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Running title: Moth communities of raised bogs

The diversity and composition of mothcommunities of protected and degraded raised bogs in Ireland.

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Abstract

1. Peatlands are a globally important habitat, which act as net carbon stores. Raised bogs in the midlands of Ireland are a diminishing and increasingly fragmented peatland habitat as a result of drainage, peat extraction and agricultural intensification. A network of protected sites has been established, which is intended to represent the best abiotic and plant community systems.

2. Lepidoteran communities are an important component raised bog biodiversity and may be useful as biodiversity indicators, yet they are a neglected area of research. We address this by surveying nocturnal lepidopteran communities on six degraded and six protected raised bogs. We collected 1,816 individuals (representing 93 species) across all sites.

3. Poisson generalised linear models were fitted to our count data and assessed using the Akaike information criterion (AIC) values. Models that included designation status were preferred for six species, three of which were more abundant on designated sites and three were more abundant on degraded sites. We discuss these findings in relation to the species' known autecologies. Larval food plant choice, particularly due to the presence of invasive and non-typical plants, explained the alignment of species with undesignated sites. Other factors such as structural heterogeneity or nectar availability, may explain the alignment of most species with designated sites.

4. Rank abundance diagrams (RADs) of the total moth community were similar between protected and degraded sites, but the RADs of bog-associated species of conservation concern were different between protected and degraded sites with rarer bog associates being relatively better represented at the protected sites. This result was supported by Multi-response permutation-procedure (MRPP) analysis.

5. In general, differences between moth communities on degraded and protected raised bogs are rather subtle, with assemblages on both site types generally similar, but there is evidence that the "coarse filter" approach to conservation is working for some of the most important moth communities i.e. those that are bog-associated and of conservation concern. However, degraded sites may have a role to play in peatland invertebrate conservation, hitherto undervalued.

Key Words: Raised Bogs, Moth communities, Protected sites, Degraded sites, Bioindicators.

Introduction

Most peatlands are important net carbon stores (Dise, 2009), but drainage for agriculture, forestry, peat extraction, infrastructure developments, pollution and fires are important causes of degradation, which continue today (Renou-Wilson *et al.*, 2011). Peatlands cover more than 4 million square kilometres worldwide, with 80% of the peatland area situated in temperate-cold climates in the northern hemisphere (Limpens *et al*., 2008). Raised bogs in Ireland are dome-shaped bodies of peat, which started to develop at least 7,000 years ago, chiefly in basins or shallow lakes formed due to impeded drainage, after the last glaciation (Mitchell, 1990). For raised bogs in good condition, the water table remains close to the surface throughout the year, with much of the rainfall held by the living and partly humified *Sphagnum* moss layer (the acrotelm) which carpets the bog. Bog habitat with a peat-forming acrotelm is called 'active raised bog' and is a priority habitat for conservation under the European Union Habitats Directive (Council of the European Communities, 1992). Although characterised by low species-richness, raised bogs are nonetheless important reservoirs of biodiversity as they contain uniquely adapted plant and animal species not found elsewhere (Renou-Wilson *et al.*, 2011). Hence, it is these distinctive species which are most important to biodiversity at a regional level.

Much of the central limestone plain of Ireland was formerly characterised by large raised bog complexes. Some have historically been cut-away entirely through exploitation as a domestic fuel source and have largely been reclaimed as agricultural grassland (Foss *et al*., 2001). The surface of a number of remaining bog complexes has been extensively cutover, with the extracted peat being used for commercial applications including domestic fuel production, fuel for electricity generating stations and as a growing medium in horticulture. Such bogs, where the surface has been stripped and is either bare or partly re-vegetating, are classified as secondary degraded bog (Fernandez *et al*., 2014).

Consequently, remaining areas of relatively intact bog, which have not been cutover, are mainly small remnants of once larger bog complexes and contain both active (peat forming) or degraded (not peat forming) raised bog habitats. The conservation status of active raised bog habitat in the Republic of Ireland has recently been assessed as “bad” and the overall trend of this habitat is “declining” (NPWS[1], 2013). 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, 2013). There has been a 99% loss of this habitat type and e.g. in 2012, only an estimated 1,639 ha remained nationally (DAHG, 2014). Irish midland raised bogs are assigned to the temperate, oceanic bog type associated with NW Europe (Cross, 1990, Kelly, 1993). Such bogs formerly occurred on a large scale in the UK, the Netherlands, Denmark and north-west Germany, as well as Ireland. However, widespread industrial peat cutting has greatly reduced the number of intact bogs of this type and the best remaining relatively intact examples are now found in Ireland (Schouten *et al*., 1992). Irish raised bogs are therefore globally important as they represent, in relative terms, the finest examples of their type (Kelly, 1993) and therefore Ireland has an international responsibility to conserve them.

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[1] NPWS is the National Parks and Wildlife Service, part of the Department of Arts, Heritage and the Gaeltacht (DAHG), one of whose statutory functions is to secure the conservation of wildlife and to promote the conservation of biological diversity in the Republic of Ireland.

In Ireland, 53 sites containing active raised bog habitat have been designated as Special Areas of Conservation (SAC’s) (DAHG, 2014), part of the European Natura 2000 conservation network (Council of the European Communities, 1992). As for most Natura 2000 sites, designation of raised bog SAC’s was based on plant community associations within habitats and hence did not directly consider the conservation of their invertebrate fauna due to limited taxonomic and distribution knowledge of these groups (Hernandez-Manrique *et al.*, 2012). The aim of SAC’s selected by habitat is to protect species occupying those habitats in a so-called ‘coarse filter’ approach (Hunter, 2005). This approach seeks to conserve a representative array of regional habitats, thereby also conserving the majority of species within the region. It is complemented by the ‘fine filter’ approach where sites are selected to conserve specific species, in particular, certain bird species listed under the European Birds Directive and other non-bird wild fauna (largely vertebrates) and flora listed under Annex II of the Habitats Directive (Cardoso, 2012). Studies have found that the ‘coarse filter’ approach is not fulfilling its promise in relation to certain invertebrates, especially when fine-scale habitat structural diversity, known to be important to invertebrates, is not taken into account (Davies *et al.*, 2007).

There is a growing recognition of the need to include invertebrates, an important component of peatland biodiversity (Cross, 1990), in planning and assessment of peatland conservation measures (van Duinen *et al.*, 2003). Due to the impracticality of monitoring the total invertebrate fauna (Sauberer *et al.*, 2004), even in a species-poor habitats such as active and degraded raised bog, surrogate species or biodiversity indicators are needed to act as proxies for other less well-known taxa (McGeoch, 1998). Consequently, a number of invertebrate species or assemblages have been used or proposed as peatland biodiversity indicators, including carnivorous ground beetles

(Williams *et al*., 2014), hoverflies (Speight *et al*., 2002) and aquatic macroinvertebrates (Hannigan & Kelly-Quinn, 2012).

Based on criteria developed by Speight (1986), night-flying macro-moths which are attracted to light (hereafter referred to as moths) appear to have good potential as biodiversity indicators. In general, species can be reliably determined without undue effort. They are extensively recorded by amateur naturalists so that their Irish and European distributions are well known (Tyner, 2014, Karsholt & Nieukerken, 2013) and there is a reliable national species list (Bond *et al.*, 2006). The biologies of many species are sufficiently well known so that their habitats can be defined (Bond & Gittings, 2008, Waring & Townsend, 2009) and they have potential for detection of site attributes that cannot be more easily detected using either vertebrates or higher plants (Bond & Gittings, 2008, Davies et *al.*, 2007). The group can be sampled using the same field collection technique and the total number of species employed is less than 1000. Two drawbacks are that moths are confined in the main to terrestrial habitats and being phytophagous represent only one trophic level. However, another advantage is that they have recently been shown to be sensitive indicators of climate change in Ireland (O'Neill et *al.*, 2012).

While typical flora has been well defined for active raised bog (Kelly & Schouten, 2002), typical terrestrial invertebrate fauna, with the exception of spiders (M. Nolan, pers. comm.), has not. The aim of this work was to establish whether there is a distinct moth fauna associated with the wettest areas of designated sites (active raised bog) by comparing the assemblages found in these study sites to those found on undesignated sites where this wet habitat has been lost (non-active raised bog). This work will inform site specific conservation objectives currently being developed for Raised Bog SACs in Ireland (DAHG, 2014). Moth species characteristic of higher quality raised bog habitat will be considered part of their typical fauna and included in conservation targets, where appropriate. This work can therefore be interpreted as boundary science, in the sense that it both advances scientific understanding and has implications for conservation managers and will be used to inform decision making (Cook *et al.*, 2013).

Materials and Methods

Study sites

Six designated and six undesignated bogs were selected for sampling. All sites were located wholly or in part in County Offaly (Fig.1) which, in the last all-Ireland assessment (Hammond, 1981), had the greatest amount of unmodified raised bog of the true midland sub-type (7875 ha) of all counties. Clara Bog is the largest remaining example of this bog sub-type and the study area is centrally located within the range of such bogs (Cross, 1990). Also, three of the SAC study sites (Clara, Raheenmore and Mongan Bogs) are Statutory Nature Reserves, protected under Ministerial Order, and are the most intensively researched raised bogs in the country (Kelly & Schouten, 2002, Fernandez *et al.*, 2014). Restoration work, mainly in the form of extensive drain blocking, has taken place on Clara, Raheenmore, Sharavogue and Mongan Bogs (Kelly & Schouten, 2002, Fernandez *et al.*, 2014).

The designated raised bog sites selected constitute six out of the seven SAC bogs in County Offaly and contain varying amounts of active raised bog habitat ranging from 21 hectares (Moyclare) to 79 hectares (Clara west). Aerial photography interpretation was used to identify the nearest highly modified but vegetated, undesignated raised bog to each designated bog site (Fig. 1). The amount of active raised bog remaining on the highly modified undesignated bogs is not known but is considered to be very low, if any.

The area of raised bog on designated sites ranged from 74 hectares (Moyclare) to 246 hectares (Clara west) and on undesignated sites from 40 hectares (Kilballyskea) to 578 hectares (Clonaltra) (Appendix 2). Distance between protected sites ranged from 2.0 km (Ferbane to Moyclare) to 49.5 km (Sharavogue to Raheenmore). Distance between each designated site and its paired undesignated site ranged from 1.5 km (Raheenmore to Old Croghan) to 5 km (Sharavogue to Kilballyskea). The average distance between designated and undesignated pairs was 3.5 km ± 0.9 (mean ± SE).

Sampling on designated sites took place in the wettest, most pristine areas of active raised bog habitat. While on undesignated bogs, central locations on the degraded 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). Active raised bog habitat consists of both central and sub-central ecotopes, i.e. areas which have generally homogeneous biotic and abiotic conditions (sensu Kelly & Schouten, 2002). Central ecotope has a very soft and often quaking surface and the microtopography usually ranges from pools to tall, well developed hummocks, with pools usually frequent to dominant. Generally, sub-central ecotope is lawn-dominated with only a few hummocks. The surface is soft and sometimes quaking. (Fernandez *et al.,* 2005a). Flushes and soaks which have active *Sphagnum* growth are also classified as active raised bog (Fernandez *et al*., 2014). The largest area of central ecotope on each designated bog, as defined by Fernandez *et al*. (2005b), was selected as a sampling point. On Sharavogue bog, an area of sub-central ecotope was selected as this bog contains no central ecotope. 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 the marginal ecotope as close to central ecotope as possible. In marginal ecotope, the acrotelm is absent or poorly developed (Kelly & Schouten, 2002). This ecotope is allocated to the degraded raised bog habitat type (Fernandez *et al.,* 2005a).

Sampling methodology

Moths were sampled using portable light traps (Heath-type actinic 15 W; Anglian Lepidopterist Supplies, UK) (Heath, 1965). Twelve bogs were sampled over a two night period with six bogs sampled on each consecutive night (2nd/3rd July, 26th/27th July, 31th July/1st August, 24th/25th September and 1st/2nd October 2011). Therefore, six dyads (designated and undesignated bog pairs) were each sampled on five occasions, giving 30 dyad-sampling events (Fig. 1). Sampling dyads on the same night ensured that variation in abundances, caused by weather or natural light condition, did not affect within-pair comparisons. Between pair comparisons may still be affected by differences in other factors like trapping microsite and habitat-specific trapping bias. These limitations are discussed below. However, on two occasions due to logistical issues, sites within a dyad had to be sampled one night apart i.e. Ferbane 26/07; Curraghalassa 27/07; Mongan 25/09; Doon 24/09). Single species analyses were conducted excluding these samples and results were the same as if these samples were included. Multivariate analysis (ordination) was carried out excluding all sites on these sample dates and similar results were found to when they were included. However, without these sample dates, the dataset was weakly structured and more species had to be excluded to reach a useful ordination. Therefore, a decision was made to include these samples as the information they provided was considered to be greater than the potential noise they added to statistical analysis. Moth surveys were conducted when forecast weather conditions were suitable, i.e. minimum night temperature > 10 ℃, maximum wind speed Beaufort 4-5; and with no persistent or heavy rain.

Trapping protocol and trap type were standardised whereby traps were deployed on the bogs before sunset and collected close to sunrise the following morning. Trapping was carried out with the assistance of three trained NPWS field staff, so that the timing of setting and collection of traps was closely aligned. Review of setting and collection times did not reveal any bias in favour of designated or undesignated sites. Traps were filled with nine standard-sized egg trays which were identically arranged in each trap to avoid noise. Traps were placed in the centre of a circle of plastic tubing, with an inner diameter of 1 metre. A timed five-minute active search of the habitat and trap surface within the circle took place in the morning to reduce bias towards more conspicuous species. Traps and batteries were arbitrarily reassigned to sites each night to remove any bias of lamp brightness or battery strength. Trap openings were sealed and traps were placed in labelled, large black plastic sacks which were then sealed for transport to the laboratory for identification. Moths were identified to species level according to Skinner (2009) and Waring & Townsend (2009).

The four *Amphipoea* species that were sampled can only be reliably distinguished by examination of genitalia where they occur together (Waring and Townsend, 2009). All four species are considered bog associates and therefore were pooled as *Amphipoea* agg. and analysed with other bog associates. The species pair *Mesapamea secalis* (L.) / *M. secalella* (Remm), which also requires genitalia preparation to separate, was analysed as *Mesapamea* agg. Both species in this pair are considered bog associates, hence the species pair was interpreted as such.

Environmental variables

Environmental variables for each study site were derived from 2004/2005 series of aerial photographs for the sites and geospatial information processed in ArcGIS 10.2.1

(ESRI, 2008). In the present study, environmental variables were calculated for Clara bog west only as this is where sampling took place. The following variables were calculated: (1) minimum distance from sampling point to bog edge, (2) bog area, (3) drain density (D), and (4) connectivity (C).

Drain density (D) was calculated by dividing the total length of drains on the high bog by the area of the high bog.

Connectivity (C) was expressed as the area of raised bog within a radius of 2 km of the sampling point, using a simple and commonly used proportional index (Winfree *et al.*, 2005):

$$C = \frac{A(r)}{\pi r^2}$$

Where A(r) is the total habitat area within radius r of the sampling point. A 2 km radius was also used in a landscape scale heathland invertebrate study by Webb, 1989 and is comparable with buffers used in more recent Lepidopteran studies: Slade *et al*. (2013) 1 km; Fuentes-Montemayor *et al*. (2012) 250 m – 3000 m. It also encompasses the largest model predicted movement rates (m/week) in a study of 87 common British non-migratory species (largest movement rate = 1707m/week) (Slade *et al*., 2013).

Species variables

Non-resident vagrants and atypical residents, whose presence was due to the invasion of bogs by non-characteristic plant species, were separated from residents whose food plants form part of midland raised bog plant communities (Kelly & Schouten, 2002; Fernandez *et al.*, 2005a). Hereafter these are termed raised bog associated species (Appendix 1). This was done using larval food plant and/or habitat preferences in Emmet (1991), Waring & Townsend (2009) and Bond & Gittings (2008).

There has been no conservation assessment of moths in the Republic of Ireland to date. To assess conservation status of raised bog associated moth species, any species classified as endangered or vulnerable by Conrad *et al*. (2006) for Great Britain were considered also to be of conservation concern in Ireland (Appendix 1). Species for which conservation status was not available were assigned a distribution status, based on the distribution maps and associated information in the Moths Ireland database (Tyner, 2014). Species assigned scarce (not encountered often or restricted in range) or rare (rarely encountered) status were considered vulnerable by virtue of their limited distribution. Distribution maps in Moths Ireland divide Ireland into 10km squares (n=1019). Rare species in this study have been found in fewer than 31 10km squares while scarce species have been found in fewer than 130 10km squares (Tyner, 2014). The database includes Northern Irish records. Species obligatorily associated with or restricted to peat bogs (Bond, 1989; Spitzer & Danks, 2006), were also considered to be of conservation concern due to loss of raised bog habitat.

Statistical analyses

The information-theoretic approach (Mazerolle, 2006) was used to compare two Poisson generalised linear models (GLMs) of the counts for the 14 species recorded in more than half of the 12 sites. The two models for each species were (i) site pair; and (ii) site pair and designation status. GLMs are mathematical extensions of linear models (McCullagh & Nelder, 1989) and offer advantages in handling nonlinear ecological data relationships (e.g. Guisan *et al*., 2002; Marmion *et al*., 2009).

The modelling of the abundance data was undertaken in R (R Development Core Team, 2013). GLMs extend the linear modelling capability of R to scenarios that involve non-normal error distributions or heteroscedasticity. The Poisson distribution is widely used for the description of count data and is a one-parameter distribution, specified entirely by the mean (Agresti, 1996; Crawley, 2007). The mean: variance ratios range for the species data were close to 1. Hence the Poisson GLM modelling assumptions were met. Here we applied two Poisson GLMs for each species; GLM1 modelled species count as a function of site-pair, while GLM2 modelled counts as a function of both site-pair and designation status. This allowed us some measure of objective evaluation on the influence of designation status for each species using the information-theoretic approach that the Akaike information criterion (AIC) provides for the GLMs applied (e.g. Burnham & Anderson, 2002). Of itself, the value of AIC for a given data set has no meaning. An AIC is most useful when compared to the AIC of other models for the same data, and the model with the lowest AIC should be favoured (e.g. Mazerolle, 2006). Hence in our interpretation we favour the species models with the lower AIC values.

Rank-abundance diagrams (RADs) (MacArthur, 1957) were used to compare species richness, evenness and dominance in the moth communities on designated and undesignated sites. These diagrams provide an effective means of comparing community structure and may provide greater detail than a single diversity statistic (Krebs, 1999). In order to elucidate patterns of interest which may be obscured by aggregation of all species, an assemblage deconstruction approach (Matthews & Whittaker, 2015) was used whereby a number of species subsets were separated from the complete assemblage.

Multi-response permutation procedure (MRPP) is a nonparametric procedure for testing the hypothesis of no difference between two or more groups (McCune & Grace, 2002). MRPP is a multivariate analogue of an ANOVA and tests the within-group homogeneity by measuring a chance-corrected within-group agreement. A permutation procedure derives a simulated *P* value to assess the effects of grouping variables on similarity among sites. The Sørensen statistic was used as the measure of ordination distance among moth assemblages because it is less influenced by absent species than other measures, which is good in sparse datasets such as this, where absence does not necessarily mean the habitat was unsuitable and the species was genuinely absent (Peck, 2010). This measure is also less sensitive to outliers, unlike other measures, in which large differences between samples are measured more heavily than several small differences (McCune & Grace, 2002). MRPP was used to test difference among groups with designated site used as a grouping variable and using log-transformed abundance data for all species (n = 93), bog associated species (n = 47) and bog associated species of conservation concern (n = 15).

Indicator species analysis (ISA), using the method of Dufrêne & Legendre (1997), was carried out on groups defined by bog type, to assess group indicators based on species constancy and distribution of abundance.

Following investigation by graphing species as discrete variables using a Poisson distribution, 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 & Grace, 2002). NMS was used to investigate patterns and differences in assemblage composition and also the relationship between assemblage composition and explanatory variables. Ordination was carried out on bog associated species only. Other non-bog associated species which may have been vagrants or 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 (Fernandez *et al.*, 2014) or due to other habitats such as mineral rich soak systems and flushes being present, were considered to be a source of noise and were excluded. A similar exclusions was carried out by Oxbrough *et al.* (2012). Singletons were also excluded in order to reduce noise. This reduced the number of species from 47 to 37. Two species out of 13 species used as the basis for this analysis were only found on two sites. *Acronicta menyanthidis* (Esp.) was present at Mongan (2) (abundance in brackets) and Clara (1) and *Eugnorisma glareosa* (Esp.) was found at Clonaltra (1), Curraghalassa (3). Five species were found at more than six sites. Due to the overriding influence of sample date, species presence-absence data was used. 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 conducted at each iteration to determine dimensionality by graphing an NMS scree plot. All five scree plots suggested a three dimensional solution. MRPP, Indicator Species analysis and ordination were performed in PC-ORD (McCune & Mefford, 2011).

Results

Species data-set

A total of 1,816 adult individuals of 93 moth species were recorded, representing 16% of the Irish macro-moth fauna (582 species) (Bond *et al*., 2006). A complete species list is given in Appendix 1. Of these, 47 species (1650 individuals) were classified as being associated with raised bog habitat. Although this number of species is somewhat small, the species accumulation curves for designated and undesignated sites approach an asymptote (Fig. 2). Ten families were recorded, with two families (Noctuidae and Geometridae) together accounting for 90% of individuals. Four species dominated the dataset: *Lycophotia porphyrea* (D.& S.), *Apamea monoglypha* (Hufn.), *Noctua pronuba* (L.) and *Dyscia fagaria* (Thunb.). *Lycophotia porphyria* was the most abundant species on all sites representing just over 50% of individuals (n= 947). Many species were rare, with 47%, or 44 of the 93 moth species, represented by only one or two individuals.

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 associated with raised bogs. For designated sites, the species-accumulation curve appeared to approach asymptote more rapidly, at a lower value of species richness (Fig. 2), indicating that there are generally fewer bog-associated species at the designated sites. However, for most of the curve, difference between bog types is only marginally significant due to the overlapping standard deviations but the curves begin to diverge as samples accumulate and standard deviations cease to overlap so that this pattern is maintained as samples accumulate.

Common species: individual species analyses

We used the strengths of the information-theoretic approach to objectively evaluate the information provided when site designation status is included as a factor in our count GLMs versus when it is excluded (Table 1). No single model had all the support of all species. However, site and designation were a better explanation of abundance for six of the fourteen species. The negative AIC measures between GLM1 and GLM2 for the other eight species was less than 2 - commonly taken to indicate little evidence of much difference in model quality. Therefore, model (i) (or GLM1) was not well supported but model (ii) (or GLM2) was. Interestingly, model (ii) was supported over model (i) in these six cases - but in no cases was there strong evidence supporting model (i) over model (ii) perhaps due to the dissimilarity in species abundance between site pairs. Of the six species where site and designation status are a better explanation of abundance, *A. monoglypha*, *N. pronuba* and *Dicallomera fascelina* (L.) were more abundant on designated sites while *Pharmacis fusconebulosa* (DeG.), *Eupithecia nanata* (Hb.) and *Thera britannica* (Turner) were more abundant on undesignated sites. *Apamea monoglypha* and *P. fusconebulosa* show strong evidence of designation status affecting their abundance, while *N. pronuba*, *D. fascelina*, *E. nanata* and *T. britannica* show some evidence (delta AIC 2-6) and the remaining species little evidence (delta AIC <2). Sizes (difference in mean counts, taken from fitted models, between designated and undesignated sites), and evidence strength (based on delta AIC values) for the six species with strong evidence of an effect of designation status are shown in Tables 1 and 2.

Rank-abundance diagrams

RADs of designated and undesignated bogs showed similar species richness, evenness and dominance patterns for all species and also when deconstructed to show species of conservation concern and bog associated species only (Fig. 3a-c). Interestingly, RADs for bog associated species of conservation concern (Fig. 3d) showed that 11 out of 14 bog-associated species of conservation concern were, paradoxically, more abundant on undesignated sites. Three high rank bog associated species of conservation concern, namely *D. fascelina*, *Selidosema brunnearia* (Vill.) and *Arctia caja* (L.), were more abundant on designated sites. In other words, on designated sites, there is a group of three bog associated species of conservation concern that are more abundant, by approximately an order of magnitude or more, than other such species. Meanwhile, on undesignated sites, bog associated species of conservation concern show a more gradual decline in abundance with decreasing abundance rank. In terms of diagram shapes, the designated sites appear to show a broken stick shape while the undesignated sites appear to show a log normal shape (Magurran, 2004).

Multi-response Permutation Procedure (MRPP)

Similar to the RADs, the difference between groups as defined by designation status was not significant for either all species (n = 93) or bog associated species (n = 47). However, a significant difference between bog types was detected when tested using bog associated species of conservation concern (n = 15). Chance-corrected within-group agreement, A was 0.046, Test statistic (T) was -1.900 and $P = 0.0418$. 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 on these groups (log-transformed abundance data, 4999 = number of randomization runs) and *D. fascelina* was found to be a significant indicator of designated sites ($P = 0.0526$).

Non-metric Multidimensional Scaling (NMS) Ordination

NMS ordination (Fig. 4 and 5) 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 variance in the communities; 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 did not cluster together, but rather formed a continuum, mainly from undesignated to designated bogs from the positive to the negative side of Axis 2. However, Old Croghan and Kilballyskea, both undesignated bogs, seems more aligned with the designated bogs on this axis while Ferbane appears to align with the undesignated bogs as an outlier from the rest of the designated bogs (Fig. 4a). In general, the designated sites were less variable than the undesignated sites. Two undesignated sites (Clonaltra and Kilballyskea), were strong outliers from the rest of the bogs on the negative side of Axis 1.

Of the four explanatory variables investigated (Appendix 2), only two showed a correlation (r^2 value = 0.300) with Axis 1 or 2. These were displayed using joint plots (Fig. 4a). The negative side of Axis 1 is correlated with drain density. Axis 2 was separated by distance of the trapping site from the edge of the bog on the negative side of this axis.

On Axis 1 the four species which had the greatest positive influence were *Eilema lurideola* (Zin.), *A. caja*, *Mythimna impura* (Hb.) and *D. fagaria* (Table 2, Fig. 5). The species with the greatest negative influence on Axis 1 scores were *Alcis repandata (L.)* and *Phlogophora meticulosa* (L.). Four species had a positive influence on Axis 2; *Syngrapha interrogationis (L.)*, *Idaea aversata* (L.), *E. nanata* and *E. glareosa* . Three species had a negative influence on Axis 2 scores; *S. brunnearia*, *Macrothylacia rubi* (L.) and *A. menyanthidis* . This side of Axis 2 is associated with designated raised bogs and, therefore, these species are of interest as potential indicators.

Discussion

The present study is the first to evaluate whether there is a distinct moth fauna associated with active raised bog habitat on designated sites by comparing them to undesignated sites where this habitat has been lost. The study did reveal differences between the faunas of each type which are discussed below. However, one of the most interesting results, revealed by RADs, was that several bog associated species of conservation concern were more abundant on undesignated sites. This result should not be interpreted as indicating that undesignated degraded sites hold similar or greater species richness of bog associates than designated sites. As found in previous raised bog studies (Bezděk *et al.*, 2006, Väisänen, 1992) many characteristic species, even species of conservation concern, may have a preference for such drier areas than central active raised bog habitat. More detailed survey work on designated sites including drier marginal habitat as well as wet active raised bog habitat is required to determine this. We suspect, given the species and their biology, designated sites would perform better than undesignated sites in terms of characteristic biodiversity maintenance under such a sampling regime. However, the contrary cannot be ruled out which would cast doubt on the efficacy of the coarse filter conservation approach for invertebrates. Ferbane Bog, where sampling took place in a dry marginal area, was the most species-rich of all designated sites but still had fewer bog associated species than the two most speciose undesignated sites. Van Duinen (2013) found that the number of characteristic macroinvertebrates is not clearly related to the presence of a characteristic raised bog vegetation.

Designations should be reviewed as more species data become available to determine sites biodiversity maintenance function. Poorly performing designated sites should be prioritised for restoration management or where evidence points to undesignated bogs performing strongly, such sites should be considered for conservation. For example, ordination shows that Old Croghan aligns more with designated sites, and if added to the suite of designated sites would presently increase the representation of bog associates by four additional species. This highlights the possible role undesignated botanically degraded raised bogs may have to play in bog associated invertebrate conservation.

The single species analysis revealed that *A. monoglypha*, *N. pronuba* and *D. fascelina* were more associated with designated than undesignated sites. Both *A. monoglypha* and *N. pronuba* are very common and widespread species (Waring & Townsend, 2009) but have been previously recorded from central areas of Irish raised bog (Bond, 1989) and are considered raised bog associated species in this study. A possible explanation for the alignment is greater species abundance in the landscape surrounding such sites due to less intensive agricultural management. Both species are highly mobile (Slade *et al.,* 2013) and are likely vagrants onto raised bog. However, paired designated and undesignated sites lie within the same landscape matrix under the same general management, with much improved agricultural grassland, other bog fragments and some conifer plantation and scrub.

As with larval stages, adult moths also have nectar host plant preferences which may explain the preference of these nectar-feeding species for designated raised bogs. Using data from a long-term German study, Altermatt & Pearse (2011) have recorded a number of adult host plants for both species (*A. monoglypha*; 4 taxa and *N. pronuba*; 13 taxa). These two species were found to be among the 25 most important pollen vectors out of a sample of 103 nocturnal moth species in a study of Scottish pine forest (Dévoto *et al,* 2011). Interactions with plants were observed indirectly through sampling pollen load, which was found to be from the pooled taxa *Erica cinerea / tetralix*. Pine forest understory contains a number of the woody ericoid scrubs, including *C. vulgaris* but *E. cinerea / tetralix* was found to be the sole structurally important taxon for all visiting moth species.

While *E. cinerea* is absent from Irish midland raised bogs, *E. tetralix* is a commonly found (Kelly & Schouten, 2002) and grows well on hummocks within central ecotope (Kelly *et al.*, 1995). This species is associated with waterlogged soil conditions (Jones & Etherington, 1970) and is widespread but found at low abundance on degraded cut-over bogs (M. McCorry, pers. comm.). It is possible that the alignment of *N. pronuba* and *A. monoglypha* with designated sites is due to the greater abundance of one of their preferred nectar sources, *E. tetralix*. Due to their mobility, it is likely that vagrants from the surrounding landscape do enter designated sites but preference may be due to the greater availability of their preferred nectar source. In addition, evidence suggests a correlation between oviposition sites and nectar-producing flowers (Altermatt & Pearse, 2011) which may increase resident populations of these species on designated sites.

Dicallomera fascelina is considered a rare peatland species in Ireland where the majority of records are from midland raised bogs (Tyner, 2014) and therefore its alignment with designated sites is of interest. Its larval food plant is *C. vulgaris*, which is widespread on peatland and so its rarity may be related to other habitat or microhabitat features not found on undesignated degraded sites. This would merit further study.

Larval food plant choices provide an explanation for the alignment of *P. fusconebulosa*, *E. nanata* and *T. britannica* with undesignated sites. *Pharmacis* *fusconebulosa* feeds on 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 & Townsend, 2009). Neither of the known food plants occur on good quality raised bog. The larval stages of *E. nanata* feed on the flowers of *C. vulgaris* (Waring & Townsend, 2009). This plant has been noted to flower abundantly under conditions of greater soil aeration in degraded bog areas (Kelly & Schouten, 2002) and provides an explanation for the alignment of this species with degraded sites. *Thera britannica* feeds on coniferous trees which are considered invasive species on raised bogs (Fernandez *et al*, 2014) and are more abundant on drier undesignated sites.

Rank abundance diagrams of the communities in the present study showed generally no difference between degraded and protected raised bogs. However, the diagram for "bog associated species of conservation concern" was different with a greater evenness of high relative abundance species on protected compared to degraded sites. Visual inspection of the graph of bog associated species of conservation concern (Fig. 3d) suggests that designated bogs show a Broken Stick distribution (MacArthur, 1957), which has been described as a more equitable distribution than the Log Normal distribution (Fattorini, 2005) and has good fits for communities with relatively high evenness between species (Giller, 1984). This finding has important conservation implications as it shows that designated sites may be more resilient than undesignated sites and thereby better able to conserve species of conservation concern associated with this habitat type. This also indicates that for this specific sub-set of species bog designation appears to be fulfilling its promise in the "coarse filter" approach.

Ordination revealed that designated sites were less variable than undesignated sites in terms of community composition, probably due to the similarity of the sampled habitat. Two undesignated sites (Clonaltra and Kilballyskea) were strong outliers from the rest. Clonaltra is a secondary degraded raised bog and has been highly modified. Kilballyskea is an intact degraded site but has been extensively drained and is covered with tall (>1m), rank heather and invasive *Pinus* species. Neither bog area nor connectivity was found 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 & Wilson, 1967). Savage *et al.* (2011) also found that bog size had no influence on species richness or diversity in a study of Nearctic bog dipteran fauna. It should, however, be noted that sample size was fairly low (6 + 6) to test the theory of island biogeography.

Ordination also showed that the directional shift in assemblage composition associated with designation status was 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 bog specialists. *Acronicta menyanthidis*, *M. rubi* and *S. brunnearia* 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 (Spitzer & Danks, 2006). One of its larval foodplants is *Menyanthes trifoliata*, a common species of bog pools, the presence of which indicates very wet conditions (Kelly & Schouten, 2002). This species was only found on Mongan and Clara Bogs, which have the largest amount of central ecotope in this study.

Macrothylacia rubi is a widespread species which overwinters as a larva on or just beneath the ground under moss or leaf litter (Waring & Townsend, 2009) and links to designated sites may be due to the availability of overwintering habitat.

Selidosema brunnearia is scarce species with a complex distribution (Skinner, 2009). In Europe, it is found on dry *Calluna* heathland on sandy soil, dry limestone steppes in the south of its range and also on wet acid bogs, mostly in Ireland and Scotland (Gelbrecht *et al.,* 1997, Waring & Townsend, 2009). On wet raised bogs in the Irish midlands and blanket bogs in the west, it may be that it uses moss hummocks which provide microhabitat conditions such as a dry environment (similar to its heathland and steppe habitat) and a specific thermal range, allowing larvae to burrow into the hummock during cold spells. For example, on bogs in Russia, Mazei & Tsyganov (2007) found a xerophilous testate amoebae community on *Sphagnum* hummocks. On raised bogs in Ireland, water table levels stay below hummock surface level all year with the lowest water table levels experienced by hummocks comprised of *Sphagnum austinii* (Kelly & Schouten, 2002). Cover of *C. vulgaris*, its food plant, is frequently high on this and certain other hummocks types (Kelly & Schouten, 2002). The reason for the restricted distribution of *S. brunnearia* merits further study, as it shows potential as an active raised bog indicator species and in addition appears to be endangered over some of its range (Gelbrecht *et al*., 1997).

The species associated with the positive end of Axis 2 (*S. interrogationis, I. aversata*, *E. nanata* and *E. glareosa*), along with species aligned with undesignated bogs in single species analysis, may have potential to be used as 'negative indicators' of degraded raised bog. *S. interrogationis* feeds on heather and has been found to be associated with peat bog margin in central Europe, which agrees with our finding (Bezděk *et al.,* 2006). Singletons of this species were found on three undesignated sites (Clonaltra, Curraghalassa, Clonlyon Glebe). Bond & Gittings (2008) also mention that it comes singly to light traps and also note that it is probably in decline in much of the Irish midlands. *Eugnorisma glareosa* is polyphagous but also feeds on heather and is associated with dry heath, a habitat more akin to degraded than wet, active raised bog. This species has declined by 90% between 1968 and 2002 (Waring & Townsend, 2009). *Idaea aversata* is a widespread species. Its food plants include *Galium* species (Waring & Townsend, 2009). *Galium saxitale* is associated with cut-over bog plant communities which explains *I. aversata's* orientation to undesignated sites (Kelly & Schouten, 2002).

Single species analysis and multivariate analysis picked out different species alignment with designated sites. An explanation for this may be that the latter analysis used abundance data while multivariate analysis used presence/absence data. The two analyses may complement each other.

Limitations

i) Trapping effects

The main limitation of this study is the numerous biases inherent in the use of light traps (Dévoto *et al*., 2011) due to the varying responses of moths to light determined by their behaviour and physiology. For example, body size, flight ability, sex, host plant specificity, flight season, weather conditions (particularly temperature) and moon phase can all influence trapping rates (Beck & Linsenmair, 2006, Betzholtz & Franzén, 2011, Jonason *et al.*,2014).

Due to the above sources of bias, light trapping is a sampling method which gives a measure of mobility and attraction to light rather than of relative or absolute abundance. The trapping protocol was standardised as far as possible so that bias remained constant. However, even when an attempt to trap on consecutive nights with similar weather conditions was made, differences in moth activity between nights masked underlying true abundance differences. Ordination analysis was therefore based on presence/absence rather than abundance counts to overcome this weakness. It is recommended that in future, sampling is exactly temporally aligned. By exploiting the higher moth activity during warm nights and having an understanding of the species' phenology, it is possible to increase the number of species caught and reduce effects of confounding abiotic factors (Jonason *et al.*, 2014). Alternatively, a range of abiotic factors, such as temperature, rainfall, wind speed, moonlight, and cloud cover should be recorded at trap events and used to correct for their effects on moth flight activity and trap efficiency during data analysis (Beck *et al.*, 2011). Our study design meant that designated and undesignated group analyses were less affected by bias than individual site by site analysis.

Differences in species’ behaviour between designated and undesignated sites may also have led to bias. For example, particular species might tend to make longer distance movements in poorer habitats, where its food plants or mates were rarer, thereby increasing the likelihood of capture. However, routine explorative (foraging) behaviour results in slower, looping flights and occurs within smaller spatial scales (Van Dyck & Baguette, 2005) and so such individuals may be less likely to end up in traps than migrating or dispersing species, associated with high population density (Betzholtz & Franzén, 2013), with strong directional flight.

Our study assumes that sampling efficiency was equivalent among sites, particularly between designated and undesignated sites. Denser vegetation, for example, invasive trees and scrub on undesignated sites, can reduce visibility of traps and hence their attraction radius resulting in a smaller sample of individuals and lower apparent species richness. Traps were placed in habitat which had good visibility for at least 20-30 m. The radius of attraction for moths, of low powered light traps, similar to those used in this study, has been found to be very small, often even below 10 m (Truxa & Fielder,

2012) and so the issue of vegetation density reducing trap visibility is not considered to be significant, except in the case of Kilballyskea where visibility is likely to have been reduced due to uniform tall >1 m heather growth. Even though sampling on Ferbane took place in marginal ecotope as close to central ecotope as possible, this bog aligned with undesignated sites in ordination analysis suggesting than light trapping can have a very limited attraction range.

Even though light trapping is the most effective technique for general moth recording (in terms of the wide spectrum of species it attracts relative to the sampling effort [Waring & Townsend, 2009], many moth species (day-flying species in particular) are rarely, if ever, attracted to light. Such bog associated species may include *Anarta myrtilli* (L.), *Ematurga atomaria* (L.), *Idaea muricata* (Hufn.), *Rheumaptera hastana* (L.), *Orgyia antiqua* (L.), *Phytometra viridaria* (Clerck), *Chiasmia clathrata* (L.), *Eupithecia satyrata* (Hub.), *Parasemia plantaginis* (L.) and *Diacrisia sannio* (L.) (Bond, 1989; Waring & Townsend, 2009). None of these species, with the exception of *E. atomaria* are known to be notably abundant on Irish raised bogs (Bond, 1989), with many considered scarce or rare (Tyner, 2014). While our sampling method is considered to have detected relative patterns of species richness / abundance between designated and undesignated sites, it has not fully described the moth fauna of these sites. Netting is considered the most appropriate sampling method for day-flying moths and a comparative study to ours using this method would be considered worthwhile, in order to investigate whether similar patterns emerged using a different suite of species and sampling methods. Netting may be more effective in sampling certain bog associated dusk flying species such as *Hypenodes humidalis* (Waring & Townsend, 2009) and *Carsia sororiata*, the latter a bog specialist (Spitzer & Danks, 2006), not recorded on Irish raised bogs in recent years as well as micromoths, which can be underrepresented at light traps (Fuentes-Montemayor *et al.*, 2012).

(ii) Flight season and optimal sampling regime:

Sample size was relatively low (6+6 sites) and sites were confined to one county. However, habitat variability is low and climatic conditions similar on designated midland raised bog sites and therefore it is considered that difference between groups is valid.

When light sampling duration is limited (< 10 nights), as in this study, it has been shown to be slightly better to concentrate on the warmest summer nights (June – August) (Jonason *et al.,* 2014). Sampling in the present study commenced at the beginning of July, however, preliminary light trapping in mid and late June 2009/2010 on six SAC raised bogs recorded 26 June flying raised bog associated species, 20 of which were recorded in July 2011 (Flynn, 2014). The six species missing in 2011 were recorded at low abundance (< 8 specimens in two years) so the impact of their absence is not considered significant. Review of 3 years of sampling data revealed that phenological factors, including perhaps adaptations to nectar availability, seem to have a strong effect on patterns of moth species richness and abundance, which is similar to the finding of Jonason *et al*. (2014). In 2011, when trapping focused particularly at the end of July and beginning of August, a number of bog associated moth species were found in significantly greater abundance than in the previous two years preliminary sampling (e.g. *A. monoglypha*; 2009/2010 = 38, 2011 = 225), *L. porphyrea*; 2009/2010 = 162, 2011 = 947), *N. pronuba*; 2009/2010 = 44, 2011 = 103) and *S. brunnearia* 2009/2010 = 1, 2011 = 32). *Selidosema brunnearia* is of interest as abundance increased from 1 to 32, indicating that this species has a particularly short flight season, which was adequately covered in 2011, but not in the previous two years. A remarkably short flight season (4-24/8) was noted by Gelbrecht *et al.* (1997) for this species. *Saturnia pavonia*, a bog associated species with a flight period April/May was not sampled in 2011. *Macrothylacia rubi* and *Ceramica pisi* (max flight season in early June) were under-recorded. As for Autumn/Winter flying species, the maximum flight season of *Xestia agathina* (late August/September) was not covered adequately in 2011 but no other important late Autumn/Winter flying bog associated species are known to have been under recorded. No species are known to fluctuate greatly on raised bogs from year to year due to natural factors other than flight season.

Conclusion

In summary, six species were correlated with designated raised bogs: *A. monoglypha, N. pronuba, D. fascelina, A. menyanthidis S. brunnearia* and *M. rubi*. One significant indicator species (*D. fascelina*) of designated raised bogs was found. Link to food plant, both adult and larval, is a useful feature of this group, which explained the alignment of species with undesignated sites than designated sites. However, it did not provide an explanation for the presence of *S. brunnearia* or *D. fascelina* indicating that other factors, such as structural diversity may be responsible for their preference for designated raised bog habitats and this link should be investigated. The study suggests that *D. fascelina, A. menyanthidis* and *S. brunnearia,* bog associated species of conservation concern, may be particularly vulnerable to the loss of relatively intact raised bog.

The results show that undesignated, degraded bogs harbour moth species of conservation concern and may have a valuable role to play in the conservation of certain species. Further research is required to fully describe the invertebrate fauna of these sites and of the marginal areas of designated sites. In general, differences between moth communities on designated and undesignated sites were rather subtle, but there is evidence that designated sites may be performing better than undesignated sites for some of the most important moth communities i.e. those that are bog-associated and of conservation concern.

The findings of this study also suggest that further research on potential active raised bog biodiversity indicator species should take place at a landscape scale and not just focus on designated sites. Further research should include a suite of carefully selected species or groups.

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Tables

Table 1. Summary of Akaike information criterion (AIC) for the Poisson generalised linear models (GLMs) on the species count data comparing site-pair only and site pair and designation status as factors for the most common fourteen species found on more than half the sites.

Species	**AIC GLM1**	**AIC GLM2**	**Δ AIC**
Apamea monoglypha (Hufn.)	174.68	155.17	19.51
Pharmacis fusconebulosa (*DeG.)*	51.41	44.68	6.73
Noctua pronuba (L.)	85.82	80.66	5.16
Eupithecia nanata (Hb.)	49.87	45.08	4.78
Thera britannica (Turner)	34.12	29.38	4.74
Dicallomera fascelina (L.)	51.04	48.42	2.62
Lycophotia porphyrea (D.& S.)	303.21	302.24	0.97
Arctia caja (L.)	43.10	43.44	-0.34
Dyscia fagaria (Thunb.)	88.12	88.87	-0.75
Eilema lurideola (Zin.)	66.18	67.82	-1.64
Selidosema brunnearia (Vill.)	73.71	75.58	-1.88
Agrotis exclamationis (L.)	28.562	30.451	-1.889
Mesapamea secalis agg.	29.941	31.83	-1.889
Laothoe populi (L.)	35.348	37.271	-1.923

Notes: GLM 1 = Site Pair only; GLM 2 = Site Pair & Designation Status

Table 2. Predicted mean counts from fitted Poisson GLMs for each site pair by species. Site Pair and Site Pair and Designation provide the mean predicted counts from GLM1 and GLM2 respectively; Site count provides the recorded species abundances for comparison. Moth species have been nominated using an abbreviated form of their name. This is formed by taking the first four letters of the genus and 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.

Site	Species	Site Pair	Site Pair & Designation	Site count	Species	Site Pair	Site Pair & Designation	Site count
Sharavogue	APAMMONO	20.25	26.45	5	EUPINANA	1.69	0.71	1
Kilballyskea		20.25	14.04	2		1.69	2.67	2
Mongan		19.62	25.64	37		1.65	0.69	1
Doon		19.62	13.60	27		1.65	2.60	0
Ferbane		19.02	24.85	33		1.60	0.67	8
Curraghalassa		19.02	13.19	16		1.60	2.53	0
Moyclare		18.43	24.09	44		1.56	0.66	1
Clonlyon		18.43	12.78	19		1.56	2.46	0
Clara west		17.87	23.34	9		1.52	0.64	2
Clonaltra		17.87	12.39	10		1.52	2.40	1
Raheenmore		17.32	22.63	19		1.48	0.62	2
Old Croghan		17.32	12.01	4		1.48	2.33	1
Sharavogue	PHARFUSC	1.29	0.43	0	THERBRIT	3.82	1.43	1
Kilballyskea		1.29	2.16	4		3.82	6.22	6
Mongan		1.37	0.46	0		2.04	0.76	1
Doon		1.37	2.28	1		2.04	3.31	4
Ferbane		1.45	0.48	1		1.09	0.41	1
Curraghalassa		1.45	2.42	2		1.09	1.76	2
Moyclare		1.54	0.51	0		0.58	0.22	0
Clonlyon		1.54	2.56	0		0.58	0.94	0
Clara west		1.63	0.54	2		0.31	0.12	0
Clonaltra		1.63	2.71	7		0.31	0.50	0
Raheenmore		1.72	0.57	0		0.16	0.06	0
Old Croghan		1.72	2.87	1		0.16	0.27	1
Sharavogue	NOCTPRON	9.88	12.47	5	DICAFASC	2.21	3.12	4
Kilballyskea		9.88	7.29	1		2.21	1.31	1
Mongan		9.32	11.77	18		2.23	3.14	4
Doon		9.32	6.88	10		2.23	1.32	0
Ferbane		8.79	11.10	17		2.24	3.16	3
Curraghalassa		8.79	6.49	9		2.24	1.33	1
Moyclare		8.30	10.47	14		2.26	3.18	2
Clonlyon		8.30	6.12	8		2.26	1.34	0
Clara west		7.82	9.88	7		2.27	3.20	5
Clonaltra		7.82	5.77	4		2.27	1.35	5

Raheenmore	7.38	9.32	4	2.29	3.22	1
Old Croghan	7.38	15.45	6	2.29	1.35	1

Table 3. Species variables correlation with NMS ordination axes, Cutoff r2 value = 0.300

Axis	**1**	
Variables	**r**	**r^2**
Eilema lurideola (Zin.)	0.771	0.595
Arctia caja (L.)	0.708	0.502
Mythimna impura (Hb.)	0.647	0.419
Dyscia fagaria (Thun.)	0.615	0.378
Alcis repandata (L.)	-0.793	0.629
Phlogophora meticulosa (L.)	-0.592	0.350
Axis	**2**	
Variables	**r**	**r^2**
Syngrapha interrogationis (L.)	0.762	0.580
Idaea aversata (L.)	0.746	0.556
Eupithecia nanata (Prout)	0.588	0.346
Eugnorisma glareosa (Esp.)	0.586	0.343
Selidosema brunnearia (Vill.)	-0.686	0.470
Macrothylacia rubi (L.)	-0.555	0.308
Acronicta menyanthidis (Esp.)	-0.547	0.299

Figure Legends

Figure 1. Map of Co. Offaly, central Ireland showing location of study sites. Black symbols represent designated sites and grey symbols represent undesignated sites. Symbol shape represents how sites were paired:

▲ Moyclare; ▲ Clonlyon; ● Sharavogue; ● Kilballyskea; ★ Mongan; ★ Doon
■ Ferbane; ■ Curraghalassa; ♦ Clara; ♦ Clonaltra; ⬟ Raheenmore; ⬟ Old Croghan.

Figure 2. Species-accumulation curves. For designated sites, based on the occurrence of 32 bog associated species in 30 subplots. For undesignated sites, based on the occurrence of 39 species in 30 subplots. Average species richness based on randomization procedure outlined in McCune & Grace (2002). Hatched lines represent ± 1 standard deviation from the mean.

Figure 3. Rank-abundance diagrams. The y axis shows the relative abundance of species (plotted using a log10 scale) while the x axis ranks each species in order from most to least abundant. (a) all species; (b) species of conservation concern; (c) bog associated species; (d) bog associated species of conservation concern.

Figure 4a. 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.

Figure 4b. 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.

Figure 4c. NMS ordination with bog-associated species of conservation concern presence-absence shown as vectors. Cutoff r2 value = 0.299; Vector lengths are relative to the correlation coefficients for each variable; Axis 1 r2 = 0.427; Axis 2 r2 = 0.243; Final stress = 6.194; Final instability = 0; Species data = presence-absence.

Figures

Fig. 1

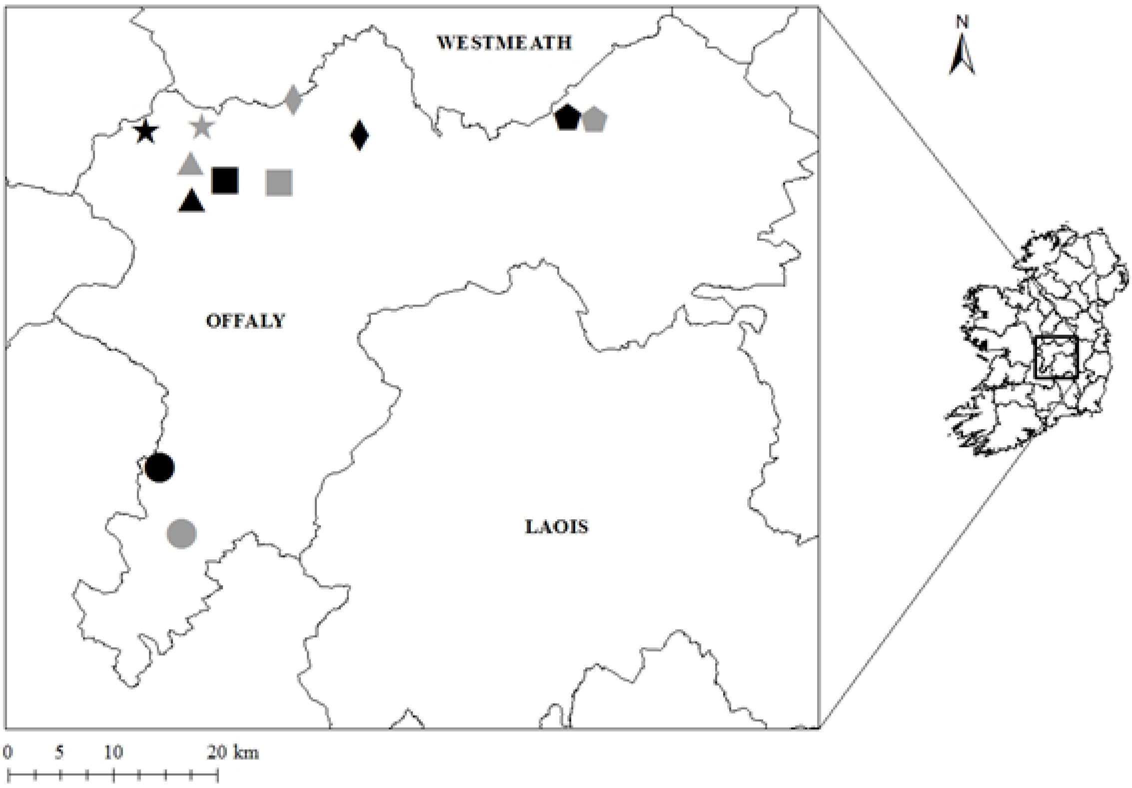

Fig. 2

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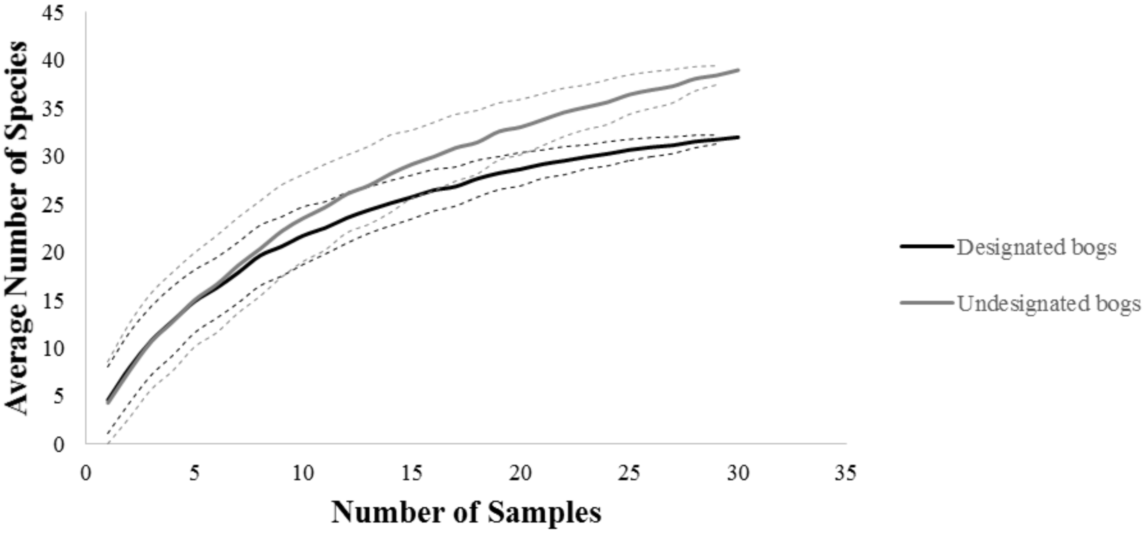
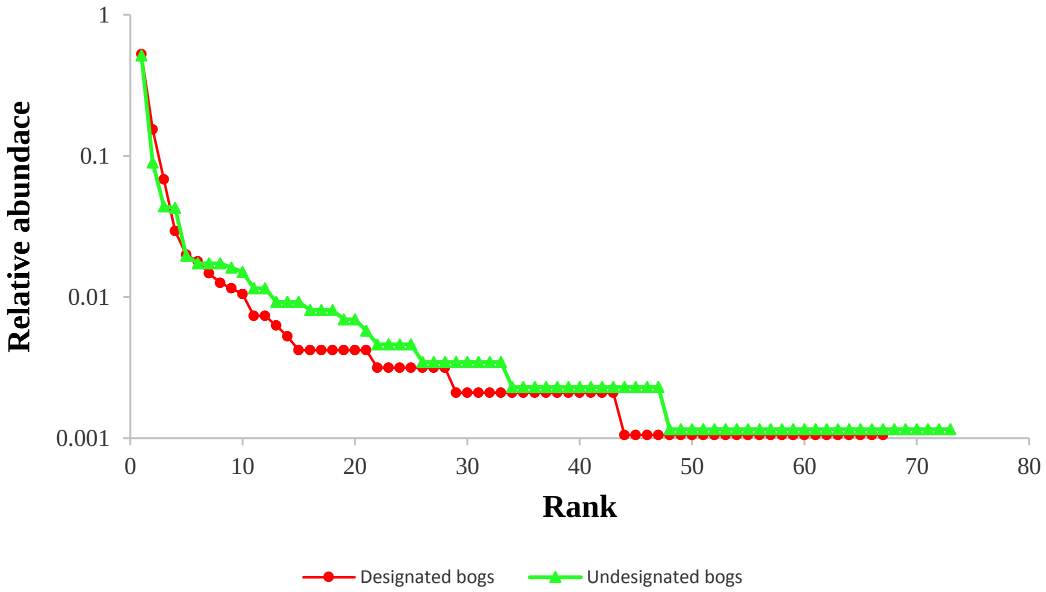

Average Number of Species
45
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
Number of Samples
Designated bogs
Undesignated bogs

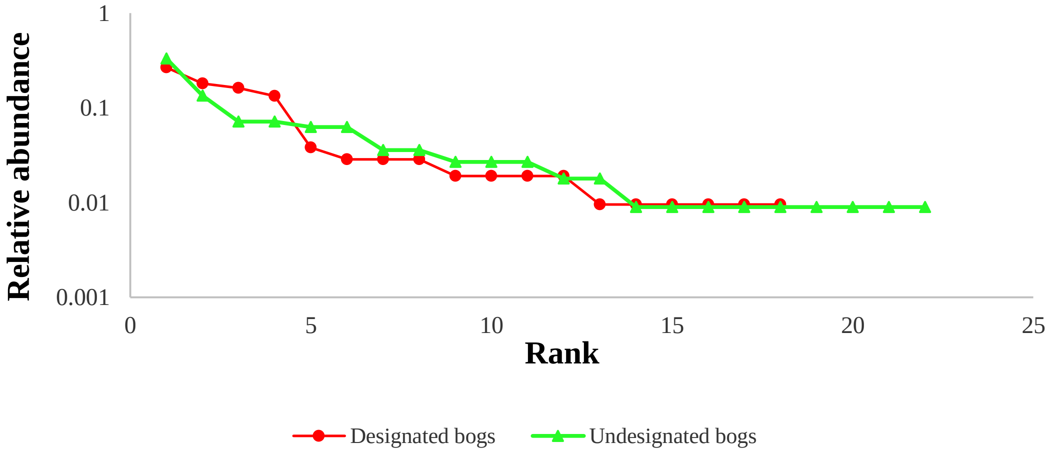
Fig. 3

–

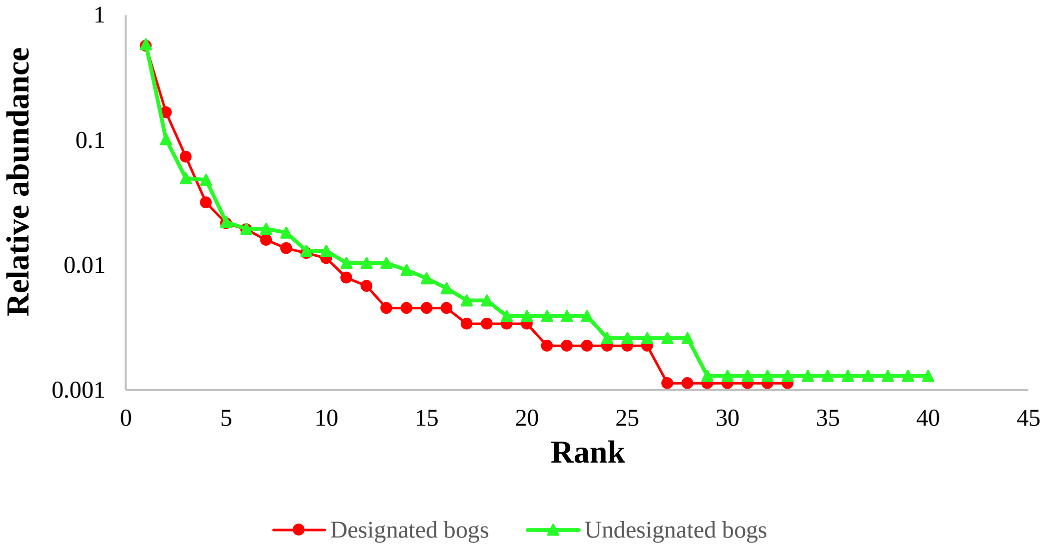
(a)


Relative abundace
1
0.1
0.01
0.001
0
10
20
30
40
50
60
70
80
Rank
Designated bogs
Undesignated bogs

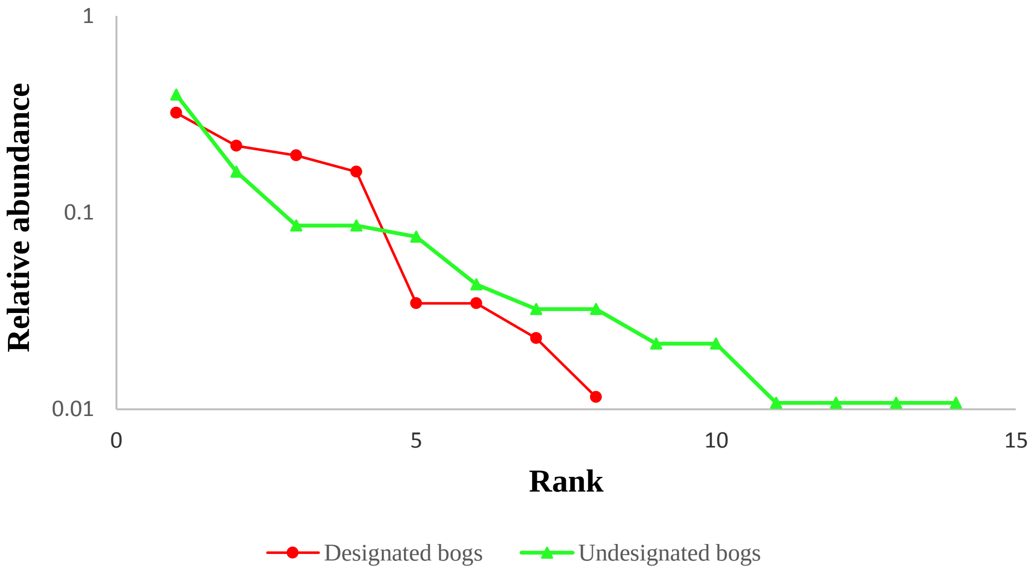
(b)


Relative abundance
1
0.1
0.01
0.001
0
5
10
15
20
25
Rank
Designated bogs
Undesignated bogs

(c)


Relative abundance
1
0.1
0.01
0.001
0
5
10
15
20
25
30
35
40
45
Rank
Designated bogs
Undesignated bogs

(d)


Relative abundance
1
0.1
0.01
0
5
10
15
Rank
Designated bogs
Undesignated bogs

–

Fig. 4

(a)_

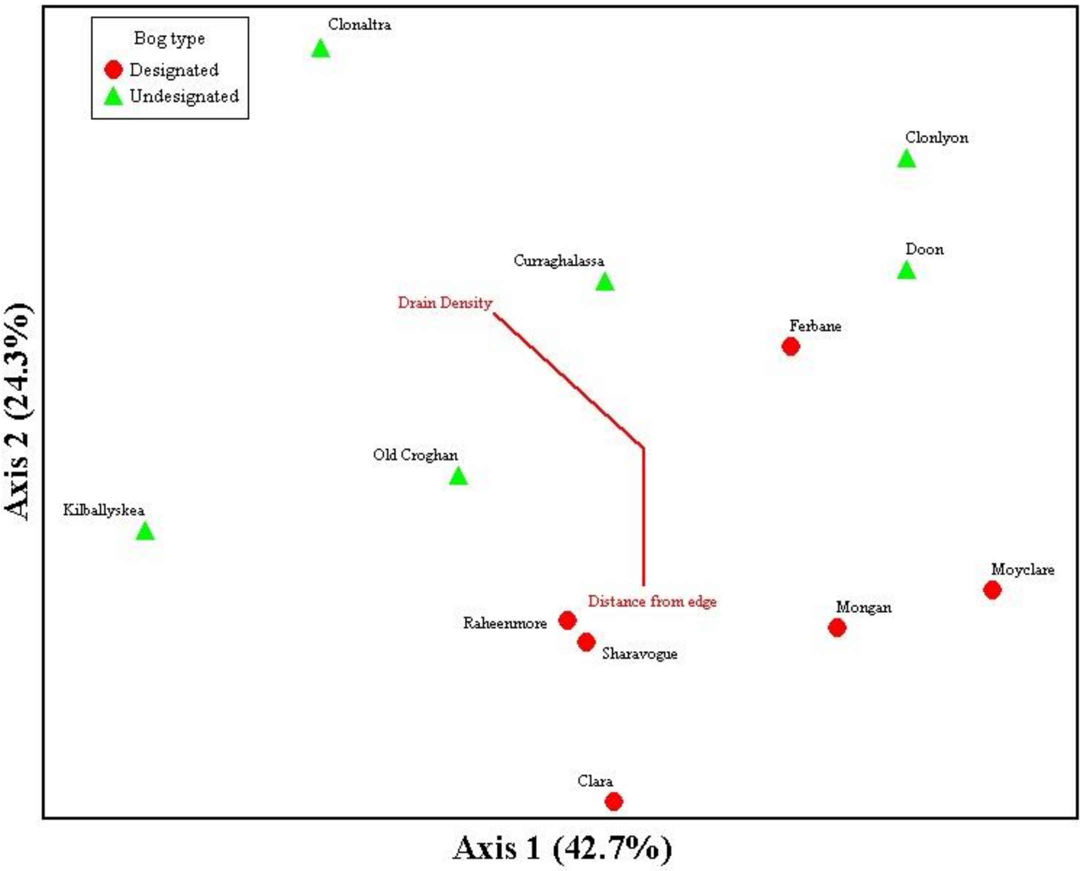

Bog type
● Designated
▲ Undesignated
Clonaltra
Clonlyon
Curraghalassa
Doon
Drain Density
Ferbane
Old Croghan
Kilballyskea
Moyclare
Distance from edge
Mongan
Raheenmore
Sharavogue
Clara
Axis 2 (24.3%)
Axis 1 (42.7%)

Fig. 4

(b)

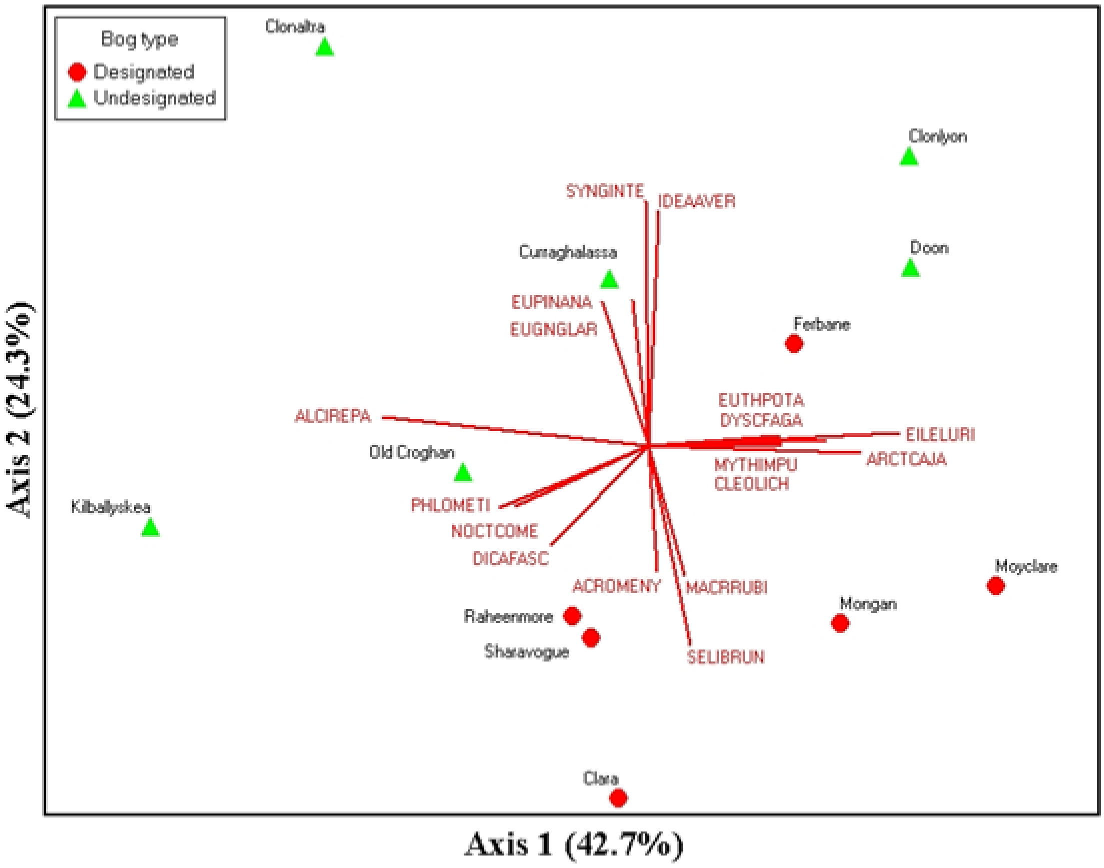
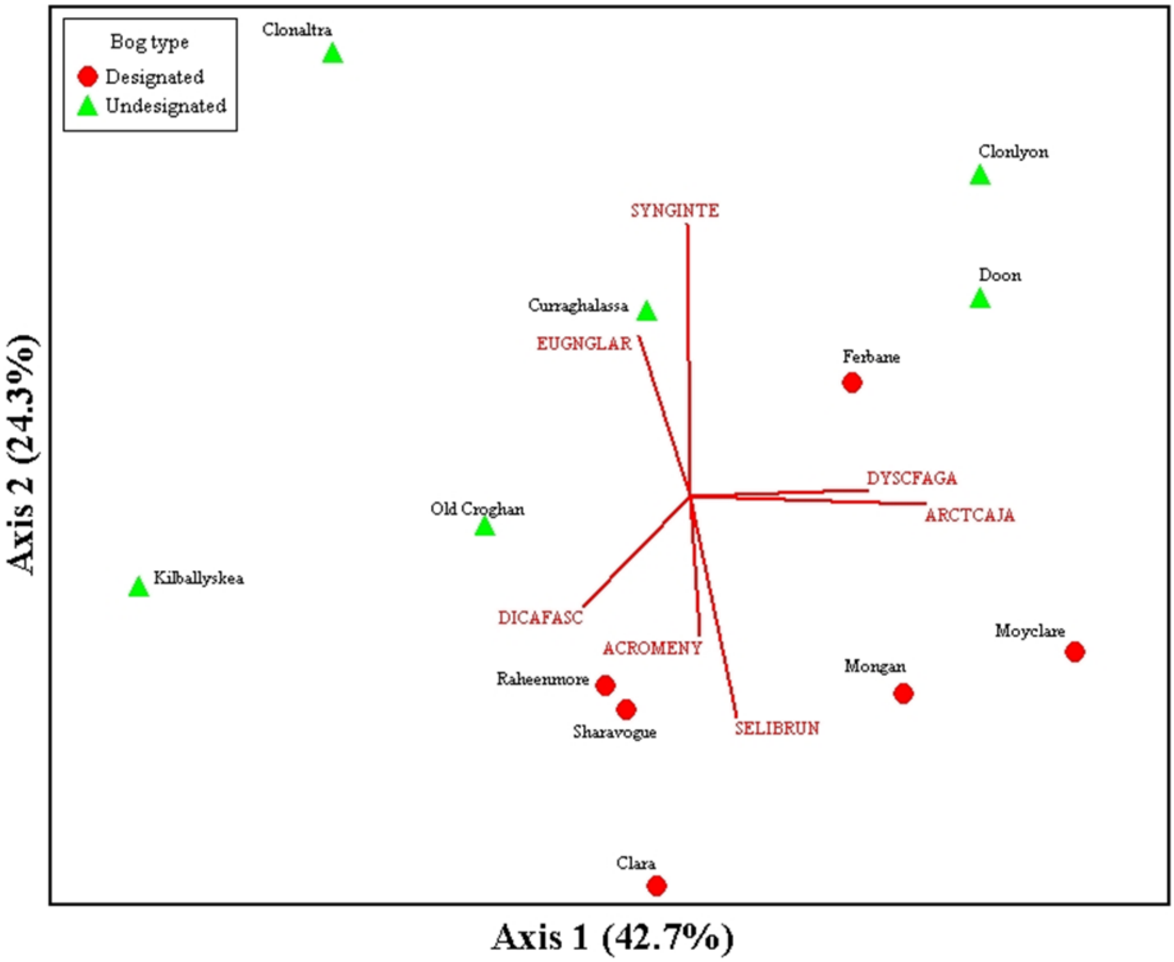

Bog type
● Designated
▲ Undesignated
Clonaltra
Clonlyon
Doon
Curraghalassa
Ferbane
Old Croghan
Kilballyskea
Moyclare
Mongan
Raheenmore
Sharavogue
Clara
SYNGINTE
IDEAAVER
EUPINANA
EUGNGLAR
ALCIREPA
EUTHPOTA
DYSCFAGA
EILELURI
ARCTCAJA
MYTHIMPU
CLEOLICH
PHLOMETI
NOCTCOME
DICAFASC
ACROMENY
MACRRUBI
SELIBRUN
Axis 2 (24.3%)
Axis 1 (42.7%)

Fig. 4c


Bog type
● Designated
▲ Undesignated
Clonaltra
Clonlyon
SYNGINTE
Doon
Curraghalassa
EUGNGLAR
Ferbane
DYSCFAGA
Old Croghan
ARCTCAJA
Kilballyskea
DICAFASC
Moyclare
ACROMENY
Mongan
Raheenmore
Sharavogue
SELIBRUN
Clara
Axis 2 (24.3%)
Axis 1 (42.7%)

Appendix 1. List of moth species recorded in the study.

Abbreviation	**Scientific Name and Authority**	**Common Name**	**Habitat Association**	**Conservation Status**	**Total no.**
ACROMENY	*Acronicta menyanthidis* (Esper, 1789)	Light Knot Grass	Raised bog	Rare	3
AGROCIRC	*Agrochola circellaris* (Hufnagel, 1766)	Brick	Other	Declining	3
AGROEXCL	*Agrotis exclamationis* (Linnaeus, 1758)	Heart and Dart	Other		9
AGROHELV	*Agrochola helvola* (Linnaeus, 1758)	Flounced Chestnut	Raised bog	Declining	1
AGROLOTA	*Agrochola lota* (Clerck, 1759)	Red-line Quaker	Other		3
AGROLYCH	*Agrochola lychnidis* (Denis & Schiffermüller, 1775)	Beaded Chestnut	Other	Vulnerable	1
AGROMACI	*Agrochola macilenta* (Hübner, 1809)	Yellow-line Quaker	Raised bog		1
ALCIREPA	*Alcis repandata* (Linnaeus, 1758)	Mottled Beauty	Raised bog		3
ALLOOXYA	*Allophyes oxyacanthae* (Linnaeus, 1758)	Green-brindled Crescent	Other	Vulnerable	2
AMPH (agg.)	*Amphipoea agg.*	Ear species	Raised bog		27
APAMMONO	*Apamea monoglypha* (Hufnagel, 1766)	Dark Arches	Raised bog		225
APAMREMI	*Apamea remissa* (Hübner, 1809)	Dusky Brocade	Other	Vulnerable	4
APLOPLAG	*Aplocera plagiata* (Linnaeus, 1758)	Treble-bar	Other	Declining	4
APORNIGR	*Aporophyla nigra* (Haworth, 1809)	Black Rustic	Raised bog		12
ARCTCAJA	*Arctia caja* (Linnaeus, 1758)	Garden Tiger	Raised bog	Vulnerable	22
AUTOGAMM	*Autographa gamma* (Linnaeus, 1758)	Silver Y	Other		2
AUTOJOTA	*Autographa jota* (Linnaeus, 1758)	Plain Golden Y	Other		2
BISTBETU	*Biston betularia* (Linnaeus, 1758)	Peppered Moth	Other		1
CABEEXAN	*Cabera exanthemata* (Scopoli, 1763)	Common Wave	Other		1
CELAHAWO	*Celaena haworthii* (Curtis, 1829)	Haworth's Minor	Raised bog	Vulnerable	1
CERAPISI	*Ceramica pisi* (Linnaeus, 1758)	Broom Moth	Raised bog	Vulnerable	8
CHLOSITE	*Chloroclysta siterata* (Hufnagel, 1767)	Red-green Carpet	Other		1
CHLOV-AT	*Chloroclystis v-ata* (Haworth, 1809)	V-pug	Other		2
CILIGLAU	*Cilix glaucata* (Scopoli, 1763)	Chinese Character	Other		2

Abbreviation	**Scientific Name and Authority**	**Common Name**	**Habitat Association**	**Conservation Status**	**Total no.**
CLEOLICH	*Cleorodes lichenaria* (Hufnagel, 1767)	Brussels Lace	Raised bog		2
COSMOCEL	*Cosmorhoe ocellata* (Linnaeus, 1758)	Purple Bar	Other		1
CROCELIN	*Crocallis elinguaria* (Linnaeus, 1758)	Scalloped Oak	Other		3
DEILELPE	*Deilephila elpenor* (Linnaeus, 1758)	Elephant Hawk-moth	Raised bog		2
DELTPYGA	*Deltote (Protodeltote) pygarga* (Hufnagel, 1766)	Marbled White Spot	Raised bog		1
DENTPYGM	*Denticucullus pygmina* (Haworth, 1809)	Small Wainscot	Raised bog		2
DIACCHRY	*Diachrysia chrysitis* (Linnaeus, 1758)	Burnished Brass	Other		1
DIARMEND	*Diarsia mendica* (Fabricius, 1775)	Ingrailed Clay	Raised bog		1
DICAFASC	*Dicallomera fascelina* (Linnaeus, 1758)	Dark Tussock	Raised bog	Rare	27
DREPFALC	*Drepana falcataria* (Linnaeus, 1758)	Pebble Hook-tip	Other		2
DYSCFAGA	*Dyscia fagaria* (Thunberg, 1784)	Grey Scalloped Bar	Raised bog	Scarce	65
EILEDEPR	*Eilema depressa* (Esper, 1787)	Buff Footman	Raised bog		3
EILELURI	*Eilema lurideola* (Zincken, 1817)	Common Footman	Raised bog		25
ENNOALNI	*Ennomos alniaria* (Linnaeus, 1758)	Canary-shouldered Thorn	Other		3
EUGNGLAR	*Eugnorisma glareosa* (Esper, 1788)	Autumnal Rustic	Raised bog	Endangered	4
EULITEST	*Eulithis testata* (Linnaeus, 1761)	Chevron	Raised bog		3
EUPINANA	*Eupithecia nanata* (Hübner, 1813)	Narrow-winged Pug	Raised bog		19
EUTHPOTA	*Euthrix potatoria* (Linnaeus, 1758)	Drinker	Raised bog		2
FALCLACE	*Falcaria lacertinaria* (Linnaeus, 1758)	Scalloped Hook-tip	Other	Declining	11
GEOMPAPI	*Geometra papilionaria* (Linnaeus, 1758)	Large Emerald	Other		1
GRAPAUGU	*Graphiphora augur* (Fabricius, 1775)	Double Dart	Other	Endangered	2
GRIPAPRI	*Griposia aprilina* (Linnaeus, 1758)	Merveille du Jour	Other		1
GYMNRUFI	*Gymnoscelis rufifasciata* (Haworth, 1809)	Double-striped Pug	Raised bog		3
HABRPYRI	*Habrosyne pyritoides* (Hufnagel, 1766)	Buff Arches	Other		2
HELOLEUC	*Helotropha leucostigma* (Hübner, 1808)	Crescent	Other	Vulnerable	2

Abbreviation	**Scientific Name and Authority**	**Common Name**	**Habitat Association**	**Conservation Status**	**Total no.**
HYDRMICA	*Hydraecia micacea* (Esper, 1789)	Rosy Rustic	Other	Vulnerable	2
HYDRFURC	*Hydriomena furcata* (Thunberg, 1784)	July Highflyer	Raised bog		5
IDAEAVER	*Idaea aversata* (Linnaeus, 1758)	Riband Wave	Raised bog		8
IDAEDIMI	*Idaea dimidiata* (Hufnagel, 1767)	Single-dotted Wave	Other		1
LAOTPOPU	*Laothoe populi* (Linnaeus, 1758)	Poplar Hawk-moth	Other		13
LASIQUER	*Lasiocampa (Lasiocampa) quercus* (Linnaeus, 1758)	Oak Eggar	Raised bog		8
LITHORNI	*Lithophane (Lithophane) ornitopus* (Hufnagel, 1766)	Grey Shoulder-knot	Other		1
LOMAMARG	*Lomaspilis marginata* (Linnaeus, 1758)	Clouded Border	Other		1
LYCOPORP	*Lycophotia porphyrea* (Denis & Schiffermüller, 1775)	True Lover's Knot	Raised bog		947
MACRRUBI	*Macrothylacia rubi* (Linnaeus, 1758)	Fox Moth	Raised bog		7
MESASECA	*Mesapamea agg.*	Common Rustic agg.	Raised bog		9
MESODIDY	*Mesotype didymata* (Linnaeus, 1758)	Twin-spot Carpet	Raised bog		1
MNIOADUS	*Mniotype adusta* (Esper, 1790)	Dark Brocade	Raised bog	Vulnerable	1
MYTHIMPU	*Mythimna impura* (Hübner, 1808)	Smoky Wainscot	Raised bog		8
MYTHPALL	*Mythimna pallens* (Linnaeus, 1758)	Common Wainscot	Other		1
MYTHPUDO	*Mythimna pudorina* (Denis & Schiffermüller, 1775)	Striped Wainscot	Raised bog	Scarce	1
NOCTCOME	*Noctua comes* (Hübner, 1813)	Lesser Yellow Underwing	Raised bog		5
NOCTPRON	*Noctua pronuba* (Linnaeus, 1758)	Large Yellow Underwing	Raised bog		103
NONATYPH	*Nonagria typhae* (Thunberg, 1784)	Bulrush Wainscot	Other		2
NOTOZICZ	*Notodonta ziczac* (Linnaeus, 1758)	Pebble Prominent	Other		9
NUDAMUND	*Nudaria mundana* (Linnaeus, 1761)	Muslin Footman	Raised bog		2
OPISLUTE	*Opisthograptis luteolata* (Linnaeus, 1758)	Brimstone Moth	Other		5
OURASAMB	*Ourapteryx sambucaria* (Linnaeus, 1758)	Swallow-tailed Moth	Other		2
PENNFIRM	*Pennithera firmata* (Hübner, 1822)	Pine Carpet	Other		3

Abbreviation	Scientific Name and Authority	Common Name	Habitat Association	Conservation Status	Total no.
PERCSTRI	*Perconia strigillaria* (Hübner, 1787)	Grass Wave	Raised bog		10
PHALBUCE	*Phalera bucephala* (Linnaeus, 1758)	Buff-tip	Other		3
PHARFUSC	*Pharmacis fusconebulosa* (DeGeer, 1778)	Map-winged Swift	Other		18
PHEOGNOM	*Pheosia gnoma* (Fabricius, 1776)	Lesser Swallow Prominent	Other		7
PHLOMETI	*Phlogophora meticulosa* (Linnaeus, 1758)	Angle Shades	Raised bog		22
PHRAFULI	*Phragmatobia fuliginosa* (Linnaeus, 1758)	Ruby Tiger	Raised bog		2
PLUSFEST	*Plusia festucae* (Linnaeus, 1758)	Gold Spot	Raised bog		1
RHIZLUTO	*Rhizedra lutosa* (Hübner, 1803)	Large Wainscot	Other	Vulnerable	3
RIVUSERI	*Rivula sericealis* (Scopoli, 1763)	Straw Dot	Raised bog		1
SELIBRUN	*Selidosema brunnearia* (de Villers, 1789)	Bordered Grey	Raised bog	Scarce	32
SPILLUBR	*Spilosoma lubricipeda* (Linnaeus, 1758)	White Ermine	Raised bog	Vulnerable	6
SUBAMEGA	*Subacronicta megacephala* (Denis & Schiffermüller, 1775)	Poplar Grey	Other	Scarce	3
SYNGINTE	*Syngrapha interrogationis* (Linnaeus, 1758)	Scarce Silver Y	Raised bog	Scarce	3
THERBRIT	*Thera britannica* (Turner, 1925)	Spruce Carpet	Other		16
THEROBEL	*Thera obeliscata* (Hübner, 1787)	Grey Pine Carpet	Other		1
THUMSENE[2]	*Thumatha senex* (Hübner, 1808)	Round-winged Muslin	Raised bog		1
XANTFERR	*Xanthorhoe ferrugata* (Clerck, 1759)	Dark-barred Twin-spot Carpet	Raised bog	Endangered	2
XESTAGAT	*Xestia agathina* (Duponchel, 1827)	Heath Rustic	Raised bog	Vulnerable	4
XESTC-NI	*Xestia c-nigrum* (Linnaeus, 1758)	Setaceous Hebrew Character	Other		6
XESTTRIA	*Xestia triangulum* (Hufnagel, 1766)	Double Square-spot	Other		2

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[2] *Thumatha senex* (Hb.) was previously classified as a tyrphobiont by Bond (1989). However its food-plant preference (lichens) (Waring & Townsend, 2009), conservation status (increasing) (Conrad *et al*., 2006) and widespread distribution (Tyner, 2014) indicate that this is not the case and, therefore, this species was not included in the list.

Appendix 2. List of explanatory variables used in the NMS ordination

	Minimum Distance to edge of high bog (m)	**Area of high bog (ha)**	**Drain density**	**Connectivity (C)**
Sharavogue	220	137.02	0.01599	22.64
Mongan	376	124.37	0.00748	17.03
Ferbane	123	119.98	0.00908	9.55
Moyclare	253	74.27	0.00512	7.49
Clara west	496	246.78	0.00071	32.77
Raheenmore	385	130.55	0.00720	12.96
Old Croghan	350	95.1178	0.03924	11.47
Clonaltra	151	578.1381	0.04637	35.57
Curraghalassa	238	65.4188	0.04181	24.19
Doon	127	47.7575	0.01048	37.99
Clonlyon	390	88.6453	0.04939	5
Kilballyskea	272	40.6374	0.06112	8