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CHIRP - Climate Change Impacts on Raised Peatbogs

A case study of Thorne, Crowle, Goole, and Hatfield Moors

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CHIRP

Climate change impacts on raised peatbogs: a case study of Thorne, Crowle, Goole and Hatfield Moors

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1.1 Peatland ecosystems

Peats are essentially deposits, over a mineral substrate, of organic matter which has not been completely oxidised because the prevailing conditions are oxygen deficient. A cool climate and rainfall levels exceeding evaporation are the primary environmental requirements for raised bogs. Approximately one tenth of organic material input to the detrivore/decomposer food chain accumulates as peat each year. The fact that decomposition is slower than deposition is because aerobic decomposers are inhibited by the oxygen-deficient conditions of the peat; just below the water table, the oxygen which has diffused from the atmosphere is consumed at a faster rate than it is replenished. Anaerobe activity is limited by substrate quality, which may be related to insufficient levels of macronutrients – for example, nitrogen concentration is linked to rate of decay.

Peatlands are the predominant wetland type on a global scale, and cover a total area of about 3.98 million km^2 worldwide, 0.1% of which is lost annually. Contributing significantly to wetland ecosystem function, peatlands provide rich biological diversity and valuable habitats for flora and fauna, and form major components in global hydrogeological cycles – either as headwaters of complete catchments or as principal factors within catchments – and are thus instrumental in the maintenance of water quality and quantity. Peatlands account for 10% of global liquid fresh water resources (Mire Wise Use, 2001). Peatlands also play a large role in the carbon cycle – they are not in carbon equilibrium (as are mature forests) and carbon is continually being deposited in deepening layers of peat. Carbon dioxide is therefore being constantly drawn out of the atmosphere, and the calculated global carbon store of peatlands, 455Pg (10^{15g}) accounts for one third of the soil carbon pool.

Raised bogs have developed over 10,000 years since the last Ice Age in a number of situations, typically arising from a succession of open water, reedswamp, and carr woodland. As they become raised above the groundwater, the nutrient-poor atmospheric precipitation gives rise to waterlogged acid conditions in which the undecomposed plant remains accumulate as peat. In the northern hemisphere *Sphagnum* mosses play an important part in the process, due to their ability to retain water and acidify the environment. Elsewhere, a similar function is provided by other plants, eg, the Restiad rushes (New Zealand). While raised bog occurs in the lowlands and in the uplands as blanket bog, it is characterised in the lowlands by its association with geomorphological situations such as floodplains, estuaries and basins.

Inputs of sulphur and nitrogen (as dry precipitation, acid rain or runoff from agricultural land) inevitably affect the chemistry of peat and have an influence on the species composition, biological processes and gaseous emissions (Chapter 2). Though sulphur deposition has drastically affected some peatland ecosystems – parts of the Pennines have lost most of their *Sphagnum* due partly to sulphur pollution and the denuded surface is being eroded – it has greatly diminished over the last forty years. In contrast to sulphur pollution and its consequences, issues relating to the effects of nitrogen oxides and ammonia on the environment have, until recently, attracted little consideration. Nitrogen oxides have become (with the reduction in sulphur dioxide emissions) a significant constituent of acid rain and play a part in ozone formation. Today, the level of nitrogen deposition has become sufficiently high that some peatlands have become degraded (Woodin and Farmer, 1993).

The European Union listed peatbog ecosystems as Priority Habitats in 1992 under the Habitats Directive. Active raised bogs are also a UK BAP Priority Habitat, as 94% of lowland peatbogs have been lost over the last five decades and are thought to be particularly vulnerable to climate change as a result of loss of suitable conditions (Hossell *et al*, 2000). They are characteristic of wetter parts of western and northern Britain, of primarily acid and oligotrophic peats and peaty mineral soils, and particularly of better-drained areas of ombrotrophic peat. Though in the UK they are associated with higher levels of rainfall than that of the Humberhead Levels, similar vegetation and floristic compositions have been recorded in Scandinavia, thus underlining the similarity between these mire complexes (and associated vegetation) and those of the Baltic. Thorne and Hatfield Moors, in addition to SSSI notification, are under consideration for Wetlands of International Importance status under the terms of the RAMSAR Convention 1971. Thorne Moor is a candidate Special Area of Conservation (SAC) under the EU Habitats Directive, and the whole of Thorne and Hatfield may be proposed as an SAC candidate by English Nature. In August 2001 Thorne and Hatfield Moors were designated as a Special Protection Area (SPA).

1.2 The site

Formerly part of the Humberhead Levels, Thorne, Crowle and Goole Moors SSSI, with Hatfield Moors SSSI (subsequently referred to as the Moors) represent the largest area of raised bog peat with semi-natural vegetation. NVC community M18 *Erica tetralix-Sphagnum papillosum* is very restricted in its distribution on these sites and does not occupy anything near the total areas. At 1900ha, Thorne Moor is the largest remaining lowland raised peat bog in Britain. Thorne and Hatfield Moors are degraded peat bogs. Although the whole no longer exists as a raised mire, species typical of raised mire are still to be found here. Indeed, some species associated with wet heath are found on Thorne Moors and not Hatfield. This community (M15; *Scirpus cespitosus – Erica tetralix* wet heath), occurs in some areas, on raised mires that have become dry and eroded, or which have been drained, frequently burned, cut-over and disturbed (Rodwell, 1991). Thorne, Crowle and Goole Moors is one site, and Hatfield Moors is another, about 5 km away, at the junction of South Yorkshire, East Riding of Yorkshire and Lincolnshire.

Plant and animal species found in these degraded raised bog ecosystems include: *Andromeda polifolia* (Bog rosemary), *Myrica gale* (Bog myrtle), *Utricularia vulgaris* (Greater bladderwort), *Potentilla palustris* (Marsh cinquefoil), herptiles (lizards), *Vipera berus* (Adder), the rare *Coenonympha tullia* (Large Heath butterfly), *Luscinia megarhynchos* (Nightingale), and an internationally important population of *Caprimulgus europaeus* (Nightjar). There are more than 5000 plant and animal species on Thorne and Hatfield Moors. The number of recorded insect species on Thorne Moors is more than 2500, the Moors have been classified as the fourth largest assemblage of rare species for any GB site in the Invertebrate Site Register, and the largest assemblage of any wetland site (Ball, 1992). The number of habitats and niches has been increased by degradation of the raised bogs. According to Wheeler and Shaw (1995), there are three principal vegetation types found on the Moors: 'Bog-Sphagnum' vegetation, as found in little or undamaged bogs (M18) and bog pool communities (M2, M3) in worked sites, though conformity to NVC vegetation types is variable; 'Para-bog-sphagnum' vegetation, widely found in peat workings and may include a range of typical bog species, but not in the same proportions or vegetation structure as in

‘Bog-Sphagnum’ communities, and; ‘Dry bog’ vegetation, includes few or no bog species and includes the wet heath, dry heath, *Molinia* grassland, birch scrub and other related communities.

1.3 The project

There has been considerable advance in our understanding of the science of climate change over the last decade and the latest Intergovernmental Panel on Climate Change report suggests that “*It is likely that the rate and the duration of the warming during the 20th century is larger than at any other time during the last 1000 years*” (Houghton *et al*, 2001). By 2100 the global temperatures are expected to increase by between 1.4 and 5.8°C, unless vigorous controls on greenhouse gas emissions are adopted (*ibid*.), but even with emission control strategies, warming will still occur because of past and present emissions of greenhouse gases and the response lags of the climate/ocean system. Some further global warming, therefore, is inevitable and it is important that its potential impacts are investigated as the Moors are thought to be in a climatically marginal area for bog development (Joosten, 1997). Also the northern range limits of many species lies close to the Humber-Mersey line (Key, 1991). It is important, however, to assess not just the potential direct impacts of climate change, but also its possible effect on hydrological processes, as a combination of the two are likely to be critical to the continuing character and biodiversity of the sites.

This was achieved by down-scaling the UKCIP98 climate change scenarios to the 10 km x 10 km grid level so that the predicted changes in a number of climatic and bioclimatic climate parameters of importance to peatlands can be derived. These scenarios also are used to drive a hydrological model that is applied to dipwell data for the Moors in order that changes in water levels can be predicted. The impact of climate change on the climate envelope of individual species is modelled, as a basis for assessing potential changes in the composition of the habitats. The results of the various techniques are then combined to give a picture of the potential impacts of climate change on the peatlands of Humberhead Levels, so that appropriate management and mitigation strategies can be identified.

1.4 Climate model

Climate change is an important driving mechanism for altering the distribution of species and, therefore, the species composition of habitats. The SPECIESv1 model has been used to investigate the effects of climate change on the potential future distributions of a range of species of importance to the Moors (Chapter 3), in order to assess the implications for their future (Chapter 4).

The SPECIESv1 (Spatial Estimator of the Climate Impacts on the Envelope of Species) model was used to simulate the impacts of climate change on the potential climatic suitability of individual species. SPECIESv1 was originally developed as part of a jointly funded project between MAFF, DETR and UKWIR *CC0337: Regional climate change impact and response studies in East Anglia and North West England (REGIS).* A detailed description of the model including the advantages and disadvantages of this modelling approach are discussed in Berry *et al* (2001a).

The model uses a neural network to integrate bioclimatic variables for predicting the distribution of species through the characterisation of bioclimatic envelopes. A schematic of the model structure is presented in Figure 1.1. A number of integrated algorithms undertake a pre-processing of input climate (temperature, rainfall and solar radiation) and soils (AWC) data to derive relevant bioclimatic variables for input to the neural-network. Five variables were used for the plant and insect species:

- Mean soil water availability for the summer half year (May - September).
- Accumulated annual soil water deficit.
- Absolute minimum temperature expected over a 20-year period.
- Annual maximum temperature.
- Growing degree days above a base temperature of 5°C.

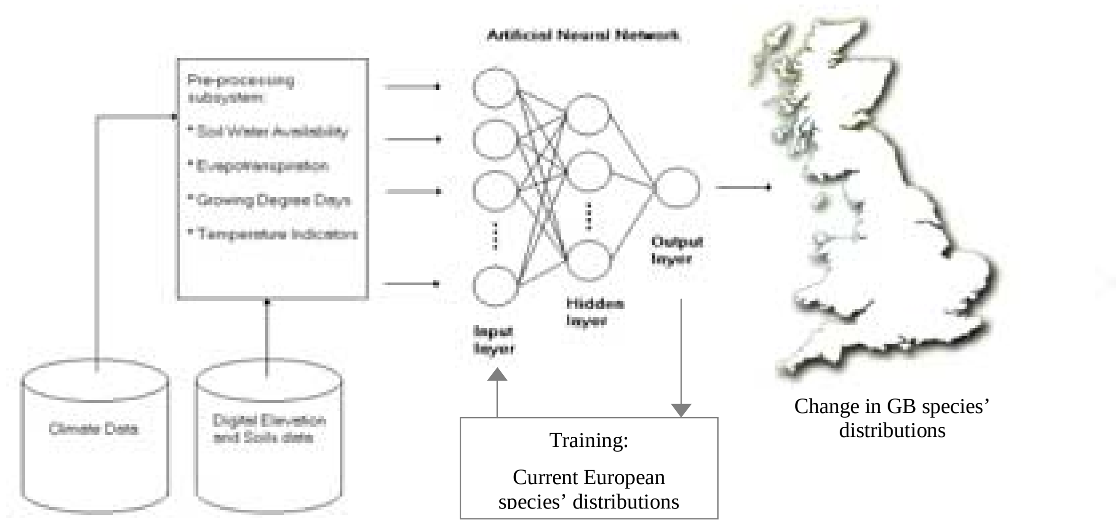

Figure 1.1 **Schematic representation of the SPECIES model.**

The model is trained using existing empirical data on the European distributions of species to enable a wide climate space to be characterised that captures the climatic range of the future scenarios. It was initially intended to use the GB distribution data nested within the European distribution data, but as there were more than twice as many GB data sets than European, the network was weighted unevenly and the results produced were confused by being based more on local land use than climate.

For modelling the bird species alternative input bioclimatic variables were calculated (as with the MONARCH project; Berry *et al*, 2001b). These were:

- Mean winter precipitation (December, January, February).
- Mean summer precipitation (May, June, July).
- Mean summer temperature (May, June, July).

- Mean summer water availability - precipitation minus potential evapotranspiration (May, June, July).
- Growing degree days above a base temperature of 5°C.
- Absolute minimum temperature expected over a 20-year period.

To overcome the problem of the wide variation of three of the (precipitation-related) variables' values at different spatial resolutions, the high resolution British data were nested within the coarser resolution European data. Therefore both temperature and precipitation extremes for the current climate and the UKCIP98 scenarios are captured within the training data set.

Observed European distributions were obtained from Johnson (1977) for *Curimposis nigrita;* Lindroth (1985) and Crossley and Norris (1975) for *Bembidion humerale;* Hulten (1959), Meusel *et al* (1965; 1978; 1992) and Jalas and Suominen (1972-91) for the plants; Tolman (1997) for the butterfly, and; Peterson *et al* (1974) for the bird. Distributions for Great Britain were provided by the Biological Records Centre for the plants, the Thorne and Hatfield Moors Conservation Forum for the beetles and Gibbon *et al* (1993) for the British distribution of the bird species. The presence and absence distributions of each species are re-mapped to a 0.5° latitude x 0.5° longitude resolution (and eastings and northings for the Great Britain data) (to match the climate and soils data sets) and a kriging interpolation function is applied to provide a smoothed probability distribution map. The data are then randomly selected into three groups for training, validating and testing the neural network prediction accuracy. The use of a validation set is to ensure that the network is not over-trained on the training data, thus losing its capability to generalise, whilst the test data is used for independent verification of the prediction performance.

The performance of each network is statistically analysed using the Spearman Rank correlation coefficient and the Kappa coefficient of agreement. The kappa statistic is used to test the similarity of spatially mapped data. Once a network is trained, validated and tested at this European (and Great Britain in the case of the bird) scale, it is then used to estimate the potential re-distribution of species in Great Britain at a finer 10 km x 10 km spatial resolution under alternative climate change scenarios.

The output from the trained neural network is a probability distribution map for suitable climate space for each species and each climate change scenario showing the likelihood of a species being present across Europe and Great Britain. A cut off value below which the level of probability is so low that the species is unlikely to be present is calculated from the kappa statistic. The probability distribution is thus converted into a presence/absence map by assuming that all areas with probabilities greater than the cut off value contain presences. Kappa statistics and probability cut off values are given in Table 3.2 for the selected plant, insect, and bird species.

1.4.1 Hydrological model

A water balance model was devised and calibrated with existing dipwell data to investigate the potential impact of climate change on this important aspect of peat bog functioning. The seasonal water balance of Thorne Moor was determined using a semi-empirical approach, based on the water balance of bogs. The model was calibrated against historical water level data and then the climate change scenarios were used to drive the model and derive the future hydrology scenarios. The water balance of an intact bog (input = output) may be simply described as:

Precipitation = Evapotranspiration + surficial runoff + lateral discharge + vertical groundwater recharge

As raised bogs are recharged by precipitation and their surface is isolated from groundwater influence they lose most of their water by evapotranspiration. This is a function of vegetation type, climate (relative humidity, air and surface temperatures, windspeed), and local topography (surface roughness). Surface runoff is governed by the slope of the water table and the permeability of the acrotelm. However, in degraded systems, such as Thorne and Hatfield Moors, the acrotelm structure is largely absent, the water table is relocated in the - now exposed - deeper peat, and evapotranspiration is enhanced. The second largest negative parameter in the annual water balance is surficial runoff. Lateral discharge through deeper peat layers constitutes only small losses in intact bogs, whilst the digging of drains results in enhanced lateral seepage from the dome of the peat (Bragg, 1995). Thus, by far the most important components in the annual water balance of intact bogs are precipitation (positive) and evapotranspiration (negative).

The distribution of bogs cannot simply be explained by mean annual precipitation and evapotranspiration. Rather, subannual and subseasonal patterns in both variables play an important role. Thus, a water balance model was created to estimate changes in the balance between precipitation and evapotranspiration for the UKCIP98 climate change scenarios at a daily time step.

The following data were used in the construction of the model:

Weather data: Daily weather data were obtained from the Meteorological Office, using the MIDAS Land Surface Station Dataset via the British Atmospheric Data Centre website at the Rutherford Appleton Laboratory (http://www.badc.rl.ac.uk). The following datasets were downloaded from the website for three stations:

- Crowle Dirtness Precipitation Station (latitude = 53.579°; longitude = -0.868°; elevation = 3m): Daily total precipitation (mm) from January 1996 to October 1999. Situated approximately three km east of Thorne Moor. Minimum and maximum temperatures for the calculation of PET were taken from the nearby station of Normanby Hall.
- Normanby Hall Station (latitude = 53.633°; longitude = -0.650°; elevation = 47m): Daily minimum and maximum temperature (°C) and daily total precipitation (mm) from January 1996 to October 1999. Situated approximately 16 km east of Thorne Moor.
- Sheffield Station (latitude = 53.383°; longitude = -1.483°; elevation = 131m): Daily minimum and maximum temperature (°C) and daily total precipitation (mm) from January 1996 to October 1999. Situated approximately 40 km south west of Thorne Moor.

Soils data: The underlying soil type at Thorne Moor is low conductivity clay, and heterogeneous sand and gravel below Hatfield. For the purposes of the modelling of Thorne Moor, a deep soil profile and a high available water-holding capacity was assumed consistent with peat soils. This meant that no restriction was used in the water balance model for the maximum amount of water that the soil could hold, ie, all effective rainfall was assumed to percolate into the soil profile rather than be lost as surficial runoff.

Dipwell data: Three sources of data were provided: two sets of dipwells for Thorne Moor and one for Hatfield Moor. The data used for model calibration was the monthly summaries for the 17 dipwells on Thorne Moor (SE 735160 and the elevation 2m). These data were used as they provided the most comprehensive record of water table height.

Daily values of potential evapotranspiration (PET) were computed using the method of Thornthwaite (1955) as only temperature data were available. Monthly values of PET computed using the method of Penman (1948), which accounts for the effects of temperature, solar radiation, humidity and wind speed, were available for the corresponding 10 km x 10 km grid cell in the UKCIP baseline climatology. These compared well with the Thornthwaite PET estimates. A simple soil water balance model was then run to quantify the balance between water supply (precipitation) and atmospheric demand (PET) in relation to generalised peat soil properties. The soil was treated as a single layer with a fixed available water holding capacity (AWC). The amount of soil moisture or the soil moisture deficit was then computed by comparing the supply and demand of water through each day with the AWC of the soil. The model was initiated from the range of borehole measurements of water levels at the start of the recorded time series (January 1996). The best fit between observed and simulated water levels was obtained by assuming that all effective rainfall percolates into the soil profile rather than a proportion being lost as surficial runoff. The implicit assumptions made then, in applying this model, were: the meteorological conditions on Thorne Moor are consistent with those measured at the weather stations; surficial lateral water movement is insignificant, and; vertical water movement into or from the underlying mineral horizon is also insignificant.

1.5 Conclusion

The CHIRP project, therefore, uses the latest UKCIP98 climate scenarios in order to examine the proposed impacts of climate change on the region covered by the Moors, as well as their implications for hydrology. The reliability of the results is dependent on the reliability of the data inputs and the assumption that the relationship between variables is unchanging in the future. Extreme events, such as runs of dry years, are not accounted for under the UKCIP98 future scenarios. A computer model is then used to examine changes in suitable climate space for a range of species associated with the Moors and the consequences of such changes for their biodiversity. Finally possible adaptation strategies for mitigation of the potential impacts are explored.

2. Future potential climate and hydrological scenarios for the region including Thorne, Crowle, Goole and Hatfield Moors

2.1 Climate

Four climate change scenarios have been developed for Great Britain and Ireland on behalf of the United Kingdom Climate Impacts Programme (UKCIP), known as the UKCIP98 scenarios (Hulme and Jenkins, 1998), for three time periods (2020s, 2050s and 2080s). These use the output from experiments undertaken with the global HadCM2 General Circulation Model. The four scenarios reflect uncertainties in future global warming rates attributable to different climate sensitivities and greenhouse gas emissions scenarios and in this project it was decided to focus on two scenarios, the low and high, which capture the range of possible response. The two scenarios were constructed as follows:

- Low - from the HadCM2 GGd experiment with a 0.5% p.a. increase in greenhouse gases scaled to the IS92d emissions scenario, with a low climate sensitivity of 1.5°C
- High - from the HadCM2 GGa experiment with a 1% p.a. increase in greenhouse gases scaled to the IS92a emissions scenario, with a high climate sensitivity of 4.5°C.

This study focuses on the changes from the baseline climate (1960-1990) to the scenarios for the 2020s and 2050s, as being the time scales most relevant to conservation planning and management.

The UKCIP98 scenarios show that there is considerable regional variation in the change in the climatic parameters and thus in this project it is necessary to examine the results at a more local scale. The changes in a range of key variables relevant to biodiversity, therefore, have been calculated for the nine 10 x 10 km grid squares, which cover the Moors (Table 2.1) and for a larger, but topographically relatively homogeneous area (Table 2.2 and Figure 2.1). These show that by the 2050s under the High scenario the average summer could increase by over 2^{o}C and the maximum temperature of the warmest month could increase by over 2.5^{o}C. Similarly winter temperatures also could increase by over 2^{o}C and the absolute minimum temperature by 3^{o}C. These temperature changes would have important implications for plant functioning and possibly survival.

Table 2.1 Climate variables for the nine grid squares covering the Moors

Variable	Base	2020s Low	2020s High	2050s Low	2050s High
Average summer temperature (JJA, ^oC)	15.27	15.87	16.68	16.08	17.52
Average winter temperature (DJF, ^oC)	3.87	4.29	5.18	4.69	5.99
Total summer rainfall (JJA,mm)	164.73	160.58	162.33	161.61	161.61
Total winter rainfall (DJF,mm)	137.27	148.54	156.67	149.27	167.19
Total summer PET (JJA,mm)	324.79	335.38	346.00	346.00	366.81
Total winter PET (DJF,mm)	30.78	30.18	31.84	31.40	31.40
Total spring rainfall - PET (MAM,mm)	-66.70	-65.42	-64.61	-64.16	-72.84
Total summer rainfall - PET (JJA,mm)	-160.06	-174.79	-183.68	-175.76	-219.92
Total autumn rainfall - PET (SON,mm)	43.43	43.71	41.94	38.71	39.02
Total winter rainfall-PET (DJF,mm)	106.51	118.39	124.79	117.87	135.78
Growing degree days greater than 5^oC	1706.58	1855.51	2092.47	1931.12	2387.51
Absolute minimum temperature over 20 year (^oC)	-20.88	-20.26	-18.96	-19.78	-17.86
Maximum temperature of the warmest month (^oC)	20.76	21.40	22.28	21.62	23.38
Accumulated soil water deficit (mm)	-76.81	-78.16	-82.74	-83.33	-120.48
Accumulated soil water surplus (mm)	0.00	0.00	1.19	0.00	2.55

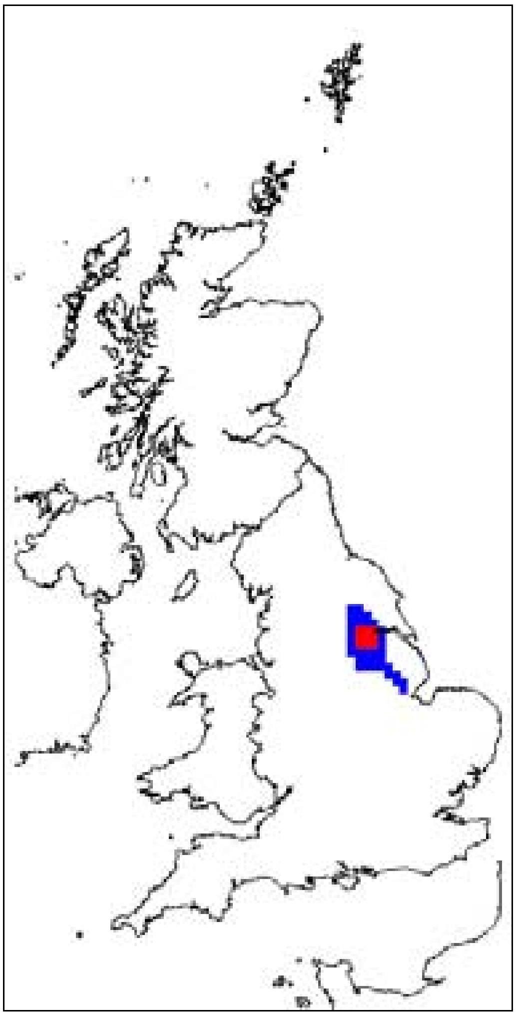

Figure 2.1 Map showing the location of the Moors – within the nine (red) grid squares, in turn within the 43 (blue) grid squares.

Table 2.2 Climate variables for the 43 grid squares covering the Moors

Variable	Base	2020s Low	2020s High	2050s Low	2050s High
Average summer temperature (JJA, ^{o}C)	15.16	15.77	16.59	16.00	17.45
Average winter temperature (DJF, ^{o}C)	3.72	4.16	5.04	4.54	5.87
Total summer rainfall (JJA,mm)	166.36	161.91	163.53	162.90	162.90
Total winter rainfall (DJF,mm)	174.53	155.81	163.97	156.67	174.53
Total summer PET (JJA,mm)	322.62	333.53	344.36	344.36	366.13
Total winter PET (DJF,mm)	28.52	28.02	29.62	29.14	29.04
Total spring rainfall - PET (MAM,mm)	-61.27	-59.88	-59.13	-58.85	-67.54
Total summer rainfall - PET (JJA,mm)	-156.25	-171.61	-180.83	-172.62	-218.95
Total autumn rainfall - PET (SON,mm)	50.54	50.19	47.97	45.22	44.60
Total winter rainfall-PET (DJF,mm)	116.17	127.79	134.36	127.54	145.48
Growing degree days greater than 5^{o}C	1676.38	1824.69	2057.39	1898.30	2348.34
Absolute minimum temperature over 20 year (^{o}C)	-21.04	-20.42	-19.13	-19.97	-18.02
Maximum temperature of the warmest month (^{o}C)	20.54	21.20	22.12	21.43	23.24
Accumulated soil water deficit	-54.46	-60.17	-66.62	-64.38	-108.34
Accumulated soil water surplus	3.58	6.58	8.98	5.67	11.94

As mire surfaces absorb and radiate long wavelength radiation so efficiently, significant diurnal and seasonal fluctuations in temperature are a factor in climatic considerations. Further, the wet conditions immediately below the surface results in a very steep temperature gradient down into the peat; this is matched by an equally sudden change in relative humidity in the opposite direction. This has been well documented (eg, Norgaard, 1951) (Table 2.3) and may greatly influence the dispersal patterns and behaviour of invertebrate species as they exhibit such high temperature sensitivity. It is possible that with climate change the diurnal temperature flux will increase.

Table 2.3 Sphagnum mire temperature and humidity (after Noorgaard, 1951)

	Diurnal temperature flux	Relative humidity
100 cm above bog surface	26°	
At surface	33°	<40%
100 cm below surface	5°	100%

Changes in precipitation are particularly significant in the peatland context and this area of Humberside seems to be close to the boundary of those northern areas that might experience slight increase in summer precipitation under the lower scenarios and those to the south that could experience a decrease. The decrease in summer precipitation, therefore, is very small (less than 2%). What is more significant is the progressive increase in winter precipitation, which reaches over 20% under the 2050s High scenario and thus more than offsets the summer decreases. Potential evapotranspiration, calculated using the Penman formula, show increases of about 14% under the 2050s High scenario, but a minimal increase in winter.

Water availability, however, will be critical for the growth of peat bogs and, as a measure of this, the seasonal rainfall minus potential evapotranspiration was calculated. This shows that in spring there could be a slight reduction in the water deficit, except under the 2050s High scenario where the increase in winter precipitation outweighs that for potential evapotranspiration. This increased deficit is much more significant in summer when it could be as much as 40% greater under the 2050s High scenario. The surplus in autumn, however, could increase by 12% and in winter by 25%, thus facilitating recharge.

Accumulated soil water deficit and surplus was calculated by the balance between precipitation, potential evapotranspiration and a soil's available water-holding capacity (AWC). Firstly the precipitation minus potential evapotranspiration was used to represent the water available for each month. The soil water reserve for each month was then calculated to give either a surplus or a deficit. If the water available in the first month is positive then this becomes the soil water reserve up to the maximum of the AWC, any excess above this being assigned as the surplus. If the water available for any month is negative then soil water reserve is reduced by that amount (to a minimum of 0), and available water is equal to a deficit. The same rules are applied in successive months and an accumulated surplus and deficit is calculated for the year. These are also used as the input variables, soil moisture surplus and soil moisture deficit, to the SPECIES model (Chapter 1). The accumulated soil water deficit could almost double by the 2050s High in the larger area and increase by 60% in the smaller area. The increased summer water deficits would lead to accelerated decay rates of peat altering the depth of the acrotelm. This will release more nitrogen and phosphorus and could, together with the increased depth and duration of surface drying, promote the growth of shrubs and grasses and the expense of sedges and *Sphagnum*. As the latter two are the most significant for peat formation this will decrease. Coupled with the increased decay rates this would lead to a net carbon loss and a gradual movement from a *Sphagnum* dominated habitat to one which, in the presence of fire and grazing, is dominated by dwarf shrubs and grasses, but in the absence of such disturbances birch and willow would invade.

The growing season could also be extended as the growing degree days above 5^{o}C increase by over 30% by the 2050s high scenario. This might mean that multivoltine insects increase the number of generations in a year and that birds which currently migrate either stay longer in autumn or do not migrate at all. This review of various climate change in the region suggests that, based on climatically-derived parameters, water availability could be an important issue in the future and thus it is important that this critical variable is investigated in more detail.

2.2 Hydrology

Thorne and Hatfield Moors have evolved in an area where rainfall is relatively low - <600 mm/yr - the minimum normally associated with raised bogs. The fact that they are in an area marginal to bog formation implies that development has taken place under special conditions, if the precipitation threshold is valid. However, as global patterns indicate, the worldwide distribution of bogs is not solely a function of rainfall – and cannot be related simply to mean annual precipitation (Glaser *et al*, 1997). Evapotranspiration is the most influential factor with regard to water loss from bogs and is therefore important in terms of water available (effective precipitation).

After drainage and peat extraction/acrotelm removal, the exposed catotelm becomes the water storage facility for the peat body. However, there is large variation between the water storage capacity of the acrotelm and catotelm, which is governed by the relationship of macropores to micropores in the peat (a function of bulk density and porosity, which can vary within and between types of peat). Strongly humified catotelm peat has a greater proportion of large pores than weakly humified (acrotelm) peat; it has a smaller proportion of free water (Wheeler and Shaw, 1995) and water table fluctuations are higher without this buffering effect.

Investigation into the relationship between land use (in this case, peat extraction) and climate have shown that while extraction would not significantly affect the precipitation levels at this site, increased differences between summer and winter rainfall rates, by exacerbating the contrasting effects on water table level, would result in the degradation of conditions for these ecosystems. In the summer months when rainfall is low, evapotranspiration results in a concomitant lowering of the water table; conversely, rainfall in the winter months leads to water table draw-up. Where there has already been a lowering of the water table (eg, Hatfield Moor) raised bog communities have become depauperate and species richness has declined (Limbert and Eversham, 1997). From a conservation point of view, water table drawdowns resulting from previous land use should be diminished and draw-ups should be maximised.

A hydrological model developed by Bromley and Robinson used measured water levels, climate observations and hydraulic conductivity values (Bromley and Robinson, 1991); the CHIRP model uses the same inputs, but substitutes generalised peat soil properties as hydraulic conductivity values vary so much across the site. Whereas the Bromley and Robinson model aimed to predict how the hydrology of the site would continue to be affected during further peat extraction, the CHIRP model is primarily concerned with the potential effects of climate change on the system. They used the model to investigate the recorded rise of between 20 and 30cm in water levels over the period 1992-1995 (Bromley *et al*, 1997). The rise followed their hydrological model and thus was probably a function of climate variation rather than an earlier attempt at ditch blocking. This underlines the importance of researching the potential impact of climate change on the Moors. The investigation also suggested that, although the water table levels are below the base of the peat, vertical leakage is unlikely to be important in this case as a layer of clay lies under the site.

2.3 Model outputs

The hydrological model was created and used according to the methodology outlined in Chapter 1. The recorded water levels for the 17 boreholes at the site of dipwell 2 on Thorne Moor show that there is a clear seasonal cycle of low water levels in summer to high water levels (Figure 2.2). The average water levels range from 391 mm AOD in July 1996 to 1297 mm AOD in February 1995. There is a considerable range about the average value across the 17 boreholes. The average range across the 17 boreholes is 492 mm, but this varies from a minimum range of 228 mm in February 1995 to a maximum range of 758 mm in September 1997.

The simulated water levels for the three climate stations are also shown in Figure 2.2. Results from the sites of Crowle and Normanby Hall capture the general seasonal pattern of water levels, but the simulated interannual variability is less than observed. Average water levels across the time series for Crowle (SIMC) are 942 mm (ranging from 751 to 1352 mm) and for Normanby Hall (SIMN) are 1005 mm (ranging from 813 to 1363 mm). These compare with corresponding observed values of 1037 mm (ranging from 391 to 1297 mm). Results for the site of Sheffield (SIMS) also follow a similar seasonal pattern, but simulated values begin to exceed the range of observed values after April 1998 due to higher precipitation totals than at the sites of Crowle or Normanby Hall. None of them capture the low values in the summers of 1996 and 1997, as precipitation at these sites was not significantly different from normal.

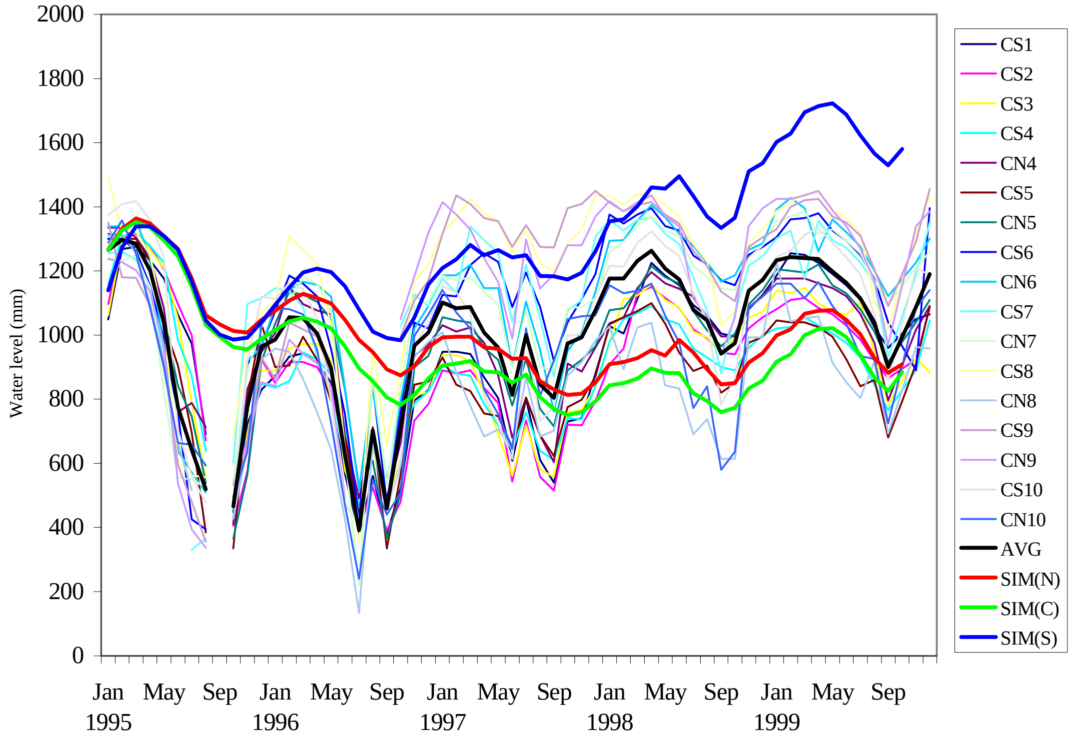

Figure 2.2 **Seasonal cycle of dipwell low and high water levels, their average (AVG) and simulated water levels for the three climate stations**

Observed and simulated water levels are also compared for the current climate in Figure 2.3 in terms of their cumulative probability distributions. The lines corresponding to Crowle and Normanby Hall are similar to the average observed values, although they are slightly to the left indicating slightly lower mean water levels and slightly steeper indicating slightly lower interannual variability than observed. The line corresponding to Sheffield is situated to the right of the observed average line indicating higher water levels.

The effects of the UKCIP98 climate change scenarios on the peat bogs at Thorne Moor was simulated for the site of Normanby Hall (for which simulations were closest to the recorded dipwell measurements). Monthly changes in temperature and precipitation were obtained for the 10 km x 10 km grid cell encompassing Thorne Moor (National Grid Reference 475000 East, 415000 North) (Figure 2.4a and b). Increases in temperature are predicted for all months and scenarios, ranging from +0.4°C in January in the Low scenario for the 2020s to +2.6°C in August in the High scenario for the 2050s. Decreases in precipitation are predicted for the months of July, August and September in all the scenarios of up to 14.5% for the 2050s High scenario. In contrast, increases in precipitation are generally predicted in all other months, with the greatest increases occurring between October and February of up to 25.7% for the 2050s High scenario.

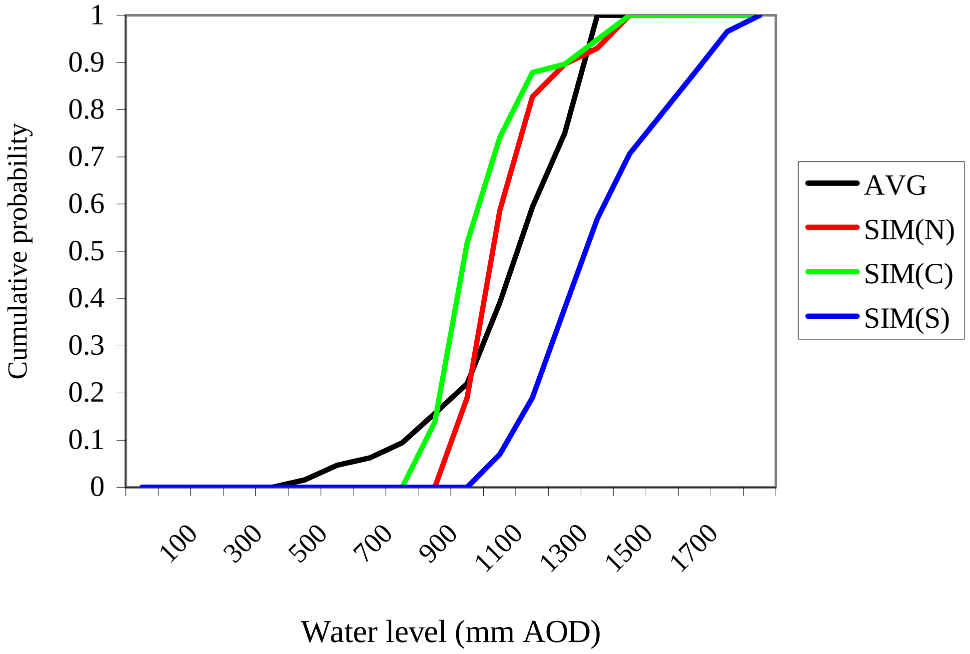

Figure 2.3　　　Comparison of simulated and observed water levels

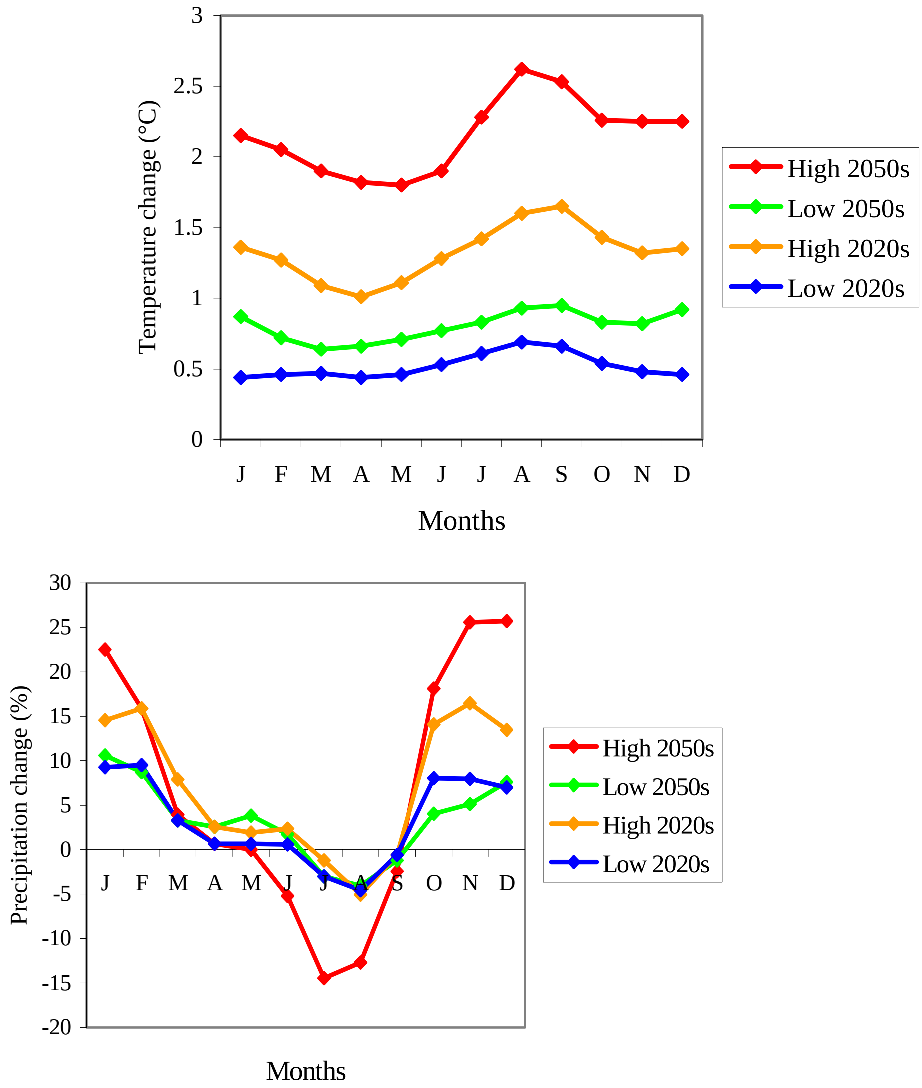

Figure 2.4 **Changes for the Thorne Moor grid square a) monthly temperature b) precipitation**

Simulated values of water levels for the UKCIP98 scenarios are shown in Figures 2.5 and 2.6. Water levels become progressively lower as the climate change scenario becomes more severe. The most extreme reduction in water levels is seen for the 2050s High scenario where average values across the time series decrease from the baseline level of 1005 mm to 636 mm (with a range from 263 to 1232 mm). The variability of the time series is also predicted to progressively increase as the scenarios become more severe, as clearly illustrated by the gradual change in the steepness of the cumulative probability lines.

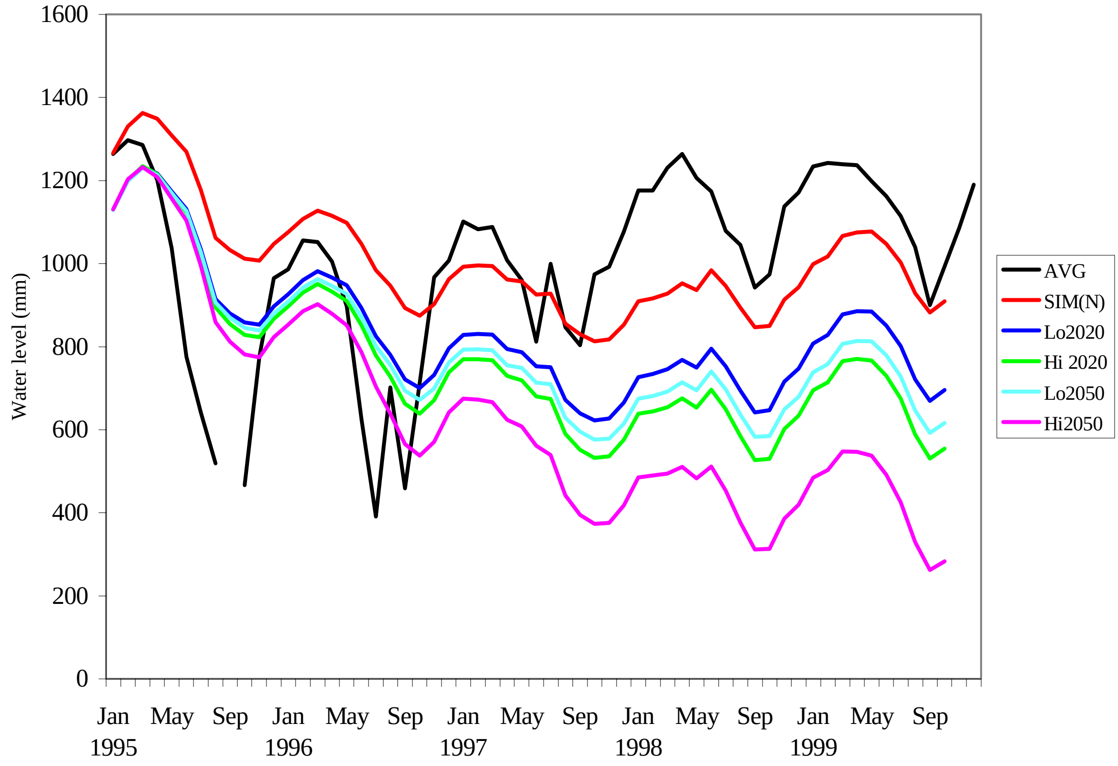

Figure 2.5 **Simulated water levels for the UKCIP98 scenarios**

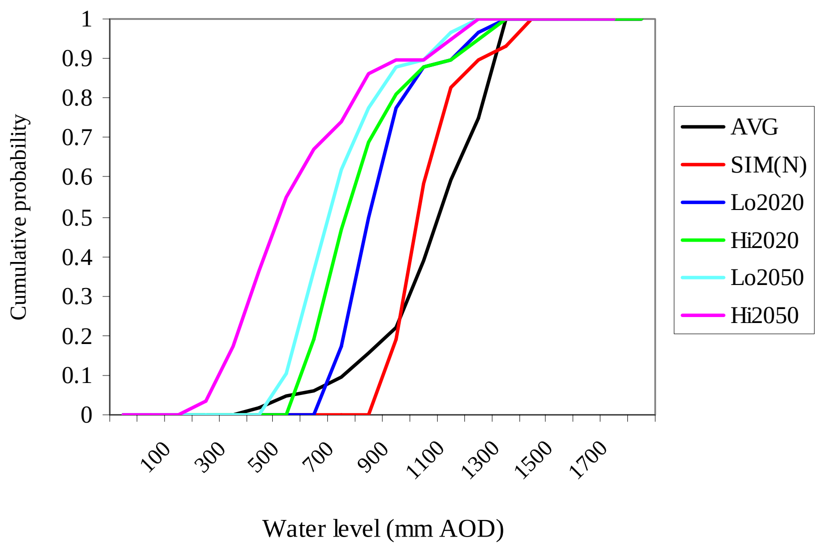

Figure 2.6 **Cumulative probabilities for the simulated water levels**

2.4 Conclusions

Under the climate change scenarios the increases in all the temperature variables is in contrast to the more seasonal variations in the precipitation related parameters. Although the Moors could experience increased winter precipitation there could be a slight reduction in summer precipitation. Increased evapotranspiration losses in summer, however, would lead to greater annual soil water deficit. This is supported by the hydrological modelling, which shows that water levels would decrease under all scenarios. These changes would have important implications for plant functioning and possibly survival and thus it is important to explore the implications for key species (Chapter 3) and the role of management in mitigating these changes (Chapter 4).

3. Species' response to climate change

Thorne and Hatfield Moors have been mined for peat for centuries, and are mosaic landscapes of habitat patches (with virtually no square inch left uncut – Kevin Bull, pers.comm.). Therefore, the Moors are not a homogeneous raised bog habitat, but a mixture of raised bog, with para-bog and wet scrub in places. Some remediation work has resulted in water level management as prevention against further peat loss through drying out and this has resulted in the expansion of range and increase in diversity of the bog plants. There is concern that higher temperature and decreased summer rainfall, leading to drought, will increase peat erosion (Hossell *et al*, 2000).

The species modelled were chosen as a combination of habitat dominants, those thought to be sensitive to climate change (bioindicators) and those of conservation importance in order to provide as complete a picture as possible of the community composition of the Thorne and Hatfield Moors habitat(s). Seven higher plant species, one bryophyte, three insects and one bird were selected (Table 3.1). Of the seven vascular plants and one moss, all but *Betula pendula* are found primarily in the peat cuttings and canals, with *B. pendula* in woodland areas and on peat baulks (Smart *et al*, 1986).

Table 3.1 List of Thorne and Hatfield Moor species studied in the CHIRP project

Higher plants	**Common name**
Andromeda polifolia	Bog rosemary
Betula pendula	Silver birch
Calluna vulgaris	Heather
Erica tetralix	Cross leaved heath
Eriophorum angustifolium	Common cotton grass
Eriophorum vaginatum	Hare's tail cotton grass
Molinia caerulea	Purple moor grass
Bryophyte	
Sphagnum papillosum	Moss (none)
Insects	
Coenonympha tullia	Large heath butterfly
Bembidion humerale	(none)
Curimopsis nigrita	Mire pill beetle, Bog hog
Birds	
Caprimulgus europaeus	European nightjar

A. polifolia, *C. tullia*, *E. tetralix*, *E. vaginatum* and *S. papillosum* were modelled as part of the MONARCH project (Berry *et al*, 2001b), and those results were made available to this project.

The Kappa statistic tests the similarity of the spatially mapped data (see Chapter 1 for full explanation). It is a coefficient of agreement and can have a value of between 0 and 1, with 0.4-0.55 considered fair,0.55-0.7 good, 0.7-0.85 very good and >0.85 excellent (Monserud,1990). For *C. vulgaris*, *E. angustifoilum* and *M. caerulea*, no Kappa statistic was calculated because at all probabilities complete coverage of Great Britain was given by the network simulation. Conversely, at no probability was *C. nigrita* predicted to occur anywhere in Great Britain.

As *Caprimulgus europaeus* was modelled using Great Britain data nested within European data, Kappa statistics were calculated at both the European and Great Britain level. The Kappa value derived for the Great Britain data was used in the creation of the distribution maps for the current and future scenarios. The Kappa value derived for the European data was much higher than that for Great Britain; at the coarser scale the climate parameters had greater weight, whereas at the finer (Great Britain) scale land use factors came into play.

Table 3.2 Kappa coefficient of agreement between observed and simulated distributions at the European scale and probability cut off values for selected plant, insect and bird species

Species	Kappa statistic	Probability cut off value
Calluna vulgaris	No Kappa;	no probability cut off
Erica tetralix	0.92	0.7
Eriophorum angustifolium	No Kappa;	no probability cut off
Eriophorum vaginatum	0.87	0.5
Molinia caerulea	No Kappa;	no probability cut off
Sphagnum papillosum	0.73	0.5
Betula pendula	0.82	0.4
Andromeda polifolia	0.91	0.5
Coenonympha tullia	0.90	0.6
Bembidion humerale	0.01	0.1
Curimposis nigrita	No Kappa;	no probability cut off
Caprimulgus europaeus	GB:0.4270	GB:0.2

On drier peat banks, *Molinia caerulea*, as well as heather and bracken, is a dominant species. *Betula* scrub often encroaches onto these areas as the water table draws down, as part of the succession to a drier ecosystem. As a result of changes in land use; drainage, peat cutting and land reclamation for agriculture, specialist plants (ie, ecologically demanding) have been lost, but the order of extinction has not been elucidated fully. It has been recorded that while plants preferring the wettest parts of the mire habitat, such as *Drosera longifolia* and *Carex limosa* (Great sundew and Bog sedge, respectively), were historically (in the nineteenth century) the first species lost after drainage at Thorne (Eversham, 1997), other such inhabitants, eg, *Sphagnum cuspidatum*, have persisted.

Calluna vulgaris (Heather) is not a typical wetland habitat species (it has a range that covers the whole of the British Isles), and prefers well-drained acidic soils. It is though, often found on tussocks of other plants (as well as elsewhere) growing in ombrogenous bog (favouring the drier peat banks on Thorne and Hatfield Moors), and is a constant species of many mire and heath communities (Rodwell, 1991). It is the most important heathland species in Britain and is a successful competitor displaying some ruderal characteristics; in areas where mature, vigorous stands are found, it will often be the only species (Grime *et al*, 1988). C. vulgaris is found almost throughout the Britain, though is absent from parts of southern and central England and East Anglia. The simulation (Fig. 3.1b) is quite a close match although it does give complete Great Britain coverage by overpredicting occurrence in these areas. This suggests that the distribution of C. vulgaris (as with many other plant species) is restricted by factors other than climate.

Under all of the future climate scenarios (see Fig. 3.1c,d,e,f), the model gives no loss of climate space anywhere in Great Britain, although the nature of the Moors community itself may change if other species found in particular community assemblages are lost. The results indicate that all future climatic variables fall within the range of tolerance of C. vulgaris.

Erica tetralix (Cross-leaved heath) is a typical constant of wet heath and mire habitats. It is tolerant to waterlogging and is found in damp areas, often in company with tussocks of *Eriophorum vaginatum.* The model predicts suitable climate space across the whole of Great Britain under the current and all future climate scenarios (Fig. 3.2c,d,e,f). The results suggest that as it is one of the dominant species of the Thorne and Hatfield Moors habitat, this component of the community assemblage would remain present under future climatic conditions.

Eriophorum angustifolium (Common cotton grass) is one of the constants of raised mire communities (Rodwell, 1991), in company with *E. tetralix* and *C. vulgaris*, predominantly on wetter ground. This species spreads primarily by means of rhizome growth and forms large clonal patches – seed establishment is very rare (Grime *et al*, 1988). While the demise of wetlands in Britain has resulted in significant decline in *E. angustifolium* in some lowland areas, its capacity for colonisation of large areas of eroded peat (after cutting and burning) means it is abundant in other regions. *E. angustifolium* has a distribution very similar to that of *M. caerulea* (see below) with fairly solid coverage across most of Scotland and Wales, and patchier occurrence in the north, central, east and south of England. The network simulation (Fig. 3.3) predicts unbroken distribution across the whole of Great Britain – suggesting that the current distribution is a function of land use as much as climate, as with *C. vulgaris, E. tetralix* and *Molinia caerulea* (see below). Its range is generally countrywide.

Under all of the future climate scenarios (Fig. 3.3c,d,e,f), the model gives suitable climate space for *E. angustifolium* over the whole country. This indicates that *E. angustifolium* will be resilient to climate change. These three stress-tolerator, constants of raised bog, *E. angustifolium*, *Erica tetralix* and *Calluna vulgaris*, will do well and continue their close association with each other under all climate scenarios.

Eriophorum vaginatum (Hare's-tail cotton grass) forms stands on peaty, wet, acidic and unproductive soil and is prominent especially in sites waterlogged in spring but drier in summer. This species is generally found north of a line between the Humber and the Severn, and also on high ground in the south west, the New Forest, and parts of Cornwall and East Anglia. Spreading mainly by seed dispersal, *E. vaginatum*, though usually found in sites with little bare soil, will colonise areas of cut peat. As a result of this widespread occurrence, the simulation (Fig. 3.4b) predicts suitable climate space across most of Great Britain – the exception being a few isolated parts of northern Scotland. The 2020s Low scenario and 2050s Low distributions (Fig. 3.4c,e) show little difference, but the distribution for the 2020s High scenario (Fig. 3.4d) gives an decrease in climate space in the north of Scotland and also south west England. This trend continues under the 2050s High scenario (Fig. 3.4f) so that all of the south west and much of the southern, south east and eastern coastal areas of East Anglia are unsuitable for *E. vaginatum*. There is also some loss of climate space in south and north Wales, and the north of Scotland, though the Humberhead levels will remain suitable.

Figure 3.1 SPECIESv1 model results for Calluna vulgaris: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario.

Figure 3.2 SPECIESv1 model results for Erica tetralix: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.3 SPECIESv1 model results for Eriophorum angustifolium: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.4 SPECIESv1 model results for Eriophorum vaginatum: (a) observed distribution; current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

Molinia caerulea (Purple moor grass) is another stress-tolerant competitor (Grime *et al*, 1988) generally scarce on raised mires, but can be occasionally abundant, for example on better-drained areas such as the drying centre of bogs or around the edges of the community. It is found as tussocks on hummocks and extends down to wetter flat areas, though is intolerant of waterlogging; here it often gives way to *E. vaginatum*. In cut over and drained bogs it may often become a pest species. The large amounts of seed produced by *M. caerulea* colonise bare ground and germinate in spring, provided the high temperature requirement has been met (Grime *et al*, 1988).

M. caerulea occurs right across Great Britain except for small absences in central and eastern England, as with *E. angustifolium*. The network simulation overpredicts frequency in central, southern and eastern England, thus giving presence across all of Great Britain. Again, as with *C. vulgaris, E. tetralix,* and *Eriophorum angustifolium,* suitable climate space for *M. caerulea* under all of the future climate scenarios covers the whole of Great Britain (Fig. 3.5c,d,e,f).

Sphagnum papillosum is another constant of raised mire communities (Rodwell, 1991) and is an important peat-forming species. The simulated distribution (Fig. 3.6b), which is a good match for the actual distribution, gives widespread occurrence of *S. papillosum* across Great Britain, with absences in East Anglia and central England. The Low 2020s scenario (Fig. 3.6c) shows an increase in occurrence across these areas. The High 2020s and Low 2050s scenarios (Fig. 3.6d,e) give only part of coastal East Anglia as unsuitable climate space, but the High 2050s scenario (Fig. 3.6f) show losses of climate space from the southern coasts of Wales, Cornwall and the rest of England, and also further inland in East Anglia (similar to the Low 2020s scenario in this area).

Betula pendula (Silver birch) is widespread across most of Great Britain, with a slightly more localised distribution in places (Fig. 3.7a) and is most abundant in areas of low pH. The simulation matches this quite closely, but gives a restricted range in the Caithness area of Scotland. The 2020s Low scenario (Fig. 3.7c) gives almost blanket coverage of Great Britain, with some restrictions in north east Scotland and small areas of Somerset and Kent. The 2020s High scenario (Fig. 3.7d) gives a further retraction of suitable climate space in the south east and south west of England, coastal East Anglia and Lincolnshire and the southern part of the Welsh border. Climate space in north east Scotland, on the other hand, has increased. The 2050s Low scenario (Fig. 3.7e) is very similar to the 2020s Low scenario, with slightly more climate space in northern Scotland and slightly less in Kent and Somerset. Under the 2050s High scenario (Fig. 3.7f) distribution is widespread across Great Britain with some patchiness in the south west and coastal north east of England, and the north of Wales.

B. pendula is an aggressive generalist species and invades wet ground and scrubland, growing best when seeds land on bare soil, due to its germination requirement of light. Under the future climate scenarios it will not be greatly limited by changes in temperature and rates of precipitation, but will continue to be widely distributed and found in many types of habitat. However, the large susceptibility of seedlings to drought means that it may become marginal in areas where rainfall is predicted to decrease and temperature to increase in future.

Andromeda polifolia (Bog rosemary) is found only in raised bogs, and is a rare species of community M18. It almost always occurs amongst sphagnum, on sphagnum peat substrate, and generally on undisturbed (not cut or burned) bogs, but also on Thorne and Hatfield

Moors, where it is very tenacious once established. *A. polifolia* often favours the tops or sides of hummocks of *Sphagnum papillosum* and *S. magellicum*, and may be associated with *Erica tetralix* and *Eriophorum vaginatum* as well as *Deschampsia flexuosa, Drosera rotundifolia and Vaccinium oxycoccus*.

Its current distribution (Fig 3.8a), is in north-western England and Wales and south-western Scotland, with a few local records in East Anglia, the north-east and the south-west. This is matched quite closely by the simulation in Wales, but not in other parts. The simulation underpredicts occurrence in the north west of Great Britain (and on Thorne and Hatfield Moors), but overpredicts (even though the Kappa value for Europe was 0.90) in North Yorkshire, parts of Durham, Northumberland and Cumbria, and in Scotland, giving a distribution that covers most of the southern central and Highland regions here.

The simulated distribution for the 2020s Low scenario shows a diminution in climate space for *A. polifolia* in England and Wales, but an increase in southern and highland Scotland (Fig. 3.8c). Under this climate scenario it would not occur on the Humberhead levels. The 2020s High scenario (Fig. 3.8d) gives a further reduction in climate space in the UK, and also in southern Scotland and the north west Highlands. The 2050s Low (Fig. 3.8e) scenario gives much the same result as the Low 2020s scenario, though with a slightly smaller climate space in the north of England, and southern Scotland. The 2050s High scenario (Fig. 3.8f) gives a very restricted distribution – across the Grampians and a small area of the north west Highlands, and with no overlap with the current distribution.

The scenarios all give an increase in both annual and winter precipitation across the areas where *A. polifolia* is currently recorded. Summer rainfall, however, decreases markedly under all scenarios, most extremely under the 2050s High Scenario across all of England and Wales. It appears that conditions would therefore be too dry for the continued survival of *A. polifolia*. Under the other three scenarios (2020s and 2050s Low and 2020s High), summer precipitation increases in Scotland and the very north of England. *A. polifolia* is a highly specialised raised bog plant and is thus highly sensitive to ecosystem disturbance and change. Potential evapotranspiration is also predicted to increase, most of all in the High 2050s scenario (more than 30% through the autumn months - see Table 2.2); unsuitable conditions for many raised mire species.

This perennial evergreen reproduces by insect pollination and wind-borne seed dispersal (of the smaller seeds) – successful seed establishment is related to a mycorrhizal association (Stewart *et al*, 1994). Changes in temperature and the increase in fluctuation of summer and winter rainfall (see Tables 2.2 and 2.3) will produce stressful environmental conditions under which *A. polifolia* will be progressively unable to exist, though it has thus far proved to be tenacious on drained areas of Hatfield.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.5 SPECIESv1 model results for Molinia caerulea: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.6 SPECIESv1 model results for Sphagnum papillosum: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

(a)

(b)

(c)

(d)

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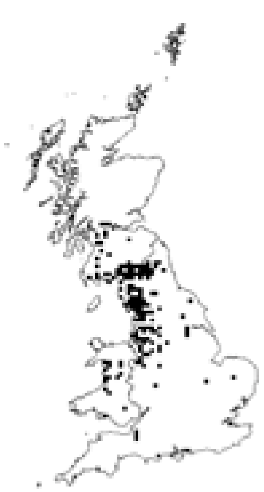
(f)

Figure 3.7 SPECIESv1 model results for Betula pendula: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario



(a)

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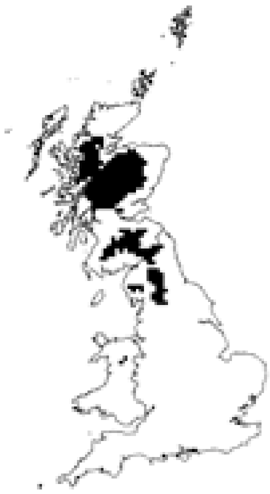

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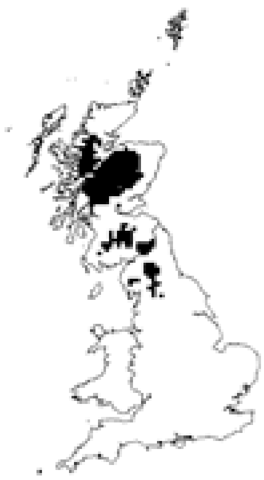

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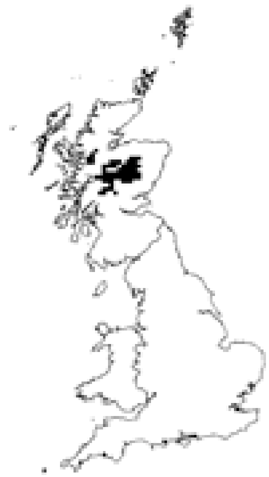

(f)

Figure 3.8 SPECIESv1 model results for Andromeda polifolia: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

Coenonympha tullia (Large heath butterfly) is a UK BAP species of conservation concern. It is found on mires associated with *Eriophorum vaginatum* and *Erica tetralix*, which provide nectar for the adults (Emmet and Heath, 1989). The simulated distribution (Fig. 3.9b) is similar to the actual distribution, though overpredicts occurrence, especially in Scotland, Wales and Cornwall, perhaps as a result of habitat availability. *C. tullia* is found throughout Scotland, with variable frequency, and across northern England and Wales in places. Its presence on the Humberhead Levels is not matched by the simulation. Under the 2020s Low scenario (Fig. 3.9c) *C. tullia* achieves more comprehensive coverage across most of Scotland and Wales and a large part of north west England. This distribution is close to that of the 2050s Low scenario (Fig. 3.9e), while under the 2020s High scenario (Fig. 3.9d) climate space is lost in central Wales, northern England and southern Scotland. Under the High 2050s scenario (Fig. 3.9f) there is a further decrease in suitable climate in Wales, the north of England and southern Scotland.

The distribution of *C. tullia* is related to that of its larval host plants, which include *Eriophorum vaginatum* (Tolman, 1997), and *Erica tetralix*, which is the primary source of nectar for adults (Asher *et al*, 2001). This has been shown to have a continuous potentially overlapping distribution with *Coenonympha tullia* (Berry *et al*, 2001b), so this aspect is unlikely to be of concern for the future of the species. There will be continued overlap in suitable climate space, especially in north west England and western Scotland (*ibid*).

The change in climate will also affect the phenology of butterflies, with warmer summers leading to earlier mean first appearance and mean peak flight dates (Roy and Sparks, 2000). For univoltine species that reproduce only once per year, like *C. tullia*, this is of less benefit than for multivoltine species that may be able to increase the number of generations in a year. What is not known is the possibility of shifts in voltinism, or number of reproductive events per year, in response to climate change, although it is thought that it may change (Roy and Sparks, 2000). It has been noted that in some northern populations larvae have a two-year life cycle (spending a second summer as third instar - insect developmental stage - larvae); this flexibility may be an advantage in terms of response to climate change and extreme weather events (Asher *et al*, 2001).

Bembidion humerale was (re-)discovered in Great Britain recently and is found only on Thorne and Hatfield Moors (Fig. 3.10a). It lives on moist, partly bare peat (often covered by algae) in lowland oligotrophic bogs, generally near water (hollows or pools) in areas colonised by *Eriophorum* spp. (Crossley and Norris, 1975). The maritime influence on the distribution of *B. humerale* is a reflection of the European distribution of both this species, and of this type of raised mire, with which it is very closely associated (Moore, 1984). It is a winged, presumably spring-breeding, species at its northern limit in Britain and southern Scandinavia. There are fossil records (Bronze Age) of the species in Britain as far south as the Somerset Levels, indicating it may be a relict species rather than an introduction (Luff, 1998). Generally, *B. humerale* is very localised across its range (which does not include alpine areas), but may be found in abundance. Its distribution in Britain is southern (Skidmore *et al*, 1997) and adults have been recorded in spring (April) and late summer and early autumn (August to October). Its Red Data Book status is ‘Endangered’.

The actual distribution in the UK then is very restricted – Thorne and Hatfield Moors only, and while the simulated distribution under the current climate does include the observed distribution, it gives a much larger occurrence across the south, south east and north of England, southern and northern Wales and parts of coastal Scotland. This could be due to the

European distribution, which while quite widespread, includes many points along the continental coastline, and thus the model has predicted occurrence in the south of England by extending this distribution northwards to cover the same climatic envelope as northern France, Belgium and the Netherlands. Under all four climate scenarios, the range of *B. humerale* increases as suitable climate space increases. The Low 2020s scenario (Fig. 3.10c) gives coverage over most of England and Wales (excluding some parts in central England and most of central Wales). This continues under the 2020s High and 2050s Low scenarios (Fig.s 3.10d,e), with the northern distribution limit moving further north. The 2050s High scenario (Fig. 3.10f) gives a distribution across most of England and Wales and all of coastal Scotland.

There is the suggestion then, that *B. humerale* will do well under future climates and could increase its range, however as its actual distribution is so much less than that of suitable climate space, other factors may have greater influence than climate. The fact that *B. humerale* is a relict species in Britain also influences the interpretation of the modelling results, suggesting that it may be a marginal species, but one with a potential for increase providing suitable habitat remains available.

Curimopsis nigrita (Mire Pill Beetle or Bog Hog), was first recorded at Thorne Waste in 1977 (Johnson, 1977). The first British record of the Bog Hog was a subfossil of late-Bronze Age date from Thorne Moor (Peter Skidmore, 2001, pers. comm.), which indicates that it is a relict species. The species remains endemic to Thorne Moors. The discovery of this species was important in terms of its limited continental distribution (southern Scandinavia, northern Germany and Poland). The British distribution of this species is southern (Skidmore *et al*, 1997) and *C. nigrita* occurs in lowland peat bogs in association with *Calluna vulgaris*. The adults and larvae feed on moss, just below the soil surface, usually in *Sphagnum* spp. or heather litter, and adults have been found in moss lined tubes. As with *B. humerale*, it favours open damp peat and is also closely associated with acrocarpous mosses, particularly *Dicranella cerviculata, D. heteromalla* and *Campylopus pyriformis.* Adults have been recorded in April, May and July.

Its extremely limited occurrence in Britain (3.11a) reflects its Red Data Book status (endangered), and also means that the neural network was trained on very few points – its European distribution is also very restricted, recorded only in southern Sweden, Denmark, north Germany and northern Poland (Johnson, 1977). As a result, under the current and all the future climate scenarios, *C. nigrita* has no suitable climate space and does not occur anywhere in Britain. As with *B. humerale*, above, this is a relict species in Britain, and it is unlikely that, even if suitable climate space existed, it would be found elsewhere. However, as it is currently found on Thorne and Hatfield Moors under the present community assemblage, it may well persist, as the species with which it is most closely associated are predicted to remain here.

Caprimulgus europaeus (Nightjar) is a migratory summer visitor to Great Britain, wintering in sub-Saharan Africa. Once widespread across Great Britain, numbers have decreased greatly, although this is not thought to be related to climate change (Gibbon *et al*, 1993), but more likely to land use changes. Breeding requirements of open space with a wooded edge, appropriate ‘churring’ points and bare nesting ground, are no longer met in areas where the make-up and nature of heathland has changed due to changes in management (eg, fire control, less grazing). The *C. europaeus* population of Thorne and Hatfield Moors is internationally important.

C. europaeus has been recorded in relatively high numbers in areas of open cut-over bog habitat – generally last cut for peat extraction before 1940. The cutting methods then used (block cutting) have resulted in the creation of a heterogenous habitat type; a mosaic of wet hollows and drier 'baulks' supporting some scrub in the driest spots, however, some of the birch stands have become too dense for Nightjar. These open areas of scrub (predominantly Birch scrub) also provide habitat suitable for Nightjar, as do the mire areas in the woodland/mire areas. An experimental plot, of 100 ha of bare peat showed no evidence of breeding bird territories (Thorne and Hatfield Papers, Vol. III).

The current Great Britain distribution of *C. europaeus* is largely southern, though with some isolated populations as far north as the Scottish Highlands (Fig. 3.12a). Coverage is patchy but widespread, including areas in north and south Wales, East Anglia and the north east of England. The model has predicted this quite well (Fig. 3.12b), although it has omitted most of the sites in northern England and has given greater coverage in southern England and the south of Wales. Under the 2020s Low and 2050s Low scenarios (Fig. 3.12c,d) the distribution increases across most of central, southern and eastern England, but with no occurrence north of the Midlands. Under the 2020s Low scenario (Fig. 3.12d) there are a few sites in the north of England and one in central Scotland, and all but the south west of England and western and central Wales provide suitable climate space for *C. europaeus*. The final scenario, 2050s High (Fig. 3.12) gives a range quite close to that of the observed, in terms of its northern limit, but with much more widespread coverage. As mentioned above, the distribution of *Caprimulgus europaeus* is not currently limited by climate and these results indicate that this will also be the case in future. It should be noted that as the model was trained on the current distribution rather than its former distribution it does not predict the occurrence of *C. europaeus* on the Moors and it probably underestimates its future suitable climate space

Figure 3.9 SPECIESv1 model results for Coenonympha tullia: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.10 SPECIESv1 model results for Bembidion humerale: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario


(a)


(b)


(c)


(d)


(e)


(f)

Figure 3.11 SPECIESv1 model results for Curimopsis nigrita: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

Figure 3.12 SPECIESv1 model results for Caprimulgus europaeus: (a) observed distribution; (b) current climate (1961-1990); (c) 2020s Low scenario; (d) 2020s High scenario; (e) 2050s Low scenario; (f) 2050s High scenario

3.1 Discussion

The results of the SPECIES modelling suggest that some of the community dominants/constants, such as *Erica tetralix*, *Sphagnum papillosum, Calluna vulgaris, Eriophorum angustifolium*, *Eriophorum vaginatum* and *Molinia caerulea* show little change, and will remain present on Thorne and Hatfield Moors under all climate scenarios; though some water level maintenance may be a requirement of their continued presence as modelling of water levels (Chapter 2) indicate that water table drawdown will increasingly be a factor under the future scenarios. *Betula pendula*, although losing some climate space, will continue as part of the Moors floral community. It is, however, quite close to areas losing climate space and if the higher new 2001 IPCC scenarios had been used, there is a possibility it will lose space on the Moors, especially if conditions at crucial growth times for seedlings become droughtlike. In terms of bog conservation, this is helpful as *B. pendula* is a strong evapotranspirator. Other, rarer species, such as *Andromeda polifolia*, and the butterfly *Coenonympha tullia*, may well become extinct at these sites, though *A. polifolia* can be very tenacious once established. *C. tullia* is currently present in isolated populations in this area, but it may be that as these dwindle, and as its southern range limit draws further north, it remains present only for a few more years.

While it is possible that the climate may remain suitable for *Bembidion humerale*, if the plant community changes greatly, habitat conditions may become unsuitable for its continued presence – if, for example, peat extraction continues and its required combination of patches of bare, moist peat, algae-covered peat and overhanging vegetation, are removed completely. Conversely, it may be that peat cutting has created suitable habitat for *B. humerale*. *Curimposis nigrita* seems unlikely to continue to be found on the Humberhead Levels, although it must be borne in mind that these mires are marginal in terms of climate and suitable conditions for development, which thus adds a caveat to any conclusions drawn. The occurrence of these peatbogs under such apparently marginal conditions may warrant further research. For *Caprimulgus europaeus* the climate will remain suitable; its presence on the Moors will be much more directly influenced by habitat.

3.2 Atmospheric emissions

Another potentially significant influence on peatland ecology is that of atmospheric emissions of sulphur dioxide and nitrogen oxides, to which raised mires and *Sphagnum* spp. are known to be sensitive (Bobbink *et al*, 1998). Mosses generally have leaves one cell thick without a cuticle, exposing the photosynthetic cells directly and continuously to deposition. It is possible that pollutants may act in concert with climate change to result in increased stress on the species of the Moors habitats, which should be taken into account when interpreting the SPECIES results.

Though the sulphur component of ‘acid rain’ has been greatly reduced in Europe over the last four decades, experiments have shown that the addition of sulphate to peat results in the reduction of both methane and carbon dioxide emissions from the peat due to the effect on microbial activity (Butt, 1998). However, *Sphagnum* spp. also are adversely affected by sulphate deposition and parts of the Pennines have lost most of their *Sphagnum* spp. due to sulphur pollution and the denuded surface is suffering erosion. While ecosystem response to low concentrations of SO_2 is difficult to quantify and separate from natural acidification processes, the broadscale absence of sulphur deficiency, even in agricultural systems, may be an indication of indirect response to atmospheric emissions and their ecological importance.

Atmospheric sulphur is one of the links between acid deposition and climate change - raised sulphur emissions lead to an increase in both acidifying deposition and in tropospheric levels of sulphate aerosols. These scatter solar radiation, modify cloud properties and may mask greenhouse gas global warming. Posch *et al* (1996) analysed future anthropogenic sulphur emissions (globally, but we are concerned only with Europe, for the purposes of this report) under two scenarios (Fig. 3.13); the 'S50 Control scenario', which accounts for planned controls in OECD Europe, Eastern Europe and CIS, as in the Second Sulphur Protocol of the Geneva Convention on Transboundary Air Pollution in Europe. Under this scenario, a limit is set on emissions after 2010, but they are allowed to fall below this level as a result of changes in energy use or fuel mix. The 'No Control scenario' is used as a way of evaluating the (more likely) S50 Control scenario. This scenario has no controls on SO_2 emissions anywhere after 1990; emission factors are constant at these levels and changes are only as a result of computed changes in regional energy consumption and industrial emissions.

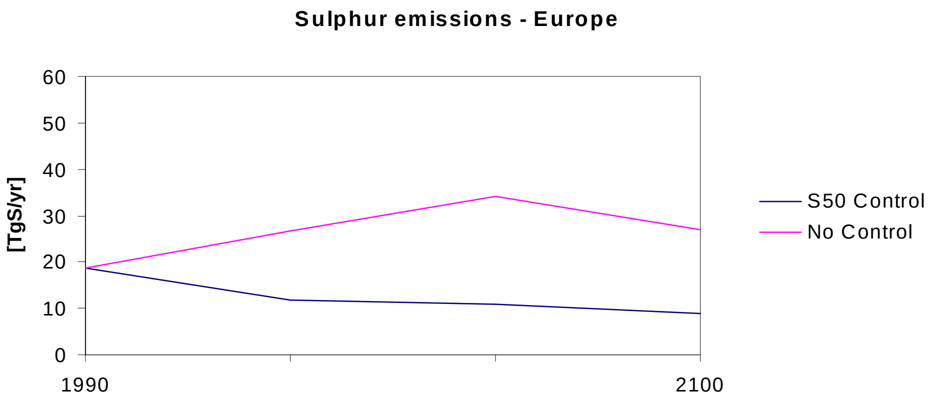

Figure 3.13 European sulphur emissions under the two scenarios. (After Posch *et al*, 1996)

Under the S50 Control scenario then, sulphate levels decline by 30% over Europe; under the No Control scenario levels rise by 60% (compared with 1990) by 2050. Exceedance of critical load (defined as 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified elements of the environment do not occur according to present day knowledge' by Nilsson and Grenfelt in 1988) follows much the same pattern under the two scenarios (Posch *et al*, 1996). Europe will be thus affected by both acid deposition and climate change over the course of this century – including the Thorne and Hatfield Moors area of Great Britain. Further analysis by Posch *et al* (*ibid*.) indicate that most of GB will undergo vegetation change as a result of acid deposition and climate change.

Nationally, however, Great Britain committed to the reduction of sulphur dioxide emissions by 60% by 2003, and the reduction of nitrogen oxides by 40% by 1998 under the European Community Large Combustion Plant Directive in 1988 (Metcalfe and Whyatt, 1995).

As far as the response, or level of resilience, of individual ecosystems is concerned, the buffering capacity of the system, specifically the soil, is the crucial factor. These abiotic conditions effect the nitrification potential and rate of nitrogen immobilisation in the system. Soils with the ability to neutralise acid deposition, such as high pH soils found on calcareous bedrock, for example, are good buffers, while low pH soils (such as peat soils) rapidly lose available cations due to leaching and hence their sensitivity to any deposition.

Emissions of nitrogen oxides (NO_x) are mainly a result of fossil fuel combustion. Analysis and prediction calculations by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000) look at many different scenarios; Figure 3.14 gives an average. Recent estimates of nitrogen loads give an approximate figure of 30-50kg N ha^{-1}, more than half of which is from nitrogen oxides, though ammonia and ammonium are increasing in importance (Bobbink *et al*, 1998).

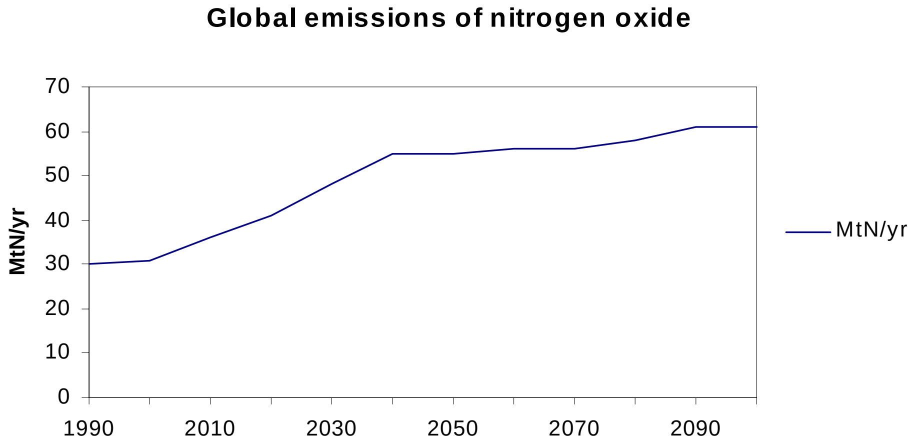

Figure 3.14 Global nitrogen oxide emissions in Mt nitrogen per year (Source: IPCC)

Peat experimentally treated with nitrate resulted in the inhibition of methane production as the denitrifying bacteria outcompeted the methanogens; and due to the suppression of acetate conversion to both methane and carbon dioxide, CO_2 production is reduced. It has been observed in southern Pennine bogs (Lee, 1998) that mosses show enhanced nitrate reductase inducibility to assimilate nitrogen, but where nitrogen deposition continues and increases, this inducibility is lost, therefore limiting nitrogen assimilation. Non-hummock-forming *Sphagnum* species invaded and dominated hollows and wet lawns, and vascular species, eg, *Molinia caerulea* and *Eriophorum* spp., colonise the hummocks. In some cases, when nitrogen inputs reach a certain level, other nutrients, especially phosphorus, can become limiting, and increased nitrogen content may also increase peat decay rate (Bobbink *et al*, 1998) through changes in the C:N ratios.

Carbon dioxide efflux from peat is enhanced by temperature increase; if water table levels are drawn down by rising temperature levels, it is likely that carbon dioxide emissions to the atmosphere will increase. Conversely, if precipitation increases and water table levels rise, methane production and emission will grow. The area in which Thorne and Hatfield Moors are sited is predicted to experience increased temperature under all future scenarios, summer and winter. Precipitation is projected to increase in the winter and decrease in the summer months, most markedly under the High 2050s scenario (Hulme and Jenkins, 1998). This means that the difference between summer and winter water table levels will increase sharply, placing the peatland systems of the Moors under greater stress (see Figure 2.6).

3.3 Discussion

It is likely then, that deposition of sulphur dioxide on Thorne and Hatfield Moors will continue to decrease (as under the 'S50 Control' scenario – more likely than any other) in the future. It is more difficult to predict the future of nitrogen oxide deposition – the graph (Fig. 3.14) gives a global mean trend, but, as stated above, in Europe this should be decreasing due to adopted measures for emission reduction. The effect of pollutants on plants and ecosystems is not to directly kill them (unless in extremely high concentrations), but to predispose species to increased vulnerability to other stresses. For example, *Betula pendula*, under conditions of atmospheric SO_2 and NO_x pollution becomes less efficient in its water use indicating that its water conservation mechanisms are adversely affected. A possible increase in nitrogen oxide deposition would make it even more unlikely that *B. pendula* will continue to exist on the Moors.

While *Calluna vulgaris* is simulated to occur right across Great Britain under all future scenarios, its actual abundance and dominance has decreased in some areas, with heathlands experiencing significant changes in species composition. In some cases, such as the outcompetition of *C. vulgaris* by *Molinia caerulea*, these changes have been attributed to air pollution, especially SO_2 and NO_x (Bobbink *et al*, 1998; Roem and Berendse, 2000). Recent work has shown (Kirkham, 2001) that shoot nitrogen content and/or assimilated nitrogen per hectare, as well as nitrogen:phosphorus ratios, were correlated significantly with NO_x deposition. Enhanced nitrogen status may lead to drought stress and damage in *C. vulgaris*, and increase winter injury, which could provide opportunity for invasion by other species (Dueck *et al*, 1990). Atmospheric nitrogen deposition on heathlands has led to eutrophication and loss of characteristic species: plants adapted to nutrient-poor conditions – *Erica tetralix* and *Calluna vulgaris*, for example (eg, Bobbink *et al*, 1998; Roem and Berendse, 2000), are unable to compete on soils that have been enriched. The resultant increased above-ground biomass is matched by a decrease in the ability of plants to endure prolonged periods of water stress.

3.4 Conclusion

In terms of climate change, it seems that the habitat dominants will find suitable climate space under all future climate scenarios, while some of the rare species here, such as *Andromeda polifolia* and *Coenonympha tullia* will lose space. The presence of the two other species that were not predicted to occur on the Moors, *Curimopsis nigrita* and *Caprimulgus europaeus*, will depend on whether their habitat requirements continue to be met. *C. europaeus* numbers, for example, have recovered in areas where conifer plantations have been clearfelled and thus their habitat areas expanded (Devon Biodiversity Action Plan).

Enhanced or increased nitrogen inputs to a system can also threaten the community (especially on very nutrient-poor ombrotrophic bogs) by means of facilitating invasion by nitrophilic species which will then outcompete the original plants, adapted as they are to nutrient-poor conditions and competing in low-nitrogen environments.

Both sulphur dioxide and nitrogen oxides occur quite commonly and have a negative impact at moderate levels of concentration – these effects are greater where both occur together. The effect on plants is more likely to be by way of weakening that species' resilience against other stresses. The most probable impact of such pollution on species in the Thorne and Hatfield Moors ecosystems will be in terms of water stress under dry or drought-like conditions. *Erica tetralix*, for example, may lose space to *Molinia caerulea* as a result of both increased nitrogen availability and water table drawdown (Berendse and Aerts, 1984). Though *Sphagnum papillosum* is especially sensitive to sulphur dioxide, as it survives under current atmospheric conditions it is unlikely to be adversely affected in the future as emissions are set to decrease (Fig. 3.13). Where water levels are maintained and managed appropriately for species' requirements (see Chapter 4), sulphur dioxide and nitrogen oxide pollution is not likely to be limiting of a species' distribution on its own.

4. Management for climate change

This establishment of appropriate water level is generally the primary step in the restoration of this type of damaged peatland. Wheeler and Shaw (1995) separate restoration into two parts: the creation of suitable environmental conditions, followed by colonisation of required species. A further step can be added to this - 'regeneration' – which refers to the reestablishment of ecosystem processes, including peat accumulation (this is vital for restoration of whole bog ecosystems, but in terms of the maintenance of species populations is less important). As raised bogs may be considered to be climax ecosystems that have evolved from different situations, renewed development can be possible under a variety of conditions, provided the two principal requirements are met. Recolonisation is dependent on the maintenance of surface level water tables, and water storage capacity is closely tied to vegetation structure.

Inundation also gives a good basis for colonisation for some Sphagna, and promotes development of floating rafts of vegetation – these can remain wet independently of water table changes. It has been established (Schouwenaars, 1990) that where *Molinia caerulea* has replaced *Sphagnum* in drained sites, evapotranspiration during dry periods is increased; the recolonisation of *Sphagnum* will thus reduce evaporative loss and also provide greater water storage capacity. In undisturbed bogs the summer water table level does not fall below 30-40cm (Schouwenaars, 1995); as a consequence of drainage and peat cutting the level drops below this. The root systems of shrub and grass species that replace *Sphagnum* species allow water extraction from deeper peat layers – in dry periods the water table drops lower than in *Sphagnum* covered areas. While flooding of the site may be helpful in terms of the restoration of a *Sphagnum*-based vegetation cover, it may have deleterious effects on other species. *Coenonympha tullia* larvae, for example, are unable to tolerate long term submersion (Asher *et al*, 2001), and as this species is vulnerable to local extinction and is a poor coloniser, in terms of conservation it is imperative that areas of habitat as large as possible are maintained.

Under the current management regime at Thorne and Hatfield Moors, when the acrotelm has been removed by peat extraction (to a depth of 0.5m), water retention methods are put into practice. These involve the creation of shallow pools and soaking of the peat above the water table by ditch-damming and building or maintaining peat bunds. This acrotelm removal means that water levels are usually too low for growth of peat building *Sphagnum* species, and that they fluctuate more than in intact bogs. The water storage capacity of the peat is also lower than that of intact bogs, and water loss may be increased by exposure of the underlying mineral soil. Inundation of the site increases surface water storage and reduces relative water level decrease. The managed water enhancement/restoration of the water storage capacity of the peat on the Moors sites aims to buffer summer water losses. Sculpting the surface of extensive milled fields before rewetting provides topography more suitable for restoration and continued development of bogs; the large shallow hollows allow water storage and are potentially more stable than a lagoon-based approach to rewetting (Wheeler and Shaw, 1995).

The maintenance of conditions suitable for colonisation for peat-forming species is an important management objective on Thorne and Hatfield Moors. Summer water table levels are especially critical to Sphagna regeneration (Mawby, 1995) (regeneration of most species is very slow if water levels are not kept high year-round). Water table fluctuations result in variable vegetation response – some species, such as *E. vaginatum, E. angustifolium, Erica* *tetralix* and *Rhynchospora alba* are quick to respond to small increases, while *Andromeda polifolia* and *Drosera rotundifolia* are slow. Sphagna vary, but the most responsive species are *S. papillosum* and *S. magellanicum*. Cooper and MacDonald (2000) concluded that dominant species can be successfully reintroduced to mined surfaces with the appropriate hydrologic conditions but intervention is necessary to rapidly re-establish these species, and that the slow rate of peat accumulation means that restoration will require hundreds, if not thousands, of years. On the Moors, however, the nature and longevity of peat extraction has resulted in a mosaic ecosystem, one where there are different patches of habitat in varying stages of mire succession. This has actually given a greater species diversity in some patches than otherwise would have occurred. Restoration on Thorne and Hatfield Moors may therefore be aided by the presence of many species, useful for restoration, on nearby patches.

In May 1991, an experiment was set up in flooded pits on Thorne Moors to investigate regeneration by various restoration techniques (Money, 1995). Plants on a floating raft remained wet, and only after the final year of the experiment, which was especially wet, was much Sphagna growth recorded. This was also the case for the *Sphagnum* spp. on a peat slope in another pit, which underlines the importance of year-round high water table levels and the reinstatement of water storage capacity. In cases of spontaneous or natural regeneration, a floating raft of aquatic Sphagna usually recolonises prior to lawn and hummock-forming species: such rafts may thus be used as a framework or base for growth of other species.

The problem with the re-establishment of *Sphagnum* relates to the low water availability and higher temperatures experienced on the bare surfaces. Experiments on the tolerances of Sphagum spp. has shown that of six species (*S. angustifolium*, *S. fallax*, *S. fuscum*, *S. magellanicum*, *S. nemoreum* and *S. papillosum*) only *S. fallax* can withstand 48 hours at 30^{o}C (Sagot and Rochefort, 1996). Also the peat mosses (*Sphagnum papillosum*, *S. magellanicum*, *S. fuscum*, *S. nemoreum*, *S. riparium*, *S. centrale*) under laboratory conditions show a decrease in net photosynthesis under desiccation conditions and recovery after short periods of desiccation is slow (Silvola, 1991). Other work has shown isolated stems of *Sphagnum fallax*, *S. fuscum* and *S. magellanicum* can survive up to 14 days without water - under conditions of approximately 20 ^{o}C and relative humidity of 60% (Sagot and Rochefort, 1996).

Experiments on the use of vegetative *Sphagnum* fragments as diaspores have shown that if a suitable microtopography of ridges and depressions is formed, then the latter can provide suitable humid conditions for the establishment of *Sphagnum* (Ferland and Rochefort, 1997). Reprofiling the site to reverse drainage gradients and adding *Sphagnum* diaspores to the concavity can increase restoration success rates (Bugnon *et al*, 1997). This combined with reintroducing appropriate companion plants, such as *Eriophorum angustifolium,* can have a positive effect on the survival of the *Sphagnum*. Reintroduction of *Sphagnum* diaspores combined with the provision of protective devices, such as plastic shade cloths to create a suitable microclimate, and irrigation can be beneficial (Rochefort and Bastien, 1998). They also recommend the use of a mix of *Sphagnum* species, due to inherent variability of climate.

A further facet of the current ‘resoaking’ programme is the inhibition of vigorous birch growth by flooding at Thorne Waste with water pumped from drains in the cutting areas into abandoned peat workings, and the clearing of dense invasive scrub minimises evapotranspirative losses from the peat. The post-cutting colonisation of competitive invaders such as birch, can often result in the development of scrub vegetation and the further loss of bog specialists. Reinstatement of water levels can prevent such invasion on some sites, and it is sometimes necessary to include vegetation removal in management practice, as on the Moors sites.

The options for natural adaptation to climate change are severely limited for lowland bogs (Hossell *et al*, 2000) as although the prime input, rainfall, changes little, increased temperatures lead to increased evapotranspiration, resulting in higher summer, and mean annual, water deficits and lower water levels. Under the UKCIP98 future climate scenarios (see Chapter 2), precipitation rates and patterns will change, which has further implications for management. While winter rainfall is expected to increase (by up to 20% under the 2050s High scenario), summer precipitation could decrease by a much smaller amount – the combined effect being a greater fluctuation between winter and summer precipitation rates. The most important factor, in terms of management for the restoration of the Moors though, is the availability of water, which is derived from evapotranspiration figures. The increases in evapotranspiration (see Chapter 2) directly impact upon water availability and the most pressing concern will be the storage of water for recharge of the site during the drier summer months. While this is the aim of current management practice, the potential changes will require further measures.

The SPECIES modelling has shown that the dominants of both the wetter and drier habitats will continue to find suitable climate space under the UKCIP98 climate change scenarios, but it is possible that the higher IPCC 2001 scenarios, when down-scaled to the British Isles, will mean that for some species, such as *Betula pendula* and *Andromeda polifolia* the moors will be climatically marginal or unsuitable. The hydrological model has also shown that species that are dependent on higher water levels also could be adversely affected. The drier summers could lead to the loss of wetter species, and a transition to wet and dry heaths. This could occur due to the drier conditions and to the availability of suitable climate space for species, such as *Calluna vulgaris,* and could then be followed by the invasion by scrub and trees, (although *Betula pendula*, a prime candidate, could find this area climatically marginal).

Chapter 2 identified three outputs in a peatland hydrological water balance and each of these represent possible management opportunities for enhancing water levels under future climate scenarios. The primary aim, the recreation of the acrotelm, will require enhanced rewetting and the possible use of external sources of water, although care would need to be taken to use water of a similar chemistry. Previously used on the northern boundary of Thorne Moors NNR, the ditch recharge system was not successful as the hydraulic gradient continued to run from the NNR to the peripheral ditches. The capacity of the outer ditch to supply water to the inner ditch was therefore limited, and the pumping merely increased the rate of water cycling between the ditches and did not buffer the water level in the NNR as intended. This failure was probably due to the steepness of the hydraulic gradient, which also resulted in significant subsurface lateral water movement to the bog margins (Heathwaite, 1995).

Well humified peat has very low hydraulic conductivity (Schouwenaars, 1995); not the case in the bog remnants on extraction sites. As water recharge is low on the Moors, and drainage for peat extraction exacerbates seepage loss, available water for ditch recharge is very restricted and efforts for hydrological stability should thus include minimising seepage loss to the edges of bog areas. A further consideration is the surrounding land use – types of agriculture less dependent on year-round low water tables would reduce the stress on the Moors sites. Under the potential future water stresses resulting from the increasing disparity between winter and summer water table levels, hydraulic conductivity and water storage capacity of the peat will become more important; the key question for management will be water storage. Another important factor is the limitation of vertical seepage loss, which becomes more important due to loss of peat thickness in cut-over areas (however, it has been indicated (Bromley *et al*, 1997) that a thick layer - >3m of clay underlies the Thorne Moors site). Vertical seepage can be impeded by a hydrological buffer zone where the water table is maintained at a high level thus raising water pressure in the underlying layers. Hydrological models can be developed in order to quantify and predict water table changes, and applied in this situation (Bromley and Robinson, 1991).

Several points thus need to be considered in the regeneration of the mire surface by raising the water table:

- Restoration to the previous surface hydrology is difficult
- Recolonisation is likely to be long term
- Achieving restoration of the habitat is likely to be costly

The increasingly marginality of the Moors, in terms of water availability, means, however, that management methodology should incorporate an integrated plan for each site, so that complementary actions are taken to restore the hydrology and preserve the diversity of habitats.

4.1 Conclusions

While the Thorne and Hatfield Moors sites will become more marginal in terms of water availability under the future climate scenarios, were peat extraction to cease and rewetting to continue, it is likely that many of the species would be secure. As these unique ecosystems have developed in an area perhaps marginal to the requirements of this type of habitat, and some of the component species are relict populations, or would not be expected to be found here, it is possible that with appropriate regeneration management, these important and singular areas could be conserved.

Work so far has suggested that while it is possible to recreate conditions appropriate for colonisation/establishment of peat forming species, timescales and levels of success may vary according to hydroseral succession and substrate. Future management should continue to address the crucial surface water storage capacity issue, as determined by, for example, the increase in fluctuation between summer and winter rainfall levels. As the importance of regional groundwater levels have not been fully elucidated, but is likely to be a factor, agricultural use of the areas surrounding the Moors sites should be complementary to the aims of restoration management on the sites themselves.

5. References

ASHER, J., WARREN, M., FOX, R., HARDING, P., JEFFCOATE, G., JEFFCOATE, S., 2001. *The Millennium Atlas of Butterflies in Britain and Ireland*. Oxford University Press.

BERENDSE, F., AERTS, R., 1984. Competition between *Erica tetralix* L. and *Molinia caerulea* (1.) Moench as affected by the availability of nutrients. *Acta Oecologica/ Oecologica Plantarum*, **5** (19), no. 1, p3-14.

BERRY, P.M., HARRISON, P.A., DAWSON, T.P. AND PEARSON, R., 2001a. Integrated impacts on biodiversity. *In*: P. Loveland *et al*, Eds. *Regional climate impact studies in East Anglia and North West England*, Final Report to MAFF, DETR and UKWIR. Silsoe: Soil Survey and Land Research Centre.

BERRY, P.M., VANHINSBERGH, D., VILES, H.A., HARRISON, P.A., PEARSON, R.G., FULLER, R., BUTT, N. AND MILLER, F., 2001b. Impacts on terrestrial environments. *In*: Harrison, P.A., Dawson, T.P., Berry, P.M., eds. 2001. *Modelling natural resource responses to climate change: The MONARCH Project*. UKCIP.

BALL, S.G., 1992. The Importance of the Invertebrate Fauna of Thorne and Hatfield Moors: an exercise in site evaluation. *Thorne and Hatfield Moors Papers,* **3**:34-65.

BOBBINK, R., HORNUNG, M. AND ROELOFS, J.G.M., 1998. The effects of air-borne nitrogen pollutants on species diversity in natural and semi-natural European vegetation. *Journal of Ecology*, **86(5)**, pp717-738.

BRAGG, O.M., 1995. Towards an Ecohydrological Basis for Raised Mire Restoration. *In*: Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A., eds. *Restoration of Temperate Wetlands*. John Wiley and Sons.

BROMLEY, J., ROBINSON, M., DIXON, A., 1997. Evaluating subsurface water losses in a cutover peatland: Thorne Moors, South Yorkshire. Wallingford: Institute of Hydrology.

BROMLEY, J., ROBINSON, M., 1991. *The likely impact of peat cutting on the hydrology of the Thorne National Nature Reserve*. Confidential report to Fisons plc Horticulture Division. Wallingford: Institute of Hydrology.

BUGNON, J-L., ROCHEFORT, L. AND PRICE, J.S., 1997.. Field experiment of *Sphagnum* reintroduction on a dry abandoned peatland in Eastern Canada. *Wetlands,* **17(4)**, 513.

BUTT, N., 1998. Investigation into the effects of ammonium, nitrate and sulphate on gas production in and efflux from peat. Dissertation at Oxford Brookes University.

COOPER, D. J. & MACDONALD, L. H., 2000. Restoring the vegetation of mined peatlands in the Southern Rocky Mountains of Colorado, U.S.A. *Restoration Ecology*, **8(2)**, 103-111.

CROSSLEY, R. & NORRIS, A., 1975. *Bembidion humerale* Sturm (Col., Carabidae) new to Britain. *Entomologist's Monthly Magazine*, November 1975, pp59-60.

DUECK, TH.A., DOREL, F.G., TER HORST, R., & VAN DER EERDEN, L.J., 1990. Effects of ammonia, ammonium sulphate and sulphur dioxide on the frost sensitivity of Scots pine (*Pinus sylvestris* L.). *Water, Air and Soil Pollution*, **54**, 35-49.

EMMET, A. & MAITLAND, HEATH, J., eds., 1989. The Moths and Butterflies for Great Britain and Northern Ireland, Vol. 7, Part 1. Colchester: Harley Books .

Eversham, B.C., 1997. The flora, vegetation and ecology of Thorne and Hatfield Moors: an overview. *Thorne and Hatfield Moors Papers,* volume 4. Thorne and Hatfield Moors Conservation Forum.

FERLAND, C. & ROCHEFORT, L. 1997. Restoration techniques for Sphagnum-dominated peatlands. *Canadian Journal of Botany*, **75(7)**, 1110-1118.

GIBBON, D., REID, J. & CHAPMAN, R., 1993. *The new atlas of breeding birds*. London: Poyser.

GLASER, P., SIEGEL D.I., ROMANOWICZ, E.A. & Y.P. SHEN., 1997. Regional linkages between raised bogs and the climate, groundwater, and landscape of north-western Minnesota. *Journal of Ecology,* **85**: 3-16.

GRIME, J.P., HODGSON, J.G., HUNT, R., 1998. Comparative plant ecology. A functional approach to common British species. Unwin Hyman Ltd.

HEATHWAITE, L., 1995. Problems in the hydrological management of cut-over raised mires, with special reference to Thorne Moors, South Yorkshire. *In*: Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A., eds. *Restoration of temperate wetlands*. John Wiley and Sons.

HOSSELL, J.E., BRIGGS, B. & HEPBURN, I.R., 2000. Climate change and nature conservation: A review of the impact of climate change on UK species and habitat conservation policy. London: HMSO DETR MAFF.

HOUGHTON, J. T., DING, Y., GRIGGS, D. J., NOGUER, M., VAN DER LINDEN, P. J., DAI, X., MASKELL, K. & JOHNSON, C. A., eds., 2001. *Climate change 2001; the scientific basis.* Contribution of working group 1 to the Third Assessment Report of the IPCC. Cambridge: Cambridge University Press.

HULME, M. & JENKINS, G.J., 1998. *Climate Change Scenarios for the United Kingdom: Scientific Report*. UK Climate Impacts Programme Technical Report No. 1. Norwich: Climatic Research Unit, 80 pp.

Hulten, E., 1959. The Amphi-Atlantic plants and their phytogeographical connection. Stockholm: Almqvist & Wiksell, 340pp.

IPCC, 2001. C*limate change 2001: the scientific basis. summary for policymakers*. Shanghai draft (21/01/01), Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

JALAS, J., SUOMINEN, J., 1972-91. *Atlas Flora Europapaeae.* Vols. 1-9. Helsinki: Societas Bilogica Fennica Vanamo.

JOHNSON, C. 1977. Notes on *Byrrhidae* (Col.); with Special reference to, and a Species New to, the British Fauna. *Entomologist's Record*, **90**, pp141-147.

JOOSTEN, J. H. J., 1997. Moor or less: a critical evaluation of the hydrological basis for denotifying parts of Thorne and Hatfield Moors as SSSI. Thorne and Hatfield Moors Conservation Forum, Technical Report No. 4.

KEY, R.S., 1991. Peat-cutting and the invertebrate fauna of lowland peatland: Thorne and Hatfield Moors in a national context. *In:* Bain, C. and Eversham B., eds. *Thorne and Hatfield Moors Papers: Volume II.* Doncaster.

KIRKHAM, F.W., 2001. Nitrogen uptake and nutrient limitation in six hill moorland species in relation to atmospheric nitrogen deposition in England and Wales. *Journal of Ecology*, **89** (6), 1041-1053.

LEE, J.A., 1998. Unintentional experiments with terrestrial ecosystems: ecological effects of sulphur and nitrogen pollutants. Presidential address to the British Ecological Society. University of Durham, December 1996. *Journal of Ecology*, **86**, 1-12.

Limbert, M. & Eversham, B.C., eds., 1997. *Thorne and Hatfield Moors Papers*, Volume 4. Thorne and Hatfield Moors Conservation Forum.

LINDROTH, C.H., 1985. The Carabidae (Coleoptera) of Fennoscandia and Denmark. *Fauna Entomologic Scandinavica*, Vol. 15, part 1. Copenhagen: Scandinavian Science Press, Leiden.

LUFF, M.L.,1998. Provisional atlas of the ground beetles (Coleoptera: Carabidae) of Britain. Huntingdon: Biological Records Centre, ITE.

MAWBY, F.J., 1995. Effects of damming peat cuttings on Glasson Moss and Wedholme Flow, two lowland raised bogs in North-west England. *In*: Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A., eds. *Restoration of Temperate Wetlands*. John Wiley and Sons.

METCALFE, S. & WHYATT, D., 1995. Who to blame for acid rain? A regional study of acid deposition in Yorkshire and Humberside. *Transactions of the British Institute of Geographers*, **20**, 58-67.

MEUSEL, H., JÄGER, E., WEINART, E., 1992.*Vergleichende Chorologie der Zentraleuropäischen Flora Vol. 3*. Gustav Fischer Jena.

MEUSEL, H., JÄGER, E., WEINART, E., RAUSCHERT, S.T., 1978. *Vergleichende Chorologie der Zentraleuropäischen Flora Vol. 2*. Gustav Fischer Jena.

MEUSEL, H., JÄGER, E. & WEINART, E., 1965..*Vergleichende Chorologie der Zentraleuropäischen Flora Vol. 1*. Gustav Fischer Jena.

MOORE, P.D., 1984. *European Mires*. London: Academic Press.

MONEY, R.P., 1995. Re-establishment of a *Sphagnum*-dominated Flora on Cut-over Lowland Raised Bogs. *In*: Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A., eds. *Restoration of Temperate Wetlands*, John Wiley and Sons.

MONSERUD, R. A., 1990. *Methods for comparing global vegetation maps*. WP-90-40, IIASA, Laxenburg.

NAKICENOVIC, N., SWART, R., eds., 2000. Emissions Scenarios 2000. *Special Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 570 p.

NILSSON, J. & GRENNFELT, P., 1988. *Critical loads for sulphur and nitrogen*. Copenhagen: Report 1988 Nordic Council of Ministers, 15.

NOORGAARD, E., 1951. On the ecology of two Lycosid spiders (*Pirata piraticus* and *Lycosa pullata*) from a Danish *Sphagnum* bog. *Oikos*, **3(1)**.

PENMAN, H.L., 1948. Natural evaporation from open water, bare soil, and grass. *Proceedings of the Royal Society, London Series A*, **193**, 120-146.

PETERSON, R., MOUNTFORT, G. & HOLLOM, P.A.D., 1974. *A field guide to the birds of Britain and Europe*. London: Book Club Associates and William Collins Sons and Co. Ltd.

POSCH, M., HETTELINGH, J-P., ALCAMO, J. & KROL, M., 1996. Integrated scenarios of acidification and climate change in Asia and Europe. *Global environmental change*, **6(4)** pp375-394.

ROCHEFORT, LINE & BASTIEN, D. F., 1998. Reintroduction of Sphagnum in harvested peatland: Assessment of various methods of protection against desiccation. *Ecoscience*, **5(1)**, 117-127.

RODWELL, J.S. (1991). *British Plant Communities,* Vol. 2. Mires and Heaths. Cambridge: Cambridge University Press.

ROEM, W.J., BERENDSE, F., 2000. Soil acidity and nutrient supply ratio as possible factors determining changes in plant species diversity in grassland and heathland communities. *Biological Conservation*, **92**, 151-161.

ROWELL, T.A., 1988. *The peatland management handbook*. Peterborough: Nature Conservancy Council, 178p.

ROY, D.B. & SPARKS T.H., 2000. Phenology of British butterflies and climate change. *Global change biology*, **6**, 407-416.

SAGOT, C. & ROCHEFORT, L., 1996. Sphagnum desiccation tolerance. *Cryptogamie Bryologie Lichenologie*. **17(3)**,171-183.

SCHOUWENAARS, J.M., 1995. The Selection of Internal and External Management Options for Bog Restoration. *In*: Wheeler, B.D., Shaw, S.C., Fojt, W.J. & Robertson, R.A., eds. *Restoration of Temperate Wetlands*. John Wiley and Sons.

SCHOUWENAARS, J.M., 1990. A study on the evapotranspiration of *Molinia caerulea* and *Sphagnum papillosum*, using small weight lysimeters. *In*: Schouwenaars, J.M. (1990). *Problem oriented research on plant-soil-water relations*. PhD thesis, Agricultural University, Wageningen, the Netherlands.

SILVOLA, J., 1991.. Moisture dependence of carbon dioxide exchange and its recovery after drying in certain boreal forest and peat mosses. *Lindbergia*, **17(1)**, 5-10.

SKIDMORE, P., 1977. Recent work on the Insects of Hatfield Moors, and a comparison with Thorne Moors. *In* Limbert, M. & Eversham, B., eds. *Thorne and Hatfield Moors Papers Vol. 4*, Thorne and Hatfield Moors Conservation Forum, pp92-95.

SMART, P.J., WHEELER, B.D. & WILLIS, A.J., 1986. Ecology of a much exploited peatland – Thorne Waste, Yorkshire, UK. *The New Phytologist*, **92**.

STEWART, A., PEARMAN, D.A. & PRESTON, C.D., 1994. *Scarce plants in Britain*. Peterborough: Joint Nature Conservation Committee..

THORNTHWAITE, C.W. & MATHER, J.R., 1955. The water balance. *Climatology*, **8,** 1-104.

TOLMAN, T., 1997. Butterflies of Britain and Europe. *Collins Field Guide*. London: Harper Collins, 320 pp.

WHEELER, B.D. & SHAW, S.C., 1995. *Restoration of damaged peatlands with particular reference to lowland raised bogs affected by peat extraction*. London: HMSO.

WHEELER, B.D., SHAW, S.C., FOJT, W.J. & ROBERTSON, R.A., Eds., 1995. *Restoration of Temperate Wetlands*, John Wiley and Sons.

WOODIN, S.J. & FARMER, A.M., 1993. Impacts of sulphur and nitrogen deposition on sites of nature conservation importance in Great Britain. *Biological Conservation*, **63**: 23-30.

5.1 Websites

Emissions scenarios http://www.grida.no/climate/ipcc/emission/index.htm

Friends of the Earth http://www.foe.co.uk/campaigns/biodiversity_and_habitats

IPCC – Intergovernmental Panel on Climate Change http://www.ipcc.ch

The Wise Use of Mires and Peatlands http://www.mireswiseuse.com

UK Biodiversity Action Plans http://www.ukbap.org.uk/plans/species

Wetlands International http://www.wetlands.agro.nl/