

The potential reintroduction of *Dicranum undulatum* to Cors Fochno: an assessment of future climate suitability



Des Callaghan (Bryophyte Surveys Ltd)

Evidence Report No 936

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Report series:	NRW Evidence Reports
Report number:	936
Publication date:	August 2025
Contractor:	Des Callaghan (Bryophyte Surveys Ltd)
Title:	The potential reintroduction of <i>Dicranum undulatum</i> to Cors Fochno: an assessment of future climate suitability
Author(s):	Des Callaghan
Technical editor:	Sam Bosanquet
Review level:	2
Peer reviewer:	Clive Walmsley & Lucia Watts
Approved by:	Liz Halliwell
Restrictions:	None

Distribution List (electronic only)

NRW Library, Bangor
National Library of Wales
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Welsh Government Library
Nature Scot Bryophyte, Lichen & Fungus Specialist
Natural England Lichen & Fungus Specialist
Phil Oliver, NRW Senior Environmental Assessment Officer

Recommended citation for this report:

Callaghan, D.A. 2025. The potential reintroduction of *Dicranum undulatum* to Cors Fochno: an assessment of future climate suitability. NRW Evidence Report No: 936, 27 pp, Natural Resources Wales.

Frontispiece: Reintroduced colony of *Dicranum undulatum* at Wybunbury Moss

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1. Crynodeb gweithredol

Mae *Dicranum undulatum* wedi'i gategoreiddio fel 'Mewn Perygl' ar y Rhestr Goch o ddata ar gyfer Cymru, ac fe'i ystyrir yn hollbwysig ar gyfer cadwraeth o dan Adran 7, Deddf yr Amgylchedd (Cymru) 2016. Gan fod mawndiroedd wedi cael eu colli ac wedi dirywio'n helaeth, mae wedi dirywio'n fawr ym Mhrydain, ac mae'r unig boblogaeth sydd wedi goroesi yng Nghymru i'w chael yn Sir Ddinbych, ar Fawnogydd Whixall a Bettisfield. Roedd y rhywogaeth yn hysbys yng Nghors Fochno, lle cafodd ei gweld ddiwethaf ym 1967. Mae'r rhesymau dros ei diflaniad yn ansicr, ond mae'n bosibl mai tanau blaenorol sydd yn rhannol ar fai. Yn dilyn ymdrechion sylweddol i wella cyflwr cynefin y gors, gan gynnwys cael gwared ar danau a gwaith adfer hydrolegol ar raddfa fawr, daeth asesiad diweddar i'r casgliad bod rhannau o'r safle i'w gweld yn cynnwys cynefin ffafriol ar gyfer *D. undulatum* ac y gallai ailgyflwyno fod yn bosiblwydd. Nod yr astudiaeth hon yw ymchwilio i weld a yw macrohinsawdd addas ar gyfer y rhywogaeth yn debygol o ddigwydd yng Nghors Fochno yn y tymor canolig.

Gan ddefnyddio modelu llinol cyffredinol, adeiladwyd dau fodel dosbarthiad rhywogaethau o *Dicranum undulatum* o newidynnau biohinsoddol diweddaraf WorldClim, y naill yn cwmpasu Prydain ac Iwerddon, a'r llall yn cwmpasu Ewrop. Oherwydd y rhesymau a drafodwyd, nid oedd yn bosibl llunio modelau o ansawdd da o'r data a oedd ar gael. Er gwaethaf eu cyfyngiadau, mae'r canlyniadau a ddarperir gan y modelau yn dangos tueddiadau tebyg ac yn ymddangos yn gredadwy. Maen nhw'n dangos bod Cors Fochno ar ymyl y gofod macrohinsawdd addas ar gyfer *D. undulatum*, yn enwedig oherwydd y gaeafau cymharol fwyn a'r hafau gwlyb, nad yw'r naill na'r llall yn nodweddiadol ar gyfer y rhywogaeth. Erbyn 2061–2080, mae'r data'n awgrymu bod risg uchel y bydd macrohinsawdd Cors Fochno yn dod yn anaddas, ac mae'n debygol y bydd yn dod yn llai felly yn y tymor hwy. Felly, er bod ailgyflwyno *D. undulatum* yng Nghors Fochno yn debygol o fod yn llwyddiannus yn y tymor byr, o ystyried y cynefin o ansawdd da a'r llwyddiant diweddar yn Wybunbury Moss, efallai na fydd y boblogaeth yn goroesi am fwy nag ychydig ddegawdau cyn i gynhesu hinsawdd achosi iddi ddiflannu.

Yn dilyn Adolygiad mewnol gan gymheiriaid, mae gan CNC rai pryderon ynghylch pa mor ddigonol yw'r data dosbarthiadol a ddefnyddir i hyfforddi'r model biohinsawdd, ynghyd â chydabod y rhybuddion a'r cafeatau generig a chyfyngiadau modelu amlen biohinsawdd yn ehangach. Er ei bod yn amlwg bod Cors Fochno ar ymyl gwasgariad *Dicranum undulatum*, nid yw'r hyder yn y canlyniadau sy'n rhagweld y bydd yr hinsawdd yn dod yn anaddas a difodiant y rhywogaeth os caiff ei hailgyflwyno yn uchel o gwbl. Fodd bynnag, nid yw'r pryderon hyn a'r hyder cyfyngedig yn y canlyniadau yn cael eu rhannu gan

awdur yr adroddiad sy'n glynu wrth y canlyniadau. Mae manylion yr Adolygiad gan gymheiriaid wedi'u cynnwys mewn Atodiad.

2. Executive summary

Dicranum undulatum is categorised as 'Endangered' on the Red Data List for Wales, and is considered to be of principal importance for conservation under Section 7 of The Environment (Wales) Act 2016. Due to the widespread loss and degradation of peatlands, it has undergone a large decline in Britain, and the only surviving population in Wales occurs in Denbighshire, on Whixall and Bettisfield Mosses. The species was known from Cors Fochno, where it was last seen in 1967. Reasons for the extinction are uncertain, but former fires may be partly to blame. Following significant efforts to improve the habitat condition of the bog, including the elimination of fires and large-scale hydrological restoration, a recent assessment concluded that parts of the site appear to contain favourable habitat for *D. undulatum* and that reintroduction may be a possibility. The aim of this study is to investigate whether a suitable macroclimate for the species is likely to occur at Cors Fochno in the medium-term.

Using generalised linear modelling, two species distribution models of *Dicranum undulatum* were constructed from the latest bioclimatic variables of WorldClim, one covering Britain and Ireland, and the other covering Europe. Due to reasons discussed, it was not possible to construct good quality models from the data available. Despite their limitations, the results provided by the models show similar trends and appear potentially plausible. They show that Cors Fochno is at the edge of the suitable macroclimate space for *D. undulatum*, in particular due to the relatively mild winters and wet summers, neither of which are typical for the species. By 2061–2080, the data suggest there is a high risk that the macroclimate of Cors Fochno will become unsuitable, and it is likely that in the longer term it will become even less so. Thus, whilst the reintroduction of *D. undulatum* to Cors Fochno is likely to be successful in the short-term, given the good quality habitat and recent success at Wybunbury Moss, the population may not survive for more than a few decades before climate warming causes its extinction.

Following internal Peer Review, NRW have some concerns about the adequacy of the distributional data used to train the bioclimate model, along with recognition of the generic caveats and limitations of bioclimate envelope modelling more broadly. While it is clear that Cors Fochno does lie at the edge of range, the confidence in the outputs predicting the climate becoming unsuitable and the species' extirpation if reintroduced is certainly not high. However, these concerns and limited confidence in the results are not shared

by the report author who stands by the results. Details of the Peer Review are included in an Appendix.

3. Background

Britain supports one of the richest bryophyte floras in Europe. A total of 1097 species have been recorded, comprising four hornworts, 796 mosses and 297 liverworts. Unfortunately, four are known to have become extinct, 20 are possibly extinct, and a further 153 are threatened with extinction (Callaghan 2023a). One of the major threats to species is the influence of climate change. A large-scale assessment of climate change impacts in Britain covering over 3000 species of plants and animals showed that the proportion of bryophytes at risk was especially high, in part because many species have a northern or north-western distribution, and are associated with cool and damp conditions (Pearce-Higgins et al. 2017). Indeed, changing climate has been shown to negatively influence bryophyte function and survival (Slate et al. 2024). For example, warming in boreal peatlands is decreasing surface soil moisture and lowering water tables, disproportionately advantaging vascular plants over bryophytes (Bao et al. 2022).

Dicranum undulatum, until recently known as *D. bergeri*, is a boreo-arctic montane circumpolar species, occurring in Asia, Europe and North America (Blockeel et al. 2014; Hedenäs and Bisang 2004; Hallingbäck et al. 2006; Hill and Preston 1998; FNA Editorial Committee 2007; Chien and Crosby 1999). It typically occupies peatlands, including treeless ombrotrophic bogs, rich fens, wooded bogs, dry pine heath forest and subalpine shrub–tundra (Anderson et al. 1995; Asada 2002; Birks 1977; Belland and Vitt 1995; Chien and Crosby 1999; Crum and Anderson 1981; FNA Editorial Committee 2007; Foster 1984; Hedenäs and Bisang 2004; Hallingbäck et al. 2006; Lockhart et al. 2013; Locky et al. 2005; Luken 1985; Nicholson and Gignac 1995).

In Europe, *Dicranum undulatum* is frequent within the boreal zone, becoming scarce and often threatened further south, for example being rare in Denmark, threatened with extinction in Britain, Bulgaria, Germany, Poland and Slovakia, near-threatened in Switzerland and possibly extinct in The Netherlands and Spain (Hallingbäck et al. 2006; Hodgetts and Lockhart 2020). It was considered extinct in Ireland (Lockhart et al. 2012) but has recently been refound. It is categorised as ‘Near-threatened’ on the IUCN Red List of bryophytes in Britain (Callaghan 2023a) and as ‘Endangered’ on the Red Data List for Wales (Bosanquet and Dines 2011). In Wales, it is considered to be of principal importance for conservation under Section 7 of The Environment (Wales) Act 2016.

In the southern half of Britain, *Dicranum undulatum* was known from nine locations, but has become extinct at Clarepool Moss (last record 1982), Cors Caron (1967), Cors Fochno (1967), Knutsford Moor (1841), Oakmere (1863), Risley Moss (1855), Woolston Moss (1842) and Wybunbury Moss (1965), largely due to destruction and degradation of these lowland peatlands. The only surviving population in southern Britain occurs at Whixall and Bettisfield Mosses (Shropshire/Denbighshire), where 238 individual-equivalents were recorded in 2019, of which about 75% occurred on the Welsh side of the site, mostly within an area known as the ‘Cranberry Beds’ (Callaghan 2020).

In November 2020, a trial reintroduction of *Dicranum undulatum* began at two locations. The donor site was the Cranberry Beds, and the receptor sites were North East Fenn’s (Denbighshire), located 2 km north-east, and Wybunbury Moss (Cheshire), 26 km north-east. Fifteen colonies of the moss, averaging 9.6 cm diameter (range = 7–14 cm), were translocated, five to North East Fenn’s and ten to Wybunbury. Subsequent monitoring has shown that whilst the Extent of Occurrence (EEO) of the translocated colonies at North East Fenn’s has increased a little since the original translocation, two of the transplants have become extinct, both due to competitive exclusion by *Polytrichum strictum*, and a third is in very poor condition, due to the development of a dense canopy of *Calluna vulgaris* above it and the deposition of associated leaf litter. Results from Wybunbury Moss are far more encouraging, where the EEO has increased over five-fold, accompanied by the establishment of many new satellite colonies at a distance of up to 30 cm from the parent transplants (Callaghan 2024).

Reasons for the extinction of *Dicranum undulatum* at Cors Fochno are uncertain, but former fires may be partly to blame. Following significant efforts to improve the habitat condition of the bog, including the elimination of fires and large-scale hydrological restoration, a recent assessment concluded that parts of the site appear to contain favourable habitat for *D. undulatum* and that reintroduction may be a possibility (Callaghan 2023b). However, given this is a boreal species, it is first necessary to understand whether a suitable macroclimate for the species is likely to survive at Cors Fochno in the medium-term. The aim of this study is to assess future climate suitability at Cors Fochno for *D. undulatum*.

4. Methods

4.1. Species Distribution Model 1 – Britain and Ireland

Presence points from where *Dicranum undulatum* has been recorded in Britain and Ireland were obtained from the national recording database of The British Bryological Society. Record details for each point were reviewed and points were removed if they were a duplicate, the record appeared doubtful for any

reason, the location was poorly localised, or the point was within 500 m of another point. All points included within the final dataset are considered to be within the natural range of the species, since no populations are known to be the result of artificial introduction.

The 19 bioclimatic variables from WorldClim v.2.1 (Table 1; Fick and Hijmans 2017) were downloaded at a resolution of 0.5 arc minutes (c. 1 x 1 km). Each was mapped, which showed five variables appeared to contain unreliable data across parts of the study area, including BIO2, BIO3, BIO4, BIO8 and BIO9, which were excluded from further consideration. For the remaining 14 variables, a Pearson's correlation matrix was computed from their values at 1000 points randomly sampled across the study area. This showed that many were intercorrelated and so to avoid multicollinearity, variables were selected with a correlation value of less than 0.7 (Dormann et al. 2013). This resulted in three variables being selected for model building, BIO1, BIO7 and BIO12.

A total of 1000 pseudo-absence points was randomly sampled across the study area using the 'spatSample' function of the 'terra' package (Hijmans 2024) in R (R Core Team 2024), which were combined with the presence points. For each presence and absence point in the combined dataset, the associated values for each of the selected bioclimatic variables were added. The final dataset was then split into a training dataset, comprising 80% of the points, and a testing dataset, comprising 20% of the points, ensuring a representative sample of both presence and absence points within each set. The training set was used to generate a species distribution model by generalised linear modelling (McCullagh and Nelder 1989), built using the 'glm' function of the 'stats' package in R. To assess the quality of the model, four diagnostic plots were inspected using the 'plot' function of the graphics package in R, including: (i) residuals vs. fitted values (to show if there were any trends in the residuals to indicate a poor model selection, or a non-constant variance); (ii) a normal Q-Q plot of the standardized residuals (to show if the error terms are normally distributed); (iii) a scale-location plot (to detect if the spread of the residuals is constant over the range of fitted values); and (iv) a Cook's Distance (D) plot (to identify any data points that may have had an unduly high influence on the derivation of the regression coefficients).

Using the 'predict' function of the 'predicts' package in R, the model was used to map the suitability of the current macroclimate across Britain and Ireland for *Dicranum undulatum*. It was then evaluated against the testing dataset using the 'pa_evaluate' function of the predicts package, from which the current distribution of suitable climate space for the species was established by using the 'no_omission' option of the 'thresholds' element of the 'glm_eval' function, which comprises the highest threshold at which there is no omission of presence points from the training dataset. Lastly, the future distribution of suitable climate

space for the species in the period 2061–2080 was predicted following the same general procedure, utilising the predicted climatic variables of the Max Planck Institute ‘ESM1.2-HR’ climate model (Müller et al. 2018).

Table 1 Bioclimatic variables from WorldClim v.2.1 (Fick and Hijmans 2017).

Code	Description	Temporal scale
BIO1	Annual mean temperature	Annual
BIO2	Mean diurnal temperature range (mean of monthly (max temp - min temp))	Variation
BIO3	Isothermality (BIO2/BIO7) ($\times 100$)	Variation
BIO4	Temperature seasonality (standard deviation $\times 100$)	Variation
BIO5	Max temperature of warmest month	Month
BIO6	Min temperature of coldest month	Month
BIO7	Temperature annual range (BIO5 - BIO6)	Annual
BIO8	Mean temperature of wettest quarter	Quarter
BIO9	Mean temperature of driest quarter	Quarter
BIO10	Mean temperature of warmest quarter	Quarter
BIO11	Mean temperature of coldest quarter	Quarter
BIO12	Annual precipitation	Annual
BIO13	Precipitation of wettest month	Month
BIO14	Precipitation of driest month	Month
BIO15	Precipitation seasonality (coefficient of variation)	Variation
BIO16	Precipitation of wettest quarter	Quarter
BIO17	Precipitation of driest quarter	Quarter
BIO18	Precipitation of warmest quarter	Quarter
BIO19	Precipitation of coldest quarter	Quarter

4.2. Species Distribution Model 2 – Europe

To put the above results in a broader context and to help understand if projected change in Britain and Ireland is similar to that projected elsewhere, the procedures outlined above were repeated for Europe, with presence points of *Dicranum undulatum* obtained from the Global Biodiversity Information Facility (<https://doi.org/10.15468/dl.r26z8x>). As above, all locations included within the dataset are considered to be within the natural range of the species, since no populations are known to be the result of artificial introduction. Once the correlation of the bioclimatic variables was inspected for Europe, following the procedure described above, those selected for model building included BIO1, BIO7, BIO12, BIO15 and BIO18.

5. Results

5.1. Species Distribution Model 1 – Britain and Ireland

Of the three variables selected for modelling, BIO7 made no significant contribution to model performance, and so was dropped from the final model. There was a significant negative association between the presence of *Dicranum*

undulatum and both BIO1 and BIO12 (Table 2), indicating a preference for the colder and drier regions of Britain and Ireland. Diagnostic plots of the data from the model showed: (i) trends in the residuals that indicated a poor model; (ii) non-normally distributed error terms; (iii) a non-constant spread of the residuals over the range of fitted values; and (iv) significant outliers ($D > 0.5$ for many data points). The model could not be improved upon from the data available, and hence the results presented below should be treated with caution.

Figure 1 shows the current macroclimate suitability for *Dicranum undulatum* in Britain and Ireland based on its probability of occurrence, as predicted by the model. Figure 2 shows the recorded locations of the species and the current distribution of its suitable macroclimatic space, and Figure 3 shows the future distribution of its suitable macroclimatic space for the period 2061–2080.

Table 2 Coefficients of the generalized linear model of the distribution of *Dicranum undulatum* in Britain and Ireland.

Parameter	Estimate	Standard error	z	p
Intercept	7.32	1.79	4.08	<0.001
BIO1	-0.855	0.161	-5.31	<0.001
BIO12	-0.003	0.0006	-4.44	<0.001

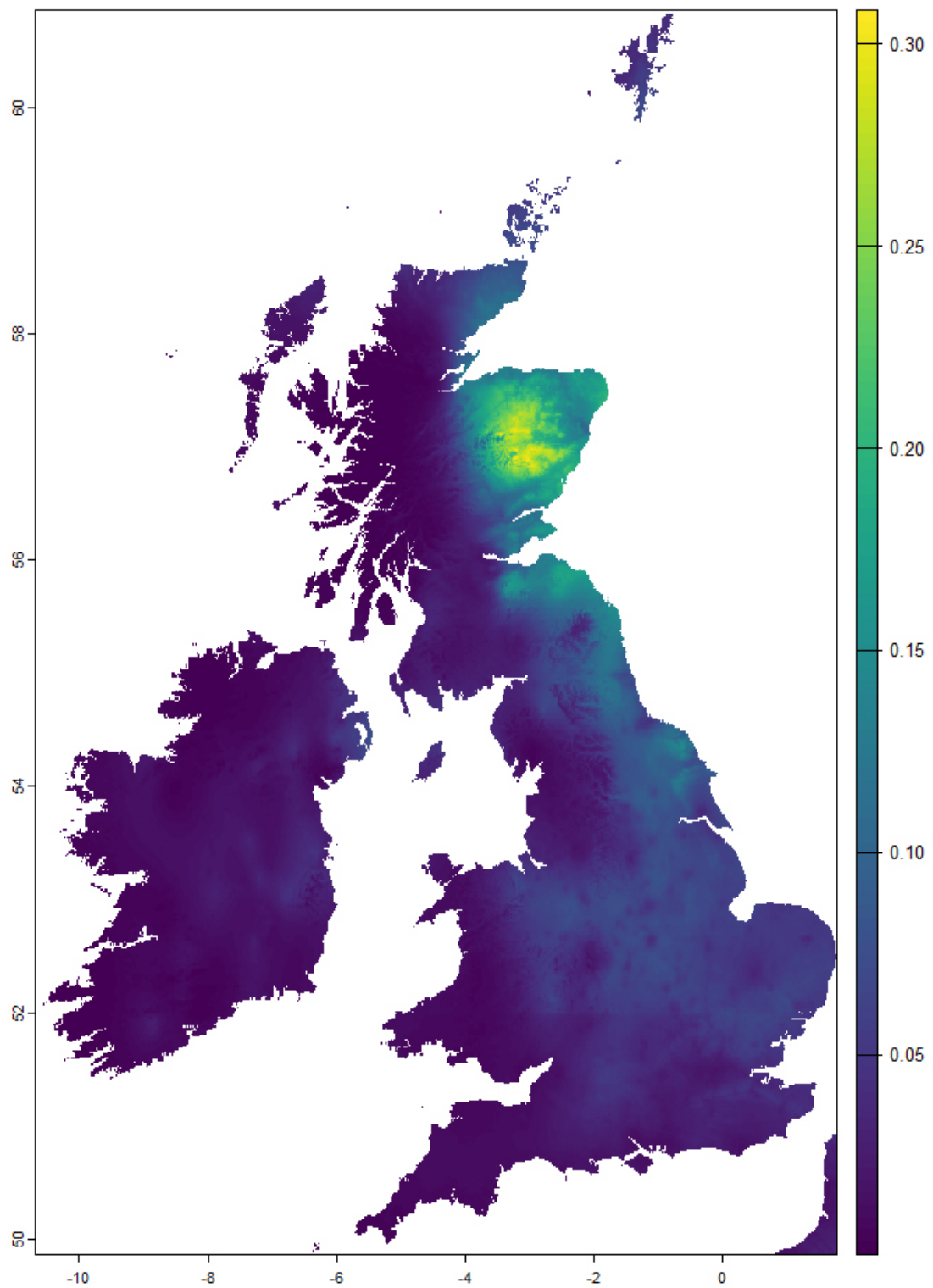


Figure 1 Current macroclimate suitability for *Dicranum undulatum* in Britain and Ireland based on its probability of occurrence.

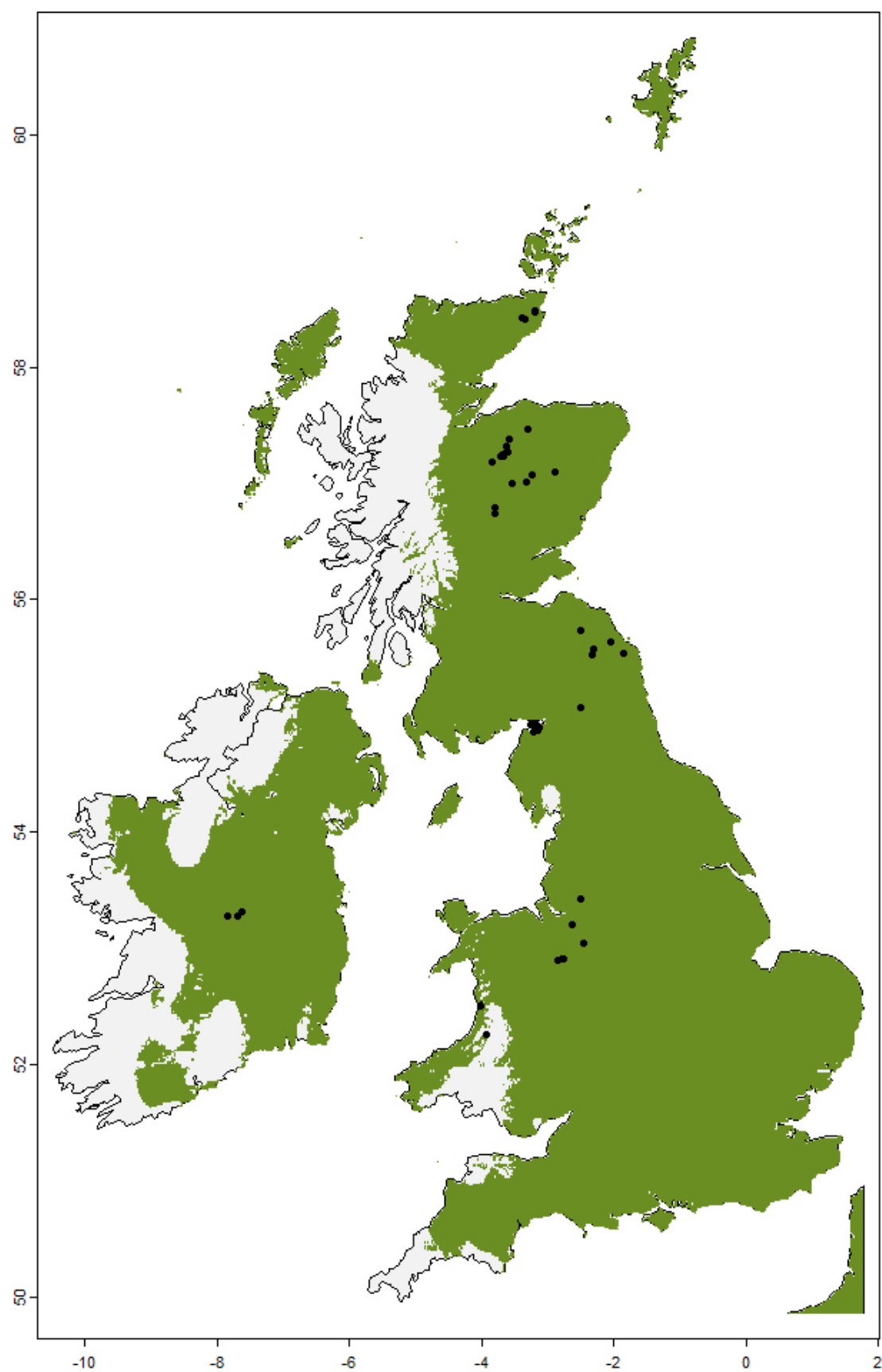


Figure 2 Recorded locations of *Dicranum undulatum* (black dots) in Britain and Ireland and the current distribution of its suitable macroclimatic space (green shading).

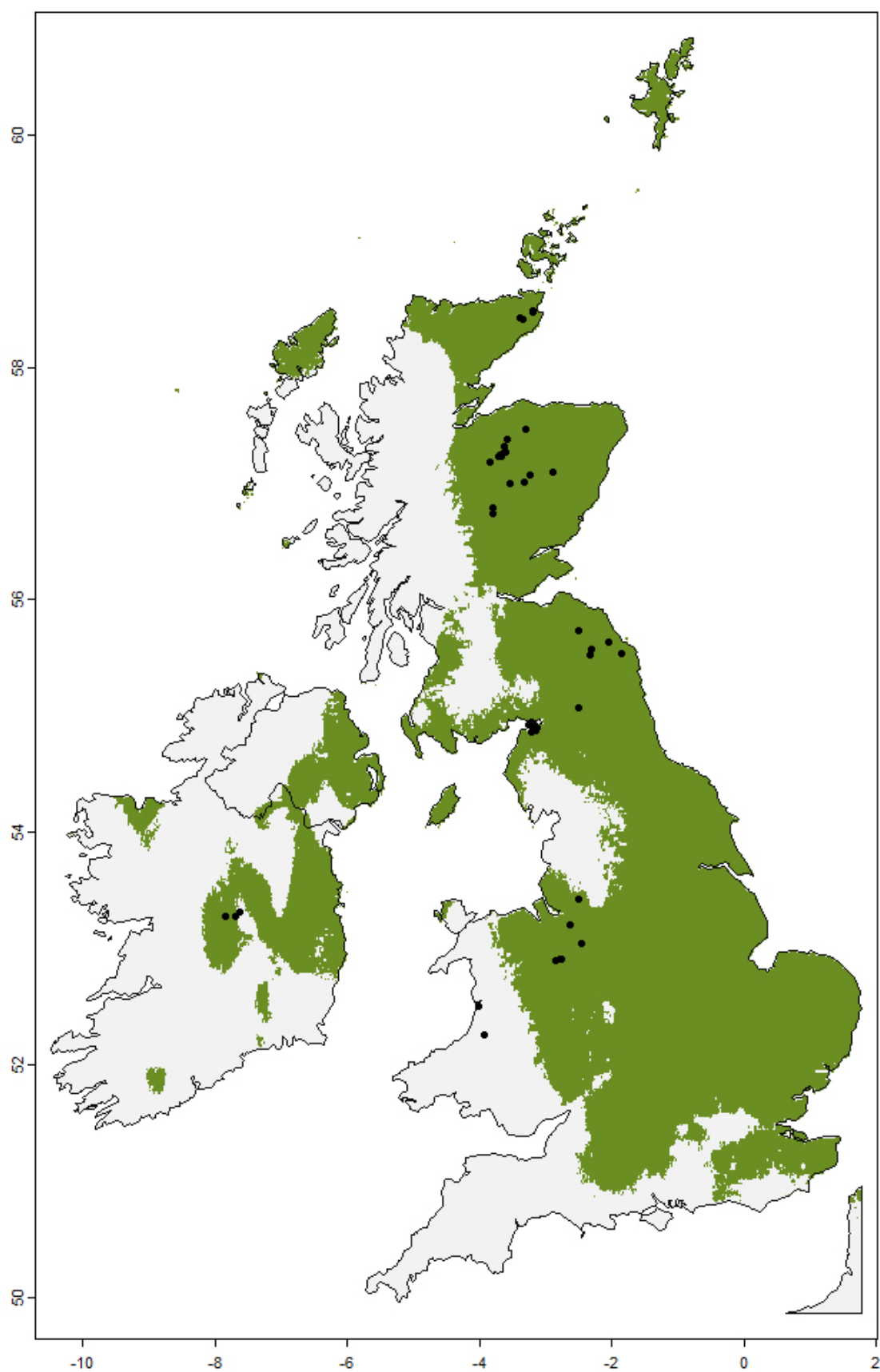


Figure 3 Recorded locations of *Dicranum undulatum* (black dots) in Britain and Ireland and the future distribution of its suitable macroclimatic space for 2061–2080 (green shading).

5.2. Species Distribution Model 2 – Europe

All of the bioclimatic variables selected for modelling made a significant negative contribution to model performance (Table 3), indicating a preference for colder and drier regions of Europe, with less range in annual temperature, less seasonality in rainfall, and less rainfall in the warmest quarter. Diagnostic plots of the data from the model showed: (i) trends in the residuals that indicated a poor model; (ii) non-normally distributed error terms; (iii) a non-constant spread of the residuals over the range of fitted values; and (iv) significant outliers ($D > 0.5$ for many data points). The model could not be improved upon from the data available, and hence the results presented below should be treated with caution.

Figure 4 shows the current macroclimate suitability for *Dicranum undulatum* in Europe based on its probability of occurrence, as predicted by the model. Figure 5 shows the recorded locations of the species and the current distribution of its suitable macroclimatic space, and Figure 6 shows the future distribution of its suitable macroclimatic space for the period 2061–2080.

Table 3 Coefficients of the generalized linear model of the distribution of *Dicranum undulatum* in Europe.

Parameter	Estimate	Standard error	z	p
Intercept	8.86	0.652	13.6	<0.001
BIO1	-0.434	0.019	-21.9	<0.001
BIO7	-0.116	0.018	-6.47	<0.001
BIO12	-0.002	0.0003	-8.0	<0.001
BIO15	-0.037	0.006	-5.87	<0.001
BIO18	-0.006	0.001	5.07	<0.001

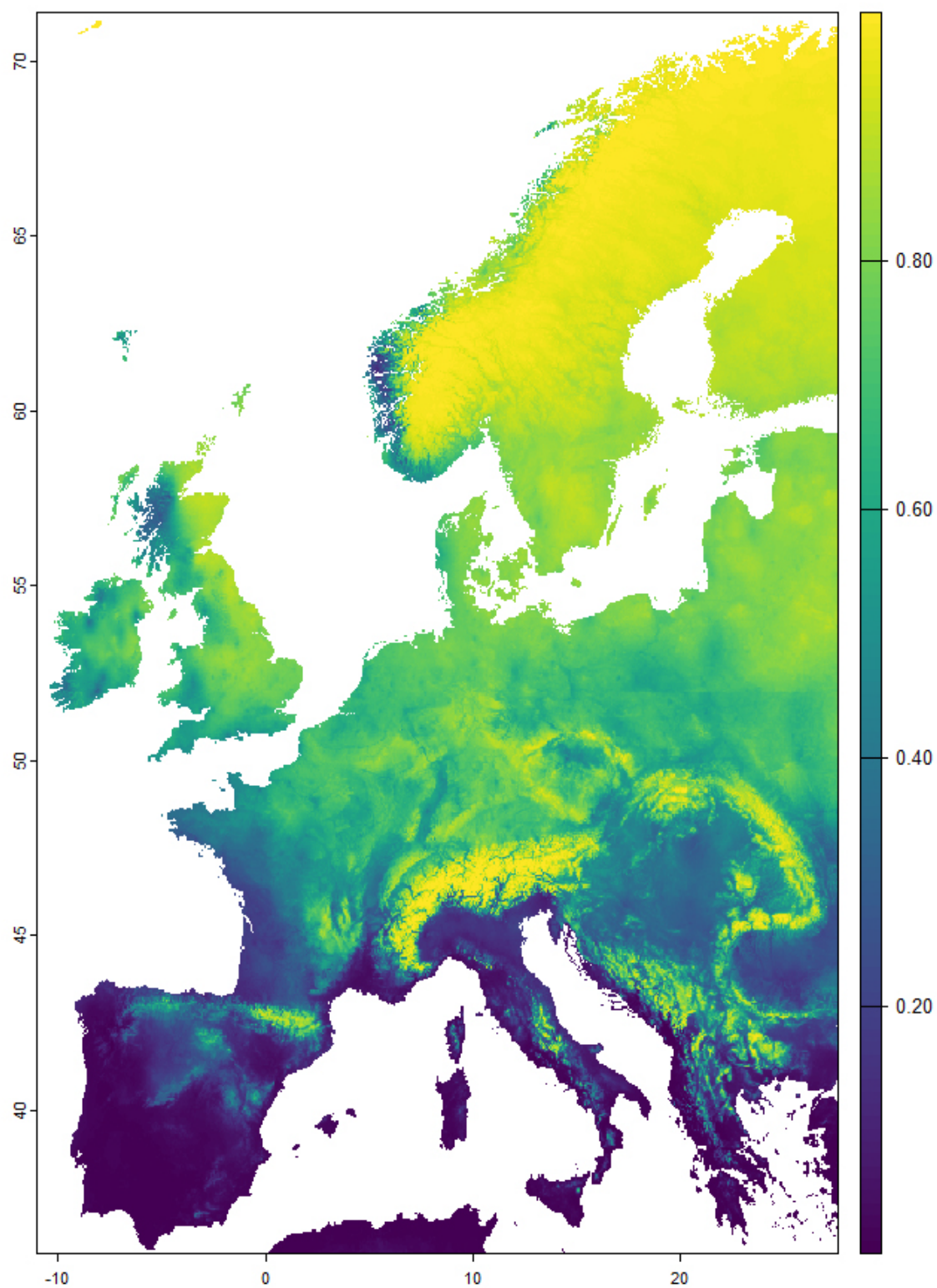


Figure 4 Current macroclimate suitability for *Dicranum undulatum* in Europe based on its probability of occurrence.

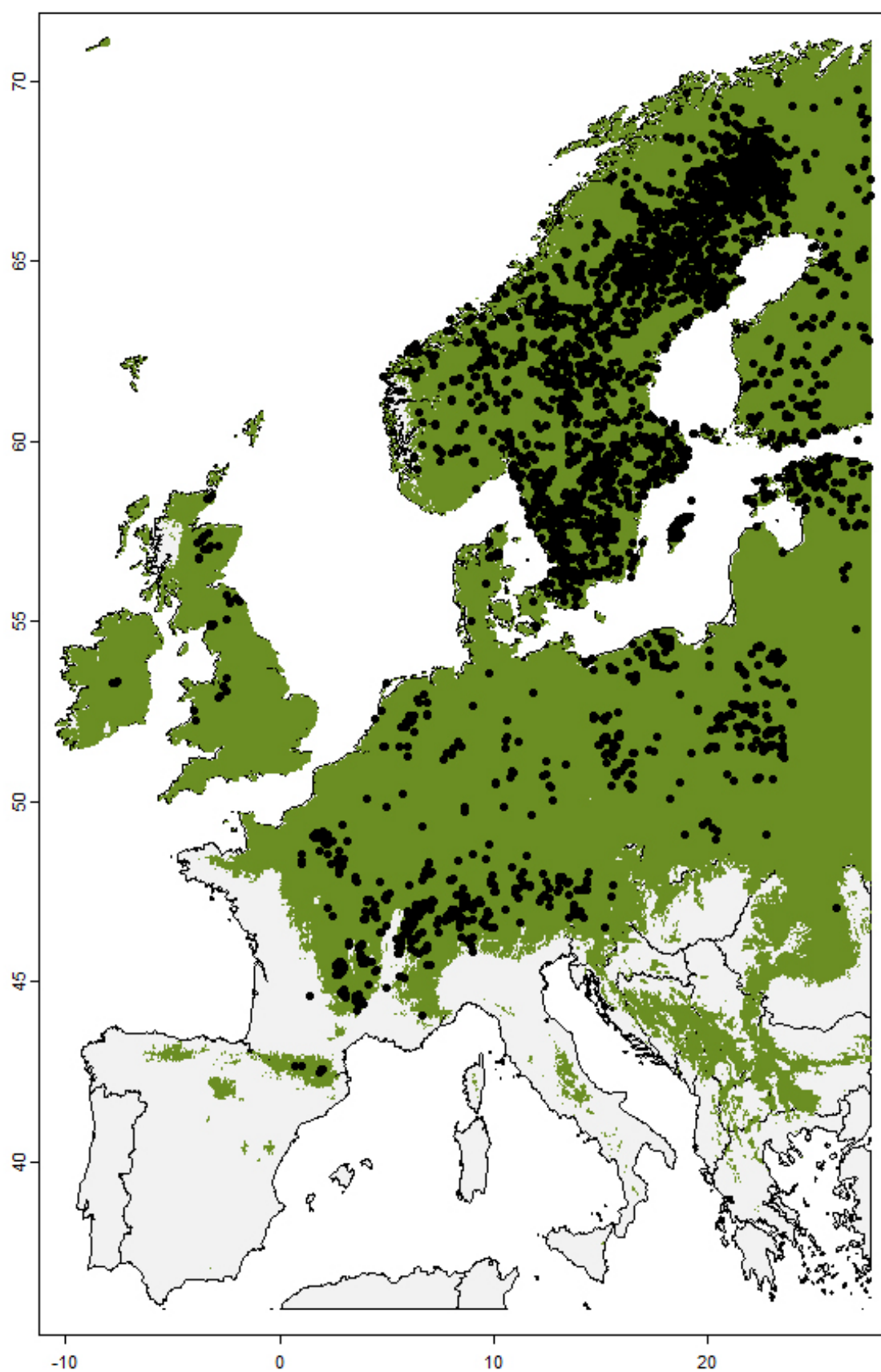


Figure 5 Recorded locations of *Dicranum undulatum* (black dots) in Europe and the current distribution of its suitable macroclimatic space (green shading).

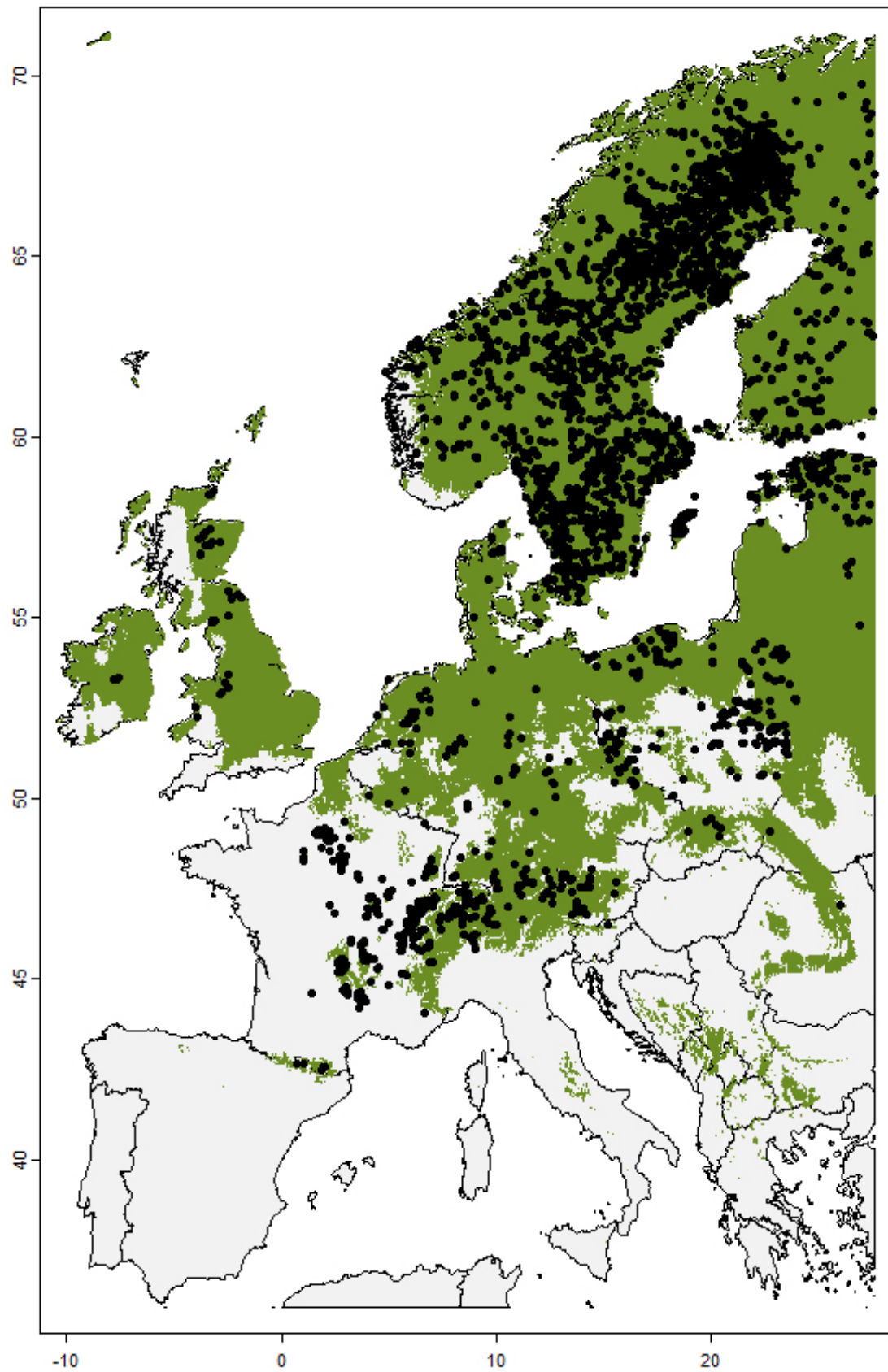


Figure 6 Recorded locations of *Dicranum undulatum* (black dots) in Europe and the future distribution of its suitable macroclimatic space for 2061–2080 (green shading).

6. Discussion

From the data included in the present study, it was not possible to construct good quality species distribution models of *Dicranum undulatum* in Britain and Ireland, or Europe. Their poor quality is due to various reasons, but in particular only macroclimatic variables were included in their construction, and other factors will have an important influence on the distribution of the species, such as habitat availability, which will be controlled by factors in addition to climate, such as topography and geology. Another issue will likely be the occurrence of false negatives amongst the absence points included within the models, whereby some of these randomly selected points will likely have supported the species, but its presence has not been recorded, either because it became extinct before locations were surveyed, for example due to widespread peatland loss and degradation, or locations have simply not been surveyed sufficiently well, the latter being a common problem for under-recorded species such as bryophytes. For the Britain and Ireland model, another important issue is sample size, whereby the total number of presence points is small ($n = 45$), meaning that the model was constructed from data that included only 36 presence points, as 20% ($n = 9$) were reserved for model evaluation.

Despite the limitations of model quality, the results they provide are broadly similar and appear to be believable. They show that the suitable macroclimate of *D. undulatum* has a clear continental bias. Similarly, in western Canada, where the species occurs in all climatic zones, it is significantly more abundant and widespread in continental mires than in oceanic and hyperoceanic ones (Gignac et al. 1991). The data also clearly show that the suitable macroclimate has a clear northern bias, with the boreal mires of Scandinavia being particularly important, and that suitable climate space becomes montane across the southern edge of its range.

Presently, Cors Fochno is at the south-westerly edge of the suitable macroclimate space for *D. undulatum*, due to the combined effect of relatively mild winters and wet summers, neither of which are typical for the species. By 2061–2080, the data suggest there is a high risk that the macroclimate of Cors Fochno will become unsuitable for the species, and it is likely that in the longer term it will become more unsuitable. Thus, whilst the reintroduction of *D. undulatum* to Cors Fochno is likely to be successful in the short-term, given the good quality habitat and recent success at Wybunbury Moss, the population may survive for no more than a few decades before climate warming causes its extinction.

7. Acknowledgements

Thanks to Justin Lyons (NRW) for managing the contract.

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9. Peer Review Appendix

Peer Review was carried out by Dr Clive Walmsley (NRW Senior Specialist Advisor, Climate Change and Decarbonisation) and Dr Lucia Watts (NRW Specialist Advisor, Climate Risk and Adaptation). Their review was sent to the author of the report, who stood by the results of his work. The Peer Review and author response are included below.

Peer Review by Dr Clive Walmsley:

Overall, I found that on the one hand this report recognises the significant generic limitations of the bioclimate modelling, along with more specific limitations of the distributional data that have been used to train the model, while concluding with confidence that the results suggest loss of the species due to climatic change at Cors Fochno in future should it be translocated there. Quoting from the discussion *'From the data included in the present study, it was not possible to construct good quality species distribution models of *Dicranum undulatum* in Britain and Ireland, or Europe. Their poor quality is due to various reasons, but in particular only macroclimatic variables were included in their construction, and other factors will have an important influence on the distribution of the species, such as habitat availability, which will be controlled by factors in addition to climate, such as topography and geology.'* It then goes on to conclude, *'By 2061–2080, the data suggest there is a high risk that the macroclimate of Cors Fochno will become unsuitable for the species, and it is likely that in the longer term it will become more unsuitable'*.

Both of us agree that it is valuable to consider climate change in such long-term projects and decision-making. However, we need to be wary about using only modelled outputs to inform these big decisions. Having lead the UK and Ireland consortium of organisations that commissioned Oxford University to undertake the MONARCH3 project that mapped bioclimate envelopes of some 120 species from a diverse range of taxa, it became clear that climate models were only good at predicting climate space for a limited number of the species and we only published the results for around a quarter of the species modelled. The distribution and rarity of *Dicranum undulatum* in Britain and Ireland (based on the NBN Atlas distribution) clearly reflects the fact that it has been lost due to habitat degradation and is also probably under-recorded, such that the distribution will not reflect the boundary of climate within which it can exist. This is the main fundamental flaw in the use of the modelling to decide on future suitability of Cors Fochno for the species. I therefore have low confidence in the UK and Ireland model as it is trained on an inadequate dataset, i.e. climate envelope modelling is not suitable for use with species whose distributions are clearly not primarily delineated based on climatic variables. While the European distribution on first consideration does show this to be a core Scandinavian

species at the limit of its range in Wales and Ireland, it is distributed across a broad climatic range in continental Europe, which suggests that climate might not be constricting in determining the boundaries of its range. Critically, the climate envelope model for Europe includes West Wales within the climate envelope, and moreover, even the Britain and Ireland model has the boundary of the envelope within Wales not more than c. 50 miles from Cors Fochno. Given the caveats to the modelling, this suggests that west Wales will remain somewhere near the edge of range as it is now. It is not clear which thresholds are used to produce the climate envelope figures, but the choice of threshold can change the location of a line of suitability. Also, there is only one modelled future presented using input from a global climate dataset rather than the UK specific UKCP18 data that would provide a better input. Also, the use of a single GCM model rather than data from an ensemble of models, which could potentially make it more robust is another limitation.

Overall, we come back to this species being unsuitable for using climate envelope modelling due to the likely variety of factors defining its distribution and limitations of the available distribution data. We conclude that this work should not prevent the reintroduction of *D. undulatum* as the models are derived from a very narrow set of variables, suffer from all the caveats of climate envelope modelling generally, and the specific issues of the UK and Ireland distribution being unsuitable for their training. While it is clear that the species is near the edge of its range, there is no clarity that Cors Fochno will be outside its future climate envelope or range. Touching on the issue of wildfire, which is clearly a risk that climate change will increase in future, we would suggest considering if it is possible to reintroduce it in a range of localities rather than putting all our translocation efforts in one site. There is clearly a risk that fire rather than climate change could result in its future loss. Reintroduction at multiple localities would be an appropriate measure to increase the Welsh population's resilience to climate change risks if suitable sites are identified.

Author response by Dr Des Callaghan

Thanks for passing on the reviewers' comments. I have spent a lot of time on this piece of work, more than originally quoted, so I am happy to see it published as is, with the reviewers comments put in an appendix. After all, their comments just come down to differences in opinion, rather than anything more serious. I do not agree with the opinion that: "The distribution and rarity of *Dicranum* in Britain and Ireland...clearly reflects the fact that it has been lost due to habitat degradation and is also probably under-recorded, such that the distribution will not reflect the boundary of climate within which it can exist." Historic records of the species, prior to losses due to habitat degradation, have been included in the model, and whilst some under-recording is inevitable, I do not think this is a substantially under-recorded species. I believe the distribution of the species in Britain and Ireland is clearly influenced by the macroclimate, shown by its

stronghold in north-east Scotland, illustrating its wider confinement to a boreal and continental climate. This is discussed in the report. I believe the available evidence suggests that future climate change is a high risk for this species, and I do not agree with the suggestion that this risk should be disregarded and that the species should be introduced to multiple localities.

10. Data Archive Appendix

Data outputs associated with this project are archived on server-based storage at Natural Resources Wales.

The data archive contains:

[A] The final report in Microsoft Word and Adobe PDF formats.

The metadata for this project is held as record no NRW_DS161364.

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