08 - SCIENTIFIC BASIS OF RAISED BOG CONSERVATION: THE APPLICATION OF A HYDROLOGICAL MANAGEMENT TOOL

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1. INTRODUCTION

A national project to assess the conservation status of European Union Habitats Directive (HD) designated raised bogs is currently underway. Ireland is obliged to protect, and where necessary, restore protected raised bogs to a condition that meets conservation objectives specified under the HD. To define and meet these objectives, a National Parks and Wildlife Service (NPWS) funded project is being carried out by RPS Consulting Engineers in conjunction with the Departments of Civil Engineering at Trinity College Dublin, and Queen's University Belfast. This requires the application of a hydrological modelling tool to estimate the restoration potential of protected raised bogs. Conservation Status (area, range and function of an ecosystem) is the means by which the status of ecosystems are assessed under the HD. Raised bog special areas of conservation (SACs) contain particularly important examples of raised bog ecosystems with active peat accumulation and are thereby considered active ecosystems. Fifty three raised bogs are designated as Scientific Areas of Conservation (SAC) in Ireland under the HD and all have suffered damage, primarily through drainage. However, the area of active raised bog (ARB) contained in these sites is small (estimated to be between 1700 and 1900 Ha,) and must be increased to meet requirements outlined in the HD. Increasing the area of active raised bog (ARB) necessitates accurate modelling of the current area of ARB, at individual bog sites, to allow implementation of focused management measures, the area of ARB can be increased (i.e. regenerated). This paper introduces approaches to analysing the occurrence of raised bog SACs in Ireland and the basis of hydrological metrics being developed to estimate raised bog restoration potential.

2. ECOHYDROLOGY

The occurrence of ecological communities of conservation value on the surface of raised bog wetlands requires that specific hydrological conditions are maintained. An intact raised bog is characterized by a domed relief with its surface typically defined by botanical communities that, when grouped together, based on eco-hydrological characteristics, form a collection of ecotopes (Van der Schaff & Streeferk, 2002). An ecotope supports a particular vegetation community arising from vegetation succession developing under a characteristic hydrological regime, determined by water table depth, fluctuation and hydrochemistry. For example, the Facebank Ecotope is the unit that experiences the driest conditions for prolonged periods, while the Central Ecotope is the wettest. In contrast to more minerotrophic wetlands the need for nutrient-poor water to support the vegetation is essential and this is derived primarily from rainfall. The duration and timing of waterlogging (water table at or above the ground surface) with nutrient-poor water is a critical element in maintaining raised bog ecotopes. Table 1 summarises the important hydro-ecological characteristics of the ecotopes as analysed from Clara Bog (after Van der Schaaf & Streefkerk, 2002).

Table 1. *Biotic and abiotic characteristics of ecotopes (after Van der Schaff & Streefkerk, 2002 and Kelly & Schouten, 2002)*

Ecotope	**Characteristics**
Facebank	*Abiotic:* No hummocks and hollows, acrotelm usually absent *Biotic*: Little or no peat forming plant communities, vegetation dominated by *Calluna vulgaris*
Marginal	*Abiotic:* No hummocks and hollows, acrotelm usually absent or poorly developed (< 0.05 m) *Biotic*: Little or no peat forming plant communities, vegetation dominated by *Calluna vulgaris* and *Trichophurum cespitosum*
Sub marginal	*Abiotic*: Some differentiation between hummocks and hollows, hollows inundated during small fraction of the year, acrotelm absent or thin (< 0.05 m) *Biotic*: Hollows dominated by *Nathecium ossifragum* and *Sphagnum tenellum*
Sub central	*Abiotic:* A micro-topography of hummocks, hollows and lawns, but no pools. Lawns are dominant. Acrotelm depth variable from 0.10 m up to locally well-developed 0.40 m. *Biotic*: Lawns dominated by *Sphagnum magellanicum*
Central	*Abiotic*: A micro-topography of hummocks, hollows and pools. Acrotelm moderate to well developed, depth up to 0.5 m *Biotic:* Pools, and hollows dominated by *Sphagnum cuspidatum*
Soak/ Active flush	*Abiotic*: Generally wet to extremely wet conditions, in the wettest parts lawns, in some parts pools and hollows and large, flat hummocks. Acrotelm well-developed > 0.4 m. *Biotic*: *Sphagnum cuspidatum* and *Sphagnum recurvum* lawns with *Carax rostrata*, in dryer places *Myrica gale* and *Betula pubescens* scrub/woodland with *Sphagnum palustre*. *Molinea caeulea* tussocks in some areas.

ARB is characterised by the presence of acrotelm, which is defined as the living, actively growing upper layer of a raised bog, the surface of which is composed mainly of living bog bosses (Sphagnum spp.) and upper poorly humified peats. The presence of the acrotelm is vital to the hydrological functioning of a raised bog as it is the peat forming layer and it strongly influences the rate of water runoff from the bog. ARB can occur only on the high bog, and encompasses the active peat forming ecotopes (central and sub-central) defined by Kelly and Schouten (2002), as well as active peat forming flushes and bog woodland (after Fernandez et al, 2013). Degraded Raised Bog (DRB), which the EU HD definition also restricts to uncut high bog, is considered to encompass sub-marginal, marginal and face bank ecotopes (Kelly and Schouten (2002)) as well as inactive flushes and dry woodland on bog. This definition identities DRB as raised bog habitat still capable of regeneration to ARB.

3. RESTORATION PROJECT

Raised bogs are a rare habitat in global terms and those found in Ireland are sites of European and international importance. ARB is particularly important as it is a priority habitat under Annex I of the HD. A significant portion of the world's remaining ARB occurs in Ireland. Between 1997 and 2002, the Irish government nominated a total of 53 raised bog sites for designation as Special Areas of Conservation (SACs) under the HD. Under the HD these sites must be protected, managed and restored to ensure they achieve their objectives in relation to conservation status (RPS, 2013). Their locations are shown in Figure 1.

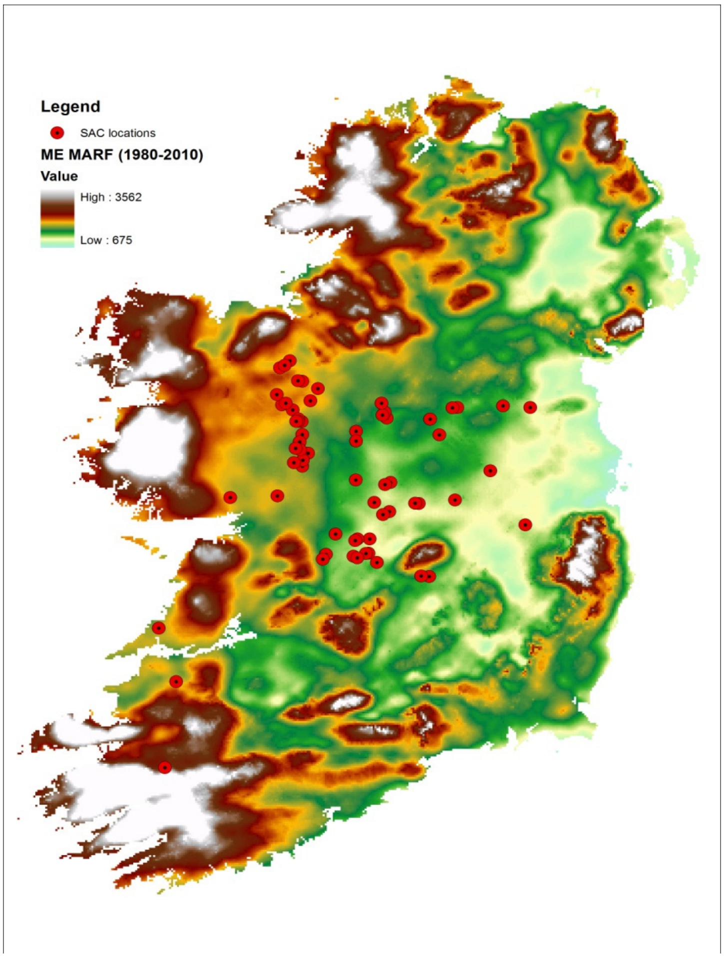

Figure 1. *Distribution of raised bog SACs superimposed upon a Met Eireann Map of Mean Annual Rainfall (1980-2010; Walsh, 2012)*

Ireland's peatlands have historically been reclaimed for a variety of purposes, including domestic and commercial turf cutting, agriculture and forestry. These uses are important socially and economically, yet the drainage associated with these activities is believed to constitute one of the principle causes of their general ecological deterioration in recent years. This has included a significant decrease in the area of ARB in most of these sites and the further loss of areas of DRB. As a result of this deterioration, the European Commission has brought legal proceedings resulting in adverse judgements against the Irish State by the European Court of Justice. To avoid significant fiscal penalties the provision of the necessary protective measures on Ireland's raised bog SACs is now urgent (RPS, 2013).

The Raised Bog Conservation Study (RBCS) involves the provision of specialist scientific and technical information and analysis to inform the development of national and site-specific conservation and restoration approaches for Ireland's raised bogs, focussing particularly on Special Areas of Conservation (SACs). This will assist Ireland in meeting its international and national legal obligations and address the concerns of stakeholders regarding the implications of conservation and restoration measures. The National Raised Bog Special Area of Conservation Management Plan will set out Ireland's strategic approach to the conservation and restoration of its raised bog SACs (RPS, 2013). Developing a quantifiable means of identifying degraded areas capable of restoration (DRBs) requires development of metrics that may be incorporated into a spatially distributed mathematical model.

4. APPROACH

Modelling and management of raised bog wetlands requires a hydrological understanding of how, where and why ARB occurs (i.e. the drivers of ARB). A key driver for the maintenance of all wetland systems is the quality and quantity of water. In the case of raised bogs, the supply is wholly rainfall. If the water source is impacted (e.g. the quantity is reduced over a sustained time period – e.g. through climatic or anthropogenic processes) it will result in a knock on impact on the bog ecosystem. Water logging must be maintained at the water source and receiving wetland body - e.g. sufficient rainfall for ARB development. Maintaining the raised bog water level necessitates a balance between supply and drainage, with a slow release of water driven by the resistance along flow paths on which the surface water travels; shallow slopes are the key factor in limiting release of this water). Artificial drainage affects the capacity of the raised bog-high bog to retain water by increasing the hydraulic gradient in the acrotelm/ upper peat layer, and thereby increases the rate at which water discharges from the bog surface. This can eventually lead to the desiccation, and ultimately loss, of the acrotelm layer. Moreover, the maintenance of hydrostatic pressures in the underlying peat body is important in maintaining a low downward seepage rate from the bog surface – i.e. most of the water that falls on a bog should stay on a bog (notwithstanding evapotranspiration).

The occurrence of central and subcentral ecotopes, and maintenance of their characteristic vegetation is primarily dependent on sustaining a suitably high and stable water level within the acrotelm on the bog surface as management of water levels are more critical than velocity of flow or rate of discharge in a groundwater controlled physiographic setting. To assess the restoration potential of Irish raised bog conservation sites the physical conditions under which ARB occurs must first be assessed by identifying the key drivers behind ARB development. Figure 2 summarises the key abiotic conditions that control the occurrence and distribution of ecotopes on the surface of raised bogs.

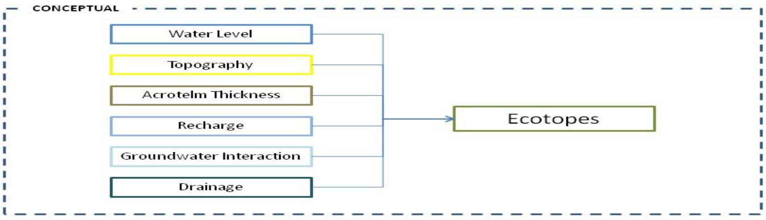

Figure 2. *Conceptual hydrological drivers for ecotope development.*

Figure 3 tabulates the procedure for identifying the key ecotope drivers using available datasets. This process requires information on hydrological, hydrogeological and meteorological variables - and high resolution topographic elevation data of each SAC raised bog, coupled with mapping of ecotope distribution. SAC-status raised bogs have been mapped for ecotope distribution/ occurrence by Fernandez (2013) between 2011 and 2013. Surveys involved a vegetation survey of the high bog while also recording of activities impacting bog ecology, such as peat cutting, high bog and cutaway drainage, burning, forestry on high bog and cutover and the occurrence of invasive species. High bog vegetation was described and mapped, based on a raised bog ecotope vegetation community complex classification developed by Kelly and Schouten (2002). LiDAR (Light Detecting and Ranging) surveys of the SACs were carried out by the Ordnance Survey of Ireland between 2011 and 2012.

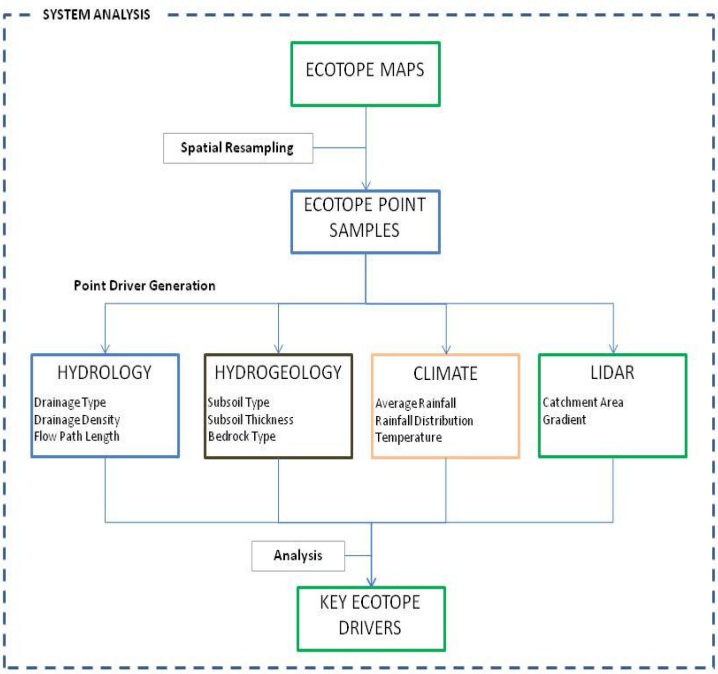

Figure 3. *Procedure for identifying the key drivers sustaining ecotopes on raised bogs*

Modelling of the LiDAR survey data (DTM models) involved relating topographic data to ecotope distributions thereby generating an empirical method for identifying suitable supporting topography to permit raised bog to permit ARB to survive. SAC ecotope maps have been spatially re-sampled in GIS (ArcMap) and exploratory statistical analysis on the combined dataset has been performed to investigate the inter-relationships between variables and ecotope occurrence. The aim of this analysis was to quantitatively determine significant associations between environmental and ecological variables within raised bog habitats, and explore the possibility of geographical differences in the supporting conditions required for acrotelm development. Using quantitative analyses aimed to permit identification of potentially suitable topography for raised bog restoration to ARB, following engineered measures such as uncut (high) bog drain blockage (removing artificial outlets for water flow – ideal conditions).

5. HYDROLOGICAL MODEL

Process

The hydrology of raised bog ecosystems is driven by rainfall. Intact bog systems are often considered to be discharge-regulating hydrologic systems due to the discharge (or flood) attenuation capacity of the acrotelm, which can be up to 80 cm thick. This effectively acts as a highly permeable porous body that can transmit groundwater laterally through the mire subsurface, which then discharges as runoff at the bog margin. A well-developed acrotelm can thus provide significant attenuation capacity in heavy rainfall events; surface channels fed by intact areas on bogs commonly display damped peak discharges and extended recessions as water is slowly released from storage within the vegetative layer.

Statistical analysis of the abiotic parameters presented in Figure 3 investigated relationships between mapped areas of ARB to (1) shallow topographic gradients in natural conditions (primary mode of occurrence) and (2) local catchment areas that receive accumulated flow due to the effects of drainage and/ or natural topographic slopes (flush zones). Central ecotopes are considered to have the highest botanical quality of any ecotope found on a raised bog. They develop in low energy environments supplied with a sufficient volume of rainfall needed to maintain water logged conditions. On this basis, gentle topographic gradients are considered to be an important physical requirement for the occurrence of central ecotopes. Grid point sampling of existing central and subcentral ecotope topographic slopes indicated that the mean areal gradient for both ecotopes is 0.125 % while the mean slopes underlying submarginal and marginal ecotopes are 0.55 % and 1% respectively (Figure 4).

However, the relationship between topographic gradient and wet ecotope occurrence is more complicated and varies according to (1) climatic conditions and (2) drainage density and type. Atlantic raised peat bog ecosystems require a surplus of precipitation (minimum of 300 mm/year), distributed throughout the year. Figure 1 shows the generated Met Eireann Mean Annual Rainfall (MARF) across Ireland between 1980 and 2010 (after Walsh, 2012), and illustrates that the bogs occur in areas where MARF is > 850 mm/year. The majority of the

SAC raised bogs occur in the midlands of Ireland, between counties Galway and Meath, with some outlying bogs in the southwest of Ireland. It can be observed that there is a general trend for MAR to increase from east to west - implying western bogs have a larger rainfall volume input than eastern bogs.

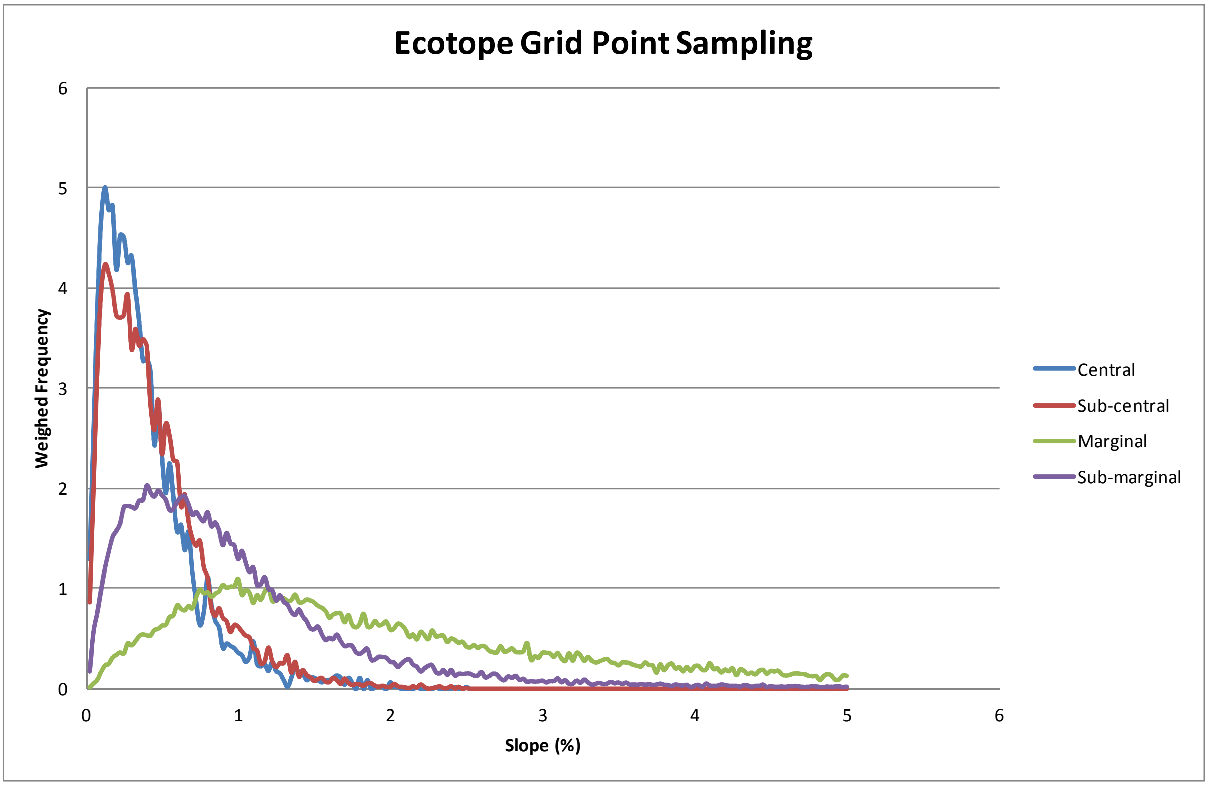

Figure 4. *Frequency of gridded slope values for ecotope types*

MARF can be adjusted to effective rainfall (ER) by taking into account potential evapotranspiration (This is typically higher from wetlands than it is from grasslands – FAO crop factors for wetlands are often between 1.1 and 1.3; Heijmans et al, 2008)). This has been done in the hydro-ecological analysis process. It is found that raised bogs occur where ER is > 300mm/ year. Analysis of the 53 raised bog SACs reveals that each bog has been drained to varying extents, both on the high bog area and in marginal/ peripheral areas. The extent of ARB is limited by the degree to which it has been drained and the amount of estimated effective rainfall it receives each year – i.e. eastern bogs with lower effective rainfall (ER) amounts (in the order of 400 mm/year) are more susceptible to drying out, when drained, than western bogs where effective rainfall amounts exceed 600 mm/year.

As an example, Shankill West Bog (Co. Galway) is supplied with an estimated ER of c. 625 mm/year. Recent ecotope mapping indicates that c. 20 % of the high bog is ARB. The bog is traversed with a functional drain through its centre and encircled by drains on its margins (drain density of c. 10 km^{-1}). Nonetheless it still maintains slopes capable of supporting central and subcentral ecotopes. In contrast, Kilcarren Bog (North Tipperary) receives an estimated ER of c. 395 mm/year. Recent ecotope mapping indicates that only c. 7 % of the high bog is ARB. Similarly the bog is punctuated with a functional drain through its centre and drains on its margins (drain density of c. 5.5 km^{-1}). However, in contrast to Shankill Bog, the central and subcentral ecotopes in Kilkarren require shallower slopes (mean of 0.12 % and 0.18 % respectively) than in Shankill West (mean of 0.25 % and 0.41 % respectively). Both of these bogs have little marginal drainage compared to other bogs - the implication is that higher ER supports the development of wet ecotopes on steeper slopes. As a corollary to this point eastern bogs are more easily affected by drainage that results in changes in raised bog topography.

Figure 5 shows the relationship between the calculated slope of central ecotopes and the square of effective rainfall estimated for each bog location. Accurate information is available on both parameters and, importantly, slope calculation is not overtly sensitive to a scale-dependency (The same grid/ mesh size has been used in the analysis to ensure slope calculations are consistent), whereas flow path length and drainage density is sensitive to scale which may skew statistical relationships. The bogs displayed in this graph are those that have been least impacted by high bog or marginal drainage (based on ecotope surveys, aerial photography and the DTM models; though no bog is completely unaffected by drainage).

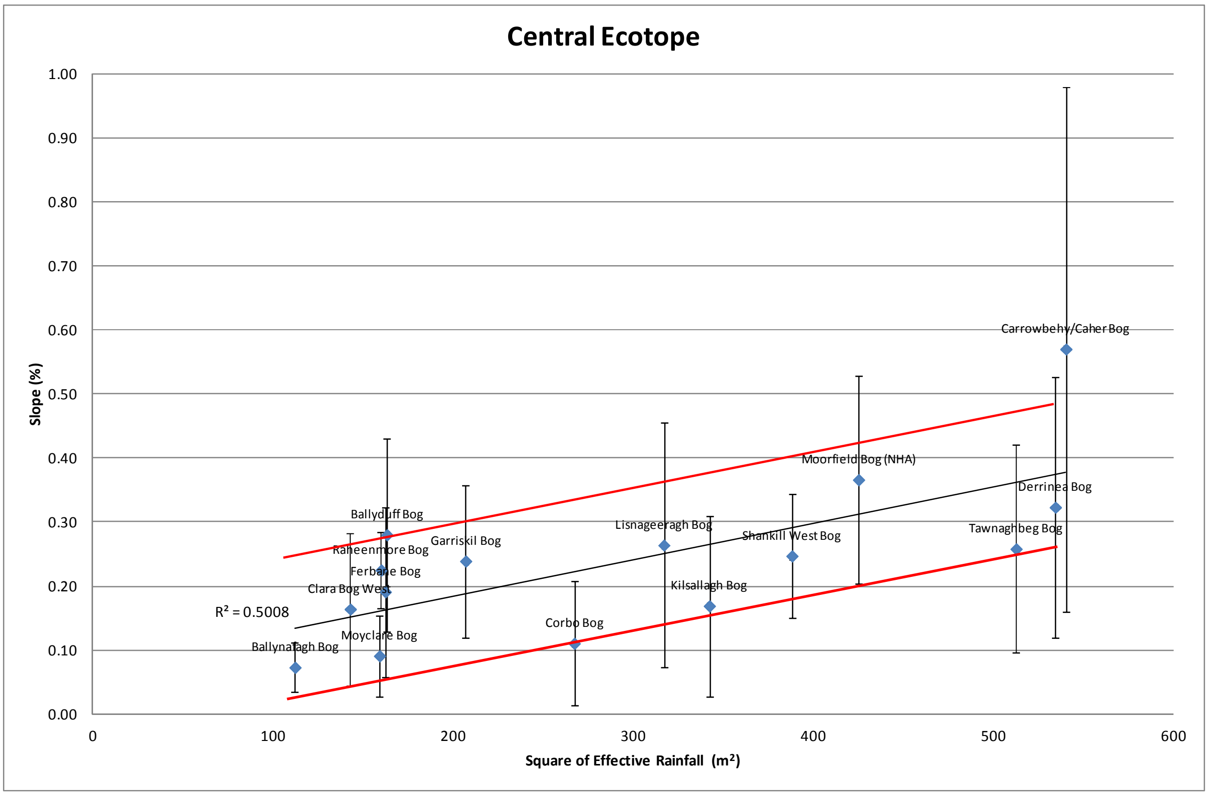

Figure 5. *Calculated mean slope, and estimated range, of central ecotope versus the square of estimated effective rainfall for bogs least impacted by high bog and/or marginal drainage*

Figure 5 shows that there is a trend for bogs with low annual ER (generally eastern bogs) to support central ecotopes with slopes < 0.3 %; whereas higher ER (generally western bogs) support central ecotopes with slopes < 0.5 %. This relationship suggests that a natural gradient in central ecotope distribution. Additionally, it appears there is a range of slopes at which central ecotope may occur, which is within c. 0.2% of the mean slope value. A similar trend is observed when plotting subcentral slopes values versus the square of ER (Figure 5), with mean slopes increasing from < 0.4 % to < 0.8 %. The range of slope which supports subcentral ecotope increases to within c. 0.4 implying central ecotope is more sensitive to changes in slope. It is also noteworthy that Carrowbehy Bog, which is an outlier in Figures 4 and 5, records central and subcentral slope values higher than the mean trend. Carrowbehy is a relatively pristine raised bog and supports an ARB area of c. 0.7 km^2. It may be that ER > 700 mm/year can be supported on even steeper slopes than that predicted from the trend shown in Figures 5 and 6.

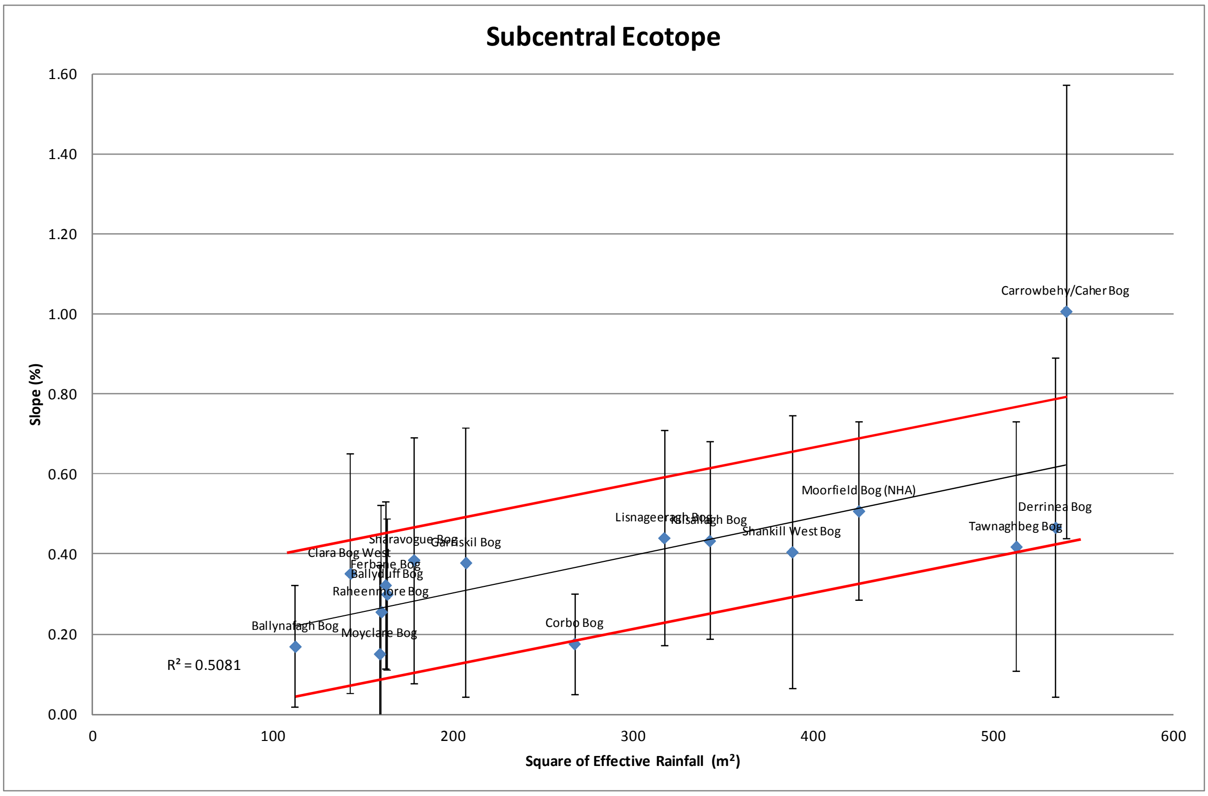

Figure 6. *Calculated mean slope, and estimated range, of subcentral ecotope versus the square of estimated effective rainfall for bogs least impacted by high bog and/or marginal drainage*

Figure 7 shows the median of central ecotope slopes versus the square of effective rainfall at bogs where there is significant drainage of the high bog and/or marginal drainage associated with current/ historic peat extraction. There is no obvious trend and steeper slopes, > 0.5 %, supporting wet ecotope are found in bogs with relatively low amounts of ER (< c. 400 mm/year); as well as the western bogs. The contrast between Figure 5 and 7 is enigmatic. The mean data fit quite well, but the divergence suggests that there may be another underlying distribution of slope gradient. The steeper slopes in Figure 7 are associated with bogs that have undergone known subsidence (e.g. Brown Bog; a bog burst has formed a topographic depression on the bog surface where flow has accumulated and formed ARB and Clara Bog East; bog slopes towards an old bog road). The significance of these observations is that wet ecotope also forms in areas where there is significant flow accumulation from a contributing catchment area. Initial studies of topographic conditions on the 53 SACs suggest that subsidence related features on uncut bogs are relatively common.

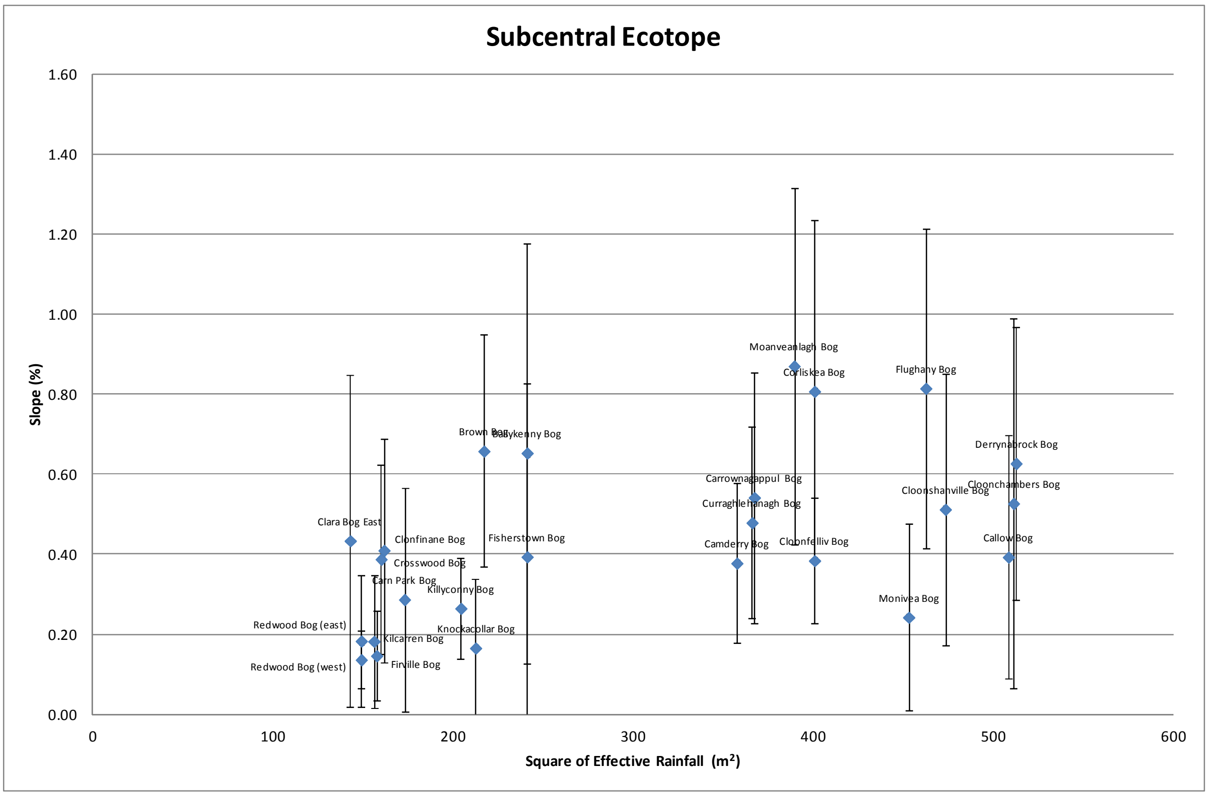

Figure 7. *Calculated median slope of central ecotope versus the square of estimated effective rainfall for bogs impacted by high bog and/or marginal drainage*

Metric

Van der Schaff and Streeferk (2002) previously developed a metric to estimate the restoration potential of a raised bog. The metric, referred to as the Potential Acrotelm Capacity (PAC), modelled the potential for ARB development by calculating the relationship between the upstream flow path length through a streamline and topographic slope. The metric was originally developed using a 100 m grid on Clara Bog and Raheenmore Bog. It states that acrotelm potential is proportional to flow path length (L) and inversely proportional to slope (s); PAC = L/s. The basis of this metric is that discharge through the acrotelm is a function of flow path length; and that there is a linear relationship between L and s, assuming a Darcian flow through the acrotelm layer. Using this metric, threshold values were estimated to assess where degraded raised bog occurs, and where ARB may be regenerated following appropriate management measures.

Analysis of the topographic conditions of the SAC bogs as part of the current study has indicated that PAC is not always the most appropriate parameter to use in assessing the bogs potential to support an acrotelm/ ARM. Flow path length appears highly scale dependent and the values used to predict the occurrence of ARB differs between sites due to the range of catchment areas from which flow path length is calculated. Consequently application often failed to identify areas of mapped as ARB. Investigations on the 53 SACs showed that an alternative metric, using the value of flow accumulation, in place of flow path length, in a manner comparable to the topographic index (Bevin and Kirkby, 1979). This modified flow accumulation capacity (MFAC) parameter is better adapted to predicting ARB occurrence, particularly when corrections for regional variations in effective rainfall are defined. The approach is more effective at predicting ARB occurrence downgradient of catchment divides in a catchment area rather than at local topographic divides where central ecotope tend to occur (gentle slopes). The approach provides an improved correspondence with ARB, but fails to fully simulate its distribution in areas with very short flow paths, e.g. at subcatchment divides.

Accordingly, a new, and simplified, metric to model the occurrence of ARB has been developed to incorporate the observed relationship between ER and central and subcentral ecotope slope. The metric, termed the Alternative Acrotelm Capacity Model (AACM), states that acrotelm capacity is proportional to the square of ER and inversely proportional to slope; AACM = ER^2/s. As water level is a function of ER and drainage, squaring ER is a measure of the energy required to saturate the bog surface where the slope is suitable for low rates of discharge – in this sense the metric is similar to the kinetic energy component of the Bernoulli Equation. Statistical analysis finds that there is a stronger relationship between the mean slopes of central and subcentral ecotopes and effective rainfall squared, rather than effective rainfall or mean annual rainfall.

AACM, combines what can be measured with some degree of confidence - rainfall and slope, which are both considered to be the primary drivers for ARB. The AACM is still inversely proportional to slope (20 m resolution) and accounts for the local topographic variations within individual bog systems. Additionally, using ER in the metric is a method of weighing the model according to regional meteorological variations, which as demonstrated, is important in determining the range of slope where central and subcentral ecotope can be supported. By way of illustration, Figure 8 shows the currently mapped wet ecotope distribution at Garriskill Bog, which is a relatively pristine bog, and Figure 9 shows the modelled wet ecotope distribution using the AACM metric. The modelled version overestimates the wet ecotope distribution by c. 30%, which is a measure of the maximum ARB potential – i.e. the model suggests abiotic conditions are in place to support ARB to a greater extent that it currently exists and focused restoration measures may achieve this.

Management threshold values are currently being estimated and calibrated to the mapped ecotopes (normalising data to the most representative sites). These will inform restoration management plans – i.e. where restoration is possible (high slopes implies low restoration potential) and where site specific investigation is required (the model assumes no subsurface water loss, which is known to be significant in particular cases, e.g. Clara Bog). The MFAC metric may also be combined where wet ecotopes occur downstream from catchment divides – e.g. flush ecotopes occur on steeper topographic gradients and require longer flow path lengths than central ecotopes. Estimating the potential for ARB may therefore be best achieved by employing MFAC and AACM. Both modelling approaches assume steady state and negligible downward seepage conditions – the relative accuracy of both models will differ depending on the drainage regimes operating at individual bog sites.

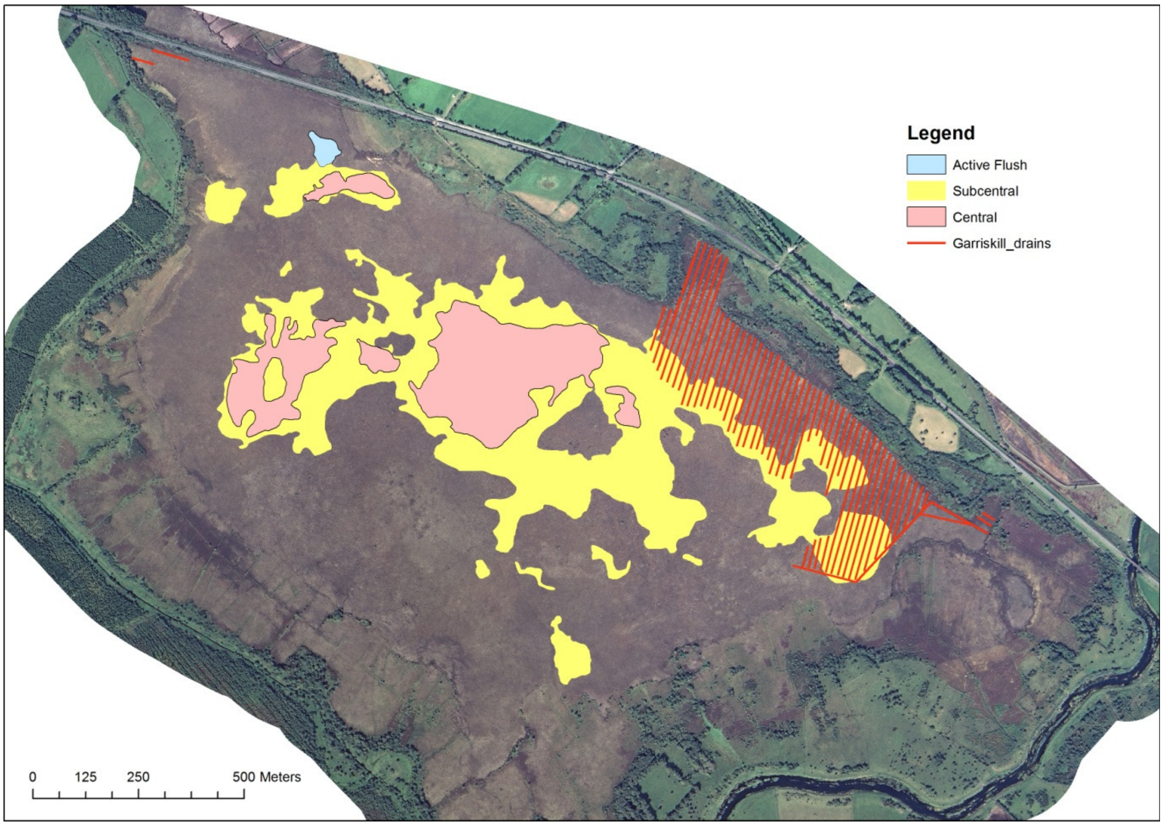

Figure 8. *Mapped wet ecotopes at Garriskill Bog SAC*

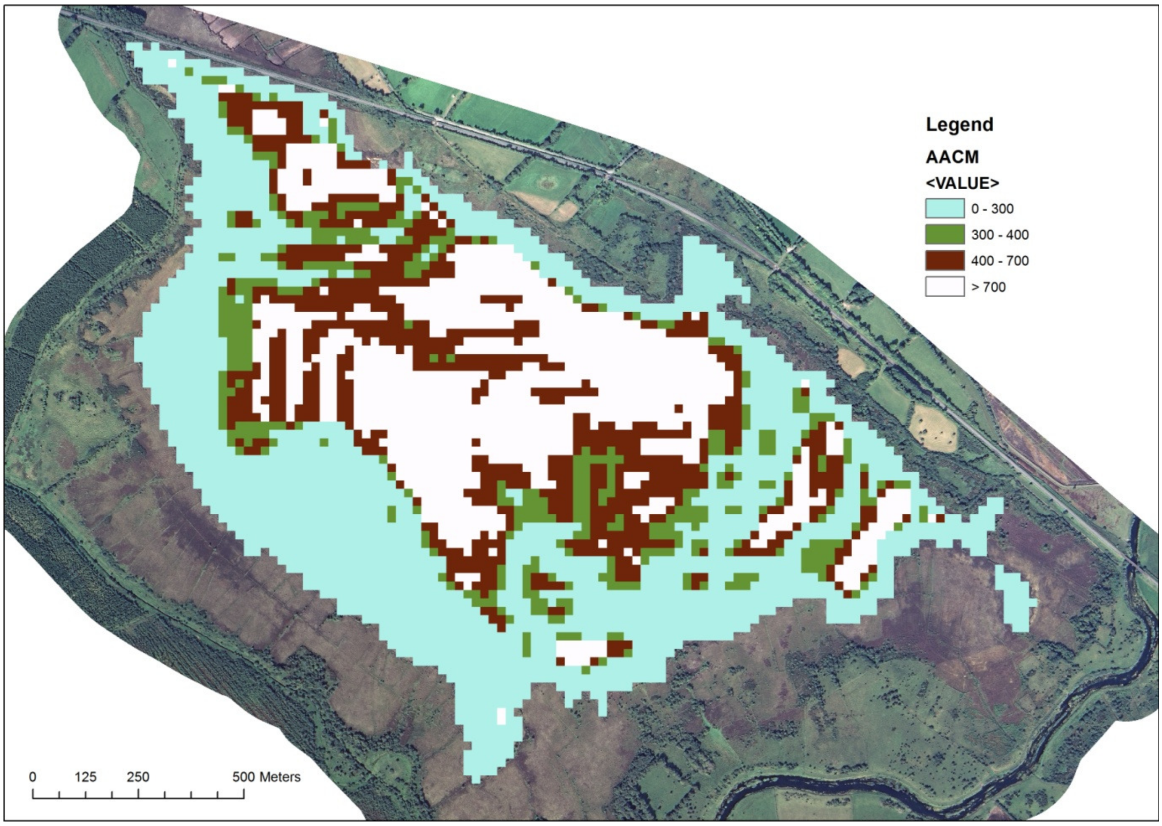

Figure 9. *Modelled wet ecotopes at Garriskill Bog SAC*

6. CONCLUSIONS

Understanding the hydrological functioning of raised bog wetlands is fundamental to their conservation and evaluation. The occurrence of ARB is a function of water level, which is controlled primarily by topographic gradient and effective rainfall for maintaining saturated conditions on the bog surface. A hydrological metric, based on topographic modelling, and weighted by effective rainfall, has been developed and is currently being calibrated against mapped ARB. The revised approach assumes water not lost to evapotranspiration stays at/ close to the bog surface, thereby driving restoration. Its predictive capacity is more questionable where deeper hydrogeological processes influence peat bog water balances, or where the morphology of the bog surface continues to subside. Restoration potential is modelled using this approach and will be used to provide a scientific basis for raised bog conservation in Ireland. The findings will be used to inform the development of conservation objectives and the proposed the rehabilitation of raised bogs as part of the state's response to EU directives.

7. REFERENCES

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