 |
| 13/07/10 | 3 |
| 28/08/10 | 4 |

## Appendix C 2011 sampling dates

Table A.2 2011 sampling dates

| | 2/07 | 03/07 | 26/07 | 27/07 | 31/07 | 01/08 | 24/09 | 25/09 | 01/10 | 02/10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sharavogue** | X | | | X | X | | | X | | X |
| **Mongan** | | X | X | | | X | | X | X | |
| **Ferbane** | | X | X | | | X | X | | X | |
| **Moyclare** | | X | X | | | X | X | | X | |
| **Clara** | X | | | X | X | | | X | | X |
| **Raheenmore** | X | | | X | X | | | X | | X |
| **Old Croghan** | X | | | X | X | | | X | | X |
| **Clonaltra** | X | | | X | X | | | X | | X |
| **Curraghalassa** | | X | | X | | X | X | | X | |
| **Doon** | | X | X | | | X | X | | X | |
| **Clonlyon** | | X | X | | | X | X | | X | |
| **Kilballyskea** | X | | | X | X | | | X | | X |

## Appendix D Full authority names

Table A.3 Authority names, after Karsholt & Nieukerken (2013).

| Authority | Abbreviation |
|---|---|
| Borkhausen | Borkh. |
| Clerck | Cl. |
| Curtis | Cur. |
| DeGeer | DeG. |
| Denis & Schiffermüller | D. & S. |
| Doubleday | Doubl. |
| Duponchel | Dup. |
| Esper | Esp. |
| Fabricius | Fabr. |
| Haworth | Haw. |
| Hübner | Hb. |
| Hufnagel | Hufn. |
| Knoch | Knoch |
| Linnaeus | L. |
| Muller | Mull. |
| Prout | Prout |
| Stainton | Stt. |
| Schreber | Schreb. |
| de Villers | Vill. |
| Zincken | Zin. |

## Appendix E Species list

### Table A.4 List of species recorded (2009, 2010 and 2011)

Species recorded in 2011 in brackets.

| Abbreviation | Scientific Name and Authority | Common Name | Habitat Association | Conservation Status | Total no. |
|---|---|---|---|---|---|
| ABRAGROS | *Abraxas grossulariata* (Linnaeus, 1758) | Magpie Moth | Other | | 2 |
| ACROLEPO | *Acronicta leporina* (Linnaeus, 1758) | Miller | Other | Scarce | 1 |
| ACROMENY | *Acronicta menyanthidis* (Esper, 1789) | Light Knot Grass | Raised bog | Rare | 4 (3) |
| ACRORUMI | *Acronicta rumicis* (Linnaeus, 1758) | Knot Grass | Other | Vulnerable | 1 |
| AGROCIRC | *Agrochola circellaris* (Hufnagel, 1766) | Brick | Other | Declining | 3 (3) |
| AGROEXCL | *Agrotis exclamationis* (Linnaeus, 1758) | Heart and Dart | Other | | 11 (9) |
| AGROHELV | *Agrochola helvola* (Linnaeus, 1758) | Flounced Chestnut | Raised bog | Declining | 7 (1) |
| AGROLOTA | *Agrochola lota* (Clerck, 1759) | Red-line Quaker | Other | | 3 (3) |
| AGROLYCH | *Agrochola lychnidis* (Denis & Schiffermüller, 1775) | Beaded Chestnut | Other | Vulnerable | 3 (1) |
| AGROMACI | *Agrochola macilenta* (Hübner, 1809) | Yellow-line Quaker | Raised bog | | 1 (1) |
| ALCIREPA | *Alcis repandata* (Linnaeus, 1758) | Mottled Beauty | Raised bog | | 7 (3) |
| ALLOOXYA | *Allophyes oxyacanthae* (Linnaeus, 1758) | Green-brindled Crescent | Other | Vulnerable | 2 (2) |
| AMPH (agg.) | *Amphipoea agg.* | Ear species | Raised bog | | 80 (27) |
| ANARMYRT | *Anarta myrtilli* (Linnaeus, 1761) | Beautiful Yellow Underwing | Raised bog | Scarce | 8 |
| APAMMONO | *Apamea monoglypha* (Hufnagel, 1766) | Dark Arches | Raised bog | | 263 (225) |
| APAMREMI | *Apamea remissa* (Hübner, 1809) | Dusky Brocade | Other | Vulnerable | 6 (4) |

| Abbreviation | Scientific Name and Authority | Common Name | Habitat Association | Conservation Status | Total no. |
|---|---|---|---|---|---|
| APLOPLAG | *Aplocera plagiata* (Linnaeus, 1758) | Treble-bar | Other | Declining | 4 (4) |
| APORNIGR | *Aporophyla nigra* (Haworth, 1809) | Black Rustic | Raised bog | | 12 (12) |
| ARCTCAJA | *Arctia caja* (Linnaeus, 1758) | Garden Tiger | Raised bog | Vulnerable | 33 (22) |
| ATETCENT | *Atethmia centrago* (Haworth, 1809) | Centre-barred Sallow | Other | Vulnerable | 1 |
| ATOLRUBR | *Atolmis rubricollis* (Linnaeus, 1758*)* | Red-necked Footman | Raised bog | | 1 |
| AUTOGAMM | *Autographa gamma* (Linnaeus, 1758) | Silver Y | Other | | 2 (2) |
| AUTOJOTA | *Autographa jota* (Linnaeus, 1758) | Plain Golden Y | Other | | 2 (2) |
| BISTBETU | *Biston betularia* (Linnaeus, 1758) | Peppered Moth | Other | | 1 (1) |
| BUPAPINI | *Bupalus piniaria* (Linnaeus, 1758) | Bordered White | Other | | 6 |
| CABEEXAN | *Cabera exanthemata* (Scopoli, 1763) | Common Wave | Other | | 1 (1) |
| CALLPUDI | *Calliteara pudibunda* (Linnaeus, 1758) | Pale Tussock | Other | | 2 |
| CAMPMARG | *Campaea margaritata* (Linnaeus, 1761) | Light Emerald | Other | | 1 |
| CELAHAWO | *Celaena haworthii* (Curtis, 1829) | Haworth's Minor | Raised bog | Vulnerable | 2 (1) |
| CERAPISI | *Ceramica pisi* (Linnaeus, 1758) | Broom Moth | Raised bog | Vulnerable | 42 (8) |
| CERARUBR | *Cerastis rubricosa* (Denis & Schiffermüller, 1775) | Red Chestnut | Other | | 4 |
| CERUVINU | *Cerura vinula* (Linnaeus, 1758) | Puss Moth | Other | | 2 |
| CHLOSITE | *Chloroclysta siterata* (Hufnagel, 1767) | Red-green Carpet | Other | | 1 (1) |
| CHLOV-AT | *Chloroclystis v-ata* (Haworth, 1809) | V-pug | Other | | 4 (2) |
| CILIGLAU | *Cilix glaucata* (Scopoli, 1763) | Chinese Character | Other | | 2 (2) |
| CLEOLICH | *Cleorodes lichenaria* (Hufnagel, 1767) | Brussels Lace | Raised bog | | 2 (2) |

| Abbreviation | Scientific Name and Authority | Common Name | Habitat Association | Conservation Status | Total no. |
|---|---|---|---|---|---|
| COLOCORY | *Colocasia coryli* (Linnaeus, 1758) | Nut-tree Tussock | Other | | 1 |
| COLOPECT | *Colostygia pectinataria* (Knoch, 1781) | Green Carpet | Raised bog | | 2 |
| CONIVACC | *Conistra vaccinii* (Linnaeus, 1761) | Chestnut | Other | | 1 |
| COSMOCEL | *Cosmorhoe ocellata* (Linnaeus, 1758) | Purple Bar | Other | | 1 (1) |
| CROCELIN | *Crocallis elinguaria* (Linnaeus, 1758) | Scalloped Oak | Other | | 3 (3) |
| DEILELPE | *Deilephila elpenor* (Linnaeus, 1758) | Elephant Hawk-moth | Raised bog | | 3 (2) |
| DEILPORC | *Deilephila porcellus* (Linnaeus, 1758) | Small Elephant Hawk-moth | Raised bog | | 1 |
| DELTPYGA | *Deltote (Protodeltote) pygarga* (Hufnagel, 1766) | Marbled White Spot | Raised bog | | 2 (1) |
| DENTPYGM | *Denticucullus pygmina* (Haworth, 1809) | Small Wainscot | Raised bog | | 2 (2) |
| DIACCHRY | *Diachrysia chrysitis* (Linnaeus, 1758) | Burnished Brass | Other | | 2 (1) |
| DIARMEND | *Diarsia mendica* (Fabricius, 1775) | Ingrailed Clay | Raised bog | | 2 (1) |
| DIARRUBI | *Diarsia rubi* (Vieweg, 1790) | Small Square-spot | Other | Vulnerable | 1 |
| DICAFASC | *Dicallomera fascelina* (Linnaeus, 1758) | Dark Tussock | Raised bog | Rare | 43 (27) |
| DREPFALC | *Drepana falcataria* (Linnaeus, 1758) | Pebble Hook-tip | Other | | 5 (2) |
| DYSCFAGA | *Dyscia fagaria* (Thunberg, 1784) | Grey Scalloped Bar | Raised bog | Scarce | 188 (65) |
| ECTRCREP | *Ectropis crepuscularia* (Denis & Schiffermüller, 1775) | Engrailed | Other | | 1 |
| EILEDEPR | *Eilema depressa* (Esper, 1787) | Buff Footman | Raised bog | | 4 (3) |

| Abbreviation | Scientific Name and Authority | Common Name | Habitat Association | Conservation Status | Total no. |
|---|---|---|---|---|---|
| EILELURI | *Eilema lurideola* (Zincken, 1817) | Common Footman | Raised bog | | 33 (25) |
| EMATATOM | *Ematurga atomaria* (Linnaeus, 1758) | Common Heath | Raised bog | | 1 |
| ENNOALNI | *Ennomos alniaria* (Linnaeus, 1758) | Canary-shouldered Thorn | Other | | 3 (3) |
| EPIRALTE | *Epirrhoe alternata* (Muller, 1764) | Common Carpet | Raised bog | | 2 |
| EUGNGLAR | *Eugnorisma (Eugnorisma) glareosa* (Esper, 1788) | Autumnal Rustic | Raised bog | Endangered | 4 (4) |
| EULITEST | *Eulithis testata* (Linnaeus, 1761) | Chevron | Raised bog | | 10 (3) |
| EUPHUNAN | *Euphyia unangulata* (Haworth, 1809) | Sharp-angled Carpet | Other | | 1 |
| EUPINANA | *Eupithecia nanata* (Hübner, 1813) | Narrow-winged Pug | Raised bog | | 23 (19) |
| EUPLLUCI | *Euplexia lucipara* (Linnaeus, 1758) | Small Angle Shades | Other | | 1 |
| EUTHPOTA | *Euthrix potatoria* (Linnaeus, 1758) | Drinker | Raised bog | | 7 (2) |
| FALCLACE | *Falcaria lacertinaria* (Linnaeus, 1758) | Scalloped Hook-tip | Other | Declining | 14 (11) |
| FURCFURC | *Furcula furcula* (Clerck, 1759) | Sallow Kitten | Other | Scarce | 1 |
| GEOMPAPI | *Geometra papilionaria* (Linnaeus, 1758) | Large Emerald | Other | | 1 (1) |
| GRAPAUGU | *Graphiphora augur* (Fabricius, 1775) | Double Dart | Other | Endangered | 10 (2) |
| GRIPAPRI | *Griposia aprilina* (Linnaeus, 1758) | Merveille du Jour | Other | | 1 (1) |
| GYMNRUFI | *Gymnoscelis rufifasciata* (Haworth, 1809) | Double-striped Pug | Raised bog | | 9 (3) |
| HABRPYRI | *Habrosyne pyritoides* (Hufnagel, 1766) | Buff Arches | Other | | 3 (2) |
| HELOLEUC | *Helotropha leucostigma* (Hübner, 1808) | Crescent | Other | Vulerable | 2 (2) |

| Abbreviation | Scientific Name and Authority | Common Name | Habitat Association | Conservation Status | Total no. |
|---|---|---|---|---|---|
| HYDRMICA | *Hydraecia micacea* (Esper, 1789) | Rosy Rustic | Other | Vulnerable | 6 (2) |
| HYDRFURC | *Hydriomena furcata* (Thunberg, 1784) | July Highflyer | Raised bog | | 6 (5) |
| HYLAFASC | *Hylaea fasciaria* (Linnaeus, 1758) | Barred Red | Other | | 1 |
| HYPEPROB | *Hypena proboscidalis* (Linnaeus, 1758) | Snout | Other | | 1 |
| IDAEAVER | *Idaea aversata* (Linnaeus, 1758) | Riband Wave | Raised bog | | 12 (8) |
| IDAEDIMI | *Idaea dimidiata* (Hufnagel, 1767) | Single-dotted Wave | Other | | 1 (1) |
| LAOTPOPU | *Laothoe populi* (Linnaeus, 1758) | Poplar Hawk-moth | Other | | 23 (13) |
| LASIQUER | *Lasiocampa (Lasiocampa) quercus* (Linnaeus, 1758) | Oak Eggar | Raised bog | | 11 (8) |
| LITHORNI | *Lithophane (Lithophane) ornitopus* (Hufnagel, 1766) | Grey Shoulder-knot | Other | | 1 (1) |
| LOMAMARG | *Lomaspilis marginata* (Linnaeus, 1758) | Clouded Border | Other | | 1 (1) |
| LUPETEST | *Luperina testacea* (Denis & Schiffermüller, 1775) | Flounced Rustic | Other | | 2 |
| LYCOPORP | *Lycophotia porphyrea* (Denis & Schiffermüller, 1775) | True Lover's Knot | Raised bog | | 1109 (947) |
| MACRRUBI | *Macrothylacia rubi* (Linnaeus, 1758) | Fox Moth | Raised bog | | 89 (7) |
| MESASECA | *Mesapamea secalis agg.* | Common Rustic agg. | Raised bog | | 16 (9) |
| MESODIDY | *Mesotype didymata* (Linnaeus, 1758) | Twin-spot Carpet | Raised bog | | 2 (1) |
| MNIOADUS | *Mniotype adusta* (Esper, 1790) | Dark Brocade | Raised bog | Vulnerable | 2 (1) |
| MYTHIMPU | *Mythimna (Mythimna) impura* (Hübner, 1808) | Smoky Wainscot | Raised bog | | 18 (8) |
| MYTHPALL | *Mythimna (Mythimna) pallens* (Linnaeus, 1758) | Common Wainscot | Other | | 1 (1) |

| Abbreviation | Scientific Name and Authority | Common Name | Habitat Association | Conservation Status | Total no. |
|---|---|---|---|---|---|
| MYTHPUDO | *Mythimna (Mythimna) pudorina* (Denis & Schiffermüller, 1775) | Striped Wainscot | Raised bog | Scarce | 1 (1) |
| NOCTCOME | *Noctua comes* (Hübner, 1813) | Lesser Yellow Underwing | Raised bog | | 23 (5) |
| NOCTJANT | *Noctua janthe* (Borkhausen, 1792) | Lesser Broad-bordered Yellow Underwing | Raised bog | | 14 |
| NOCTPRON | *Noctua pronuba* (Linnaeus, 1758) | Large Yellow Underwing | Raised bog | | 147 (103) |
| NONATYPH | *Nonagria typhae* (Thunberg, 1784) | Bulrush Wainscot | Other | | 2 (2) |
| NOTOZICZ | *Notodonta ziczac* (Linnaeus, 1758) | Pebble Prominent | Other | | 13 (9) |
| NUDAMUND | *Nudaria mundana* (Linnaeus, 1761) | Muslin Footman | Raised bog | | 20 (2) |
| OLIGFASC | *Oligia fasciuncula* (Haworth, 1809) | Middle-barred Minor | Other | | 3 |
| OPISLUTE | *Opisthograptis luteolata* (Linnaeus, 1758) | Brimstone Moth | Other | | 17 (5) |
| ORTHVITT | *Orthonama vittata* (Borkhausen, 1794) | Oblique Carpet | Raised bog | Vulnerable | 2 |
| ORTHGOTH | *Orthosia (Semiophora) gothica* (Linnaeus, 1758) | Hebrew Character | Raised bog | | 1 |
| OURASAMB | *Ourapteryx sambucaria* (Linnaeus, 1758) | Swallow-tailed Moth | Other | | 2 (2) |
| PAPEBIRE | *Papestra biren* (Goeze, 1781) | Glaucous Shears | Raised bog | Scarce | 5 |
| PENNFIRM | *Pennithera firmata* (Hübner, 1822) | Pine Carpet | Other | | 3 (3) |
| PERCSTRI | *Perconia strigillaria* (Hübner, 1787) | Grass Wave | Raised bog | | 11 (10) |
| PERIALBU | *Perizoma albulata* (Denis & Schiffermüller, 1775) | Grass Rivulet | Other | Endangered | 1 |
| PHALBUCE | *Phalera bucephala* (Linnaeus, 1758) | Buff-tip | Other | | 5 (3) |

| Abbreviation | Scientific Name and Authority | Common Name | Habitat Association | Conservation Status | Total no. |
|---|---|---|---|---|---|
| PHARFUSC | *Pharmacis fusconebulosa* (DeGeer, 1778) | Map-winged Swift | Other | | 19 (18) |
| PHEOGNOM | *Pheosia gnoma* (Fabricius, 1776) | Lesser Swallow Prominent | Other | | 8 (7) |
| PHLOMETI | *Phlogophora meticulosa* (Linnaeus, 1758) | Angle Shades | Raised bog | | 22 (22) |
| PHRAFULI | *Phragmatobia fuliginosa* (Linnaeus, 1758) | Ruby Tiger | Raised bog | | 9 (2) |
| PLUSFEST | *Plusia festucae* (Linnaeus, 1758) | Gold Spot | Raised bog | | 13(1) |
| PTILCAPU | *Ptilodon capucina* (Linnaeus, 1758) | Coxcomb Prominent | Other | | 1 |
| RHIZLUTO | *Rhizedra lutosa* (Hübner, 1803) | Large Wainscot | Other | Vulnerable | 3 (3) |
| RIVUSERI | *Rivula sericealis* (Scopoli, 1763) | Straw Dot | Raised bog | | 2 (1) |
| SATUPAVO | *Saturnia (Eudia) pavonia* (Linnaeus, 1758) | Emperor Moth | Raised bog | | 1 |
| SCOTCHEN | *Scotopteryx chenopodiata* (Linnaeus, 1758) | Shaded Broad-bar | Other | Vulnerable | 1 |
| SELIBRUN | *Selidosema brunnearia* (de Villers, 1789) | Bordered Grey | Raised bog | Scarce | 33 (32) |
| SMEROCEL | *Smerinthus ocellata* (Linnaeus, 1758) | Eyed Hawk-moth | Other | | 6 |
| SPILLUBR | *Spilosoma lubricipeda* (Linnaeus, 1758) | White Ermine | Raised bog | Vulnerable | 13 (6) |
| SPILLUTE | *Spilosoma lutea* (Hufnagel, 1766) | Buff Ermine | Raised bog | Vulnerable | 7 |
| SUBAMEGA | *Subacronicta megacephala* (Denis & Schiffermüller, 1775) | Poplar Grey | Other | Scarce | 5 (3) |
| SYNGINTE | *Syngrapha interrogationis* (Linnaeus, 1758) | Scarce Silver Y | Raised bog | Scarce | 4 (3) |
| THERBRIT | *Thera britannica* (Turner, 1925) | Spruce Carpet | Other | | 17 (16) |
| THEROBEL | *Thera obeliscata* (Hübner, 1787) | Grey Pine Carpet | Other | | 4 (1) |
| THOLCESP | *Tholera cespitis* (Denis & Schiffermüller, 1775) | Hedge Rustic | Raised bog | Endangered | 11 |

| Abbreviation | Scientific Name and Authority | Common Name | Habitat Association | Conservation Status | Total no. |
|---|---|---|---|---|---|
| THUMSENE | *Thumatha senex* (Hübner, 1808) | Round-winged Muslin | Raised bog | | 5 (1) |
| THYABATI | *Thyatira batis* (Linnaeus, 1758) | Peach Blossom | Other | | 2 |
| XANTICTE | *Xanthia (Cirrhia) icteritia* (Hufnagel, 1766) | Sallow | Other | Vulnerable | 3 |
| XANTFERR | *Xanthorhoe ferrugata* (Clerck, 1759) | Dark-barred Twin-spot Carpet | Raised bog | Endangered | 2 (2) |
| XANTFLUC | *Xanthorhoe fluctuata* (Linnaeus, 1758) | Garden Carpet | Other | | 16 |
| XANTMONT | *Xanthorhoe montanata* (Denis & Schiffermüller, 1775) | Silver-ground Carpet | Raised bog | | 2 |
| XESTAGAT | *Xestia (Xestia) agathina* (Duponchel, 1827) | Heath Rustic | Raised bog | Vulnerable | 198 (4) |
| XESTC-NI | *Xestia (Megasema) c-nigrum* (Linnaeus, 1758) | Setaceous Hebrew Character | Other | | 6 (6) |
| XESTTRIA | *Xestia (Megasema) triangulum* (Hufnagel, 1766) | Double Square-spot | Other | | 4 (2) |

## Appendix F The database of Irish Lepidoptera

Table A.5 The Database of Irish Lepidoptera, (Bond and Gittings, 2008)

| | **Raised bog** | **Cutover bog** | **Blanket bog** | **Bog (Gen.)** | **Total No. of Individuals** | **Total 2011** |
|---|---|---|---|---|---|---|
| *Lycophotia porphyrea* (D.& S.) | 3 | 3 | 3 | 3 | 1109 | 947 |
| *Xestia (Xestia) agathina* (Dup.) | 3 | 3 | 3 | 3 | 198 | 4 |
| *Anarta myrtilli* (L.) | 3 | 2 | 3 | 3 | 8 | 0 |
| *Syngrapha interrogationis* (L.) | 3 | 2 | 3 | 3 | 4 | 3 |
| *Acronicta menyanthidis* (Esp.) | 3 | 3 | 3 | 3 | 4 | 3 |
| *Mniotype adusta** (Esp.) | 3 | 3 | 3 | 3 | 2 | 1 |
| *Celaena haworthii* (Curt.) | 3 | 3 | 3 | 3 | 2 | 1 |
| *Noctua pronuba* (L.) | 2 | 1 | 2 | 2 | 147 | 103 |
| *Ceramica pisi* (L.) | 2 | 0 | 2 | 2 | 42 | 8 |
| *Noctua comes* (Hb.) | 2 | 3 | 2 | 3 | 23 | 5 |
| *Orthosia (Semiophora) gothica* (L.) | 2 | 3 | 2 | 3 | 1 | 0 |
| *Xestia (Xestia) castanea* (Esp.) | 2 | 3 | 3 | 3 | 0 | 0 |
| *Orthosia (Cororthosia) gracilis* (D.& S.) | 2 | 3 | 2 | 3 | 0 | 0 |
| *Apamea crenata* (Hufn.) | 2 | 3 | 2 | 3 | 0 | 0 |
| *Phytometra viridaria* (Cl.) | 2 | 2 | 2 | 2 | 0 | 0 |

## Appendix G Rank abundance curve 2009, 2010 and 2011 dataset.

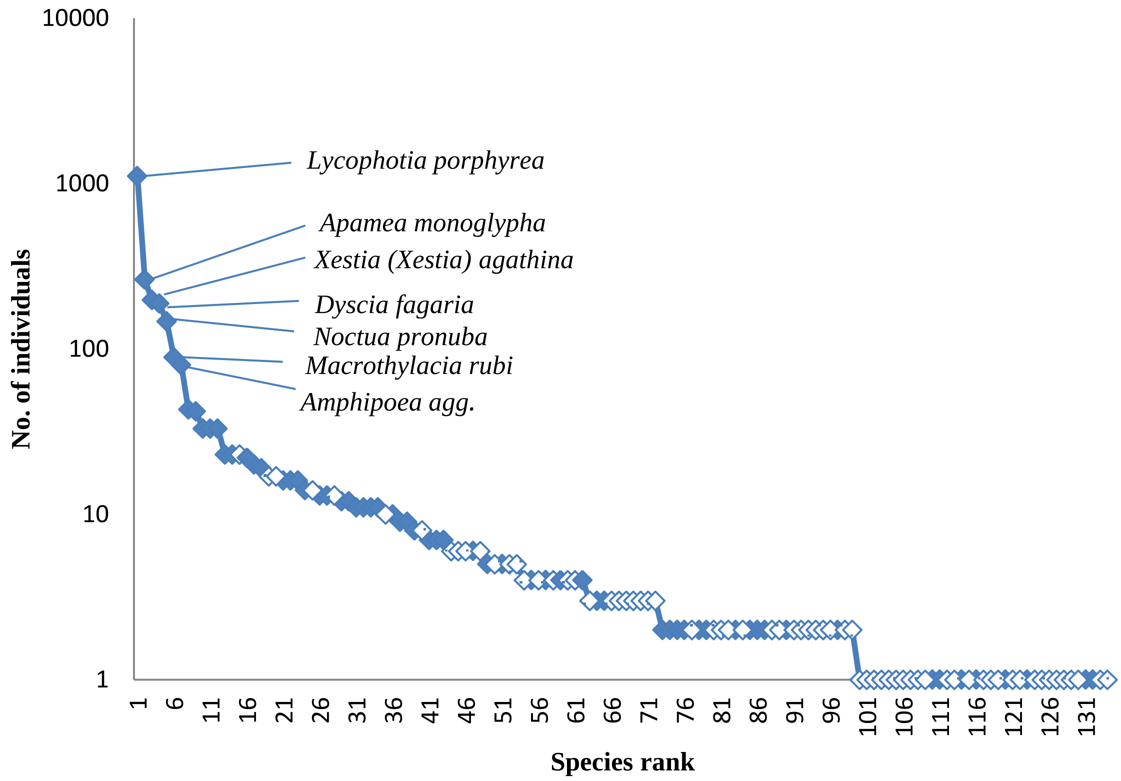


**Figure A1 Rank abundance curve 2009, 2010 and 2011 dataset.**

2009, 2010 and 2011 dataset with log-transformed ($y' = \log_{10}(y)$) scale on the y axis. The named species are those comprising more than 2% of the total abundance. Filled diamond = raised bog associated species, Open diamond = other species

## Appendix H Explanatory Variables

Table A.6 Explanatory Variables

| | **Minimum Distance to edge of high bog (m)** | **Perimeter (m)** | **Area of high bog (ha)** | **Drain length on high bog (km)** | **Drain density** | **High Bog Fragment Shape (R)** |
|---|---|---|---|---|---|---|
| **Sha** | 220 | 6689 | 137.02 | 21.912 | 0.01599 | 1.611456 |
| **Mon** | 376 | 5995 | 124.37 | 9.305 | 0.00748 | 1.516 |
| **Fer** | 123 | 5080 | 119.98 | 10.889 | 0.00908 | 1.308 |
| **Moy** | 253 | 4680 | 74.27 | 3.8 | 0.00512 | 1.531 |
| **Cla** | 496 | 8113 | 246.78 | 1.741 | 0.00071 | 1.4564 |
| **Rah** | 385 | 5552 | 130.55 | 9.4 | 0.00720 | 1.37028 |
| **Old** | 350 | 5041 | 95.1178 | 37.323 | 0.03924 | 1.458 |
| **Clon** | 151 | 19402 | 578.1381 | 263.054 | 0.04637 | 2.2755 |
| **Cur** | 238 | 4830 | 65.4188 | 27.352 | 0.04181 | 1.684 |
| **Doon** | 127 | 5635 | 47.7575 | 5.003 | 0.01048 | 2.299 |
| **Clonly** | 390 | 4821 | 88.6453 | 43.786 | 0.04939 | 1.444 |
| **Kilbal** | 272 | 3039 | 40.6374 | 24.836 | 0.06112 | 1.344 |

Table A.7 Explanatory Variables

| | **Elevation (m)** | **Isolation (I)** | **Total moth abundance** | **Heather feeder abundance** | **Tree feeder abundance** |
|---|---|---|---|---|---|
| **Sha** | 51.60 | 22.64 | 113 | 81 | 9 |
| **Mon** | 43.86 | 17.03 | 185 | 109 | 10 |
| **Fer** | 62.39 | 9.55 | 238 | 155 | 8 |
| **Moy** | 53.77 | 7.49 | 168 | 97 | 5 |
| **Clar** | 56.00 | 32.77 | 98 | 58 | 8 |
| **Rah** | 103.93 | 12.96 | 149 | 96 | 4 |
| **Old** | 94.54 | 11.47 | 176 | 134 | 11 |
| **Clon** | 59.87 | 35.57 | 147 | 108 | 9 |
| **Cur** | 50.28 | 24.19 | 114 | 47 | 11 |
| **Doon** | 50.05 | 37.99 | 257 | 172 | 7 |
| **Clonly** | 46.16 | 22.41 | 116 | 69 | 3 |
| **Kilbal** | 78.09 | 3.24 | 55 | 29 | 5 |

Table A.8 Explanatory Variables

| | **Oligotrophic and Monotrophic** | **Polytrophic** | **Heather feeder abundance** | **Scrub/Tree feeder abundance** | **Lichen feeder abundance** |
|---|---|---|---|---|---|
| **Sha** | 15 | 8 | 81 | 9 | 1 |
| **Mon** | 14 | 8 | 109 | 10 | 1 |
| **Fer** | 19 | 14 | 155 | 8 | 8 |
| **Moy** | 13 | 4 | 97 | 5 | 4 |
| **Clar** | 17 | 7 | 58 | 8 | 1 |
| **Rah** | 13 | 9 | 96 | 4 | 0 |
| **Old** | 16 | 11 | 134 | 11 | 0 |
| **Clon** | 19 | 5 | 108 | 9 | 0 |
| **Cur** | 21 | 15 | 47 | 11 | 4 |
| **Doon** | 21 | 12 | 172 | 7 | 14 |
| **Clonly** | 11 | 5 | 69 | 3 | 1 |
| **Kilbal** | 11 | 8 | 29 | 5 | 0 |

Table A.9 Explanatory Variables

| | **Heather Feeder** | **Lichen Feeder** | **Grass Feeder** | **Broad-leaved plant feeder** | **Scrub / Tree feeder** | **Sedge feeder** | **Deciduous tree feeder** | **Conifer feeder** |
|---|---|---|---|---|---|---|---|---|
| **Sha** | 8 | 1 | 3 | 10 | 17 | 0 | 12 | 2 |
| **Mon** | 9 | 1 | 3 | 6 | 16 | 0 | 8 | 2 |
| **Fer** | 9 | 3 | 3 | 9 | 19 | 1 | 12 | 3 |
| **Moy** | 6 | 2 | 2 | 4 | 10 | 0 | 4 | 1 |
| **Clar** | 6 | 1 | 5 | 5 | 12 | 2 | 9 | 0 |
| **Rah** | 4 | 0 | 6 | 9 | 12 | 1 | 4 | 0 |
| **Old** | 10 | 0 | 4 | 11 | 17 | 1 | 11 | 3 |
| **Clon** | 7 | 0 | 3 | 4 | 17 | 0 | 11 | 2 |
| **Cur** | 9 | 2 | 5 | 11 | 20 | 3 | 11 | 2 |
| **Doon** | 9 | 3 | 7 | 12 | 17 | 1 | 13 | 3 |
| **Clonly** | 6 | 1 | 3 | 6 | 8 | 1 | 5 | 2 |
| **Kilbal** | 5 | 0 | 4 | 7 | 12 | 0 | 6 | 2 |