Vol. 45: 105–118, 2010
doi: 10.3354/cr00926

CLIMATE RESEARCH
Clim Res

Published online November 9

Contribution to CR Special 24 'Climate change and the British Uplands'

Climate change and the future occurrence of moorland wildfires in the Peak District of the UK

Kevin Albertson[1], Jonathan Aylen[2,*], Gina Cavan[3], Julia McMorrow[3]

[1]Department of Economics, Manchester Metropolitan University, Manchester M15 6BG, UK
[2]Manchester Institute of Innovation Research, Manchester Business School, The University of Manchester, Manchester M13 9PL, UK
[3]School of Environment and Development, The University of Manchester, Manchester M13 9PL, UK

ABSTRACT: We investigated the impact of climate change on the number of wildfires in the Peak District uplands of northern England. Wildfires in peat can result in severe carbon loss and damage to water supplies, and fighting such fires is difficult and costly in such a remote location. The Peak District is expected to experience warmer, wetter winters and hotter, drier summers. Local weather simulations from a weather generator were used to predict the future incidence and timing of fires. Wildfire predictions were based on past fire occurrence and weather over 27.5 yr. A Probit model of wildfire incidence was applied to simulated weather data, which were generated by a Markov process and validated against actual baseline weather data using statistical criteria and success in replicating past fire patterns. The impact of climate change on the phenology and ecology of moorland and on visitor numbers was considered. Simulations suggest an overall increase in occurrence of summer wildfires. The likelihood of spring wildfires is not reduced by wetter winter conditions; however, the chance of wildfires rises as rainfall decreases. Temperature rise has a non-linear impact, with the risk of wildfire occurrence rising disproportionately with temperature. Recreation use is a major source of ignition. Little change in wildfire incidence is projected in the near future, but as climate change intensifies, the danger of summer wildfires is projected to increase from 2070; therefore, fire risk management will be necessary in future. In addition, moorlands may have to be managed to reduce the chance of summer wildfires becoming catastrophic, with consequent damage to ecosystem services such as water supplies and peat carbon storage. Management measures may include controlled burning, grazing or mowing to remove fuel.

KEY WORDS: Wildfires · Climate change · Weather simulations · Ecosystem services · Forecast · Plant phenology · Probit · Peatland · Drought

1. INTRODUCTION

Hotter, drier conditions associated with projected changes in climate bring increased wildfire activity to forests, moorlands and heathlands. The rising incidence of wildfires is an issue commanding particular attention in the western US (Flannigan et al. 2000, Brown et al. 2004, Fried et al. 2004, 2008, Westerling & Bryant 2008). Increases in total annual area burned there have been linked to rises in air temperature (Balshi et al. 2009) and, in the Mediterranean, to winter precipitation in the preceding year (Viegas 1998). The greater frequency and longer duration of burns and longer wildfire season in the northern Rockies of the US is strongly associated with higher spring and summer temperatures and earlier spring snowmelt (Westerling et al. 2006). However, these effects are still little understood and are complicated by other drivers (Krawchuk et al. 2009). Increased frequency of severe fires in the western US since the 1980s has been attributed to the accumulation of flammable woody biomass following the introduction of a national fire suppression policy in the 1940s (Miller et al. 2009). The problem of a growing fuel load has been exacerbated by regional climate changes. Meyn et al. (2007) suggest that large infrequent fires worldwide are naturally controlled by the limiting factors of fuel accumula-

*Email: jonathan.aylen@manchester.ac.uk

tion and fuel moisture, but emphasise that human factors such as managed burning to reduce fuel load and grazing by farm animals obscures these relationships. Important anthropogenic factors in wildfire include the increased density of ignition sources as the wildland–urban interface expands (Moritz & Stevens 2008). Another concern is fuel accumulation due to land abandonment (Martínez et al. 2009) or fewer land management burns (Burrows et al. 2006).

Wildfires in the UK are an under-recognised semi-natural hazard with similar weather and human drivers as those in the western USA (Davies et al. 2008, McMorrow et al. 2009). Wildfires are especially important on remote peat uplands, where they can be costly to fight, can damage water catchments and other ecosystem services, can cause substantial carbon loss and damage to wildlife, and require costly restoration (Orr et al. 2008, Hubacek et al. 2009). Wildfires are not always severe; vegetation recovery can be rapid after cooler fires and this is the principle behind management of fire-adapted ecosystems such as heather moorland.

Climate change projections for the Peak District of England suggest that weather conditions will become milder, with warmer, wetter winters and hotter, drier summers (Jenkins et al. 2009). The UK Climate Projections (UKCP09), the latest and most comprehensive information on the potential future climate for the UK, provided through the UK Climate Impacts Programme (UKCIP), suggest that under the medium emissions scenario, a central estimate of the increase in summer mean daily maximum temperature in northwest England for the 2080s (2071–2100) is 4.8°C, with the rise very unlikely to be <1.6°C or >8.3°C (UKCIP 2009). Further, considerable changes in rainfall are expected; for the 2080s, under the medium emissions scenario, the central estimate of change in winter mean precipitation is a 16% increase (a wider range of uncertainty is 3 to 50%). By contrast, the central estimate of change in summer mean precipitation is a 22% decrease (with an associated range of –51 to 3%) (UKCIP 2009). Existing rainfall distributions show that lower average rainfall is associated with a higher likelihood of drought episodes (Waggoner 1989). An increase in drought occurrence for the UK, including soil moisture drought in summer, has been predicted by Burke et al. (2010). Their forecasts through to 2100 are sensitive to climate modelling uncertainty and location, and so the spread of predictions is considerable, ranging from a slight decrease in drought frequency or no change to a significant increase. The likelihood of drought is skewed towards an increase in frequency in the northwest of England. Climate change scenarios for wind speed, a key factor in wildfire spread, are much more uncertain, and no confidence can be attached to them (Hulme et al. 2002).

Wildfires burning into peat are of particular concern. Peat is the largest terrestrial carbon store (Evans et al. 2006), and accounts for just over half of all the soil carbon in Britain (Milne & Brown 1997). There is concern that climate change will convert peat from a carbon sink to becoming a carbon source (Worrall & Evans 2009). Increased incidence of wildfires would be one mechanism increasing carbon flux. Wildfires which penetrate peat cause carbon loss both during the burn and from exposed, eroding peat surfaces afterwards.

Evidence for carbon loss is lacking in a UK context. The potential for serious carbon loss has been shown by severe peat fires elsewhere. The peat and forest fires in Indonesia in 1997 are estimated to have released between 0.81 and 2.57 gigatonnes of carbon to the atmosphere, an amount of carbon equivalent to 13–40% of the mean annual global carbon emissions from all fossil fuels (Page et al. 2002).

The mechanism of carbon loss from UK peat uplands is beginning to be understood. Worrall et al. (2007) have shown that carbon loss from eroding peat occurs through soil CO_2 respiration, increased gaseous CH_4 flow to the atmosphere, particulate and dissolved organic carbon flux in stream flow and excess dissolved CO_2 pathways. Their study relates to Moor House in the North Pennines, which is less degraded than the Peak District, where carbon loss is potentially more severe. Studies at 2 sites on Bleaklow in the Peak District have shown that erosion of fire-damaged peat also releases atmospherically deposited lead and other heavy metal pollution into water supplies (Rothwell et al. 2007), where it accumulates in catchment reservoirs (Shotbolt et al. 2006).

In the Peak District, climate change may increase not only the biophysical fire hazard but also human-caused ignition sources (McEvoy et al. 2006). Evidence on visitor use is equivocal. Agnew & Palutikof (2006) suggested that warmer weather generated an increased number of visitors during the hot summer of 1995. But Albertson et al. (2006) have shown that weather has no long-term impact on visits to an outdoor attraction. Instead, visitors are redistributed from wet days to dry days.

The aim of the present study was to establish how the number of wildfires in the Peak District uplands of northern England is likely be altered by climate change. A previous statistical model of wildfire incidence (Albertson et al. 2009) is combined with new simulations of local weather to assess the effect of changing temperature and rainfall and the likelihood of fires under future climate conditions in the Peak District. Predictions of the number of fires as a result of climate change will inform decisions about moorland management, help plan fire-fighting resources and anticipate possible carbon loss. Climate change may alter moorland ecology, including the onset of spring, the length of growing season and the distribution of plant species. Ecosystems will also adapt to a wildfire regime.

1.1. Study area

The Peak District National Park (PDNP) was established in 1951 as Britain's first National Park, following the enactment of the National Parks and Access to the Countryside Act in 1949. It covers an area of 1438 km^2 of uplands, surrounded by fertile lowlands and large conurbations, including Sheffield and Manchester (Fig. 1). It is the most visited national park in Britain, receiving an estimated 22 million visitors each year (PDNPA 1998), which is of relevance here because visitor levels may increase with warmer summers.

Most moorland wildfires have occurred in the north of the PDNP, known as the Dark Peak, which is characterised by blanket peat deposits up to 4 m thick at 400 to 600 m above sea level, with further wildfires clustered on the southwest moorland and the eastern fringe. Daily data on wildfire incidents are available for a 32.5 yr period from 1 June 1976 to 31 December 2008 from reports by rangers in the PDNP. There were a total of 399 wildfires in this period, recorded on 279 days. Multiple wildfires were recorded on 66 days. More wildfires were reported on weekends and bank holidays (which generally occur on Mondays), reflecting the impact of recreation activity as a source of ignition (Fig. 2b). Most fires occurred on warm days; 319 of the 399 wildfires occurred on days when the daily maximum temperature exceeded the mean for that month over the total time period. The simple mean number of wildfires per year, i.e. the number of fires divided by the number of years, is 12. However, this is not representative of the distribution, as just 2 clusters — summer 1976 and spring 2003 — account for a quarter of all fires in this period. One of the largest fires covered 8 km^2 in April 2003. Evidence on wildfire characteristics, such as area burnt, depth of burn or duration of incident, has not been recorded in the past. Diary records may understate the occurrence of wildfires, as small incidents may be dealt with locally and pass unreported, or burn out by themselves. In addition, there is spatial bias in recording wildfire incidents: fires are more likely to be started and reported close to roads and footpaths (Fig. 1).

The PDNP lies at the southeast boundary of blanket peat distribution in the UK (Radley 1965). It currently experiences drier conditions than those forecast for other UK peatlands under future climate change scenarios (McMorrow et al. 2009). These characteristics make the Peak District a suitable analogue for a study on climate change and wildfire in more northerly and western moorlands. Tallis (1985) highlighted peat pollution, along with excess grazing and wildfires, as one

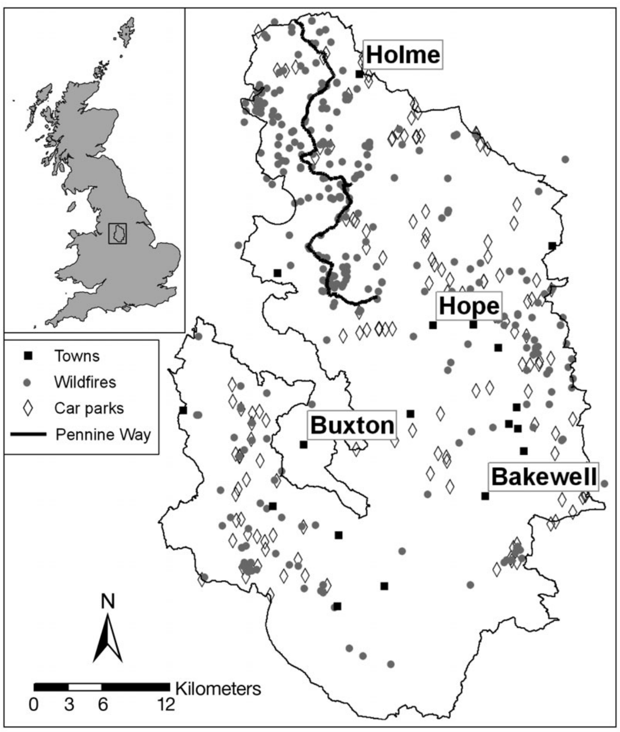

Fig. 1. Peak District wildfires, 1976–2006

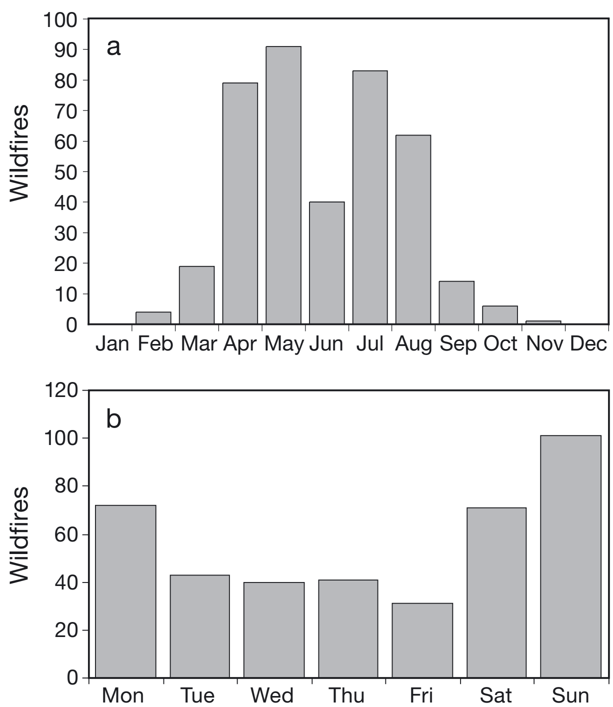

Fig. 2. Total number of wildfires in the Peak District National Park recorded by (a) month (June 1976 to December 2008) and (b) day of week (June 1976 to December 2008)

of the 3 biotic factors contributing to severe erosion of blanket peat in the area. Bare eroded peat may be vulnerable to 'deep burn' and very significant carbon loss. Atmospheric pollution, in particular acid rain, has severely diminished the prevalence of *Sphagnum*, which is largely responsible for peat formation (Holden et al. 2007), although rainfall acidity has halved since 1986. Severe wildfires burn into peat and destroy seed banks, preventing natural regeneration and encouraging erosion (Tallis 1987). Wildfires are therefore recognised as a significant threat to biodiversity in the park (PDNPA 2001).

The Peak District uplands provide a range of other ecosystem services, including regulation of water flow and quality, recreation and aesthetic services, wildlife conservation and game shooting (Hubacek et al. in press). These ecosystem services are vulnerable to wildfire. Work in North America (Meigs et al. 2009) has shown that wildfire impact on ecosystems depends on the fire regime (fire intensity, duration, area, frequency and seasonality), yet very little is known about current UK fire regimes. Other impacts are clear: wildfires in spring affect ground-nesting birds, while larger-scale wildfires may discourage tourism and result in temporary closure of major transport links. Costly restoration is required to avoid rapid erosion of bare peat following a wildfire (Anderson et al. 1997, 2009). Restoration may also improve resilience against future wildfire and help overcome the legacy of severe environmental degradation (Holden et al. 2007).

The remote location of the moors away from road access makes fighting wildfires difficult and costly. Suppression costs for incidents in the Peak District have ranged from £8500 for a small wildfire close to an urban area to a broad estimate of £132 000 for a typical fire in a remote location on a Pennine moor (Aylen et al. 2007). An upland wildfire at Stalybridge just outside the National Park perimeter cost around £1 million in public resources to fight in July 2006 over a period of 12 d with follow-up surveillance for 19 d.

Higher temperatures and lower moisture levels brought by climate change may increase the probability of wildfires breaking out by: (1) increasing the risk of wildfire due to human ignition sources; (2) increasing the hazard of wildfire due to flammability of vegetation; (3) increasing wildfire severity because milder winters increase fuel load; and (4) extending the wildfire season. The danger period for wildfires on the moors may stretch into autumn if soil moisture takes longer to recover after warmer, drier summers, even with the increased nighttime moisture that comes with shorter day length. Mackay & Tallis (1996) provided an historical analogy, showing how an earlier 20th century drought on the heather moorland of the Bowland Fells, Lancashire, and a shortage of keepers for fuel-load management, resulted in a catastrophic fire, thought to be in 1921 (a very severe drought year; Craddock 1976), which accelerated erosion, a process reinforced by subsequent overgrazing by sheep.

The present study uses a previously developed model of wildfire occurrence in the PDNP (Albertson et al. 2009), estimated using Probit analysis on daily data. The danger of wildfire occurrence increases non-linearly with maximum temperature, and dry spells or recent wildfires also increase the likelihood of fires. Certain days of the week are more fire prone due to human activity, and some months of the year are more hazardous, reflecting the changing flammability of moorland vegetation with the seasons. There is no systematic evidence on the impact of increased visitor numbers, as the PDNP is open to public access and is crossed by major roads. In the absence of suitable records of daily visitor numbers, we used days of the week, bank holidays and school holidays as proxies for this.

2. METHODS

The overall approach here was to apply the Probit model of fire incidence reported in Albertson et al. (2009) to simulated weather data up to the year 2100 and thus show how wildfire occurrence would change under 2 different climate change scenarios. The Probit model (Table 1) was used to assess the chance of wildfires in the Peak District at different times of the year, different days of the week and under various weather conditions. The model is calibrated to provide the best 'forecast' of known data. This was applied to simulated weather data for Buxton, using a weather generator (see section 2.4). The simulated data were used to predict the future incidence and timing of fires up to the 2080s. In effect, the Probit model was used as a transfer function, making predictions about wildfires given an underlying set of physical weather mechanisms that hold under an altered climate (Stainforth et al. 2007, 2157). At the same time, we accept these underlying climate models may be imperfect.

The sample of fires was drawn from records kept by rangers for the PDNP Authority. Daily data on the occurrence, number and size of fires run from June 1976 to December 2008. The period February 1978 to July 2004 was used for estimation. Data for the second half of 1976 and 1977 were used for out-of-sample forecasting to validate the model. Weather data are for Buxton (NGR SK 058734; 53.26° N, 1.91° W), from the UK Meteorological Office Land Surface Observation Stations database, provided through the British Atmospheric Data Centre (http://badc.nerc.ac.uk).

Table 1. Probit model of the likelihood of a moorland wildfire day. Estimated using maximum likelihood (no. observations = 7287; log likelihood = –614.1; likelihood ratio $\chi^2(14) = 525.4$; $p > \chi^2 = 0.0000$; pseudo $R^2 = 0.2996$). Base month: October; base day: Wednesday. See Albertson et al. (2009) for a full explanation of variables and estimation methods

Variable	Coefficient	SE	*z*	p > *z*	Variable description
Fire past week	0.463	0.107	4.31	0.000	Dummy variable, takes value 1 if fire during previous week
Precipitation	–0.080	0.023	–3.47	0.001	Daily precipitation (mm)
Minimum temp	–0.082	0.016	–5.21	0.000	Minimum daily temperature (°C)
Maximum temp	0.108	0.013	8.51	0.000	Maximum daily temperature (°C)
Bank holiday	0.606	0.158	3.85	0.000	Dummy variable, takes the value 1 on bank holidays, else zero
Friday	–0.300	0.142	–2.11	0.035	Dummy variable, takes the value 1 on Fridays, else zero
Saturday	0.250	0.104	2.42	0.016	Dummy variable, takes the value 1 on Saturdays, else zero
Sunday	0.280	0.101	2.76	0.006	Dummy variable, takes the value 1 on Sundays, else zero
April	0.592	0.116	5.10	0.000	Dummy variable, takes the value 1 in April, else zero
May	0.442	0.103	4.30	0.000	Dummy variable, takes the value 1 in May, else zero
P21	–0.101	0.037	–2.74	0.006	21 d precipitation shadow
P56	–0.111	0.046	–2.43	0.015	56 d precipitation shadow
IP7	0.237	0.092	2.57	0.010	Dummy variable, takes the value 1 during a 'dry spell', else zero
T28	0.094	0.027	3.46	0.001	28 d temperature shadow
Constant	–3.51	0.164	–21.5	0.000	

2.1. Probit modelling of wildfires

Calculating the probability of a fire or fires, conditional on all contributing factors, is not straightforward. As outlined above, Albertson et al. (2009) applied Probit analysis to daily meteorological data and a subset of our wildfire data to model the likelihood of a 'fire day' (defined as a day on which 1 or more fires were reported). Probit analysis allows estimation of a probability model with an observed dependent variable, y, which takes the value either zero (in this case, no fire reported) or unity (fire or fires reported). Thus, y_i is the outcome of a binomial process over time (Johnston & DiNardo 1997). Consider an implicit latent variable y^*, such that:

$$y_i = \begin{cases} 1; & \text{if } y_i^* = X_i\beta + \varepsilon_i > 0 \\ 0; & \text{else} \end{cases} \quad (1)$$

where X_i is a vector of observable explanatory variables; ε_i is an unobservable stochastic element, which is assumed to be normally distributed with a standard deviation of σ; y^* is normally distributed, conditional on X; and β can be estimated using maximum likelihood techniques. Therefore:

$$\Pr(y_i = 1) = \Phi\left(\frac{X_i\beta}{\sigma}\right) = \int_{-\infty}^{\left(\frac{X_i\beta}{\sigma}\right)} \frac{1}{\sqrt{2\pi}} e^{\left(\frac{-z^2}{2}\right)} dz \quad (2)$$

where Pr is the probability of a fire or fires, and Φ is the cumulative distribution of a standard normal random variable z. With this approach, fluctuations in daily fire incidents were modelled using meteorological data and deterministic seasonal variables (Albertson & Aylen 1996) as explanatory factors.

2.2 Predicting the probability of a fire day

Clearly some factors contribute to raising fire risk more than others, especially the influx of visitors to the PDNP as proxied by the day of the week and occurrence of bank holidays. Visit levels are directly associated with wildfire occurrence. Daily precipitation, past rainfall shadows, temperature shadows and the indicator function representing dry spells are significant — all of which point to the role of moisture in reducing wildfire hazard. Yet these weather variables have a relatively slight effect. The increase in risk associated with a typical British bank holiday Monday (compared to a regular Monday) is almost 5 times bigger than the risk associated with 7 d of dry weather. Nevertheless, higher daily maximum temperatures are clearly associated with greater fire danger, as are fluctuations in the level of precipitation. For precise definitions of the variables used and the modelling process, see Albertson et al. (2009).

Albertson et al. (2009) forecast a high chance of wildfires, given the prevailing deterministic and meteorological conditions, by classifying a day as dangerous when the probability of a fire or fires is higher than a threshold, p^*, that is, a day is classified as a high risk day when $\Pr(y_i = 1) > p^*$. Fires require an ignition source; flammable vegetation and dry weather do not guarantee fire. Albertson et al. (2009) found that wildfires occurred only on 55% of days classified as dangerous where the threshold level is set at $p^* = 5\%$. Our concern here is to estimate the likely number of fires, not the number of days when there is a high fire danger. We set p^* so that the forecast number of fire days (based on the simulated weather data for 1981–1990) is equal to the total number of days on which fires were reported.

2.3. Simulated weather data

The weather data used for modelling wildfires included daily precipitation and minimum and maximum daily temperature recorded at Buxton, the closest weather station to the study area for which long-term data series were available (Fig. 1). Earlier analysis (McMorrow et al. 2005) shows that the impact of climate is just the sum of short-run responses to daily and seasonal weather variation. That is, a relatively warm summer in our data set, for example 1976, might serve as a proxy for a typical summer under climate change projections. In statistical terms, it is hard to disentangle climate trends from natural fluctuations in weather patterns (Kallache et al. 2005). Taking monthly data, the weather in the Peak District is stationary over a 27 yr period (Albertson et al. 2009). In time-series terms, there is no indication of a unit root in the autocorrelation function of the monthly meteorological data, indicating no significant trend in the mean and variance of the data. This is consistent with the results of Thompson (1999), who found no trend in actual precipitation across Britain over last 150 yr, notwithstanding substantial variations from year to year. The picture is complicated by seasonal shifts in rainfall patterns. Maraun et al. (2008) show evidence of long-run increases in winter precipitation intensity and similar trends in spring and, perhaps, autumn. Summer rainfall patterns displayed considerable inter-decadal variability with no clear trend. Their results were not subjected to unit root testing.

2.4. Stochastic weather generation

There is controversy over the best approach to stochastic weather generation (e.g. Wilks & Wilby 1999, IPCC 2005, Gill 2006). In this case, we took daily weather simulated by a first-order Markov chain model of the type suggested by Katz (1977), developed by Jones & Salmon (1995) and outlined in Watts et al. (2004). This Climatic Research Unit (CRU) daily weather generator data has been widely used for climate change research and has been recently modified (Goodess et al. 2007, Kilsby et al. 2007) and developed for use with UKCP09 (Jenkins et al. 2009).

The effects of climate change are modelled here using an earlier version of the CRU daily weather generator to produce simulations for future climate (Watts et al. 2004). The model is calibrated so as to provide the best forecast of known data. This is applied to simulated weather data for Buxton, from a weather generator developed for the Built Environment Weather Scenarios for Investigation of Impacts and Extremes (BETWIXT) project, as part of the Building Knowledge for a Changing Climate (BKCC) programme (Table 2).

Table 2. Mean (±SD) of the Climatic Research Unit daily weather generator (WG) climate simulation. WG_lo and WG_hi: CRU weather generator simulations for the low and high emissions scenarios, respectively

	Precipitation (mm)	Min. temp. (°C)	Max. temp. (°C)
March/April/May			
Actual: 1979 to 2008	3.18 ± 8.57	3.52 ± 3.33	10.52 ± 4.33
WG_Validation 1961 to 1990	2.77 ± 8.18	3.10 ± 3.44	9.59 ± 3.92
WG_lo: 2011 to 2040	2.71 ± 8.58	3.79 ± 3.53	10.39 ± 3.99
WG_lo: 2041 to 2070	2.8 ± 8.64	4.07 ± 3.53	10.47 ± 3.99
WG_lo: 2071 to 2100	2.79 ± 8.53	4.56 ± 3.50	11.19 ± 4.25
WG_hi: 2011 to 2040	3.01 ± 9.07	3.96 ± 3.60	10.31 ± 4.06
WG_hi: 2041 to 2070	2.89 ± 8.97	4.70 ± 3.50	11.30 ± 3.99
WG_hi: 2071 to 2100	2.79 ± 9.21	6.22 ± 3.42	12.86 ± 4.15
June/July/August			
Actual: 1979 to 2008	2.99 ± 8.68	10.16 ± 2.53	17.96 ± 3.54
WG_Validation 1961 to 1990	3.11 ± 9.62	9.56 ± 2.69	16.39 ± 2.97
WG_lo: 2011 to 2040	2.47 ± 8.33	10.66 ± 3.06	17.63 ± 3.23
WG_lo: 2041 to 2070	2.18 ± 7.60	11.17 ± 3.04	18.29 ± 3.30
WG_lo: 2071 to 2100	1.63 ± 6.45	11.88 ± 3.14	19.46 ± 3.49
WG_hi: 2011 to 2040	2.13 ± 7.30	10.67 ± 2.91	17.87 ± 3.15
WG_hi: 2041 to 2070	1.63 ± 6.68	12.05 ± 3.30	19.47 ± 3.46
WG_hi: 2071 to 2100	1.04 ± 5.63	13.98 ± 3.68	22.22 ± 3.93
September/October/November			
Actual: 1979 to 2008	4.27 ± 10.66	5.82 ± 3.97	11.74 ± 4.17
WG_Validation 1961 to 1990	4.04 ± 10.91	5.56 ± 3.57	11.19 ± 4.04
WG_lo: 2011 to 2040	4.09 ± 11.75	6.41 ± 3.82	12.15 ± 4.22
WG_lo: 2041 to 2070	4.01 ± 11.75	7.09 ± 3.87	12.83 ± 4.29
WG_lo: 2071 to 2100	3.49 ± 10.96	7.71 ± 4.17	13.43 ± 4.62
WG_hi: 2011 to 2040	3.92 ± 11.60	6.42 ± 3.92	12.20 ± 4.42
WG_hi: 2041 to 2070	3.8 ± 11.56	8.06 ± 3.99	13.88 ± 4.66
WG_hi: 2071 to 2100	3.38 ± 11.17	10.36 ± 4.38	16.17 ± 5.05
December/January/February			
Actual: 1979 to 2008	4.32 ± 10.05	0.54 ± 3.45	5.43 ± 3.24
WG_Validation 1961 to 1990	4.02 ± 10.67	0.33 ± 3.38	5.31 ± 3.35
WG_lo: 2011 to 2040	4.54 ± 11.84	0.95 ± 3.33	5.75 ± 3.40
WG_lo: 2041 to 2070	4.61 ± 11.53	1.35 ± 3.25	6.13 ± 3.27
WG_lo: 2071 to 2100	4.95 ± 12.21	1.90 ± 3.20	6.72 ± 3.33
WG_hi: 2011 to 2040	4.66 ± 11.88	1.13 ± 3.25	5.81 ± 3.26
WG_hi: 2041 to 2070	4.94 ± 12.22	1.92 ± 3.10	6.69 ± 3.24
WG_hi: 2071 to 2100	6.5 ± 14.25	3.34 ± 3.00	8.18 ± 3.13

This weather generator uses measurements of past meteorological observations from the Buxton weather station to estimate the model parameters, which are then used in a stochastic model to generate daily weather variables. Thus, the model is trained using a 30 yr daily time series of observed station data. The weather generator parameters are then perturbed to be consistent with the UKCIP02 climate change scenarios to construct future daily weather scenarios that incorporate climate change. The data generated for Buxton cover 140 yr of daily weather simulations. The simulated data are in the form of a validation set, representing the baseline climate, from 1 January 1961 to 31 December 1990, and 3 future 30 yr time slices, centred on the 2020s (2011–2040), the 2050s (2041–2070) and the 2080s (2071–2100). Each of the future time slices incorporate climate change projections calculated by the Hadley Centre's HadCM3 regional climate model, and these are generated for 2 emissions scenarios: the UKCIP02 high and low emissions scenarios (equivalent to the IPCC A1FI and B1 emissions scenarios). The UKCIP02 data are consistent with the latest UKCP09 suite of information on the future climate of the UK, and thus results remain valid and up-to-date.

These climate change projections are not transient within each 30 yr period; thus, the 30 simulated years comprising each period can be taken in any order. There are clear step changes between periods, as shown in Table 2.

2.5 Comparing simulated and actual weather

As noted above, the CRU daily weather generator is trained using observed weather data from the Buxton weather station from 1961 to 1990, inclusive, although actual recorded rainfall data are missing for 1969. The simulated weather data should have the same distribution and statistical characteristics as this training set. Precipitation is the primary variable produced by the CRU weather generator. Forecasts of minimum and maximum temperature are then derived from precipitation estimates. Calibration checks suggest that the CRU weather generator overestimates precipitation in July–August for Buxton, which leads to a lower simulated maximum daily temperature compared with actual data. As the maximum temperature in the CRU calibration set is lower than that observed, our forecasts for wildfires based on these estimates will be biased slightly downwards.[1]

The Probit model for predicting wildfires is sensitive to the distribution of weather across the year. To determine whether it is sensible to condition our forecasts on the CRU weather generator data, we compared the mean, variance, skewness and kurtosis of the actual and simulated weather distributions, month by month. Briefly, simulated data showed more monthly variability, more skewness and displayed a different spread of precipitation throughout the year. Precipitation was lower in February and March and higher in July, August and November compared with actual observations. All else being equal, the use of simulated data would cause us to anticipate more spring fires and fewer summer fires compared to actual data. In particular, summer precipitation was overestimated and temperature was underestimated. Therefore, our forecasts will understate the seriousness of the wildfire problem in July and August.

The true position is complicated by a shift in the seasonal distribution of actual rainfall over time. Osborn et al. (2000) and Osbourne & Hulme (2002) have shown that daily precipitation has become more intense in winter and less intense in summer over the period 1961–2000, the exact opposite of the divergence between the simulated weather data and observed weather station data. This enhanced seasonal cycle of increasing winter precipitation, heavier downpours and drier summers with fewer wet days may reflect changes in the mid-latitude westerly circulation (Mayes 1996). Mayes (1996) showed that there was more rainfall in northwest England in early spring, which would moisten the moors before of the hazardous fire season in April and May. These results are crucial for modelling incidence of moorland fires, as a pattern of more intermittent summer rainfall may increase the fire hazard. These CRU weather generator simulated climate changes indicate a shift towards drier springs and drier summers under both emissions scenarios up to 2100.

Turning to temperature, the means and variances of minimum and maximum temperature show strong similarity between the observed weather at Buxton and the simulated data for the baseline period. However, skewness of the temperature distributions is markedly different and excess kurtosis differs substantially between the actual meteorological data and the validation set. Notwithstanding, as these differences relate mainly to December and January they are of little practical significance in this context: winter wildfires are extremely rare.

In summary, there are statistically significant differences between the actual meteorological data and the

[1]Note that the distribution of daily rainfall for the Peak District is captured by a univariate gamma distribution (Coe & Stern 1982, Stern & Coe 1984, Wilks 1990). On most days, precipitation is <1 mm. The median rainfall at Buxton is 0.7 mm, but mean daily rainfall is 3.6 mm because the mean is pulled upward by extreme events, such as downpours and heavy snowfalls

CRU weather generator validation set that affect the precision of forecasts of wildfires based on simulated weather (Table 2). These inexactitudes in data generation are relatively trivial compared to uncertainty about the likely extent of climate change itself and, after all, this is a known data set on which to base our heuristic forecasts. So, with this caveat, we continued to use the CRU daily weather generator simulated future data to investigate the impact of climate change on the future incidence of moorland wildfires. The model provides detailed temporal simulations for the Peak District itself. The fact that the simulated data is specific to our exact location and problem makes it particularly valuable.

2.6. In-sample fitting of wildfire incidence

Here we set the critical probability of a wildfire, p, to allow comparisons between the number of wildfires predicted by the CRU weather generator data set in the period 1 January 1981 to 31 December 1990 (the last decade for which CRU weather generator validation is available) and the actual number of wildfires in the Peak District over the same 10 yr.

The Probit model forecasts the probability of a fire day, whereas it is our objective to forecast the number of fire days. Thus, we compared the forecast probability of a fire to a threshold level, p^*. Quite simply, if the forecast probability exceeds p^*, that day is classified as a fire day. A higher threshold means fewer false alarms, but more fires that are not forecast. Here we use $p^* = 0.132$ or greater as representing the likelihood of moorland wildfire. This level was chosen to set the number of fires forecast in the decade 1981–1990, based on the CRU weather generator, to the number actually observed at that time, namely 65.

We calculated the probability of a moorland wildfire using Eqs. (1) and (2) with the parameters listed in Table 1. The CRU validation set was used to generate the matrix of predictors, X. Indicator variables, such as dry spells or hot spells, are not generated by the Markov process. The distribution of these dry and hot intervals were calculated relative to weather that prevailed across the base period used by Albertson et al. (2009) for estimation, namely 1 October 1977 to 1 August 2004. We also interpolated a leap year in the CRU weather generator baseline data as required (there are no leap years in the simulated data) and established future dates of Easter and Whitsun. The CRU weather generator data set does not aim to replicate the exact weather on any given day, but merely to replicate the typical pattern of weather at a particular time. Hence, the accuracy of our forecast was not judged on whether or not a fire is reported on a particular day, but on whether the model can forecast an approximate number of wildfires per decade.

3. RESULTS

The impact of climate change on wildfires, under both the low and high emissions scenarios, is to make summer the more hazardous season, compared with spring, as summer begins to experience longer, hotter dry spells. This is not to say we expect fewer fires in spring — there is an increased chance — but wildfire danger in summer increases disproportionately. These effects are slow to take effect and the odds of wildfire do not increase substantially until after 2070.

The potential impact of climate change on the probability of wildfires is complex. Immediate effects are caused by small rises in peak temperatures and slight reductions in summer precipitation. There is likely to be an indirect effect due to the cumulative impact of lower precipitation and higher temperatures on soil moisture and evapotranspiration from moorland vegetation.

The CRU daily weather generator simulations are provided for 3 separate 30 yr time slices, with clear structural breaks between the sets. Given the discrete changes implied, and the fact that the CRU weather generator does not aim to simulate weather on specific days, we can summarise the data in each set as denoting typical weather which might be observed within these 3 decades. Results from the daily simulations are captured by a forecast of a feasible distribution of fires for each data set. The cumulative distributions of these years are shown in Fig. 3.

Under the low emissions scenario, we expect relatively little change in the distribution of wildfires for the next 50 or so years. Fig. 3a,b plots the expected number of fires as a distribution for the spring and summer seasons of each 30 yr time slice, assuming low greenhouse gas emissions. We expect the distribution of spring fires to change relatively little even by the end of the 21st century. By contrast, the situation deteriorates in summer, with a typical median of 15 fire days each summer after 2070. Many of these wildfires may be small. The prediction assumes there will be ignition sources.

Conversely, under the high emissions scenario, we expect the spring and summer distribution of wildfires to shift markedly within 20 to 30 yr (Fig. 3b,c). Beyond 2070, we expect an average of 5 wildfires each week, because every summer is likely to have a profile similar to the ‘great’ summer of 1976 (Hulme et al. 2002). Fire-free days will then become the exception under the high emissions scenario by 2100.

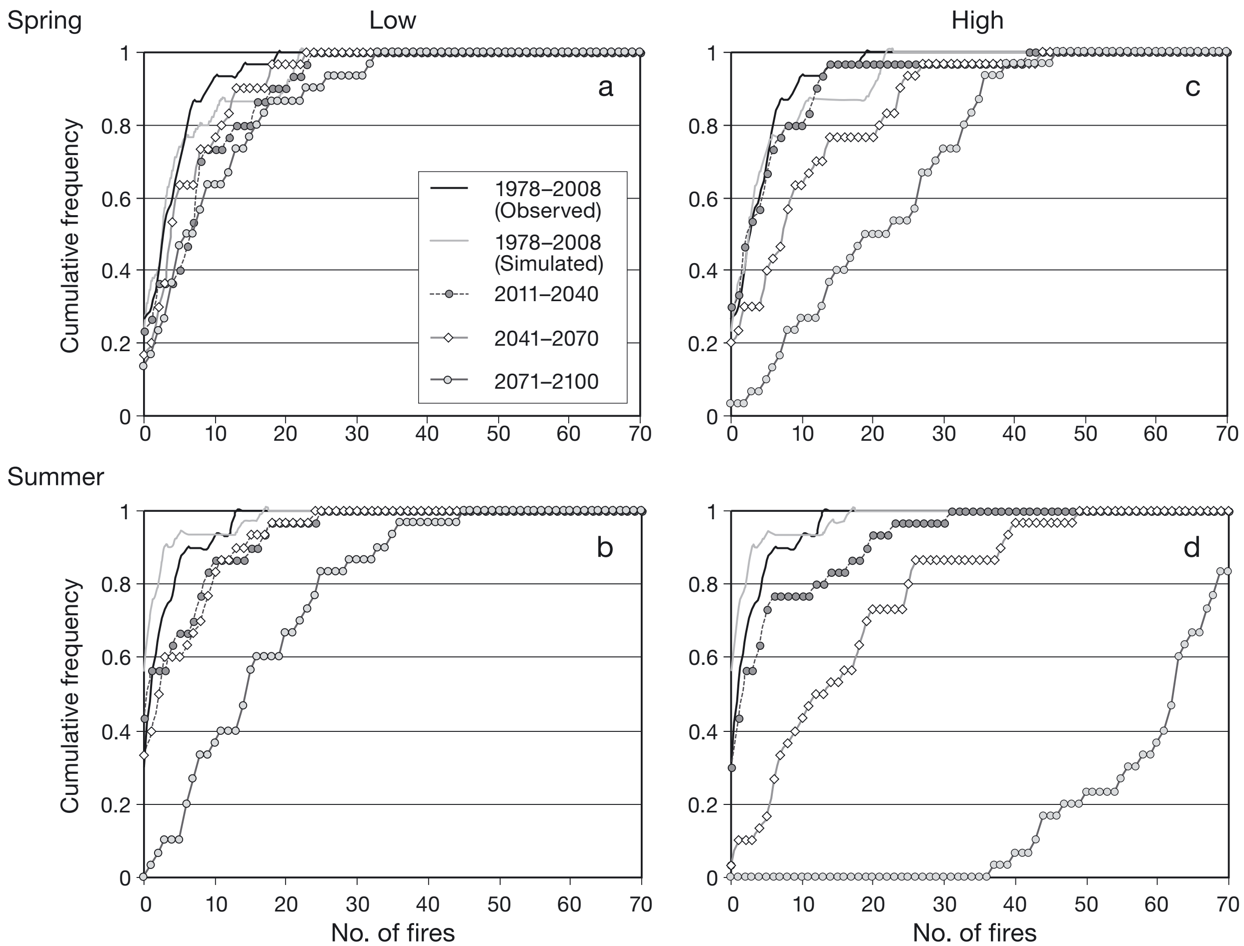

Fig. 3. Observed and projected future cumulative distribution of wildfires in the Peak District National Park under a (a,b) low and (c,d) high emissions scenario in (a,c) spring and (b,d) summer

At face value these projections suggest things will remain much as they are at present for the next 20 to 30 yr, but after that time, danger of wildfires increases sharply. Depending on the actual amount of greenhouse gas emissions worldwide, long, dry summers may become the norm rather than (as at present) the exception. Recreational users of Peak District moorland might welcome such weather, but the moors themselves are likely to suffer and, unless substantial extra resources are put into fire prevention and fire fighting, the cost to ecosystem services of climate change in this upland region is likely to be high.

4. DISCUSSION

These forecasts of future fire incidence are incomplete in 4 respects. Specifically, they do not take into account: changes in species composition and plant phenology resulting from climate change; changes in human behaviour; forecasts of the severity of fires; or the reliability of simulated weather data. Predictions based on recent and historical weather overlook ways in which climate change may alter the phenology and ecology of the moors, including the onset of spring, the length of growing season and the distribution of plant species.

The effect of climate change on the likelihood of wildfire is not straightforward (Cavan & McMorrow 2009). As Legg & Davies (2009) have stated, there are 3 conditions necessary for vegetation to burn: a suitable source of fuel, appropriate weather conditions and a source of ignition. So, occurrence of wildfires varies on different time scales: with time of year, in a complex seasonal pattern, within each week, and diurnally. Vulnerability to wildfires therefore alters daily as plant phenology and weather change the moisture content, load and structure of fuel. The peak months for fires in the PDNP are April–May and July–August (Fig. 2a). These are times when weather is warmer and drier and fuel is available either in the form of dead vegetation from winter or as plants dried by summer heat. There is a dip in wildfire occurrence in June as plants increase their green leaf area and, consequently, their fuel moisture content, but before summer drying begins. Almoustafa et al. (2009) have shown that fuel moisture in *Calluna* fell during the transition from spring to summer in their Peak District study area. Experiments by Davies & Legg (2010) have shown that fires spread rapidly through *Calluna*-dominated vegetation with moisture contents of less than 60% but fail to take hold above 70%. The rise in wildfires in spring and late summer also reflects the annual pattern of Easter and summer holidays, when more people visit the PDNP and so there are more possible ignition sources.

Climate change may cause the timing of moorland wildfires to shift later in the season in response to a damper and more verdant spring, a drought-stressed summer and low rainfall in early autumn. Spring fire outbreaks would be reduced by increased winter precipitation, making soil and vegetation wetter in spring, with fewer winter frosts to dry out vegetation. This assumes that warmer winter temperatures do not add significantly to evapotranspiration. Higher maximum temperatures increase the fire hazard, yet higher nighttime minimum temperatures advance the onset of plant growth. (Notice the chance of fire decreases with higher nighttime minimum temperatures in Table 1.) This effect should not be exaggerated, as day length and available light will not change and photosynthesis is still constrained. Warmer, drier summers cause soil moisture to fall and evapotranspiration from vegetation to rise, thus 'curing' the fuel, even though plants respond by conserving moisture. In hot conditions, surface peat dries out with a hydrophobic crust, making subsequent re-wetting difficult. There is little evidence for a corresponding delay in the onset of autumn (Sparks & Menzel 2002), so it is purely speculation that plants will remain greener for longer.

In the longer term, plants adapt to changing climatic conditions (Watt 1954) and the prevailing fire regime. Summer droughts are likely to alter species composition (Buckland et al. 1997), tipping the balance of survival for plant communities susceptible to low moisture. This assumes that plant communities are in equilibrium with the climate and will therefore adjust as climate changes (Webb 1986), and ignores the influence of land management. Trivedi et al. (2008) have suggested that temperature is a significant factor in all upland plant distributions and that climate-driven shifts in species are particularly likely in upland terrain where local climate may depart from trends in the wider area. Even so, the effects are not straightforward. Berendse et al. (2001) have shown that increased CO_2 does not accelerate *Sphagnum* growth because atmospheric deposition of reactive nitrogen compounds encourages vascular plants and tall mosses to develop at the expense of *Sphagnum*. Feedback relationships also exist between plants and fire regimes, for instance, those favouring more fire-resistant vegetation (Hanley 2009). Much of the heather moorland in the UK is a fire-adapted community that has developed in response to prescribed burning used in grouse moor management.

Indirect changes in upland vegetation may alter the fire hazard of an area. Climate-induced, socioeconomic or legislation-induced changes in land use may lead to increased fire hazard. This has been observed in Spain, for example, where socioeconomic change has led to abandonment of rural farms and reduced management of woodlands (Martínez et al. 2009). With fewer people involved in conservation and land management scrub has replaced cultivated fields in parts of Spain, making these abandoned areas more susceptible to wildfires. Similar patterns may be seen in the English uplands, with local trends such as reductions in farm labour and grazing intensity. As Chapman et al. (2009) have demonstrated, there is a complex balance between climatic and land-use drivers in the Peak District, with environmental stewardship influencing the semi-natural ecosystem. Mackay & Tallis (1996) have suggested that a relative shortage of gamekeepers after the First World War led to a decline in heather management on the Bowland Fells and was a contributing factor in a 'catastrophic burn' in the 1920s. Land management burns in winter, sometimes erroneously called 'cool burns', are used to encourage new shoots for game birds and grazing animals. In grouse moor management, mature heather is intentionally set alight in late autumn or winter and the resulting cool burn causes little damage to underlying peat soil as long as it remains a fast-moving canopy fire. Managed burns reduce fuel loading, thereby lowering the chance of severe accidental fires later in the year. Land managers have expressed concern that a decrease in heather management for grouse shooting, including restrictions on burning or climatic conditions less suitable for grouse, will lead to rising fuel loads and, in their view, increase the chance of severe fires. By contrast, conservation bodies favour restrictions on burning to meet biodiversity targets, coupled with moorland restoration, such as rewetting through gully blocking, to improve moorland resilience to wildfire (Cavan 2009) and to help active bogs to recover (Yallop et al. 2009). Grazing or mowing may be required to reduce fuel load in fire-sensitive areas.

Visitor numbers are assumed to be stationary, conditional on weather. If visitor numbers to the PDNP do increase as summers become drier, there are likely to be more ignition sources and, therefore, more fires. The importance of the deterministic dummy variables representing holiday periods indicates the culpability of human involvement in starting fires, either inadvertently or on purpose. Increased human activity on weekends and holidays in response to more clement weather is one of the effects captured by the climate variables.

There is potential feedback from climate change to human behaviour. Growing appreciation of the danger of wildfire may reduce incidence of fires because of awareness-raising programmes, the use of alarm systems such as fire watchers and preventative methods such as fuel removal and fire breaks. Visitors to the moors are encouraged to be more careful in their behaviour at times of extreme fire hazard. However, warmer and drier weather may well lead to increased visits to the moors for recreation and, hence, an increase in the risk of malicious or accidentally ignited fires. Policy response to climate change such as promotion of UK-based holidays under a low carbon economy could increase the density of ignition sources. More vigorous public awareness campaigns, car park closures and closure of public rights of way, in addition to closure of access land, may need to be considered. Rapid-response fire-fighting equipment such as helicopters and all-terrain vehicles offer a cost-effective solution to suppression in these circumstances (Aylen et al. 2007). A swift response halts fire spread and preempts a long, damaging and costly incident.

There remains a question as to how well simulated data capture the accumulated effect of dry spells and hot spells. Rainfall in the UK tends to set in for 3 days at a time and so weather in the Peak District shows a third-order autocorrelation process in daily precipitation. The meteorological reasons are clear: slow-moving fronts across Britain persist for up to 3 days, but seldom stay in place longer. Yet the CRU weather generator data is generated using a first-order Markov process, effectively changing from day to day. Ideally, the autocorrelation structure of simulated weather should be similar to that of weather experienced in Buxton. The implication is that forecasting based on the CRU weather generator data may understate fire incidence as rainfall shadows will be shorter and more volatile and, hence, dry spells will be briefer compared to the weather actually observed. By their nature, weather simulations are not expected to capture occasional extremes of weather observed in the British Isles, e.g. so-called 'Acts of God' (Katz et al. 2005). Mandelbrot & Wallis (1968) coined the terms 'Noah effect', for findings that extreme precipitation can be very extreme indeed, and 'Joseph effect', for evidence that long periods of high or low precipitation can be extremely long. It is reassuring that a Gaussian model such as the Probit model of wildfires used in the present study back-predicted fire outbreaks in the extreme summer of 1976 with great accuracy (Albertson et al. 2009, their section 6).

5. SUMMARY AND CONCLUSIONS

A probability model was used to explain and predict the chance of wildfires in the PDNP at different times of the year and days of the week and under various weather conditions. Time series of future daily weather under 2 contrasting scenarios for future climate change were generated using the CRU weather generator stochastic simulations for rainfall and temperature at Buxton. The probability model was applied to the daily weather data to predict the incidence of wildfires in the Peak District up to the year 2100.

Climate change projections suggest that climate change is likely to bring wetter winters but hotter and drier summers to the uplands of the Peak District. The danger of summer wildfires will become far more severe after 2070. Increased winter rainfall will (relatively) lower the chance of fires in spring, offsetting the warmer weather to some extent. Reduced summer rainfall will result in an increase in the danger of moorland fires. The non-linear nature of our Probit model suggests that incidence of wildfires in the PDNP is likely to be episodic, coinciding with dry spells and hot intervals. It is possible that fire-free summer days will be the exception rather than the rule by the last 30 yr of this century under the worst-case high emissions scenario.

Active environmental management of the sensitive uplands of the Peak District will be necessary, including management of fuel loads, fire watching and awareness programmes. In the near future, these measures should be sufficient to contain the threat of wildfire to ecosystem services posed by climate change, at least over the next half century, and to reduce the chance of summer wildfires becoming catastrophic.

Acknowledgements. The Climate Research Unit at the University of East Anglia provided the CRU daily weather generator dataset for Buxton, with thanks to C. Goodess. A Fortran programme on the gamma distribution which we used to check our calculations was kindly provided by D. Wilks. Aspects of this research were presented at International Symposia on Forecasting in 2009 and 2010 and we are grateful to respondents for comments. The precision and acuity of 4 conscientious referees and 2 patient editors helped to substantially improve earlier versions. The authors alone are responsible for errors.

LITERATURE CITED

Agnew MD, Palutikof JP (2006) Impacts of short-term climate variability in the UK on demand for domestic and international tourism. Clim Res 31:109–120

Albertson K, Aylen J (1996) Modelling the great lakes freeze: forecasting and seasonality in the market for ferrous scrap. Int J Forecast 12:345–359

Albertson K, Aylen J, Cavan G (2006) Visitor attraction figures in relation to climate: the potential impact of global climate change on zoos. Fifth International Zoo and Aquarium Marketing Conference, Allwetterzoo, Münster, Germany, 1–4 Jun 2005. Stämpfl Publikationen, Bern, p 79–87

Albertson K, Aylen J, Cavan G, McMorrow J (2009) Forecasting the outbreak of moorland wildfires in the English Peak District. J Environ Manage 90:2642–2651

Almoustafa T, Armitage R, Danson FM (2009) Hyperspectral remote sensing for measuring fuel moisture content: case study for fire risk assessment in the UK. Proc Remote Sensing and Photogrammetry Society Conf, Leicester, 8–11 September YEAR. Remote Sensing and Photogrammetry Society, Nottingham

Anderson PA, Tallis JH, Yalden DW (1997) Restoring moorlands: the Moorland Management Project Phase 3 report. Peak Park Joint Planning Board, Bakewell

Anderson PA, Buckler M, Walker J (2009) Moorland restoration: potential and progress. In: Bonn A, Allott T, Hubacek K, Stewart J (eds) Drivers of environmental change in uplands. Routledge, London, p 432–447

Aylen J, Cavan G, Albertson K (2007) The best strategy for mitigating moorland wildfire risk: a report to Moors for the Future. Moors for the Future small grant A79419, Moors for the Future, Castleton

Balshi MS, McGuire AD, Duffy P, Flannigan M, Walsh J, Melillo J (2009) Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Global Change Biol 15:578–600

Berendse F, Breemen NV, Rydin H, Buttler A and others (2001) Raised atmospheric CO_2 level and increased N deposition cause shifts in plant species composition and production in Sphagnum bogs. Global Change Biol 7: 591–598

Brown TJ, Hall BL, Westerling AL (2004) The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective. Clim Change 62:365–388

Buckland SM, Grime JP, Hodgson JG, Thompson K (1997) A comparison of plant responses to the extreme drought of 1995 in Northern England. J Ecol 85:875–882

Burke EJ, Perry RHJ, Brown SJ (2010) An extreme value analysis of UK drought and projections of change in the future. J Hydrol 388:131–143

Burrows ND, Ward B, Robinson AD, Behn G (2006) Fuel dynamics and fire behaviour in spinifex grasslands of the Western desert. Life in a fire-prone environment: translating science into practice. Bushfire Conference 2006, Brisbane, 6–9 June 2006, available at www.griffith.edu.au/conference/bushfire2006/pdf/fuel-dynamics-and-fire-behaviour.pdf

Cavan G (2009) Policy panel and discussion. Seminar 4. Fire interdisciplinary research on ecosystem services. Economic impacts of wildfires, wildfire policy and the use of adaptive land management to reduce wildfire risk and impact. Fire and Climate Change in UK Moorlands and Heaths (FIRES), Losehill Hall, Peak District National Park, 13–14 May 2009, available at www.fires-seminars.org.uk/downloads/seminar4/fires4_day1_gcavan.pdf

Cavan G, McMorrow J (2009) Summary report. FIRES: Interdisciplinary Research on Ecosystem Services. Fire and climate change in UK moorlands and heaths. Summary report prepared for Scottish Natural Heritage. Available at www.fires-seminars.org.uk/downloads/SNH_report_v1.pdf, accessed 18 October 2010

Chapman DS, Termansen M, Quinn C, Jin N and others (2009) Modelling the coupled dynamics of moorland management and upland vegetation. J Appl Ecol 46:278–288

Coe R, Stern RD (1982) Fitting models to daily rainfall data. J Appl Meteorol 21:1024–1031

Craddock JM (1976) Annual rainfall in England since 1725. Q J R Meteorol Soc 102:823–840

Davies M, Gray A, Hamilton A, Legg C (2008) The future of fire management in the British uplands. Int J Biodivers Sci Manage 4:127–147

Davies GM & Legg CJ (2010) Fuel moisture thresholds in the flammability of *Calluna vulgaris*. Fire Technol doi:10.1007/s10694-010-0162-0

Evans M, Warburton J, Yang J (2006) Eroding blanket peat catchments: global and local implications of upland organic sediment budgets. Geomorphology 79:45–57

Flannigan MD, Stocks BJ, Wotton BM (2000) Climate change and forest fire. Sci Total Environ 262:221–229

Fried JS, Torn MS, Mills E (2004) The impact of climate change on wildfire severity: a regional forecast for northern California. Clim Change 64:169–191

Fried JS, Gilless JK, Riley WJ, Moody TJ and others (2008) Predicting the effect of climate change on wildfire behavior and initial attack success. Clim Change 87(Suppl 1): 251–264

Gill SE (2006) Climate change and urban greenspace. PhD thesis, School of Environment and Development, University of Manchester

Goodess CM, Hall J, Best M, Betts R and others (2007) Climate scenarios and decision making under uncertainty. Built Environ 33:10–30

Hanley ME (2009) Thermal shock and germination in North-West European Genisteae: implications for heathland management and invasive weed control using fire. Appl Veg Sci 12:385–390

Holden J, Shotbolt L, Bonn A, Burt TP and others (2007) Environmental change in moorland landscapes. Earth Sci Rev 82:75–100

Hubacek K, Beharry N, Bonn A, Burt T and others (2009) Ecosystem services in dynamic and contested landscapes: the case of UK uplands. In: Winter M, Lobley M (eds) What is land for? The food, fuel and climate change debate. Earthscan, London, p 167–188

Hulme M, Jenkins G, Lu X, Turnpenny JR and others (2002) Climate change scenarios for the United Kingdom: the UKCIP scientific report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich

IPCC (2005) About stochastic weather generators. IPCC Data Distribution Centre, available at http://ipcc-ddc.cru.uea.ac.uk/ddc_weather_generators.html

Jenkins GJ, Murphy JM, Sexton DMH, Lowe JA, Jones P, Kilsby CG (2009) UK climate projections: briefing report. Met Office Hadley Centre, Exeter, available at http://ukclimateprojections.defra.gov.uk/images/stories/briefing_pdfs/UKCP09_Briefing.pdf

Johnston J, DiNardo J (1997) Econometric methods, 5th edn. McGrawHill, New York

Jones PD, Salmon M (1995) Development and integration of a stochastic weather generator into a crop growth model for European agriculture. MARS project, final report to Institute of Remote Sensing Applications, Agricultural Information Systems (ISPRA), Varese

Kallache M, Rust HW, Kropp J (2005) Trend assessment: applications for hydrology and climate research. Nonlinear Process Geophys 12:201–210

Katz RW (1977) Precipitation as a chain-dependent process. J Appl Meteorol 16:671–676
Katz RW, Brush GS, Parlange MB (2005) Statistics of extremes: modelling ecological disturbances. Ecology 86:1124–1134
Kilsby CG, Jones PD, Burton A, Ford AC and others (2007) A daily weather generator for use in climate change studies. Environ Model Softw 22:1705–1719
Krawchuk MA, Moritz MA, Parisien MA, Van Dorn J, Hayhoe K (2009) Global Pyrogeography: the Current and Future Distribution of Wildfire. PLoS ONE 4:e5102 doi:10.1371/journal.pone.0005102
Legg CJ, Davies GM (2009) What determines fire occurrence, fire behaviour and fire effects in heathlands? In: Alonso I (ed) Managing heathlands in the face of climate change. Natural England Commissioned Report no. 014. Natural England, Peterborough, p 45–55
Mackay AW, Tallis JH (1996) Summit-type blanket mire erosion in the forest of Bowland, Lancashire, UK: predisposing factors and implications for conservation. Biol Conserv 76:31–44
Mandelbrot C, Wallis JR (1968) Noah, Joseph, and operational hydrology. Water Resour Res 4:909–918
Maraun D, Osborn TJ, Gillett NP (2008) United Kingdom daily precipitation intensity: improved early data, error estimates and an update from 2000 to 2006. Int J Climatol 28:833–842
Martínez J, Vega-Garcia C, Chuvieco E (2009) Human-caused wildfire risk rating for prevention planning in Spain. J Environ Manage 90:1241–1252
Mayes J (1996) Spatial and temporal fluctuations of monthly rainfall in the British Isles and variations in the mid-latitude westerly circulation. Int J Climatol 16:585–596
McEvoy D, Handley J, Cavan G, Aylen J, Lindley S, McMorrow J (2006) Climate change and the visitor economy: challenges and opportunities for England's northwest. Final Report. Sustainability Northwest (Manchester) and UK Climate Impacts Programme, Oxford, available at www.sed.manchester.ac.uk/geography/staff/documents/CCVE_Summary_Report.pdf
McMorrow JM, Aylen J, Albertson K, Cavan G, Lindley SJ, Handley J, Karooni R (2005) Moorland wild fires in the Peak District National Park. Technical Report 3: climate change and the visitor economy (CCVE). CURE, University of Manchester, Manchester, available at www.sed.manchester.ac.uk/geography/staff/documents/Moorland_Wildfires_Final_Report_Technical_Report3.pdf
McMorrow JM, Lindley SJ, Aylen J, Cavan G, Albertson K, Boys D (2009) Moorland wildfire risk, visitors and climate change: patterns, prevention and policy. In: Bonn A, Allott T, Hubacek K, Stewart J (eds) Drivers of change in upland environments. Routledge, London, p 404–431
Meigs GW, Donato DC, Campbell JL, Martin JG, Law BE (2009) Forest fire impacts on carbon uptake, storage, and emission: the role of burn severity in the eastern Cascades, Oregon. Ecosystems 12:1246–1267
Meyn A, White PS, Buhk C, Jentsch A (2007) Environmental drivers of large, infrequent wildfires: the emerging conceptual model. Prog Phys Geogr 31:287–312
Miller JD, Safford HD, Crimmins M, Thode AE (2009) Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12:16–32
Milne R, Brown TA (1997) Carbon in the vegetation and soils of Great Britain. J Environ Manage 49:413–433
Moritz M, Stevens SL (2008) Fire and sustainability: considerations for California's altered future climate. Clim Change 87(Suppl 1):265–271
Orr HG, Wilby RL, McKenzie Hedger M, Brown I (2008) Climate change in the uplands: a UK perspective on safeguarding regulatory ecosystem services. Clim Res 37: 77–98
Osborn TJ, Hulme H (2002) Evidence for trends in heavy rainfall events over the UK. Philos Trans R Soc Lond A 360: 1313–1325
Osborn TJ, Hulme H, Jones PD, Basnett TA (2000) Observed trends in the daily intensity of United Kingdom precipitation. Int J Climatol 20:347–364
Page SE, Siegert F, O'Rieley J, Boehm HDV, Jaya A, Limin S (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420:61–65
PDNPA (Peak District National Park Authority) (2001) Action plan, blanket bog. Peak District National Park Authority, Bakewell, available at www.peakdistrict-nationalpark.info/_pdf/moorland/bap_blanket_bog.pdf
PDNPA (Peak District National Park Authority) (1998) Peak District National Park visitor survey – 1998. Peak District National Park Authority, Bakewell
Radley J (1965) Significance of major moorland fires. Nature 215:1254–1259
Rothwell JJ, Evans MG, Liddaman LC, Allott THE (2007) The role of wildfire and gully erosion in particulate Pb export from contaminated peatland catchments in the southern Pennines, UK. Geomorphology 88:276–284
Shotbolt L, Hutchinson SM, Thomas AD (2006) Stratigraphy and heavy metal fluxes to reservoirs in the southern Pennine uplands, UK. J Paleolimnol 35:305–322
Sparks TH, Menzel A (2002) Observed changes in seasons: an overview. Int J Climatol 22:1715–1725
Stainforth, DA, Allen, MR, Tredger, ER and Smith LA (2007) Confidence, uncertainty and decision-support relevance in climate predictions. Philos Trans R Soc Lond A 365: 2145–2161
Stern RD, Coe R (1984) A model fitting analysis of rainfall data. J R Stat Soc [Ser A] 147:1–34
Tallis JH (1985) Mass movement and erosion of a southern Pennine blanket peat. J Ecol 73:283–315
Tallis JH (1987) Fire and flood at Holme Moss: erosion processes in an upland blanket mire. J Ecol 75:1099–1129
Thompson R (1999) A time-series analysis of the changing seasonality of precipitation in the British Isles and neighbouring areas. J Hydrol 224:169–183
Trivedi MR, Morecroft MD, Berry PM, Dawson TP (2008) Potential effects of climate change on plant communities in three montane nature reserves in Scotland, UK. Biol Conserv 141:1665–1675
UKCIP (2009) Key findings for north west England, 2080s. UKCIP, Oxford, available at www.ukclimateprojections.defra.gov.uk/content/view/292/499
Viegas DX (1998) Weather, fuel status and fire occurrence: predicting large fires. In: Moreno JM (ed) Large forest fires. Backhuys, Leiden, p 31–48
Waggoner PE (1989) Anticipating the frequency distribution of precipitation if climate change alters its mean. Agric For Meteorol 47:321–337
Watt AS (1954) Frost and the advance and retreat of bracken. New Phytol 53:117–130
Watts M, Goodess CM, Jones PD (2004) The CRU daily weather generator. BETWIXT Technical Briefing Note 1, version 2. Climatic Research Unit, University of East Anglia, Norwich, available at www.cru.uea.ac.uk/cru/projects/betwixt/documents/BETWIXT_TBN_1_v22.pdf
Webb T (1986) Is vegetation in equilibrium with climate? How to interpret late Quaternary pollen data. Plant Ecol 67: 75–91
Westerling AL, Bryant BP (2008) Climate change and wildfire in California. Clim Change 87(Suppl):231–249

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943

Wilks DS (1990) Maximum likelihood estimation for the gamma distribution using data containing zeros. J Clim 3: 1495–1501

Wilks DS, Wilby RL (1999) The weather generation game: a review of stochastic weather models. Prog Phys Geogr 23: 329–357

Worrall F, Evans MG (2009) The carbon budget of peat soils. In: Bonn A, Allott T, Hubacek K, Stewart J (eds) Drivers of change in upland environments. Routledge, London, p 93–112

Worrall F, Burt TP, Adamson JK, Reed M, Warburton J, Armstrong A, Evans MG (2007) Predicting the future carbon budget of an upland peat catchment. Clim Change 85: 139–158

Yallop AR, Clutterbuck B, Thacker JI (2009) Burning issues: the history and ecology of managed fires in the uplands. In: Bonn A, Allott T, Hubacek K, Stewart J (eds) Drivers of change in upland environments. Routledge, London, p 171–185

Submitted: August 3, 2009; Accepted: August 17, 2010

Proofs received from author(s): October 22, 2010