



Moorland Wild Fires in the Peak District National Park, Technical Report 3

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

McMorrow, J., Ayles, J., Albertson, K., Cavan, G., Lindley, S., Handley, J., & Karooni, R. (2006). *Moorland Wild Fires in the Peak District National Park, Technical Report 3*. (Climate Change and the Visitor Economy (CCVE)). University of Manchester, Centre of Urban and Regional Ecology.
http://www.sed.manchester.ac.uk/geography/staff/documents/Moorland_Wildfires_Final_Report_Technical_Report_3.pdf

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.



**‘CLIMATE CHANGE AND
THE VISITOR ECONOMY’**

**Technical report 3:
Moorland Wild Fires in the Peak
District National Park**

January 2006

**CENTRE FOR URBAN & REGIONAL
ECOLOGY,**
School of Environment and Development,
Humanities Building – Bridgeford Street
University of Manchester,
Oxford Road, Manchester, M13 9PL

Tel: 0161 275 6938 Fax: 0161 275 6917
<http://www.art.man.ac.uk/PLANNING/cure>





*Smoke plume from Bleaklow and two other moorland fires, 18 April 2003.
(Image courtesy of Defra).*

Notes:

This report is the *Peak District Case Study Technical Report* carried out by the Centre for Urban & Regional Ecology, University of Manchester, as part of the DEFRA-funded 'Climate Change and the Visitor Economy' (CCVE) project. The overall project is managed by Sustainability Northwest, with additional funding provided by the North West Development Agency and the Environment Agency.

Authors:

Julia McMorrow School of Geography, University of Manchester
Jonathan Ayles PREST, University of Manchester
Dr Kevin Albertson Manchester Metropolitan University
Gina Cavan CURE, University of Manchester
Dr Sarah Lindley CURE, University of Manchester
Prof. John Handley CURE, University of Manchester
Richard Karooni School of Geography, University of Manchester

<i>Abstract</i>	5
1. Introduction.....	7
2. Research Context and Methodology.....	9
2.1 <i>Causes of wildfires</i>	9
2.2 <i>Environmental consequences of wildfires</i>	10
2.3 <i>Factors in the risk of wildfire outbreaks</i>	10
2.4 <i>Climate scenarios</i>	11
2.5 <i>Relationships between climate change, visitors and environmental capacity</i>	15
2.6 <i>Research Methodology</i>	20
3. Spatial modelling of fire risk.....	21
3.1 <i>Aims</i>	21
3.2 <i>Role of GIS</i>	21
3.3 <i>Conceptual model</i>	22
3.4 <i>Data sources</i>	23
3.5 <i>Stratifying the fire data base</i>	24
3.6 <i>Multi-criteria evaluation</i>	25
3.7 <i>Habitat layer</i>	29
3.8 <i>Aspect layer</i>	34
3.9 <i>Road layer</i>	35
3.10 <i>Pennine Way layer</i>	37
3.11 <i>Eroded path layer</i>	38
3.12 <i>Trampled Path Layer</i>	39
3.13 <i>Car park layer</i>	40
3.14 <i>Access Land layer</i>	42
3.15 <i>Open water layer</i>	43
3.16 <i>Weighted models</i>	43
3.17 <i>Sources of error recommendations and further work</i>	47
3.18 <i>Applying the model to managing fire risk</i>	49
3.19 <i>Conclusion</i>	50
4. Forecasting the Outbreak of Moorland Wildfires (Temporal Analysis).....	52
4.1 <i>Aims</i>	52
4.2 <i>The Seasonal nature of wildfires</i>	52
4.3 <i>Analysis of time-series properties</i>	54
4.4 <i>Modelling the probability of fires</i>	56
4.5 <i>Methodology and estimation</i>	59
4.6 <i>Forecasting outbreaks of fires</i>	59
4.7 <i>Simulating the effect of climate change</i>	65
4.8 <i>Further developments</i>	62
4.9 <i>Conclusions</i>	66
4.10 <i>Notes on Data Source</i>	67
5. Implications for management.....	68
5.1 <i>Climate change, fire risk and implications for management</i>	65
5.2 <i>Wildfire management</i>	70
5.3 <i>Policy recommendations</i>	74
5.4 <i>Acknowledgements</i>	77
6. References.....	78

Abstract

Warmer, drier summers brought by climate change increase the risk of frequent wildfires on the moorland of the Peak District National Park (PDNP) of northern England. Fires are costly to fight, damage the ecosystem, harm water catchments, cause erosion scars and disrupt transport. Fires release carbon dioxide to the atmosphere. Accurate forecasts of the timing of fires and high fire risk locations will aid the deployment of fire fighting resources.

Both spatial modelling (identifying *where* risk of fire is highest, based on past fires) and temporal analysis (predicting *when* that risk is likely to be highest, based on preceding weather) were applied in this analysis. Firstly, multi-criteria evaluation (MCE) was used to spatially model the risk of reported wildfires in the Dark Peak area (northern part of the PDNP), based on a 28-year record of fires from the PDNP rangers' fire log. Fire risk was investigated using habitat and aspect maps to represent vulnerability to ignition, and distance from access features as a proxy for the likelihood of ignition sources. This showed that bare peat, eroding moorland and bilberry bog were the habitats with the most reported fires. Moorland restoration measures to revegetate bare peat and raise water tables should, therefore, also serve to reduce fire risk. Heather communities had the fewest reported fires, which suggests that management of heather, including rotational burning, is successful in reducing vulnerability to wildfire. Risk of a fire occurring and being reported is increased around access routes, with most fires occurring within 300m of roads and eroded paths, 750m of trampled paths, and within 2km of the Pennine Way. Additionally, there were significantly more reported fires on Access Land, with implications for increased fire risk since the extension of access land under CroW, but also for increased reporting. Topographic aspect has a considerable influence on the fire risk, with fires fewest on east-facing slopes.

Secondly, a non-linear probit model is used to assess the chance of fires at different times of the year, days of the week and under various weather conditions. Analysis concludes that current and past rainfall damps fire risk, and the danger of fire increases with maximum daily temperature. Dry spells or recent fire activity also signal extra fire hazard. Certain days are fire prone, especially spring bank holidays, due to increased visitor numbers. Some months of the year are more risky, notably the April-May and July-August periods, reflecting the interplay between visitor numbers and the changing flammability of moorland vegetation. Flammability varies as seasonal plant phenology (the spring green wave) is superimposed upon summer soil moisture deficit. The model back-predicts earlier fires accurately. The number of fires is then forecast using future climate projections. Changes in climate variability and weather extremes generate most extra fire risk. Finally, a gradual rise in mean temperature was found to have only slight effect.

The combination of climate modelling, temporal and spatial analysis is a powerful tool for predicting and managing future fire risk. There is much potential to produce a decision-making tool able to identify areas and times of highest risk, and to model the potential impact of fire risk management strategies under climate change scenarios.

Keywords: climate change; wildfires; probit analysis; seasonality; risk assessment; backcast; tourism; time-series; plant phenology; national parks; multi-criteria evaluation; GIS; spatial modelling.

1. Introduction

The rural uplands are a key visitor attraction in England, with the Peak District National Park (PDNP) receiving up to 30 million visits each year. The Peak District extends into a number of regions and local authorities including; Derbyshire, Greater Manchester, NE Staffordshire, Cheshire and SW Yorkshire. Thus, this region is within easy reach of major urban areas. The North West and Greater Manchester in particular are key catchment areas for visitors, with one-sixth of visitors to the Peak Park coming from the Greater Manchester area (PDNPA, 2001; McMorro and Worman, 2002).

The PDNP was established in 1951 as Britain's first National Park. The purpose of National Park designations was primarily established to conserve and enhance the natural beauty, wildlife and cultural heritage of areas in the countryside, but also to promote opportunities for the enjoyment of natural areas.

The park has a long history of popularity for walkers, being the site of the Kinder Scout mass trespass in 1932. It also has the most popular section of the Pennine Way, running northwards from Edale for 275 miles to the Scottish border. More recently, access across the park has increased as a result of the Countryside Rights of Way Act (CRoW). Despite increasing protection, habitats and species loss has continued. Pressure from the high number of visitors to the Peak District has forced the implementation of visitor management and restoration schemes (PDNPA, 2001).

Upland landscapes and their plant communities are sensitive to both natural and man-made disturbances (Milne and Hartley, 2001), and the rural uplands have been highlighted as particularly vulnerable to climate change (Shackley *et al.*, 1998). Climate change bringing increased temperatures and changes in rainfall distribution is likely to have a significant impact on the Peak Park e.g. on habitats such as blanket bog; as well as on biodiversity and increases in wildfire outbreaks. It is the latter impact that we are most concerned with in this study.

Fires pose a significant and costly environmental threat to habitats and species, as well as social and economic costs terms of fire control and management (Trotter, 2003). Five thousand acres were accidentally burnt alone in Spring 2003 in the Peak District. One moor, around 3000 acres in size, was completely burnt out. Much of this was grouse moor, which had an estimated capital value before the fire of £2.31m, not including loss of revenue from sheep grazing and the considerable costs of fire fighting, and was almost worthless after the fires (Baynes and Bostock, 2003). Fire fighting resources are expensive and impacts on infrastructure are often considerable. Large fires may cause closure of major roads such as M62 and also rerouting of flights at Manchester airport for short periods at considerable costs. Thus, wildfires incur direct and indirect environmental, social and economic costs.

This paper is divided into four sections; firstly it outlines the research context and methodology; secondly, it summarises work on the relationship of fires to visitors - a spatial analysis looking at historic fire locations and their relationship to habitats, topographic aspect and access routes across the PDNP. Maps of fire regimes (fire frequency, severity, size, pattern etc.) are useful for planning, assessing risk, and evaluating ecological conditions. Mapped data provide understanding of how spatial

factors such as climate, topography and vegetation dynamics influence fire regimes. Fire regime refers to the 'nature of fires occurring over an extended period of time' (Brown, 1995). Fire regimes reflect the fuel environment, and influence the type and abundance of fuel, thereby affecting fire behaviour and fire effects through time (Morgan *et al.*, 2001). Thirdly, the paper investigates the relationship between weather and fires – a temporal analysis using a non-linear probit model to assess the chance of fires reported fires occurring at different times of the year, days of the week and under various weather conditions. It is possible that as the climate changes and fuels accumulate, severe fires may become more common (Morgan *et al.*, 2001). This is investigated by forecasting the number of fires using future climate change scenarios. Finally, the paper concludes with some implications for future management.

2. Research Context and Methodology

The Peak District National Park extends into the counties of Derbyshire, Cheshire and Staffordshire, Greater Manchester and SW Yorkshire. Land in the PDNP is mostly privately owned. Major landowners include the National Trust and water companies, such as United Utilities and Severn Trent Water. Thirty per cent of the park is designated as Sites of Special Scientific interest, by English Nature. In addition, the Park has National Nature Reserves (NNR) and two Environmentally Sensitive Areas (ESAs). The park is very popular with visitors, receiving around 30 million visitors each year (PDNPA, 2002).

Over the past 27 years there have been 353 moorland wildfires reported in the Peak District National Park rangers' fire log. Nearly one third of all fires took place during just four individual months: the very hot, dry summer of July and August 1976, and the dry spring of March and April 2003. Records are sketchy before 1976. In 1959, before our sample begins, the Derbyshire fire brigade alone received 700 reports of moorland fires between September 1st and 11th - an under-estimate of fires at the time as the Peak District is also covered by neighbouring fire authorities (Radley, 1965). A small change in the weather can alter the chance of a wild fire occurring from a rare event to a commonplace but severe nuisance.

2.1 Causes of wildfires

Moorland wildfires have a number of causes. The majority of fires are caused by humans; fires started accidentally or maliciously, or managed fires that get out of control. Accidental causes include cigarette burns and the lens-effect of glass litter. A small number of fires are also started by natural causes such as by lightning. All of these above causes are included in the definition of a wildfire, and it is these burns that are recorded in the rangers' fire log. Thus, wildfires do not include controlled managed fires within the prescribed burning period.

Fire is also a natural component of heathland ecosystems, and prescribed burning is used for habitat management for grouse. The burning season is limited by law to between 1st October and 15th April (Defra, 1996). Most controlled burning activity takes place in February and March when the ground is wet and the superficial vegetation is dry (CCVE 2005). These burning regimes usually occur on an 8-15 year cycle to create a network of habitats of different ages of heather, preferable to grazing by grouse (Bruce, 2002). Significantly, managed heather burning also reduces the risk of wildfire outbreaks by controlling fuel loading.

There is concern about a potential for increasing heather fuel loads in the future. This is likely to occur due to a reduction in grazing pressures caused by the rationalisation of upland farms and pressure from conservation interests to reduce wild deer populations. There has also been a reduction in staff available for heather burning operations due to economic pressures (Bruce, 2002).

2.2 Environmental consequences of wildfires

It should first be stressed that fire is a natural component of moorland ecosystems, and that managed fire is an integral part of their management. In this section, we are concerned with damage caused by uncontrolled fire.

Plant damage during fire is determined by a combination of temperature and duration. A slow-moving fire has greater environmental consequences, as it has a greater residency time and can pass heat down through the ground, burning the moss layer, impacting on the soil and killing roots and seeds (Davies, 2003).

Vegetation type influences the intensity and spread of fire, and, thus, its environmental effect. Vegetation with a high proportion of woody or grassy material has a higher combustibility, and will cause a high temperature fire. Fire in old stands of heather may cause particularly intense burns. Heather fuel loads peak in older stands, around 30 years old (Gimingham, 1972).

Intense fires may cause peat to ignite, causing major losses of soil organic matter and nutrients and exposing it to erosion (Shaw *et al.*, 1996). Fire-damaged peat is eroded and deposited in reservoirs where it discolours drinking water supplies and reduces water storage capacity. Heavy metals deposited from airborne industrial pollution in previous centuries are disturbed by burning and leach into water catchments from exposed peat. Peat covering much of the north and eastern parts of the PDNP is an important carbon store. Burning results in a loss of carbon to the atmosphere and itself contributes to climate change. The fire scars of exposed peat are also persistent (Mckay and Tallis, 1996; Anderson *et al.*, 1997).

2.3 Factors in the risk of wildfire outbreaks

There are two main factors in the risk of wildfire outbreaks: flammability, or vulnerability to ignition, and ignition sources.

Flammability is a function of weather conditions and fuel loading, which are in turn related to habitat type and moorland management. The weather conditions at the time of a fire are important in determining its effects, particularly wind speed and direction (Shaw *et al.*, 1996). As discussed, older heather stands are very woody and have a high amount of woody matter, therefore they are more vulnerable to fire, as they have an increased fuel loading (Figure 2.1). Vulnerability therefore depends on the level of management. Wetter habitats such as *Juncus*-dominated marshy grass are less likely to be the site of wildfire outbreaks. Additionally, heather and grasses are considered to be potentially flammable ‘one-hour fuels’, as they have a very short drying time due to their small particle sizes (Bruce, 2002).

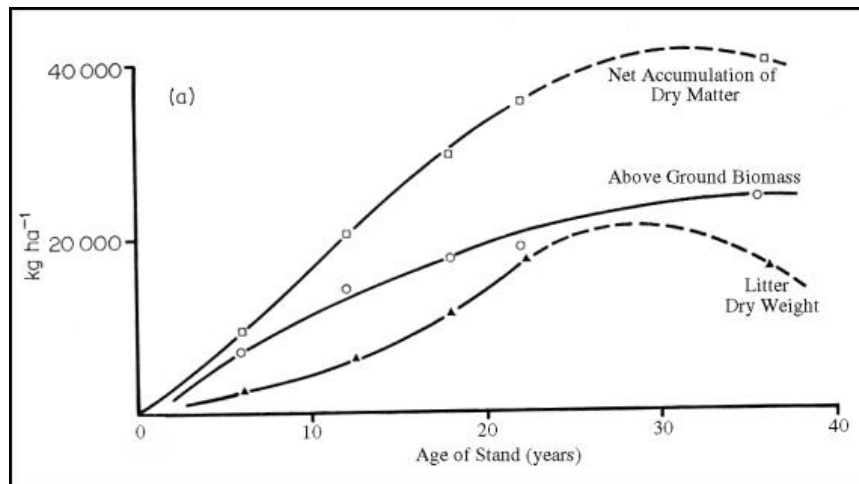


Figure 2.1: Fuel load of heather over time (net dry matter)
 Source: Gimingham (1972) cited in Bruce (2002:4).

Ignition sources are a function of accessibility and attractiveness of habitat to visitors. Of the area of moorland burnt in England and Wales in 2003, an estimated 76% was directly or indirectly caused by the actions of members of the public, either on open access areas or near to roads and footpaths (Baynes and Bostock, 2003). Therefore, increases in access areas, and increasing popularity of rural areas is likely to result in an increase in fire risk.

2.4 Climate scenarios

The climate is changing, and there is now convincing evidence for a growing human influence on climate change (Hulme *et al.*, 2002). The pace of change is accelerating, with the 1990s being the warmest decade since records began, and 2001 to 2003 being three of the five hottest years on record, the other two being in the 1990s (Hulme *et al.*, 2002). The impacts are already being felt. The Energy White Paper (DTI, 2003) highlights some of the global changes linked to the rise in temperature, such as the thinning of polar ice sheets, global reduction in snow cover and more frequent and intense El Niño events during the last 20-30 years. Although climate change is a global phenomenon, scientific advances have made it possible to present a local perspective on the debate. The UK Climate Impacts Programme (UKCIP) has produced climate change scenarios for Northwest England, originating from models developed by the UK Met. Office Hadley Centre and the Tyndall Centre for Climate Change. These are based on different amounts of greenhouse gas emissions, which reflect different global futures.

The changes in climate for the PDNP under UKCIP 2002 scenarios are illustrated in Figures 2.2-2.5. Of the four UKCIP02 emissions scenarios, the high (H) and low (L) scenarios are chosen to reflect the uncertainties about future greenhouse gas emissions and to account for fullest range of change. Scenarios are included for the 2020s, 2050s and 2080s. There is little difference between 2020s high and low scenarios, as the emissions levels have largely been determined by emissions already in the system since the 1950s. Slow-down of Gulf Stream activity is accounted for in the models.

2.4.1 Temperature

It is likely that there will be minimal change in either annual or seasonal average temperature by the 2020s, even under the high emissions scenario. This is because the change in climate over the next 30 to 40 years has already been determined by historic emissions, and also due to the inertia in the climate system. Annual and seasonal change becomes much more evident by the 2050s. Figure 2.2 shows that the south and east of the area were the warmest in the 1961-1990 period, with the Dark Peak area over 2°C cooler. Under the high emissions scenario, summer maximum temperature is likely to increase by 3°C to 5.5°C over the whole of the Peak District by the 2080s, reaching an average daily maximum of approximately 20.5°C to 23°C.

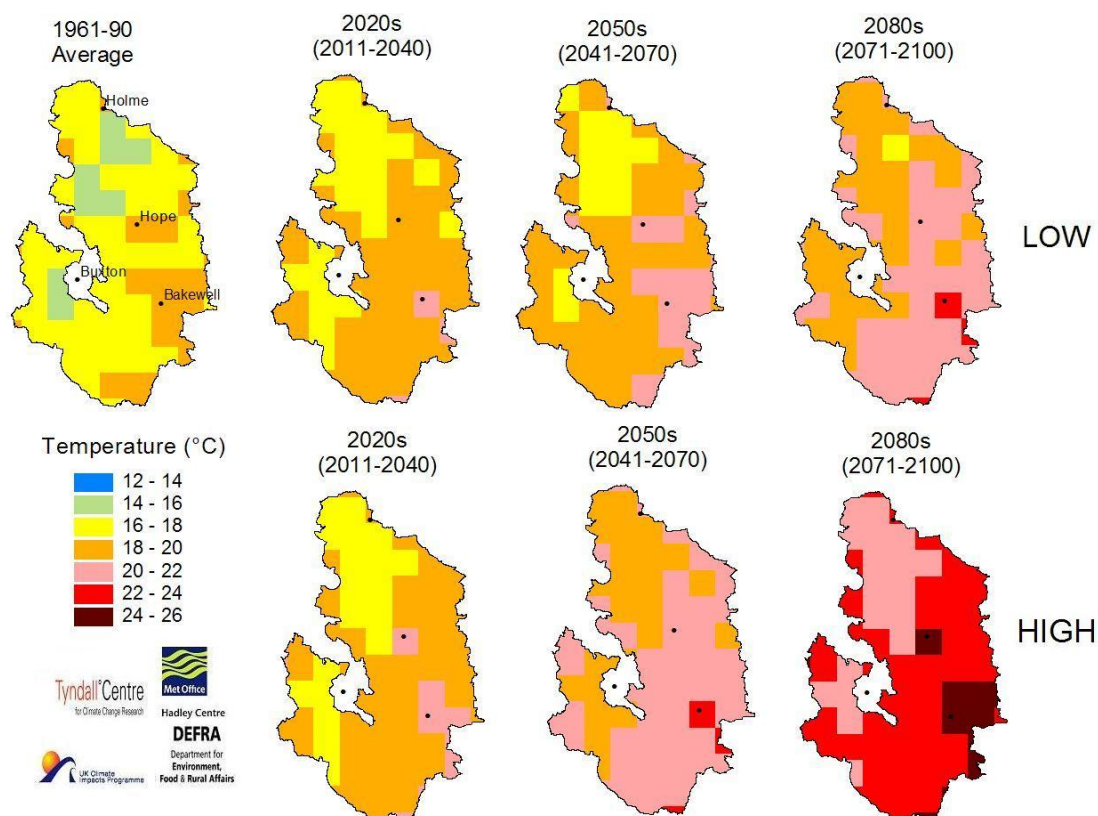


Figure 2.2: Climate scenarios for average summer maximum temperature

Figure 2.3 illustrates that winter temperatures are also likely to increase. The 1961-90 average winter minimum temperature in the Peak District was 0°C. By the 2050s, the whole of the Peak Park will have average winter minimum temperatures above freezing; and by the 2080s, warming is likely to be between 1.8 °C to 3.3°C.

Warmer winters and summers are likely to lead to a significant lengthening of the thermal growing season for plants. The Peak District will experience an increase of between 40 and 80 days per year in the growing season, depending on the scenario. This does, however, not account for water availability or day-length (Hulme *et al.*, 2002).

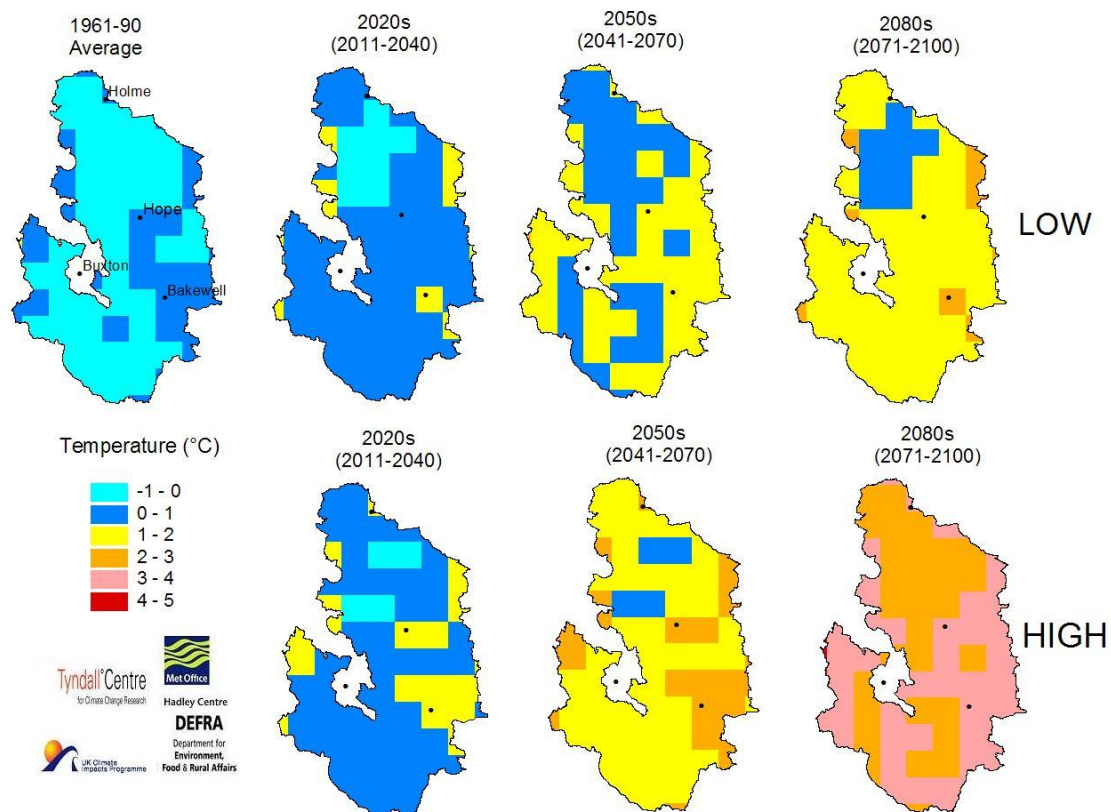


Figure 2.3: Climate scenarios for average winter minimum temperature

2.4.2 Rainfall

The climate scenarios show little change (or a slight decrease) in the annual average precipitation, but this masks a significant change in the seasonality and spatial distribution of future rainfall. Rainfall patterns in the PDNP follow relief, with the high Dark Peak area receiving the most rainfall in summer and winter, around 400mm. Figure 2.4 shows that by the 2020s, average summer precipitation is likely to decrease by about 10%, and by the 2080s, a decrease of between 23-45% is expected in the Peak District. These changes in rainfall will have significant consequences for many habitats such as blanket bog, which requires a high number of rain days and total rainfall.

In contrast, winter precipitation is expected to increase, with a 12%-23% increase likely by the 2080s, depending on the emissions scenario (Figure 2.5). Thus, there will be a greater contrast in the seasonal distribution of rainfall. Additionally, there will be increased probability of intense rainfall events in winter, and reduced probability of such intense events in summer (Hulme *et al.*, 2002).

Although most rainfall occurs in the Dark Peak area, most fires occur at the top of hills, where there is little storage of water.

The Peak District will experience significant reductions in snowfall, with a likely reduction between 50 and 90% by the 2080s.

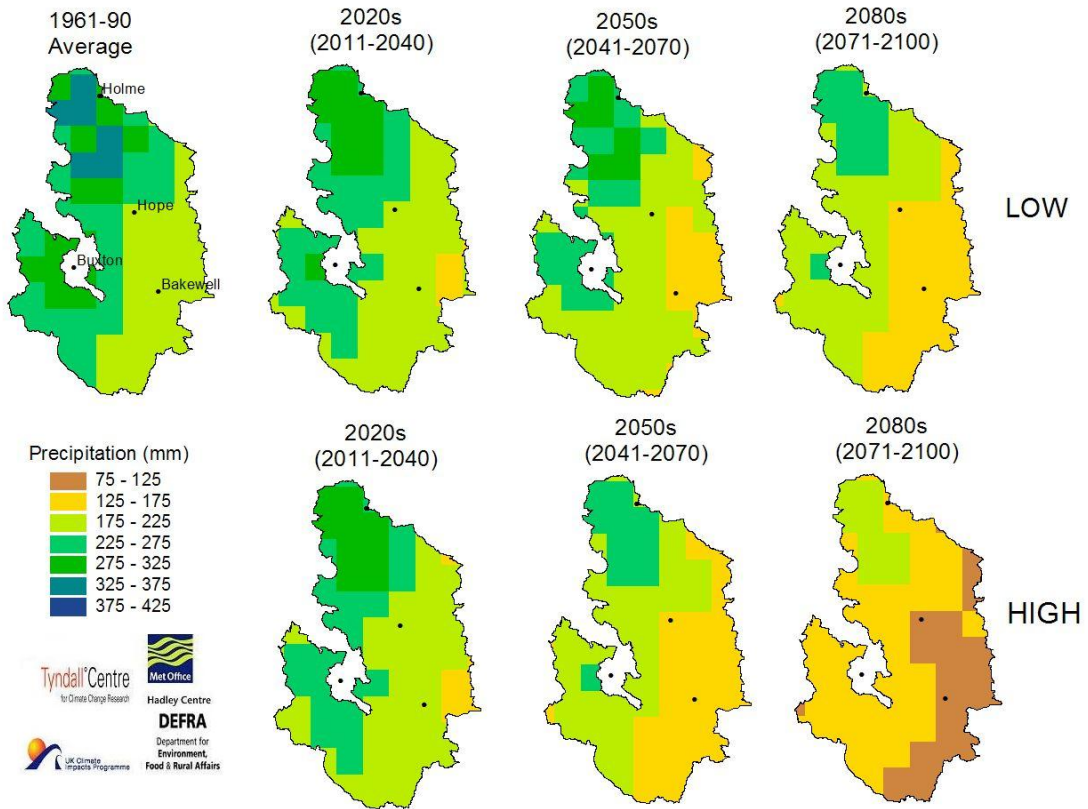


Figure 2.4: Climate scenarios for average summer precipitation

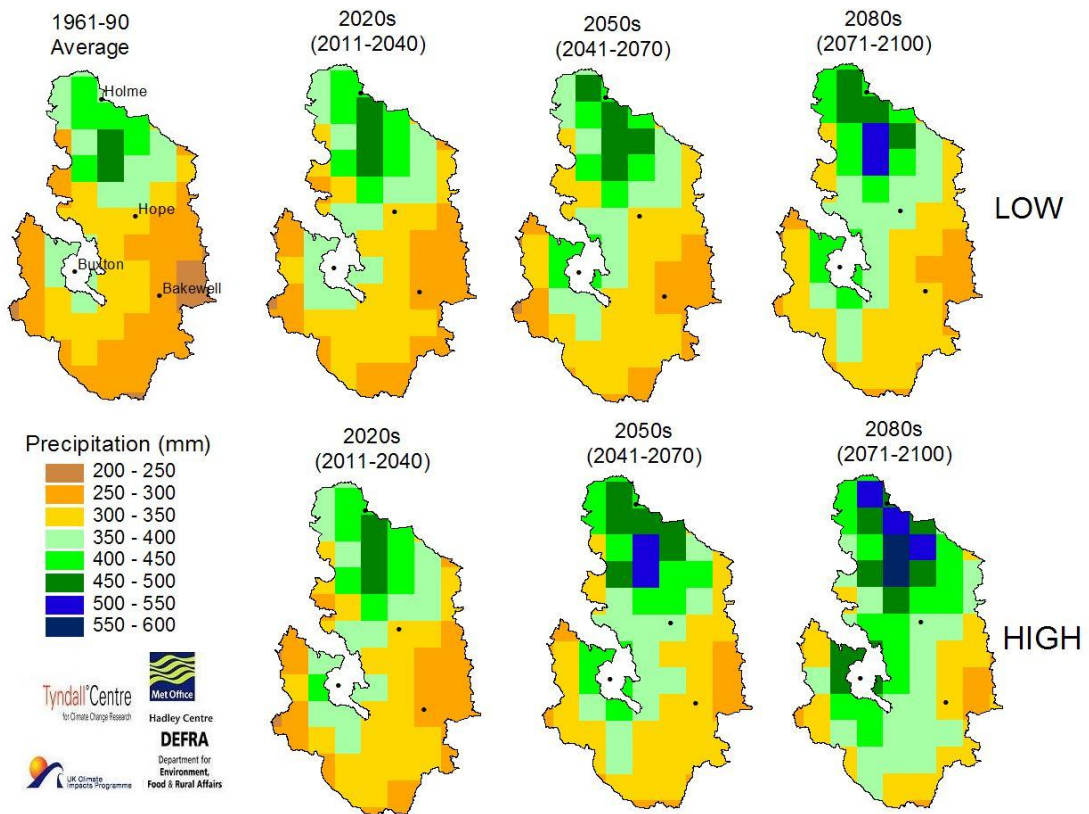


Figure 2.5: Climate scenarios for average winter precipitation

2.5 Relationships between climate change, visitors and environmental capacity

The relationships between the key issues that are of interest in this project are shown in Figure 2.6. These are discussed in further detail in the following sections with specific focus on moorland wildfires in the Peak District National Park.

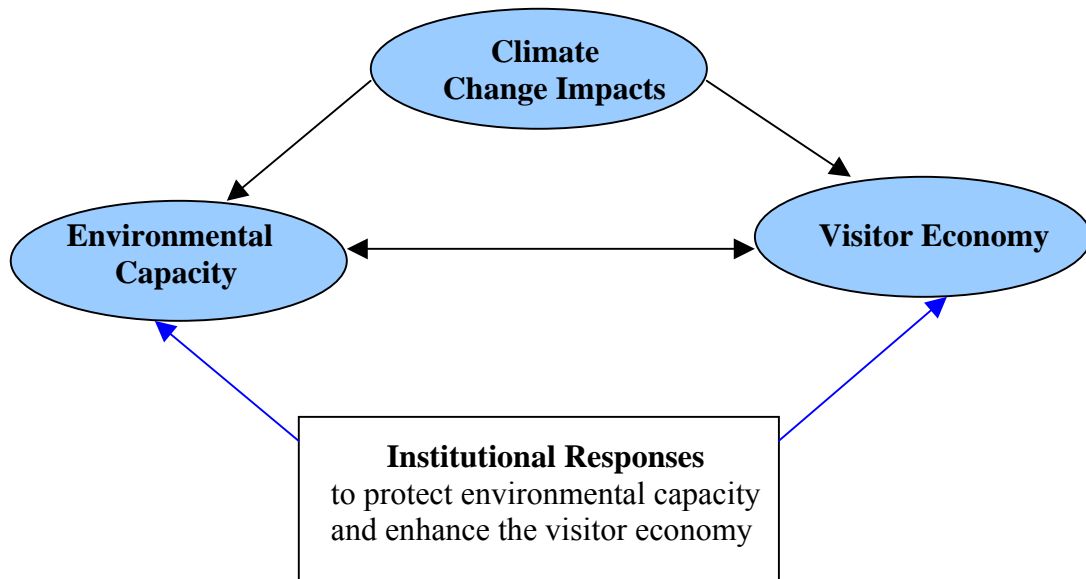


Figure 2.6: Relationships between key issues of importance in the project

2.5.1 Climate - Environmental capacity

Few attempts have been made to assess systematically the effect of weather, soil and plant conditions upon the prevalence of wildfires in the UK. Research has cited a relationship between the incidence of wildfires and the preceding weather conditions (e.g. Anderson, 1986; Palutikof, 1997; Bruce, 2002), since prolonged dry weather makes vegetation more flammable. A study of Peak District fires by Anderson (1986) concludes that the recent months' rainfall deficit relative to that which might have been expected for the time of year is a good predictor of wildfires. Bruce (2002) notes that the trend in the number and size of fires is related largely to the weather, both in spring, the main prescribed burning season, and in the summer. He notes that large heather fires can happen in any year because of the short drying time of this 'one-hour' fuel. Palutikof (1997) finds a positive relationship between the number of fires and temperature, and a negative relationship between fires and rainfall between 1984-1995 in England and Wales. In particular, a strong relationship was found in the increase of secondary fires, occurring mainly in grass and heathland in the hot, dry summer of 1995.

Wildfires reduce the environmental capacity of vegetation, since existing fire scars are more likely to dry out again, increasing the chance of recurrent burning. Climate change is not only likely to increase hot and dry conditions favourable to the incidence of fires, but also threatens to increase the length of the fire season. This has

been researched by modelling forest fires, where a doubling of carbon dioxide levels in the atmosphere was found to significantly lengthen the fire season (Wotton *et al.*, 1993). The fire season may shift into the autumn, as soil moisture will take a longer time to restore after increasingly hot and dry summers.

Complex feedback relationships exist between climate, vegetation and fire (Figure 2.7). Vegetation distribution is strongly influenced by climate, which also determines the composition and structure of vegetation, occurring both along altitudinal and latitudinal gradients (Ryan, 1991). Changes in the structure and composition of plant communities, driven by changes in climate, will affect fire risk by altering the physical properties and availability of fuels (Ryan, 1991). Changes in fire regimes will not only modify vegetation by encouraging fire-tolerant species, but also directly affect the atmosphere by emitting gases and particulate matter.

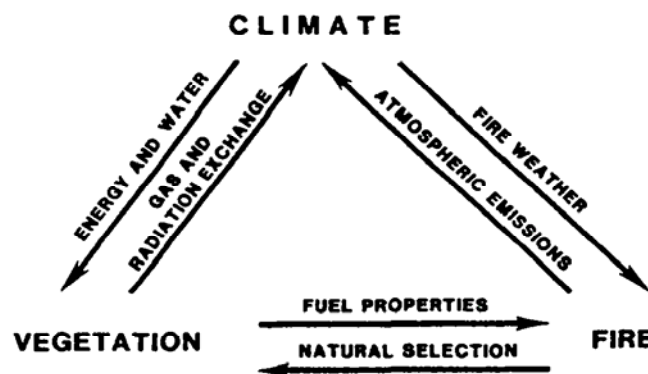


Figure 2.7: Climate, vegetation and fire interactions
Source: Ryan (1991: 170).

Bardgett *et al.* (1995) suggest that although the current extent of moorland and heather in England and Wales is not sensitive to the predicted mean increases in temperature (up to about 3°C), there may be changes in its distribution. However, when looking at individual vegetation types, blanket bog was found to be particularly sensitive, and shows a strong negative linear relationship with temperature. Increases in mean temperature around 3°C may result in a reduction of 25% in its current extent. Loss of blanket bog could result from increased evapotranspiration from waterlogged peat soils, resulting in reduced soil moisture and aeration. Together with an increase in oxidation of peat soils (enhancing decomposition of organic matter providing nutrients for plant growth), this is likely to result in a change in vegetation type to dry heath and acid grassland. These possible changes in vegetation are likely to increase fire risk.

Plants adapt to environmental conditions, and therefore the potential effect of climate change on wildfire risk is not straightforward. The vulnerability of the Peak District to wildfires alters seasonally with plant phenology. Increased winter precipitation means that plants and soil will be wetter in spring. As spring arrives, new green shoots supplant fire-prone dead plant tissue from the previous year. Higher maximum temperatures raise the risk of fire (and encourage more visitors) but at the same time, higher minimum temperatures advance plant growth. The precise date for the onset of spring varies with altitude. As plants progress through into summer, the amount of

fuel accumulated in woody biomass is correspondingly higher at a time when seasonal availability of water is reduced. Warmer, drier summers mean soil moisture will fall and evapotranspiration from vegetation will rise. Climate change may cause the timing of moorland wildfires to shift from a damper and more verdant spring to drought-stressed summer and early autumn.

2.5.2 Climate – Visitor Economy

The Peak District is recognised as the most visited area in the UK, with peak visitor usage occurring from late February through to Easter, and peaking in May. The majority of visits are day visits, and tend to be influenced by day-to-day weather conditions; nice weather on a particular day or a good weather forecast (CCVE, 2005). However, hot weather does not automatically result in an increase in visitors to the moors, and anecdotal evidence suggests that the summer of 2003 was so hot that people tended to visit the coast instead (CCVE, 2005). Since most wildfires are caused by human carelessness, more visitors will increase the risk of ignition. Wildfire outbreaks reported in the PDNP rangers' log frequently occur next to public paths (Figure 2.8).



*Figure 2.8: Local burn scar next to Pennine Way.
(Photograph © Jonathan Aylen)*

Warmer, drier summers and milder winters may encourage tourism and outdoor recreation, though the evidence is equivocal. Albertson, *et al.* (2005) find visits to a country leisure site are unaffected by temperature. Rainfall was found to have a small influence on the number of visits, and acted to postpone visits to the next dry day. Non-climate factors were found to have a greater influence on visitor numbers, such as school holidays and marketing. This suggests that climate change is likely to have a relatively small affect on visitor behaviour. In contrast, other research suggests that the UK tourism industry benefits from warm summers (Giles and Perry, 1998). Agnew (1997) estimates that 5% more domestic holidays and 30% more short breaks were taken in the hot summer of 1995.

Evidence from time-use studies suggests that visitor numbers will not increase considerably. Research has found increasing fragmentation and specialisation in leisure activities in the United Kingdom, as we become increasingly time-poor, having less time to spend on an ever-increasing range of leisure activities, and we therefore solve this by becoming increasingly specialised in our social activities (Southerton *et al.*, 2003). This suggests that there may be fewer walkers, and those who appreciate the countryside, but it is likely that those that do will devote more time to the activity. This is likely to have a positive effect on the PDNP. Since walkers and visitors will be devoted, they would hopefully be more open to education on wildfire risk and also would stay longer and spend more whilst on visits, so benefiting the local economy.

Climate change may affect behaviour in another way. It is likely that cities will become increasingly polluted and hot. The Peak District is extremely accessible, with over 20 million people living within one hour's drive to the National Park, evidenced by its high amount of day visitors. The countryside and wilderness areas are likely to become more popular (CURE, 2004).

2.5.3 Visitor Economy – Environmental Capacity

The level of recreational pressure is largely dependant on the nature of the physical and biological environment. Factors most important include the geology, soil type, slope, aspect, past management, species composition, and the weather conditions during recreational use. Additionally, impacts of visitors on environmental capacity are site and season-specific, and depend on the nature of usage (Defra, 1999).

Visitors impact on the environmental capacity through trampling. Trampling makes heather more vulnerable to desiccation, and physical damage can also occur, especially in older stands which have brittle stems that can easily be broken underfoot (Defra, 1999). Persistent trampling reduces both its height and cover. Bilberry is also very vulnerable to trampling pressure. Heavy trampling kills off vegetation on deep peats (PDNPA, 2001), exposing the surface to erosion and fires. Some species are more vulnerable to trampling than others. Anderson (1990) notes that low-growing grass swards are more resistant to trampling than mature dwarf shrub heath or blanket bog. Recovery rates also differ; for example, rates of recovery of heather are slower than for grassland swards (Harrison, 1981). With continued high levels of trampling pressure, some species will not recover, but will decline and be replaced by other more resistant species (Defra, 1999). Changes in species and vegetation caused by

trampling could have implications for fire risk by encouraging changes to more flammable habitats. This loop feeds back, since fires cause long-term damage to soils, vegetation and fauna, and further trampling reduces the capacity to recover after a fire.

Increased visitors will increase the damage caused by trampling, and, therefore, increase the fire risk. Higher levels of public access to moorland are also likely to decrease environmental capacity and increase the fire risk.

Visitors also impact on environmental capacity in other ways. Creation of new paths as a result of recreational pressure, and especially due to increased access, can result in a reduced perceptual capacity. This is especially the case in remote areas to which there was previously no public access, and the feeling of remoteness and peacefulness is likely to decline (Defra, 1999), thus affecting the visitor experience. Where new access leads to loss of vegetation cover and soil erosion, effects on landscape quality and visual effects are likely to be even more significant. Serious erosion often occurs on steep slopes, and can be visible from a wide area (Defra, 1999).

Presence of recreational users can also cause direct disturbance to birds and other fauna. The Peak District moorlands have many wildlife breeding sites, and there are sometimes conflicts with recreational users such as walkers and climbers. Sites such as Hen Clough and Stanage Edge are especially important breeding sites. Grouse are particularly sensitive to disturbance during the breeding season, especially by dogs. Hudson (2000) suggests that dogs should be under tighter control between April 15th and December 10th, and additionally, increased awareness of nesting sites and management procedures is required through the usage of signs at key access points. Impacts of dogs on nature conservation are the focus of much recent research, such as by the RSPB and English Nature (Telltale and Countryside Training Partnership, 2004).

Creation of new access areas may also result in new roadside parking, increasing the spread of damage caused by vehicle tracks in areas without formal car parking (Defra, 1999).



Figure 2.9: Exposed peat across Bleaklow.
(Photography © Jonathan Aylen).

2.6 Research Methodology

Climate scenarios for the Peak District National Park (illustrated in figures 2.2-2.6) were developed using the UKCIP02 climate scenarios. These were produced by interpolating the 50 km climate change scenarios generated by the UK Met Office Hadley Centre and Tyndall Centre for Climate Change models, with the 5km observed baseline climate data from the UK Met Office. They were mapped using an extension in ArcView Version 3.2.

A risk workshop on *Moorland Wildfires in the Peak District* was held at Sustainability North West on the 28th January 2005 (CCVE, 2005). This provided an opportunity for members of the research team to engage with interested experts and stakeholders to help scope out the key issues for the study, that is, those climate-related impacts of most concern to experts and stakeholders. The workshop structure followed the UK Climate Impacts Programme risk management framework, and included an interactive session to explore issues in depth. The workshop was considered extremely successful and has provided an excellent input into the research process for this case study. Continuing interaction with these stakeholders has aided the project.

Both spatial modelling and temporal analysis were applied in this study. Firstly, multi-criteria evaluation (MCE) was used to spatially model the risk of reported wildfires in the Dark Peak. Methodology for the spatial analysis is detailed in section 3 of this report. Secondly, a non-linear probit model was used to assess the chance of fires at different times of the year, days of the week and under various weather conditions. Methodology for the temporal analysis is outlined in section 4.

3. Spatial modelling of fire risk

3.1 Aims

The Met Office's Fire Severity Index has recently replaced MORECS as an automated 5 day *forecast* of active fire risk severity using weather forecasts and established relationships between weather and fire at a coarse 10 km grid square resolution (Met Office 2005, Opengov, 2005). In contrast, the work reported in this section for the Dark Peak area of the PDNP seeks to produce a *retrospective* assessment of wildfire risk, at a *fine scale*, based on GIS-based spatial modelling of the relationship of reported fires since 1976 to habitat, aspect and accessibility. It differs, therefore, in the currency of the data sources used and the spatial scale of the analysis. It extends the work begun by Anderson (1986) and Anderson *et al.* (1997).

The aims are:

- To devise a methodology to map reported wildfire risk for the Dark Peak area of the Peak District National Park, using the relationship between spatial variables and reported moorland wildfires since 1976.
- To suggest how the method could be refined and applied for managing fire risk and predicting fire risk under climate change scenarios.

3.2 The role of GIS

Wildfire risk can be modelled using Geographical Information Systems (GIS) (Chuvieco and Congalton, 1989; Chuvieco and Salas, 1996; Jaiswal *et al.*, 2002; Aguado *et al.*, 2003; Vakalis *et al.*, 2004). Often this uses a multi-criteria based approach using layers of spatial data to represent the criteria of interest (Figure 3.1). The resulting model can be used to guide the location of fire prevention measures and for 'what if' scenario modelling; for example, to take account of the impact of climate-related or other changes in habitat or accessibility on fire risk.

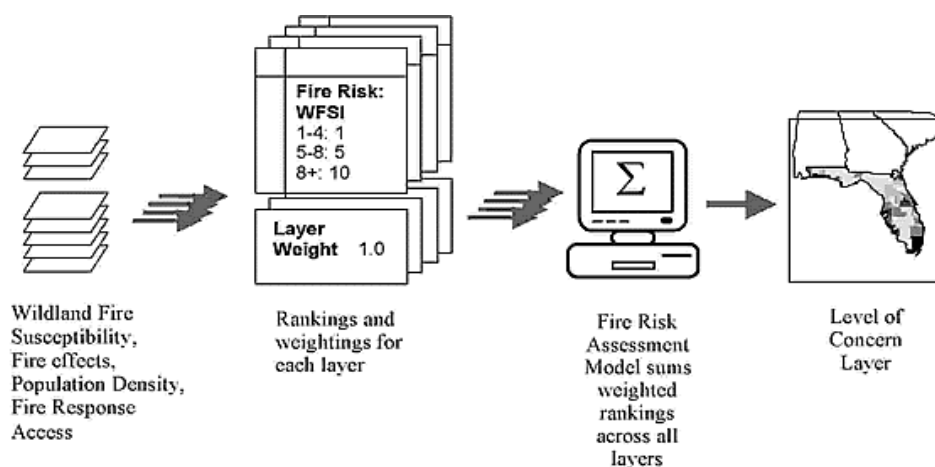


Figure 3.1: A GIS-based multi-criteria evaluation (MCE) approach to fire risk assessment for Florida (Brenner *et al.*, 2001)

One caution is the subjectivity of the modelling process. Any number of variants of fire risk maps (models) can be produced by modifying the factors used, their scoring or the relative weights of each layer. Models must be validated against an independent test set of data.

A second caution is that outputs are only as good as the data used. There will be errors arising from the size and accuracy of the fire database and the accuracy of map layers (their currency, scale, geometric accuracy, thematic accuracy, *etc.*). Errors will also occur where factors have been omitted, either due to a lack of appropriate spatial data or due to the effect of an unknown or poorly understood process. The limited metadata available (Table 3.1) means that a quantitative statement of error in the fire maps is not possible. However, it is possible to give a qualitative assessment of error for some layers which is useful for interpreting the final model results.

3.3 Conceptual model

There are many different ways that risk, and its constituent components, can be defined (Brookes, 2003).

The *hazard* with which we are concerned is moorland wildfire. A wildfire is a fire started accidentally or maliciously, or managed fires which get out of control.

Wildfire *risk* refers to the spatial likelihood of the fire hazard occurring. This risk results from habitat vulnerability and the presence of an ignition source (Figure 3.2). Habitat vulnerability arises from fuel loading (especially the presence of above ground brown biomass) and is a function of habitat type and soil moisture, management, topographic aspect and weather. The likelihood of ignition sources is increased by accessibility, itself a function of roads, paths, car parks and Access Land, and attractiveness to visitors. A change in any one of these factors will affect the fire risk. There are also many other non-spatial factors such as public fire awareness.

In this section, maps are produced showing the predicted spatial variation in wildfire risk. Strictly speaking, the maps produced show the predicted risk of *reported* wildfires, because they are based on fires recorded in the PDNP rangers' fire log. The feedback loop in Figure 3.2 acknowledges this potential spatial bias in reporting, in that increased accessibility increases the likelihood of reporting. However, it will also result in smaller, more quickly extinguished fires. Fires in less accessible locations may remain unreported for longer, but are likely to grow and eventually be reported. The relationship between fire size and distance from access points should be investigated in future work.

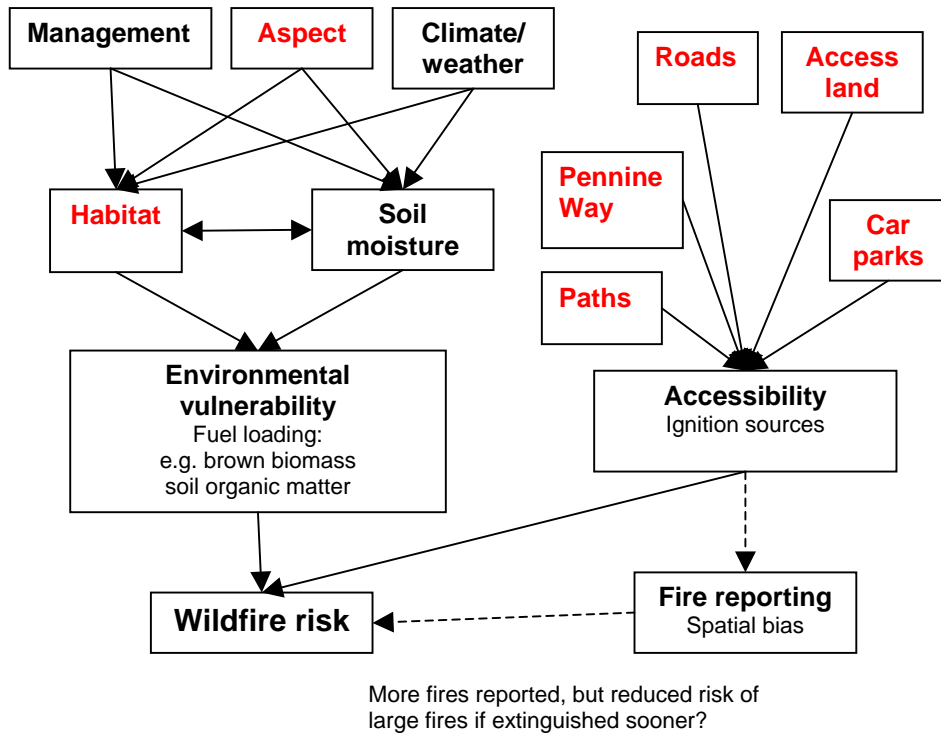


Figure 3.2: Conceptual model: spatial components of moorland wildfire risk. Modelled factors in red

3.4 Data sources

The data sources available and the processing undertaken in creating the geospatial database for the fire work are shown in Table 3.1. No spatially distributed data on climate or soil moisture were available. The fire database and all spatial data were clipped to match the North Peak ESA habitat map, thus, excluding all fires and spatial data not within the extent of the North Peak ESA.

	Spatial data	Metadata	Data source
1	Reported fires	Supplied as an Excel file compiled from paper records. Converted in-house into ArcGIS format, allowing display of fires as point data and associated (incomplete) database of fire date, size, cause, duration. Locations edited to six-figure eastings and northing format (centre of grid square used for locations reported as two-figure kilometre grid square). Fire points and database clipped to match extent to North Peak ESA habitat map.	Peak District rangers' fire log, via Moors for the Future (MFF)
2	Habitat map	North Peak ESA, 1991, polygon labels updated 1995 and 1998. Produced by interpretation of 1:10,000 aerial photography (type, scale and date unknown) with field checking.	GIS unit, Rural Development Service, Defra

		Supplied as ArcView files with database containing information on habitat codes at the three dates.	
3	Open water constraint	Open water class extracted from habitat map	As for habitat map
4	Aspect	Generated in-house from digital elevation model (DEM), compiled by Ordnance Survey from brown plate of 1:50,000 topographic mapping, with a grid cell size of 50m.	EDINA Digimap website
5	Roads	Extracted from Ordnance Survey Meridian 1:50,000 scale map tiles.	EDINA Digimap website
6 7 8	Paths: <ul style="list-style-type: none"> • Pennine Way • Eroded Paths • Trampled paths 	Waylines and Public Right of Way data. Waylines interpreted from aerial photos of 'section 3 moorland' and digitised at 1:1500 scale for MFF (MFF, 2005a). Supplied as 4 feature codes in polyline format unless otherwise specified: <i>(i) Eroded paths</i> ; paths with unvegetated surface but excluding gullies. <i>Pennine Way</i> extracted as separate layer and supplemented from Digimap for sections following gullies. <i>(ii) Vehicle tracks</i> ; double track paths. Not used. <i>(iii) Trampled paths</i> ; paths with vegetated surface. Used unchanged. <i>(iv) Sheep Tracks</i> ; many parallel vegetated tracks mapped as polygons and polylines. Not used.	Moors for the Future (MFF)
9	Access Land	Supplied in polygon format. Pre-2004 areas to relate to time period of fires.	MFF
10	Car parks	Locations of car parks digitized in-house	MFF

Table 3.1: Summary metadata¹ for spatial model of reported wildfire risk

3.5 Stratifying the fire data base

The rangers' fire database for the whole of the PDNP was edited to include only fires within the Dark Peak area. It was then randomly sampled into a training database containing 60% (138) of the Dark Peak fires, known here as the training set and used to develop the reported fire risk models. The other 40% (88) comprised the test database used to evaluate the models.

¹ Metadata is information on the data sources themselves, including date, type of sources used to compile the layers, mapping scale, geometric accuracy, thematic accuracy, etc.

3.6 Multi-criteria evaluation

Multi-criteria evaluation or modelling (Setiawan *et al.*, 2004) was used to construct the fire risk maps in four stages:

1. Identification of criteria affecting risk (factors and constraints)
2. Creating and scoring factor layers
3. Weighting and combining scores to produce a risk map
4. Testing the risk map

Each stage will be briefly outlined in this section. The following sections discuss the stages in greater depth. The final maps of risk of reported fires are entirely dependent on decisions made at each stage. All processing was carried out in ESRI ArcGIS.

3.6.1 Identification of criteria affecting risk: constraints and factors

Criteria can be constraints or factors. Constraints are criteria which totally limit risk, and are represented as ‘on-off layers’ (fire risk, no fire risk). They can be combined with other layers by multiplication, so that cells with value of zero cancel the effect of all other layers, setting the final fire risk value to zero. In site selection modelling, this is described as a ‘risk adverse strategy’, so called because it plays safe by letting a single criterion override all others to rule out certain locations (Evans *et al.*, 2004).

One *constraint* was used, Open water (grey in Figure 3.3), since fire risk should be zero over water bodies. Other criteria were treated as *factors*, that is, criteria which enhance or reduce fire risk (blue in Figure 3.3). Factors are combined by addition so that each contributes numerically to the final fire risk score, a process normally described as a ‘risk-taking’- strategy.

Two factors were used to represent *vulnerability*; habitat type and aspect. *Habitat* type influences vulnerability to ignition, or flammability (see section 2.5). The habitat map used was that produced by Defra for the North Peak Environmentally Sensitive Area (ESA). The ESA classes reflect the depth of peat and the dominant species, which vary with soil drainage. Therefore, habitat was used as proxy for differences in potential fuel loading and soil moisture. Fuel loading varies with natural factors such as the physiognomy² (appearance) and phenology³ of the vegetation, and with land use management practices.⁴

Aspect of the surface is a key influence on near-soil climate. In the northern hemisphere, south-facing slopes receive up to 6 times more insolation than north-facing slopes (Auslander *et al.*, 2003). The effect is more pronounced during winter. The imbalance of insolation produces drier conditions on south – facing slopes, thus these areas are likely to feature increased vulnerability to fire.

² Plant physiognomy may be thought of as the overall appearance of the plant community, such as the height, shape and woodiness of the vegetation canopy.

³ Plant phenology refers to changes associated with seasonal or longer term growth cycles

⁴ For instance, woody dwarf shrubs containing phenols (notably crowberry) are more flammable and tend to prefer better drained sites. Cotton grass bog, in comparison, contains like wet sites and relatively less flammable. Equally, grazing and rotational burning both reduce potentially flammable brown biomass

As explained in section 2, ignition sources are a function of attractiveness to visitors and accessibility. Arguably, attractiveness is captured to some extent by habitat type. Accessibility is a highly significant factor in fire hazard (Chuvieco & Salas, 1996; Jaiswal *et al*, 2001). Human activities such as rambling and camping are likely to result in the accidental deposition of burning material such as cigarette butts or lit matches or debris that can act as a lens to sunlight (CCVE, 2005). There is also the possibility of arson. Access routes such as roads and paths are therefore likely to increase fire risk, and the reporting of resulting fires, with a lowering of likelihood with distance away from the feature(s) of interest.

Five factors representing *accessibility* were considered: distance to roads; distance to the Pennine Way; distance to eroded paths; distance to trampled paths; and distance to car parks (Table 3.1). A further factor, representing the influence of Access Land, was included. This layer had two possible scores, 10 for cells within the Access Land boundary and a score of 1 for areas outside the Access Land boundary. Areas that were not Access Land retained fire risk values above zero in recognition that people do not necessarily restrict themselves to Access Land so that fires can and do occur here.

All the layers were scored using a 0-10 scale and the scores for each unique grid cell were summed to generate an aggregate score. The aggregate score was then multiplied with the Boolean Open Water layer to mask out areas not subject to fire. Calculations were performed within the Spatial Analyst *Raster Calculator*.

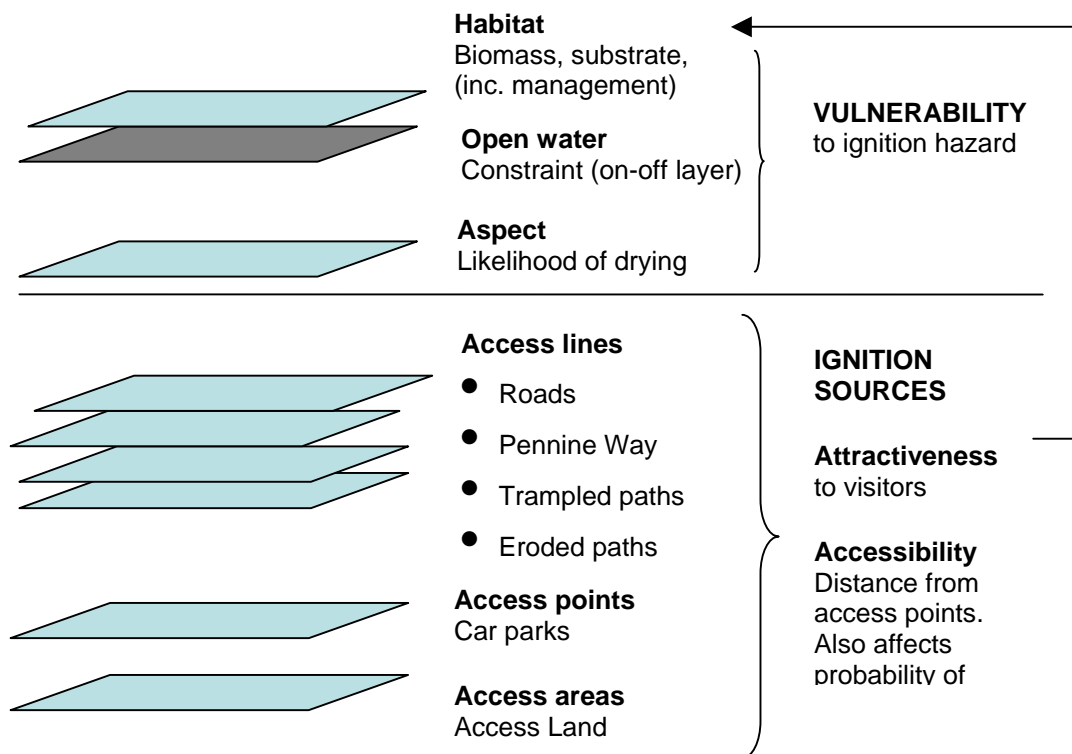


Figure 3.3: Criteria used to model risk of reported moorland wildfires. Open water treated as a constraint, all others as factors.

3.6.2 Creating and scoring factor layers

A raster grid was created for each of the factors using a cell size of 50m. Each grid layer shows the spatial variation in the influence of the factor on reported wildfire risk as a score from zero (lowest risk) to 10 (maximum risk). The procedure varies depending on whether the layer represented thematic or continuous data. Both will be outlined and discussed in greater detail in the appropriate section.

For all thematic layers, namely habitat and Access Land, the vector maps were rasterised to a spatial resolution of 50 m to match that of the DEM. This reduced the precision of some of the data layers, for example all paths are represented with a width of 50 metres. This issue was less important for other layers, such as Access Land. Aspect was produced as a 10-class thematic image. An area-weighted frequency anomaly method was used to assign the same score to all pixels in a given habitat class. Classes receiving the highest scores were those where more fires had been reported than would be expected from the percentage area covered by the habitat. A simpler frequency-based method was used for aspect. Further details of creating and scoring the habitat and aspect layers are given in sections 3.7 and 3.8, respectively, together with a discussion of the results.

Accessibility layers consist of continuous data. Proximity images showing the distance to access lines or points were constructed. The data were scaled to fall within the 0-10 range, essentially rescaling to a maximum of 11 classes. Two different methods of scoring were used: (i) *linear distance decay*, in which the proximity image was linearly divided into zones of equal distance; and (ii) an empirical *frequency-based* method, in which larger scores were assigned to zones with more fires within a critical zone identified by inspection of the histograms of fire frequency with distance from access feature. Outside the zone, the score was set uniformly to one. The method and results will be discussed in sections 3.9 to 3.14.

3.6.3 Weighting and combining factors

Several different models were developed using different combinations of layers and weights. The method is outlined here and the results are discussed in section 3.16.

First, the layers to be combined were selected, choosing from 13 layers (eight factors, five of which had two variants produced by linear and frequency-weighted scoring).

Second, weights were chosen for the selected layers. Weighting changes the relative importance of factors, with factors considered to be of greater significance being given higher weightings.

Third, the weighted layers were added to produce a fire risk image, where the value for each pixel was the sum of the scores in each layer.

Finally, the combined layers were multiplied by the open water constraint layer to set water bodies to zero risk (section 3.15). The multiplication could have been done separately on each layer (as seen in some of the Figures), but it is computationally more efficient to do this in one step at the end.

3.6.4 Testing the fire risk models

The choice of layers and their weights introduces subjectivity. Many different models can be generated and alternative models need to be tested against an independent test

set of fires, that is, the 40% of fires not used to construct the models. The method is outlined here using a worked example and results for the other models are presented and discussed in section 3.16. All tests were conducted using SPSS©.

If a model performed well, the histograms for final fire risk scores of training and test set fires would be as similar as possible (Figure 3.4a and b). If the two datasets have approximately normal distributions, the parametric *t*-test can be used to test if the means of training and test fire scores are significantly different. The magnitude of the *t* statistic and its significance could then be used to compare models. However, the distributions are negatively skewed towards high scores, so a non-parametric goodness of fit test such as the Kolmogorov-Smirnoff (K-S) is required. The K-S test measures the maximum difference between the cumulative frequency distributions (Figure 3.4c).

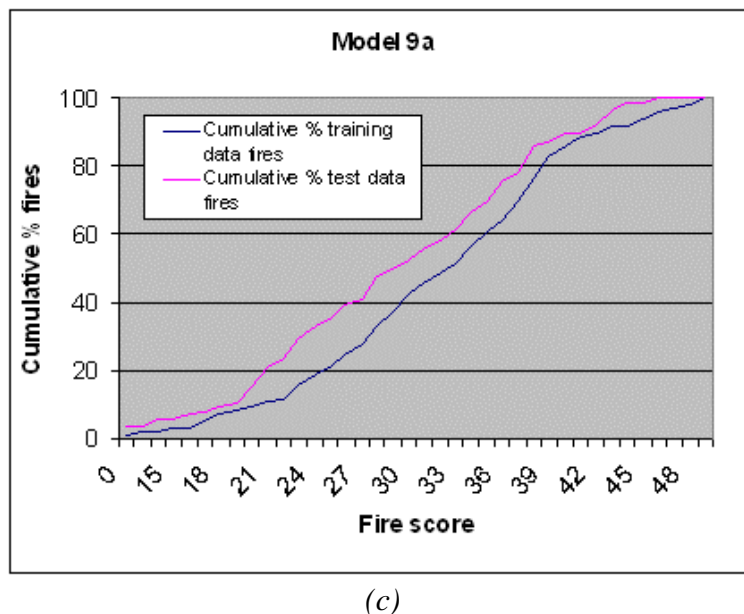
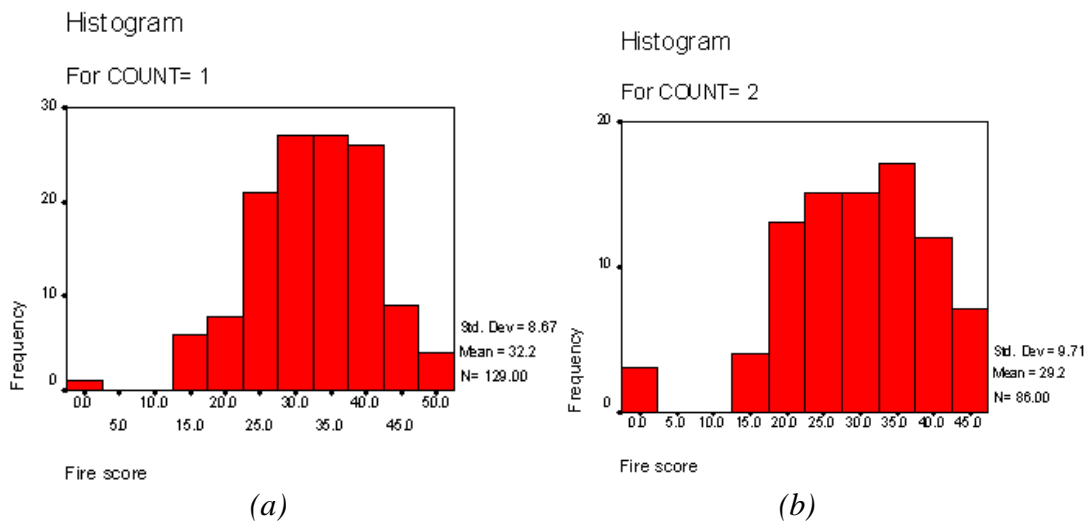


Figure 3.4 Distribution of aggregated fire scores for Model 9a: (a) training data fires; (b) test data fires; (c) cumulative frequency distribution of training and test data.

An example will be given for Model 9a. The null hypothesis, H_0 , is that the training and test data come from the same population, that is, that there is no significant difference between them at the 0.05 level. In this case, the Kolmogorov-Smirnov calculated Z statistic, 0.151, is greater than the critical value at the 0.189 level of significance, therefore, we can be 81.1% certain that the H_0 can be rejected and the training and test data have similar distributions. This model has, therefore, performed relatively well against the test data.

Further detail on the construction of each layer and a discussion of the findings now follows in sections 3.7 to 3.15.

3.7 Habitat layer

3.7.1 Method

Habitats were allocated a score for vulnerability to fire to represent their degree of flammability. Scores were devised by an empirical frequency-based method, using the expected minus the actual occurrence of reported fires in the fires in the training set, where expected fires were proportional to the area of each habitat. Habitat groups having more fires than expected, based on the areal extent of the habitat patch, were given higher scores. In view of the importance of this layer for determining overall fire risk, two versions of the habitat layer were constructed.

Method 1:

- The expected number of fires was calculated for each habitat according to the percent area occupied. Habitats covering half the area, would be expected to have half the training set of 138 fires.
- The habitat at each fire point was extracted for the 138 fires in the training set using the ArcGIS Spatial Analyst *Zonal Statistics* command. The number of actual fires was totalled for each habitat.
- The frequency of actual minus expected fires was calculated. Positive values indicate more fires than expected, suggesting more vulnerable habitats.
- Habitats were grouped into fewer classes according to the similarity in their observed-minus-expected frequencies, and using knowledge of the effect of plant physiology and habitat on fuel-loading. In retrospect, this step could have been omitted, since aggregation occurred in the final step.
- Values were re-scaled by adding 17 (the lowest value being -17) so that all values became positive.
- The largest value was assigned a score of ten to represent the most vulnerable habitat class, that is, the one with the lowest environmental capacity to resist fire.
- Other habitats were assigned scores pro-rata as a proportion of the largest. For instance, the largest score was 38 for bare and eroding peat. The next at 24 (bilberry bog), was given a score of 6.3 $[(24/38)*10]$, rounded to 6. Scores are shown in Table 3.2 and the habitat layer in Figure 3.6a.

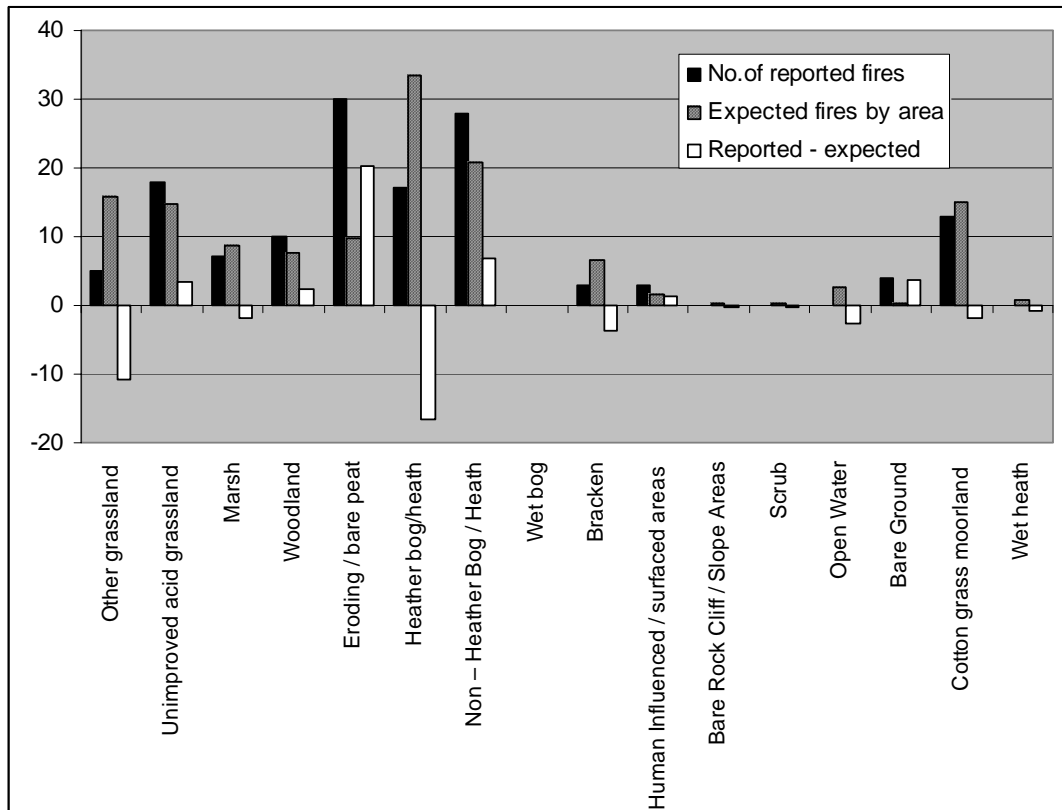


Figure 3.5: Frequency of training data fires reported, expected fires by area and reported fires minus expected fires. Method 1

	Habitat Class	Reported fires	% of training data fires	Expected fires by area	Anomaly: Reported–Expected fires	Scaled to positive (+ 17)	Method 1 score
1	Other grassland	5	4	16	-11	5	1
2	Unimproved acid grassland	18	13	15	3	19	5
3	Marsh	7	5	9	-2	14	4
4	Woodland	10	7	8	2	18	5
5	Eroding / bare peat	30	22	10	20	36	10
6	Heather bog/heath	17	12	33	-16	0	0
7	Non – Heather Bog / Heath	28	20	21	7	23	6
8	Wet bog	0	0	0	0	16	4
9	Bracken	3	2	7	-4	12	3
10	Human Influenced / surfaced areas	3	2	2	1	17	5
11	Bare Rock Cliff / Slope Areas	0	0	0	0	16	4
12	Scrub	0	0	0	0	16	4
13	Open Water	0	0	3	-3	13	4
14	Bare Ground	4	3	0	4	20	5
15	Cotton grass moorland	13	9	15	-2	14	4
16	Wet heath	0	0	1	-1	15	4

Table 3.2: Area-weighted frequency scores for the habitat layer, method 1.

Method 2 was introduced to prevent habitats such as wet heath with no reported fires receiving scores of three or four:

- Habitats with no reported training set fires were allocated scores of zero.
- Reported minus expected fires were calculated for habitats where fire had been reported, as described for method 1. The habitats were not grouped.
- The highest score of 10 was assigned to the habitat with the largest positive anomaly (+25, bare peat) and 1 to the one with the largest negative anomaly (-9, dry bog heather dominated). Other scores were assigned linearly between these extremes, so that an anomaly increment of 2.65 equated to a score increment of 1. Scores are shown in Table 3.3 and the resulting habitat layer in Figure 3.6b.

Habitat Class	Area (m ²)	% Cover	No. Fires	% Fires	Expected Fires by Area	Reported minus expected	Method 2 score
1 Bare Peat	11287087	2.05	19	13.77	3	16	10
2 Dry bog non - heather dominated	43473738	7.91	18	13.04	11	7	7
3 Eroding Moorland	23651575	4.30	11	7.97	6	5	7
4 Broad Leaved Plantation	3771909	0.69	5	3.62	1	4	6
5 Bare Ground	1266381	0.23	4	2.90	0	4	6
6 Unimproved acid grassland	58370498	10.62	18	13.04	15	3	6
7 Mixed plantation	2082475	0.38	2	1.45	1	1	5
8 Quarry	326918	0.06	1	0.72	0	1	5
9 Urban	6085709	1.11	2	1.45	2	0	5
10 Dry Dwarf shrub heath, non heather	38939400	7.08	10	7.25	10	0	5
11 Wet bog	35981	0.01	0	0.00	0	0	0
12 Mixed semi - natural woodland	57964	0.01	0	0.00	0	0	0
13 Cliff	217513	0.04	0	0.00	0	0	0
14 Amenity Grassland	430083	0.08	0	0.00	0	0	0
15 Scrub	587274	0.11	0	0.00	0	0	0
16 Scree	1012784	0.18	0	0.00	0	0	0
17 Arable / Short Term Lay Grassland	5001641	0.91	1	0.72	1	0	5
18 Semi - improved acid rough pasture	5074441	0.92	1	0.72	1	0	5
19 Semi - improved neutral rough pasture	2441127	0.44	0	0.00	1	-1	0
20 Juncus dominated marshy grass	2486614	0.45	0	0.00	1	-1	0
21 Wet Heath	2892183	0.53	0	0.00	1	-1	0
22 Broad Leaved Semi Natural Woodland	3541154	0.64	0	0.00	1	-1	0
23 Acid Flush	3641917	0.66	0	0.00	1	-1	0
24 Molinia dominated Grassland	32295868	5.87	7	5.07	8	-1	4
25 Improved grassland	10190431	1.85	1	0.72	3	-2	4
26 Semi - improved acid grassland	10462828	1.90	1	0.72	3	-2	4
27 Cotton Grass Moorland	59371898	10.80	13	9.42	15	-2	4
28 Coniferous Plantation	20830858	3.79	3	2.17	5	-2	4
29 Open Water	10365839	1.89	0	0.00	3	-3	0
30 Continuous Bracken	26645089	4.85	3	2.17	7	-4	3
31 Semi - improved neutral grassland	29584273	5.38	1	0.72	7	-6	2
32 Dry Dwarf shrub heath, heather	64502372	11.73	9	6.52	16	-7	2
33 Dry bog heather dominated	68868881	12.53	8	5.80	17	-9	1
Total	549794703	100.00	138	100.00	138	0	

Table 3.3: Modified area-weighted frequency scores for the habitat layer, method 2.

3.7.2 Results and discussion

In method 1 (Table 3.3), most reported fires in the training set occurred on the combined bare peat/eroding moorland class (22%), non-heather bog/heath (20%), and unimproved acid grassland (13%). Twelve percent of fires occurred on heather bog/heath, far fewer than would be expected by area. There were no reported fires on the wetter habitats, such as wet bog and wet heath.

Method 1 resulted in the highest scores being assigned to *bare peat/eroding moorland*. According to the Fire Brigade, completely bare peat rarely ignites (CCVE, 2005), but two explanations may be offered for its high vulnerability score. First, the presence of patches of exposed peat in a *mosaic* of up to 75% grasses and dwarf shrub patches (the definition of the ESA eroding moor class), may increase fire risk. The vegetation ignites and the fire can spread into the peat causing large and persistent fires. It would be instructive to investigate whether fires on peat/eroding moorland are larger and burn longer.

Second, there is the issue of *locational precision*, a limitation that applies equally to all classes, especially those habitats mapped as small polygons, and requires further investigation using a circular buffer (section 3.17.1). Some fires are only reported to the nearest kilometre grid square, so that the locational error can be +/- 500 m. Mineral soil tends to occur in small patches adjacent to thin peat on exposed summit locations like Bleaklow Head, where fires mapped on peat and eroding moorland are common (it is found where both peat and vegetation have been stripped away). In these circumstances, the fire could have been located in adjacent vegetation. A buffer analysis is recommended to investigate sensitivity to locational precision in reporting – results from the point analysis used here could be compared to those using the modal habitat in circular buffers of different sizes. Any trends in the degree of precision over the 28 year period of record should also be investigated; it would be expected that locational precision and accuracy has improved since GPS has become more widely available.

However, there is a third consideration; the fact that the dates of *fire and habitat mapping are not concurrent*. The habitat map was compiled in 1991 with updates to class labels in 1995 and 1998, although the polygons were not redrawn. This is a problem for pre-1991 fires. We cannot confirm that a fire falling on bare peat as mapped in 1991 was, in fact, bare peat at the time of an earlier fire. To resolve this, we would need to use aerial photography or other sources to interpret the habitat at the date of each fire on falling on a bare peat polygon. Some locations may have been vegetated at the time of the fire and it is simply that the last fire prior to habitat mapping in 1991 exposed the peat. Fortunately however, it is more likely that exposed peat scars created by old fires have persisted. For instance, the large Y-shaped area of bare peat on Sykes Moor has existed for over 35 years (Anderson, 1986) until it was reseeded in 2003. Where a deep burn has occurred once, thinner peat is left and gullyng is common which locally lowers the water table. Both favour a drier peat surface and regeneration of flammable species like bilberry and crowberry, as after the Bleaklow fire in April 2003.

It could be argued then, that exposed peat increases vulnerability to fire, causing fire scars to persist and fires to recur on these scars. However, to investigate if indeed 'fire begets more fire', a study of fire spatial persistence over time would be needed. One way to investigate the presence of this phenomenon in the study area would be to

use a time series of aerial photography close to dates of fires to map the recurrence of burn scars at fire prone locations such as Bleaklow Head. Another related issue is the degree to which the dataset exhibits spatial autocorrelation in patterns of fire occurrence, that is, the extent to which points close to each other have similar characteristics, which would mean that they could not be regarded as independent samples.

The second highest positive anomaly was for *bare ground* (mineral soil), with a score of 6. It is likely that this arises from imprecision in the location of fire reporting, as discussed above, since relatively small patches of mineral soil occur in close proximity to bilberry and bare peat. Open water has a score of 4 for the same reason, but was masked out as a constraint in the last stage of the analysis.

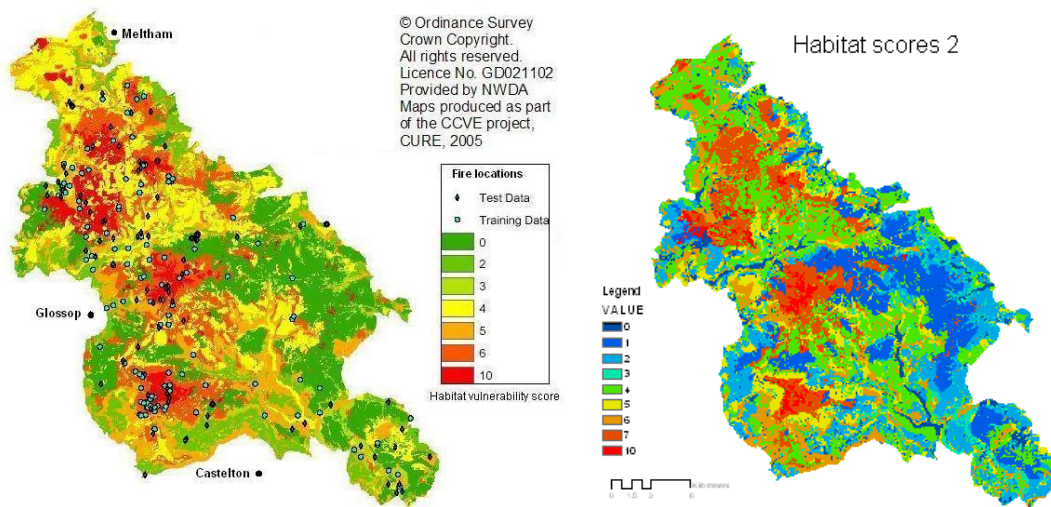


Figure 3.6: (a) Habitat layer, method 1, showing location of training and test set fires (b) Habitat layer method 2.

Heather dry bog and dwarf shrub heath had the largest negative anomaly, suggesting that management by controlled burning is successful controlling fuel loading. Patrolling by moorland managers and game keepers may also mean that any accidental fires are dealt with before they are reported.

Method 2 (Table 3.3) confirmed the importance of bare peat and eroding moorland as the most vulnerable classes to reported fires, and the two heather communities as the least vulnerable.

Stakeholder consultation could be explored as means of obtaining alternative scoring (Evans *et al.*, 2004; Carver *et al.*, 2002;). It would be interesting to see to what extent the perceived relative flammability of habitats varies between interest groups and how this affects the final risk map.

3.8 Aspect layer

3.8.1 Method

An aspect image was produced from the DEM, yielding a 10-class image (Figure 3.8a). Note that data have to be combined for the two north sub-classes (0-22.5 and 337.7-360). The aspect class at each fire point was extracted for the 138 fires in the training set using the Spatial Analyst *Zonal Statistics* function. The number of fires was totalled for each aspect class (Figure 3.7a). To allow for the relative areal coverage of each aspect, the area-weighted frequency method was used to score aspect classes, as for habitat (Figure 3.7b). All cells in the maximum, north-facing class were assigned a score of 10, and the other scores proportional to their area-weighted frequency. No fires were found on flat land, so were assigned a score of zero.

3.8.2 Results and discussion

The predominance of fires on north-facing slopes (17%) is unexpected, since they receive less insolation and normally have lower evapotranspiration rates. Southern facing slopes also had a higher than expected number of fires and received relatively high scores. Fewest fires were found to occur on east-facing slopes and flat land, which therefore received the lowest scores (Figure 3.7b).

The most likely explanation for the lack of fires on flat land is the low number of cells categorised as being flat. This is due to the 50 m cell resolution of the Ordnance Survey DEM and the nature of analysis functions used to produce the slope and aspect maps which allocates slopes of even a fraction of a degree to an aspect class. Indeed, a preliminary analysis showed that 15% of fires occurred on slopes of less than 2 degrees (corresponding to 9% of the land area), but unless they had zero slope, they would be allocated an aspect class. Further investigation of the reliability of the aspect layer could be carried out by analysing a finer scale DEM for a subset of the study area, comparing this to the results obtained using the coarser resolution data.

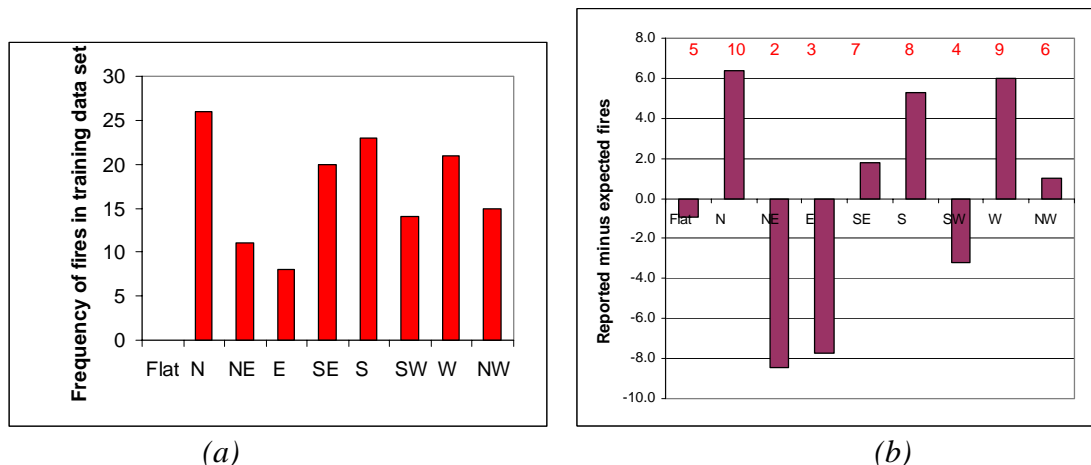


Figure 3.7: (a) Frequency of training set fires in aspect classes; (b) Observed minus expected fires in aspect classes, where expected fires are proportional to area of aspect classes. Scores shown in red on the top line.

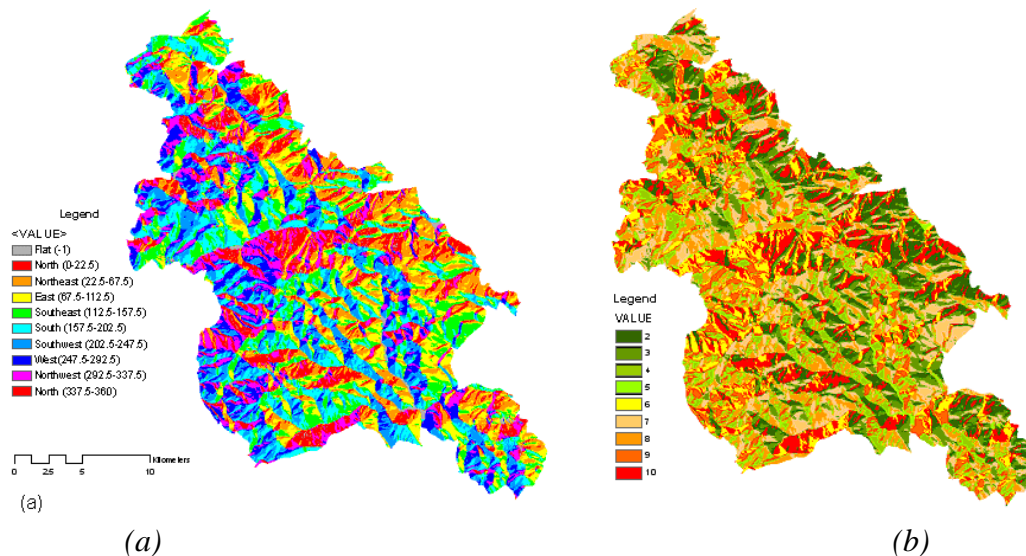


Figure 3.8: (a) Aspect image; (b) Aspect layer with scores proportional to frequency of training data fires, also showing roads, training and test set fires.

3.9 Road layer

3.9.1 Method

The relationship between roads and reported fire incidence was investigated by creating a raster layer showing distance decay from roads, referred to as a proximity grid, using the *Distance* function of the ArcGIS *Spatial Analyst*. Training data fires were plotted over each distance decay layer and the *Zonal Statistics* feature used to extract the distance of each fire from the nearest road. The frequencies of fire distance from access features were displayed as histograms using the SPSS statistical analysis program (Figure 3.9). These were used to determine a non-linear distance decay function to use as the basis for scoring the access feature layers.

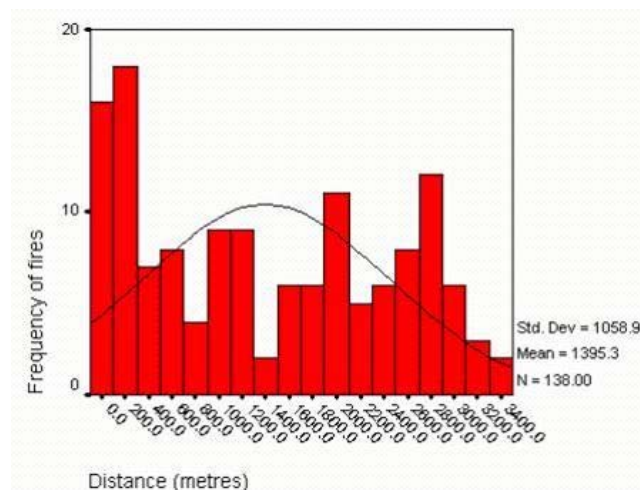


Figure 3.9: Histogram of frequency of fires with distance from roads

Two versions of the road layer were produced. The linear distance decay method divided the proximity image into equal classes, assuming a uniform reduction of influence with distance from each feature (Figure 3.10a). The frequency-weighted

method identified a zone of influence, in this case within 300m of the road, where fires were more frequent and where the number of visitors would be expected to be higher. The nearest class (0-100m), where fires were most frequent, was assigned the highest score of 10 and scores for the next two 100m classes as a proportion of this. A uniform score of 1 was assigned beyond the zone of influence (Figure 3.10b). This was used in preference to a score of zero to reflect the fact that fires still occur at distances beyond the main zone of influence estimated from the relevant frequency histogram.

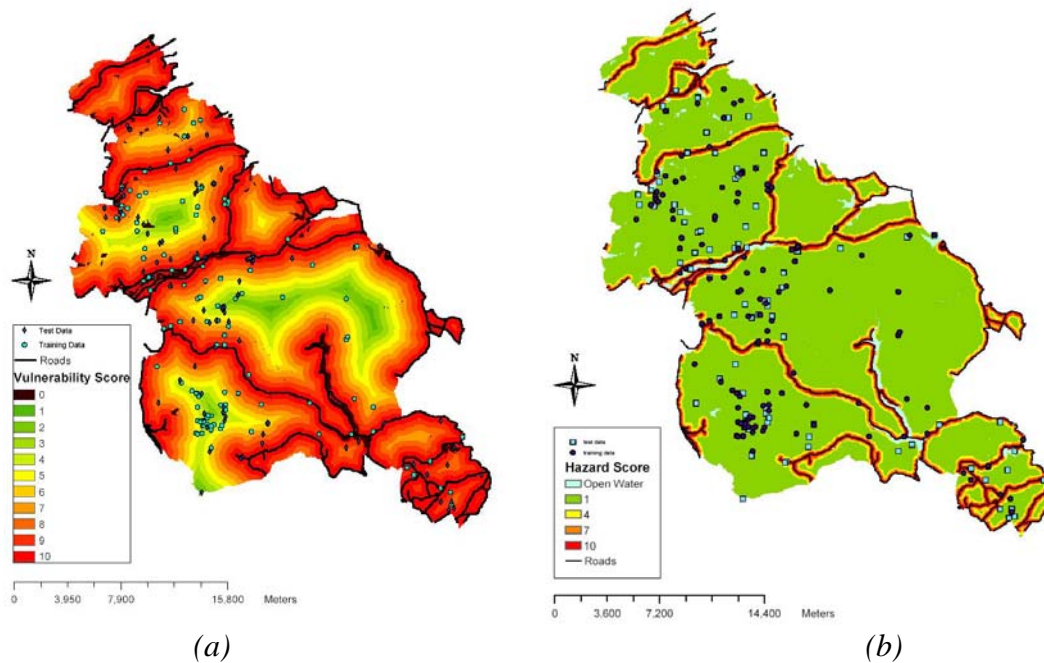


Figure 3.10: (a) Road layer produced by linear decay method of scoring. Location of training and test set fires shown; (b) Road layer produced by frequency-weighted decay method of scoring. Location of training and test set fires shown on both.

3.9.2 Results and discussion

Most fires occurred within 300m of the road, but fire frequency does not decay linearly with distance. We cannot exclude the effect of spatial bias, that is, that fires close to roads are sighted more easily so reporting incidence is likely to be higher. It may be even higher if Fire Brigade data were also included.

As for all histograms, class interval affects the detailed shape of the distribution and therefore the frequency-based scores. Broader classes, as used for the Pennine Way (Figure 3.11) would smooth the secondary peaks in fire frequency at 2000 and 2800m seen in Figure 3.9. These are likely to be due to the presence of other access features. This is a problem underlying all the accessibility layers. We cannot easily control for these other features to isolate the effect of the road. One alternative approach would be to produce an aggregate accessibility index layer to assess the areas which are relatively more accessible (and therefore likely to receive higher visitor numbers) compared to those which are relatively more remote (and therefore likely to receive lower visitor numbers). This could also include factors such as elevation and slope which may change the patterns of visitor usage along specific paths in the network. The narrow zone of influence with its steeper distance decay of score shown in Figure 3.10b is arguably more a realistic representation of car users as sources of ignition.

Visitor survey data, such as that collected by Moors for the Future, would be able to confirm the typical distance from the road walked by visitors travelling to the Dark Peak by car, and the zone of influence could then be refined accordingly.

3.10 Pennine Way layer

3.10.1 Method

A proximity image for the Pennine Way was constructed and distances of training data fires extracted and summed, as described for roads. The frequencies of fire with distance from the Pennine Way are shown in Figure 3.11.

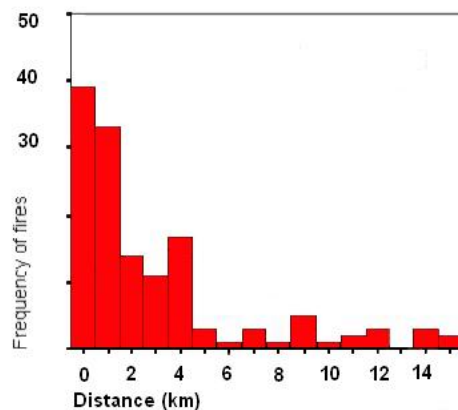
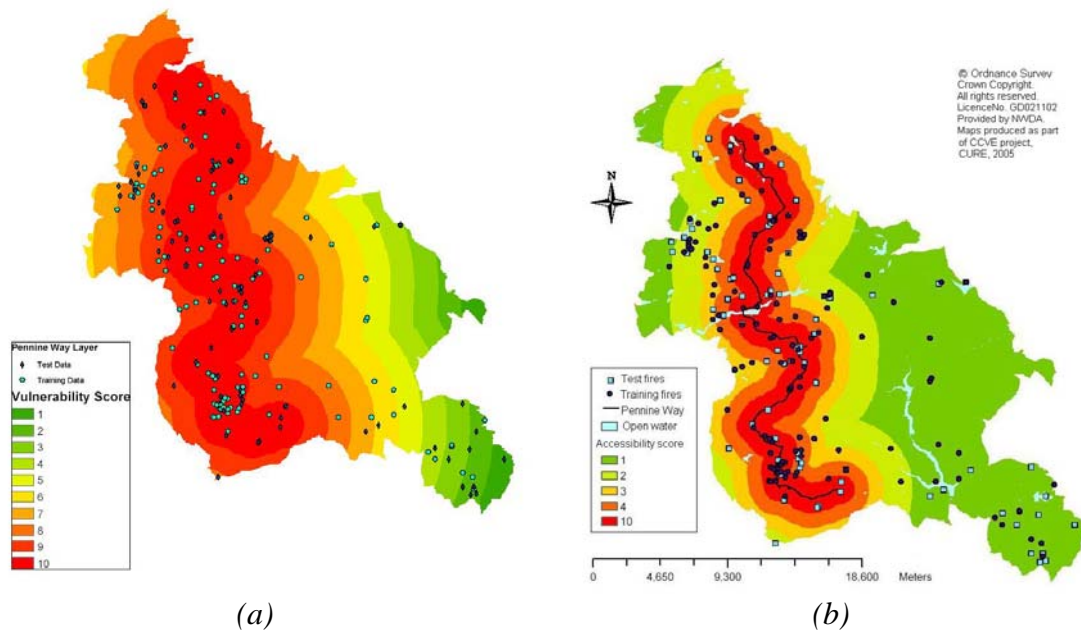


Figure 3.11: Histogram of frequency of fires with distance from Pennine Way

As for roads, two versions of the Pennine Way layer were produced. A linear distance decay layer with equal classes (Figure 3.12a) and frequency-weighted layer (Figure 3.12b). The maximum zone of influence identified from the histogram (Figure 3.11) was 5km. A uniform score of 1 was assigned beyond this.

3.10.2 Results and discussion

There is a strong distance decay effect away from the Pennine Way, with most fires found within 2km of the Pennine Way. As before, this concentration is not solely due to the Pennine Way, but to the combined effect of the Pennine Way and the network of other paths connecting to it. Once again, reporting bias exists in that heavy use means that not only are there more opportunities for ignition, there are also more people to report fires. However, the evidence does suggest that this 2km buffer around the Pennine Way is the critical zone for implementing fire prevention measures.



(a) (b)
 Figure 3.12: (a) Pennine Way layer, produced by linear decay method of scoring; (b) Pennine Way layer, produced by frequency-weighted method of scoring. Location of training and test set fires shown on both.

3.11 Eroded path layer

3.11.1 Method

Linear and frequency-weighted layers (Figure 3.14 a and b) were produced for eroded paths using the method described for roads and the Pennine Way. The zone of influence used for frequency weighting was 400m, as seen in the histogram (Figure 3.13).

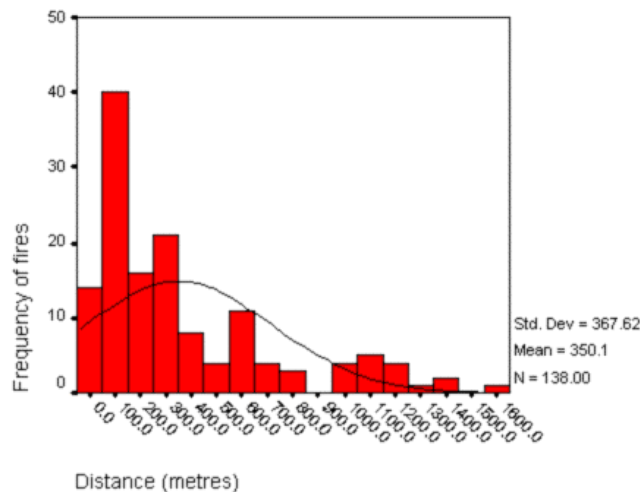


Figure 3.13: Histogram showing frequencies of fire at distances from eroded paths

3.11.2 Results and discussion

Relatively strong distance decay within a narrow 400m buffer zone is seen for eroded paths. There are no eroded paths mapped in the extreme north and the abrupt line suggests that mapping is incomplete here (Figures 3.14a and b), implying a relatively low confidence in the resultant fire risk maps for these areas (Figures 3.20a and b).

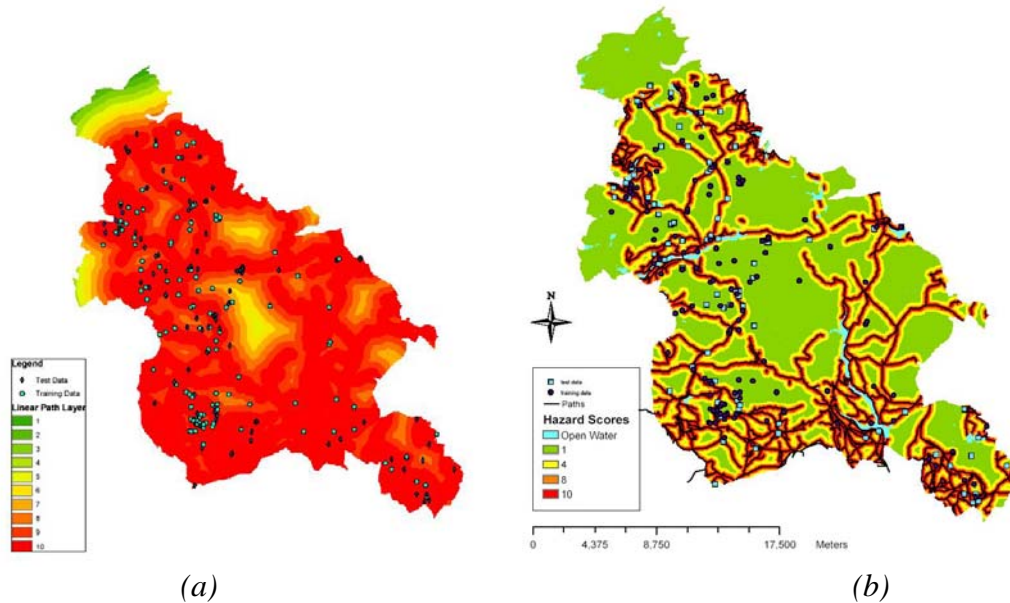


Figure 3.14: Eroded path layer: (a) linear scoring, showing the location of training and test set fires; (b) frequency-weighted scoring

3.12 Trampled Path Layer

3.12.1 Method

Linear and frequency-weighted layers (Figures 3.16a and b) were produced as described for roads and the Pennine Way. Frequency-based weighting was applied inside a 750 m zone of influence, as seen in the histogram (Figure 3.15).

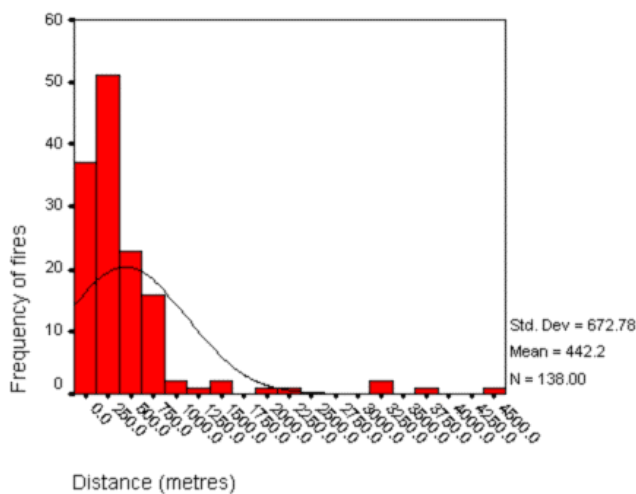


Figure 3.15: Path layer histogram showing frequency of fire at distances away from trampled paths

3.12.2 Results and discussion

There is strong distance decay, with most fires found within 750 m of trampled paths. The network of trampled paths is dense so that there is little variability in scores over a large area when the linear distance decay method of scoring is used. The lack of paths in the extreme north and south and the abrupt line, again, suggests that mapping is incomplete here (Figure 3.16b). This implies a relatively low confidence in the resultant fire risk map in relation to areas to the extreme north and south of the study area.

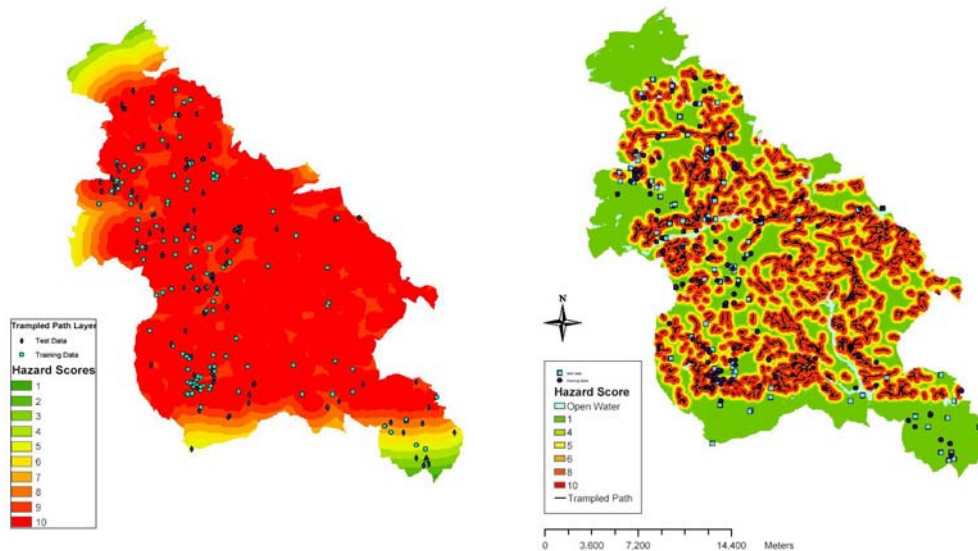
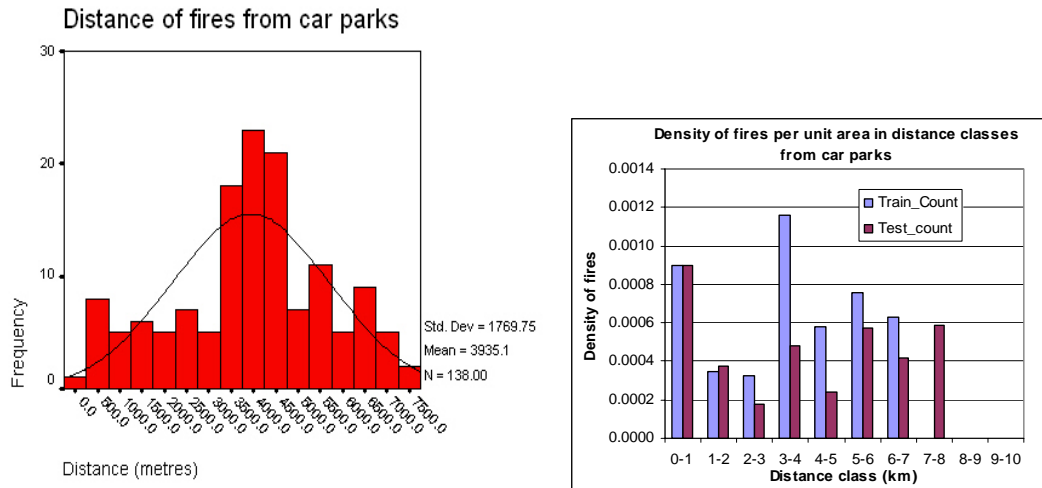


Figure 3.16: Trampled path layer produced by: (a) linear decay method of scoring; (b) frequency-weighted method of scoring. Location of training and test set fires shown on both.

3.13 Car park layer

3.13.1 Method

The proximity grid for car parks was produced as for other access feature layers. However, due to the lack of relationship of fire frequency to distance (Figure 3.17 a and b), only a single linearly scored layer was produced, with 1km zones of decreasing score (Figure 3.18).



3.17: (a) Histogram showing frequencies of training data fires with distance from car parks; (b) density of fires per unit area with distance from car parks for training and test fires.

3.13.2 Results and discussion

Most fires tend to occur in remoter areas away from car parks, except for car parks on main roads, such as those in Longdendale and the Upper Derwent valley. There was no real evidence of distance decay in the number of fires with distance from car parks. Instead, the histogram (Figure 3.17a) showed a normal distribution, with most fires occurring 3-4km from car parks. However, if we normalise for the relative area of the distance classes by plotting the density per unit area, a concentration is seen within 1km of the car parks. Finer class intervals may also produce a more pronounced concentration of reported fires close to car parks. Equally, it is possible that more fires occur close to car parks but are reported to the Fire Brigade and are not recorded in the PDNP rangers' fire log

The analysis conducted suggested that the presence of car parks did not contribute strongly to fire risk. For this reason, the car park layer was omitted from the models tested. The lack of an influence, which contradicts stakeholder expectations (CCVE, 2005), could be due to the data layer only representing relatively large, formal car parks. It is likely that parts of the study area are associated with informal parking arrangements (such as road or kerbside parking) or smaller, formal parking areas. To some extent, the road layer is expected to pick up part of this effect, but further work could be undertaken to assess the degree of informal parking behaviour and its contribution to fire risk.

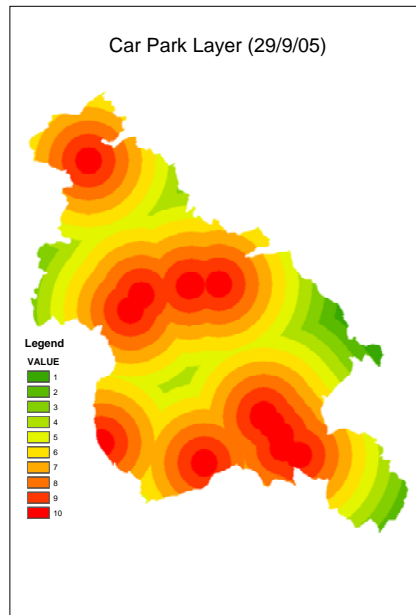


Figure 3.18: Car park layer, linear scoring.

3.14 Access Land layer

3.14.1 Method

A layer showing the 35% of land open to public access before the Countryside Rights of Way (CROW) Act 2000 came into force was created (Figure 3.19). Pre-CROW Access Land was appropriate because the act was implemented in September 2004, after the date of the last fire the rangers' fire log in May 2004. The premise is that more fires occurred in areas open to the public, or that, where fires were started away from access routes, they were more likely to occur on land open to the public. To reflect this, Access Land was given a value of 10, with other areas assigned a value of 1 (Figure 3.19). The number of fires on and off Access Land were extracted and used as the basis for scoring.

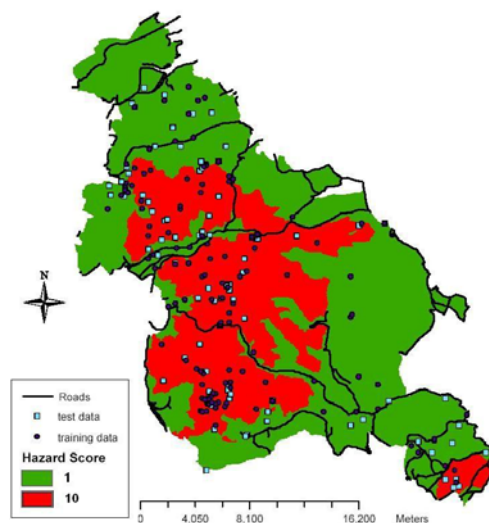


Figure 3.19: Access land layer, showing the location of training and test set fires.

3.14.2 Results and discussion

Fifty nine percent of the training data fires (81) occur on Access Land, even though it only comprises 35% of the area. This appears to support the connection between public access and ignition hazard, or public access and increased likelihood of reporting.

A chi-squared test was carried out to determine if the number of fires per unit area was significantly greater on Access Land than on non-Access Land (Table 3.4). The one-tailed null hypothesis was that the number of fires per unit area occurring on Access Land was not significantly greater than those not on Access Land. Since the calculated value of Chi-squared, is greater than the critical tabled value of 6.64 at the 0.01 level, the null hypothesis can be rejected; there is a significant difference in fires per unit area at the 99% significance level.

	Outside Access Land	Inside Access Land
Reported No. Fires	57	81
Expected No. fires weighted by area	89	49
Chi-squared (1 df)	32.4	[Prob. = 1E-08]

Table 3.4: χ^2 test for Number of fires on Access Land against those not on Access Land

3.15 Open water layer

Open water bodies are a constraint on fire – they should always have zero fire risk. A separate layer for open water was created from the habitat map. A value of zero was assigned to open water pixels as they can have no fire risk, with values of one everywhere else. All the fire risk models discussed below (section 3.16) were multiplied by this layer to produce the final aggregate scores.

3.16 Weighted models

3.16.1 Method

Layers were added to produce fire risk maps whose scores were aggregates of the input layers. There were eight layers, but 13 variants. Weights can also be varied. Many combinations are therefore possible (see for instance, Table 3.5). Only a sample is presented here.

A measure of the performance of models so far developed was obtained by visually comparing the training and test distribution of fire risk aggregate scores, both visually as histograms (*e.g.* Figure 3.4a and b) and by significance testing. The Kolmogorov-Smirnov test was used as most distributions were skewed or multi-modal (Table 3.6).

Model	Habitat		Aspect	Road		Pennine Way		Eroded paths		Other paths		Car park	Access Land	Max score
	Method 1	Method 2		Linear	Freq-wt	Linear	Freq-wt	Linear	Freq-wt	Linear	Freq-wt			
4a	x 4		x 1		x1		x1		x1		x1			90
4b		x 4	x 1		x1		x1		x1		x1			90
7a	x 4		x 2		x 1		x 1		x 1		x 1		x 1	110
7b		x 4	x 2		x 1		x 1		x 1		x 1		x 1	110
8a	x 4		x 1	x1		x1		x1		x1				90
8b		x 4	x 1	x1		x1		x1		x1				90
8c	x 4		x 1	x1		x1		x1		x1			x 1	100
8d		x 4	x 1	x1		x1		x1		x1			x 1	100
9a	x 1		x 1		x 1		x 1		x 1		x 1			60
9b		X 1	x 1		x 1		x 1		x 1		x 1			60
10a	x 1		x 1		x 1		x 1		x 1		x 1		x 1	70
10b		x 1	x 1		x 1		x 1		x 1		x 1		x 1	70

Table 3.5: Summary of model layers and weights

3.16.2 Results and discussion

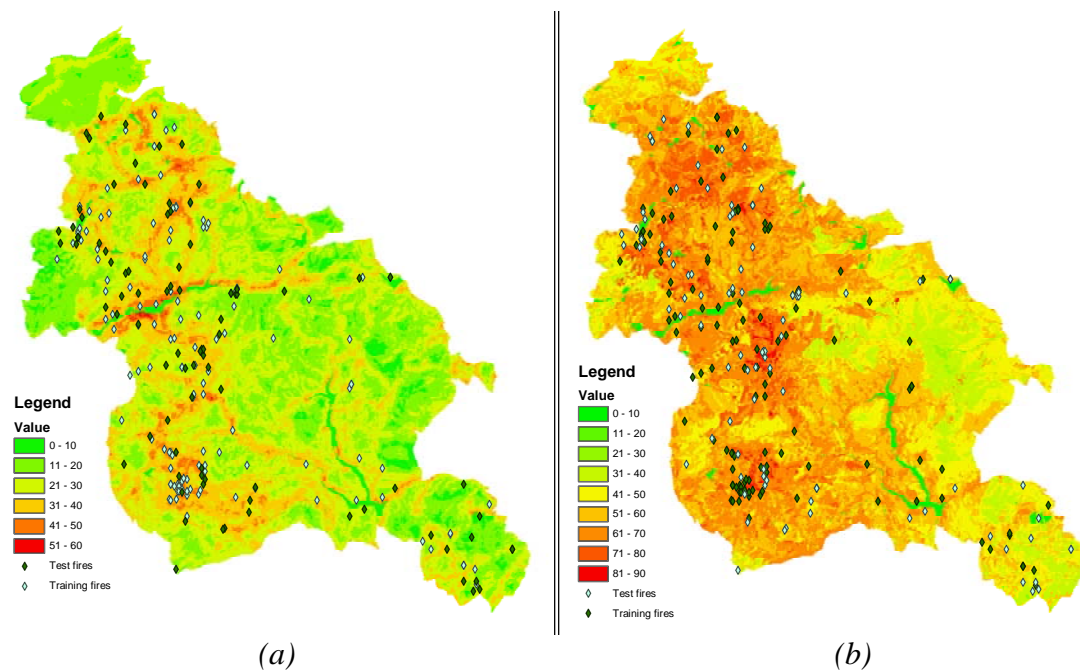


Figure 3.20: Examples of fire risk models with the location of training and test fires shown: (a) Model 9a = [habitat layer method 1 *1] + [aspect layer * 1] + [four access line layers produced by frequency-weighted distance decay, each *1] (excluding car parks and Access Land) x [open water layer]; (b) Model 8b = [habitat layer method 2 *4] + [four access line layers produced by linear distance decay, each *1] (excluding car parks and Access Land) x [open water layer].

Pattern of risk: Both models in Figure 3.20 show higher risk for the western moorlands near the Pennine Way and areas of eroded peat. The southeastern and

eastern moors around Hallam, Derwent, Broomhead and Thurlstone Moors have lower risk of reported fires. Statistical testing does not show *where* the anomalies occur. It would be instructive to examine if fires with low scores are spatially concentrated. Due to known problems with some of the input layers (Figures 3.14 and 3.16), it should be noted that scores are less reliable for the extreme north and south of the study area.

Comparison of Figures 3.20a and b show the extremes produced and demonstrates the dependence of the risk map on the layers used and their weights. Figure 3.20a is dominated by access factors; it has high risk concentrated around a relatively narrow sphere of influence around the access lines. In contrast, Figure 3.20b has expanded areas of high risk due a combination of the four fold weight given to habitat to balance the four access line layers, and the linear weighting used for the four access lines, which spreads the zone of influence away from roads and paths.

Range of fire scores: Table 3.6 shows that mean and median aggregated scores for test data were consistently lower than that for the training data. Models tested to date underestimate the number of fires with high risk scores; test data had fewer fires with high aggregated scores than the training data. There were usually no fires in the top 10 values, which suggests that scoring and weighting need further work.

Shape of the distributions: Distributions for the training and test aggregated fire scores were negatively skewed (Table 3.6); more fires had large aggregate risk scores than low ones, as would be expected. Skewed, non-normal distributions justify the use of the K-S test over the *t*-test.

Sensitivity to habitat scoring method: The effect of habitat scoring methods can be seen if a- and b-variants of models are compared. Models which used method 1 generally performed better than those using method 2. 'Better' here is taken to be a better match between training and test data, as indicated by a low Z value and high 2-tailed significance in the last two columns of table 3.6. For instance, model 4a is better than 4b, 7a better than 7b, 8a better than 8b, and 9a better than 9b. However, the opposite was true for model 8d relative to 8c, and 10b relative to 10a.

Sensitivity to habitat layer weighting: Models in which a weight of one was used for either of the habitat layers performed better than when the weighting was four (model 9a better than 4a, 9b better than 4b). This tentatively suggests that access factors are more important than habitat in fire risk.

Sensitivity to access layer weighting method: The effect of using the frequency-weighted method for access layers compared to linear distance decay was equivocal. Frequency weighted layers sometimes performed better (4a relative to 8a). However, the opposite was true for 8b relative to 4b.

Sensitivity to incorporating Access Land: Surprisingly, models which did not include Access Land generally performed better (model 8a relative to 8c, 8b to 8d, and 9a to 10a). However, the converse was true for model 10b relative to 9b.

Further work is required to test sensitivity to sources of error, particularly the choice of factors and their scoring and weighting, and to refine the method of testing (section 3.17). This would allow the model to be refined and a validated map suitable for operational use to be developed (section 3.18).

	Mean		Median		Skewness		Standard Deviation		Largest absolute difference	Positive differences	Negative differences	Kolmogorov-Smirnov Z	Asymp. 2-tailed significance
	Train-ing	Test	Train-ing	Train-ing	Test	Train-ing	Train-ing	Test					
Model 4a	48.75	43.45	49.00	44.50	-.341	-.472	15.66	16.49	<u>.159</u>	.000	-.159	1.142	.148
Model 4b	49.16	43.17	50.00	45.00	-.315	-.801	14.39	14.70	.217	.000	-.217	1.559	.015
Model 7a	62.02	55.15	61.00	57.50	-.310	-.662	18.13	18.97	.171	.000	-.171	1.225	.099
Model 7b	62.42	54.87	62.00	56.00	-.375	-.883	16.89	17.41	.190	.000	-.190	1.364	.048
Model 8a	63.66	58.80	64.00	61.00	-.846	-1.225	13.85	17.28	.163	.012	-.163	1.169	.130
Model 8b	64.06	58.52	66.00	61.00	-1.125	-1.895	12.34	15.32	.167	.000	-.167	1.197	.114
Model 8c	70.43	64.37	71.00	67.50	-.998	-1.256	14.33	18.79	.178	.016	-.178	1.281	.075
Model 8d	70.43	64.09	71.00	66.00	-.998	-1.761	14.33	16.99	.174	.004	-.174	1.253	.087
Model 9a	32.19	29.15	33.00	29.50	-.453	-.760	8.67	9.71	.151	.000	-.151	1.086	.189
Model 9b	32.29	29.08	33.00	29.00	-.401	0.797	8.53	9.56	.163	.000	-.163	1.169	.130
Model 10a	38.56	34.72	39.00	36.00	-.455	-.976	10.34	11.12	.167	.000	-.167	1.197	.114
Model 10b	38.66	34.65	39.00	35.50	-.460	-.996	10.15	10.98	<u>.159</u>	.000	-.159	1.142	.148

Table 3.6: Descriptive statistics and Kolmogorov-Smirnov test results for models listed in Table 3.5.

3.17 Sources of error; recommendations and further work

The sources of error are summarised under two headings; those from the input data and those arising from the MCE technique. Recommendations are made to address the issues raised. Summary recommendations are included in section 5.3.

3.17.1 Data-related errors

- ***Spatial bias in reporting:*** fires in the database are more likely to be associated with paths not only because this is where ignition sources are likely to be found, but because this is where they are likely to be seen and reported. How big a problem is this? Only small fires distant from paths are likely to go unreported, that is, those which burn themselves out, or are extinguished naturally or by individuals. Fires occurring away from access features may go unreported for longer and become larger, but would eventually be reported in an area as small as the PDNP. If it could be confirmed that there was a positive relationship between fire size and distance from access points, it would be reasonable to assume that reporting bias was not a major problem.

One form of spatial bias does, however, remain; fires at edge of the park, close to centres of population, tend to be reported to the Fire Brigade and should be included in any future analysis.

It is recognised that the models produced here are of *reported* fire risk, but is an accepted limitation for modelling based on historic fire records. If spatial bias needs to be minimised in future work, it is recommended that archive and current airborne or satellite remote sensed images are used to detect the *active* fire locations, especially on critical fire days predicted from the temporal modelling. Using archive images for critical fire years would allow an independent test of spatial bias in reporting.

- ***Currency of habitat layer in relation to the date of fires:*** as discussed in section 3.7.2, the dates of fire and habitat mapping are not concurrent. We cannot confirm that a pre-1991 fire falling on an area mapped as bare peat in 1991 was bare peat at the time. It is recommended that aerial photos or documentary evidence are sought to confirm the habitat type at the time of pre-1991 fires. Also that a study spatial persistence of fire over time is carried out to establish if bare peat fire scars beget more fire.
- ***Locational precision of fire records:*** The worse case scenario in reporting precision +/- 500m, where only the kilometre grid square reference is given in the ranger's fire log. Precision may not be temporally consistent throughout the 28 year period of the fire record as GPS has become more widely available. Further, we know little about fire size; database entries on areal extent are sparse and very large fires, such as that at Bleaklow Head in 2003, are mapped as a single point. The point recorded may vary with ease of access to the physical site of a fire; for instance, the point recorded may be the fire centre, edge or inferred location of ignition.

It is recommended that an analysis is carried out using buffer zones of different sizes centred on the reported locations to test the sensitivity of the models to locational precision. Further, precise and consistent information on fire extent is needed for all future fires. It is recommended that GPS is used to record the *boundary* of every fire. Where possible, the inferred ignition point should also be recorded with GPS and the cause (both tagged with a simple confidence rating).

- **Accuracy of map layers.** Thematic accuracy of input layers, especially the habitat layer, is a function of the purpose for which they were compiled. Purpose influences the classes chosen and the data source used (*i.e.* type of photograph or digital image, including panchromatic, true colour false colour; scale or spatial resolution; pre-processing, such as compression; scan resolution if digitised). The classes used for the ESA habitat map for the Dark Peak did not match those for the Southwest Peak, so park-wide spatial modelling could not be undertaken. If modelling is to be extended to the whole PDNP and to other moorland areas, it is recommended that a national published map of vegetation/habitat is used, such as the CEH Land Cover map 2000 (CEH, 2005), or that a single data source is used to construct a bespoke habitat map using a standardised set of classes devised with stakeholder consultation on relative flammability of habitats.

Geometric accuracy is also related to mapping scale, spatial resolution of grid-cell data and the method used to extract the information. It is recommended that LiDAR-derived DEMs are used in place of the OS DEM for future spatial modelling because of their superior height accuracy, good spatial resolution and geometry.

The overlay process in MCE compounds thematic and geometric error, so that error in final maps is the lowest common denominator of input layers (*i.e.* lowest geometric and thematic accuracy). The lack of detailed metadata precludes quantitative error statements. It is recommended that metadata are compiled for all the layers used in future modelling, including an independent test of thematic and geometric accuracy. Moors for the Future have already begun this essential process.

3.17.2 MCE-related errors

The models presented are produced by subjective weighting and based on empirical evidence from the 28 year record and literature sources, with some limited input from stakeholders. An initial evaluation of the results is provided but it is strongly recommended that further work be carried out to refine the both the models and the evaluation method. Areas to be addressed include:

- Inclusion of other potentially significant layers such as vehicle tracks, slope angle and visitor density
- Experimentation with alternative scoring and weighting of layers, including stakeholder consultation. Scoring of the access layers is affected by the fact that they are not independent; for instance, most fires occurred within 4 km of the Pennine Way, but other paths occur here too, so access line layers could be combined into a single layer for scoring.
- Refine the method chosen to evaluate the fire risk maps.

3.17.3 Further work

It is clear that there is great potential to use spatial techniques with existing data to model moorland wildfire risk. In summary, further work to refine the model should address the following issues:

- Relationship of fire size and duration with distance from access points
- Currency of habitat layer in relation to the date of fires
- Sensitivity to locational precision
- Evaluation of alternative map data sources

- Inclusion of additional sources of reported fires
- Inclusion of other spatial layers such as visitor density
- Work on scoring and weighting layers
- Refining statistical testing procedures
- Development of seasonally-constrained models

Alternative approaches should also be explored:

- A pilot study to evaluate satellite remote sensing for locating *active* fires against documentary database(s) of *reported* fires.
- A study of how perceptual models of fire risk vary with interest group, using stakeholder consultation in the selection layers, scoring and weighting of layers.

3.18 Applying the model to managing fire risk

A methodology has been developed using spatial modelling to identify where risk of fire is highest, based on past fires. Once refined and validated, it could be used as a management tool to minimise current fire risk and future fire risk under climate change scenarios.

3.18.1 Location of fire prevention measures

It could be used as resource allocation tool for fire prevention and management, to identify areas of highest risk where fire fighting equipment or additional water sources should be located, or where additional patrolling is required.

3.18.2 Spatial effects of management strategies

As a modelling tool, it could be used to estimate the spatial effects of alternative strategic planning and management options (see for example Lindley, 2001). Furthermore, the creation of ‘What-if’ scenarios would also allow an assessment to be made of changes in fire risk in response to climate change or other drivers of change in the PDNP. The objective would be to answer questions such as:

- ‘How might the pattern of fire risk change due to changes in access such as the CRoW Act’, (by incorporating a post-CRoW Access Land layer).
- ‘What would be the effect of increased public awareness?’ (for instance, by reducing the weight of access layers).
- ‘How might fire risk patterns change if a footpath is closed or re-routed?’ (by removing or relocating an access line). Equally, ‘How might risk patterns change if visitor use increases with no improvement in fire awareness, or if a new car park or path is designated?’ (by increasing the weight around an access feature or adding a new one).
- ‘How might fire risk change if habitat changes?’ Habitat changes such as those produced by gully blocking, reseeded moorland restoration measures could be modelled by substituting the score for the predicted habitat. The impact of climate-induced habitat changes predicted under UKCIP climate change scenarios could also be modelled, as could changes in habitat or accessibility arising from land use and economic policies, for example, a reduction in grazing pressure.

3.19 Conclusion

Multi-criteria evaluation (MCE) was used to spatially model the risk of reported wildfires in the Dark Peak based on a 28-year record of fires from the PDNP rangers' fire log. Fire risk was modelled using habitat and aspect maps to represent vulnerability to ignition, and distance from access features as a proxy for the likelihood of ignition sources. Data were processed using the ArcGIS package. The main conclusions were that:

- Most fires occurred on bare peat, eroding moorland and bilberry bog, with fewer fires on grassland and wet bog communities. If climate change encourages a transition from wet bog to dry bog and grassland, fire risk will increase.
- This finding also suggests that recent moorland restoration measures (to re-vegetate bare peat and gully-blocking to raise the water table) should also reduce fire risk by improving environmental capacity. One concern, however, is that exclusion of grazing from reseeded areas may lead to seasonal build up of brown biomass. The restoration work is being overseen by the Moors for the Future (MFF) partnership, a heritage lottery-funded consortium of public and private stakeholders. MFF is an excellent example of a partnership approach, which, it is recommended, should be more widely adopted to manage predicted climate change impacts.
- Heather communities had the fewest reported fires, which suggests that management of heather, including rotational burning, reduces vulnerability to wildfire and should be continued. However, heather is a rapid-burning fuel, so rotational burns will need to be even more carefully managed in view of predicted increases in soil moisture deficit.
- Most fires occurred around access routes; within 300m of roads, 2km of the Pennine Way, 400m of eroded paths and 750 m of trampled paths. This suggests that restoration measures, patrolling and warning signs should be concentrated close to major paths. It also suggests that, although recognised as a responsible, environmentally-aware group, walkers of all kinds can continue to exert peer pressure and play a vital role in fire awareness campaigns.
- The evidence for car park access was equivocal. There is some evidence for a concentration of fires close to car parks, so these sites should continue to be targeted for public awareness campaigns. The provision of new physical capacity in car parking places is likely to increase fire risk.
- There were significantly more reported fires on Access Land than on non-Access Land. This implies that fire risk is likely to increase with the extension of access land under CRoW. However, as with walkers on paths, increased access also means more rapid reporting of fires, perhaps resulting in more frequent but smaller, less damaging fires.
- Topographic aspect has a considerable influence on the fire risk, with fires concentrated in north and south-facing slopes and fewest on east-facing slopes., but better DEM data are required to confirm this.
- Limitations of the data include spatial bias in reporting and imprecise location of some of the fires. It is recommended that in future, the default is to record fire *boundaries* with GPS, and (where possible) the inferred point of ignition. The incompleteness of some of the layers makes the final risk maps less reliable in the extreme north and south of the study area; mapping in these areas needs to be reviewed and metadata for all map layers compiled. Limitations of the MCE technique are the dependence of the risk map on the choice of layers, scoring and weighting and validation technique.
- Further work is required, including combining spatial and temporal modelling. However, there is much potential to produce a decision-making tool able to identify areas of highest risk and to model the potential impact of fire risk management strategies under climate change scenarios.

Spatial analysis identifies *where* risk of fire is highest, based on past fires. Temporal analysis (section 4) predicts *when* that risk is likely to be highest, based on preceding weather. Temporal modelling used with UKCIP climate models shows how fire risk can be expected to increase under climate change scenarios. Spatial modelling can be used to show how that risk varies across the Dark Peak and how it would be changed by management decisions. The combination of climate modelling, temporal and spatial analysis is a powerful tool for predicting and managing future fire risk.

4. Forecasting the Outbreak of Moorland Wildfires

(Temporal Analysis)

4.1 Aims

The impact of weather and human activity on fire risk has to be established in order to forecast the effect of changing visitor numbers and climate. Development of statistical models allows us to assess the efficiency of existing predictive models based on meteorological considerations. Accurate forecasts of the likely timing and location of fires helps deployment of fire fighting resources.

This section reports development of a non-linear probability model to assess the chance of fires at different times of the year, different days of the week and under various weather conditions, allowing for seasonality in the data.

The section aims are:

- To use temporal analysis to statistically model the probability of occurrence of moorland wild fires in the Peak District National Park;
- To use the model to predict the probability of fire occurrence under climate change scenarios and their anticipated changes in visitor behaviour.

In section 4.2, the sample of wildfires and its seasonal character is discussed. Section 4.3 analyses the time-series properties of the data. Section 4.4 outlines a probit model for the likelihood of moorland wild fires and section 4.5 discusses the general-to-specific methodology used and estimation of the results. This model is tested against an earlier data set for a severe fire year in Section 4.6. The next section provides forecasts of fires under alternative global warming scenarios. Section 4.8 considers extensions of the model and draws conclusions about the implications of climate change for wildfires.

4.2 The Seasonal Nature of Wildfires

Our sample of daily fires is drawn from record books on fire incidents kept by rangers in the Peak District National Park. Data is available for the period 1st June 1976 to 1st August 2004, though the data for 1976/7 was retained for out of sample forecasting. Two limitations of the fire data must be acknowledged; record books understate fire, as some incidents may be dealt with locally and pass unreported. There is also likely to be spatial bias in reporting, in that fires close to roads and footpaths are more likely to be reported, or that they are reported more quickly than those farther away.

The seasonal nature of fires is complex. The occurrence of fires varies with the time of year and varies within each week. The peak months for fires are April and May (Figure 4.1a). The chance of a fire in the month of April or in May is approaching one-in-ten. However, this conceals fluctuations from year to year. Nearly one third of all the 353 moorland wildfires in the Peak District in the sample took place during just four individual months: the very hot, dry summer of July and August 1976 – which is outside the sample used for estimation – and during the dry spring of March and April 2003. Fires are not

confined to warm weather. One fire in January ignited at a temperature as low as -0.5°C . Fires can burn across dry winter vegetation above frozen soil.

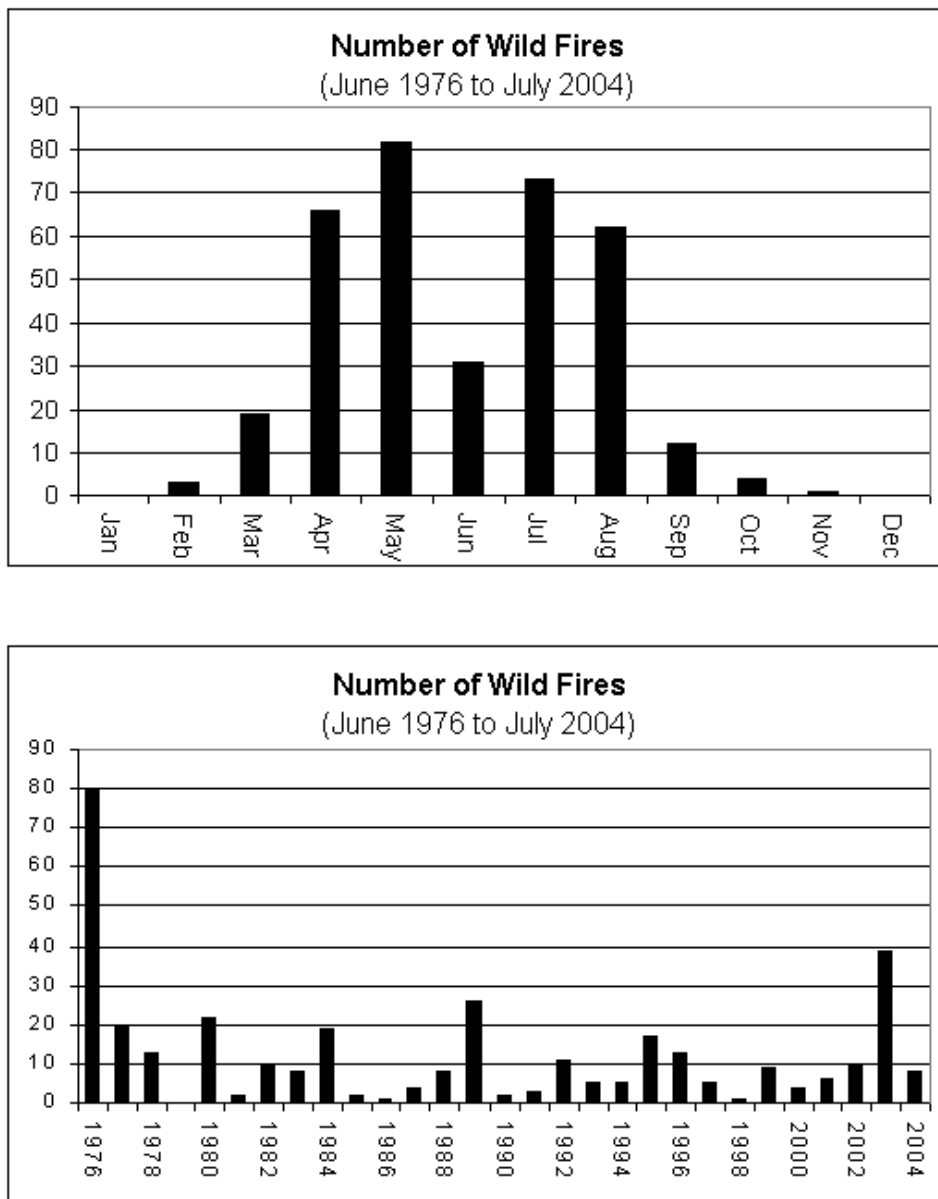


Figure 4.1: The Occurrence of Wild Fires June 1976 to July 2004: (a); by month; (b) by year. N.B. On some days, several fires are reported. Thus the number of fires is greater than the number of "fire days".

Although data for 1976 (and 2004) are incomplete, it can clearly be seen in Figure 4.1b that 1976 was a much higher risk year than any in the "fitted" sub-sample.

More fires are reported at weekends and bank holidays, reflecting the impact of recreation activity⁵. There may be a distinction between the ignition of a fire and the date it is

⁵ Bank-holidays are statutory holidays in the UK.

reported. It is said that weekend fires are often reported on a Monday. However, we find no statistical confirmation of this particular fire-lore. There is no direct evidence on variations in visit levels, since the Peak District National Park is readily open to public access and crossed by major roads. Days of the week were used as a proxy for visit levels, with extra dummy variables for bank holidays and school holidays.

4.3 Analysis of Time-series Properties

The weather data used were daily precipitation and rainfall from Buxton, a town close to the centre of the Peak District National Park. A surprising feature of this weather data is its long-run stability. Climate change may be defined, in time-series terms, as a persistent change in the first two moments (mean and standard deviation) of meteorological data. Non-stationarity implies long-run climate behaviour dominates the impact of short-run weather effects. Yet the impact of climate was found to be no more than the sum of short-run responses to daily and seasonal weather variation. There was less evidence of climate change itself in the 28 years of data, apart from a shift in the seasonal distribution of rainfall, but this should not be expected in such a short run of data.

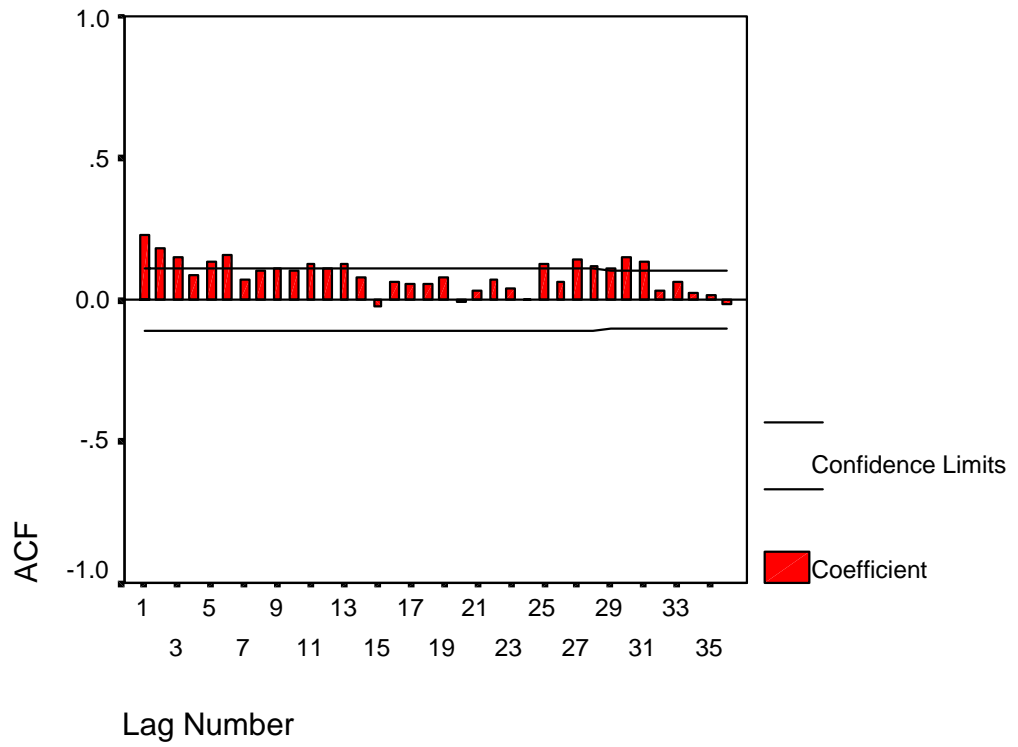
Taking monthly data, the weather in the Peak District appears stationary over the 28-year period. That is to say, neither the average nor the variance in the level of temperature and precipitation alters systematically over time. The winter weather at Buxton appears to have got slightly warmer over time – at least since 1987 – but this is not statistically significant. Autocorrelation functions show no evidence whatsoever of a unit root at regular intervals in the residuals of a seasonally adjusted auxiliary regression equation, for rainfall, maximum or minimum temperature, or temperature range (Figure 4.2). By the same count, there are no seasonal unit roots. These findings are consistent with Thompson (1999), who finds no particular trend to precipitation in Britain over the last 150 years, although there have been substantial variations from year to year.

However, Osborn *et al.* (2000; 2002) show daily precipitation has become more intense in winter and less intense in summer over the period 1961-2000. This enhanced seasonal cycle of increasing winter precipitation, heavier downpours and drier summers, with fewer wet days and lighter rainfall, may reflect changes in the mid-latitude westerly circulation (Mayes, 1996). Mayes (1996) shows there has been more rainfall in the north-west in early spring, which would damp the moors ahead of the high risk fire season in April and May. These results are crucial for modelling the incidence of moorland fires, as more intermittent and less intense summer rainfall may add to the risk of fire.

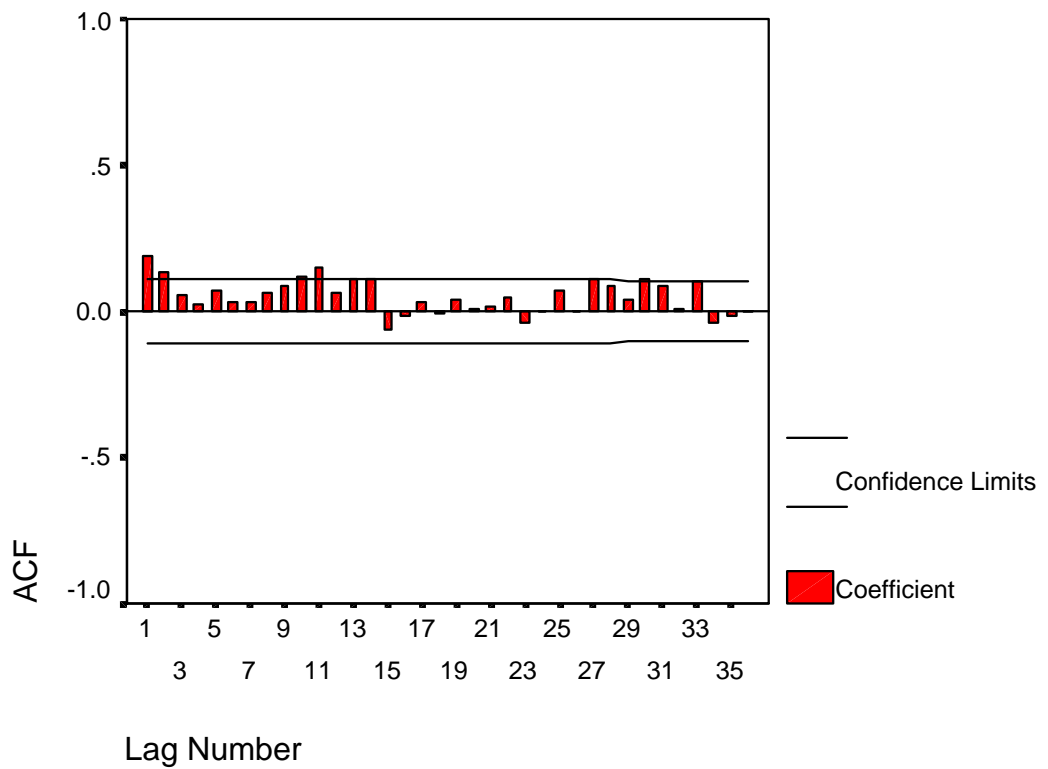
The pattern of weekend recreation in the peaks is captured by the chorus of the folk song *Manchester Rambler*, by Ewan MacColl:

“I’m a rambler, I’m a rambler from Manchester way,
I get all my pleasure the hard moorland way,
I may be a wage slave on Monday,
But I am a free man on Sunday.”

TMaxA (seasonally adjusted)



TMinA (seasonally adjusted)



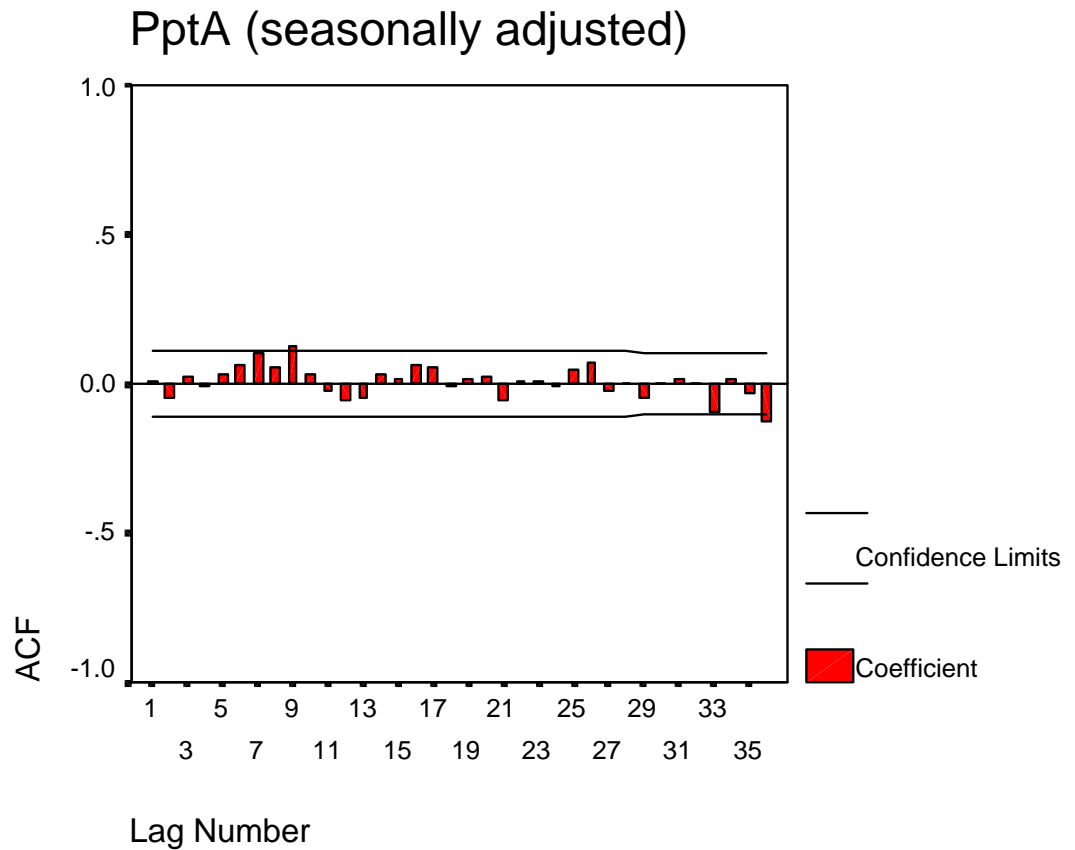


Figure 4.2: Autocorrelation Functions of Weather Variables: residuals from auxiliary regressions on monthly seasonal dummy variables. (a) maximum temperature; (b) minimum temperature; (c) precipitation

4.4 Modelling the Probability of Fires

The standard approach to modelling ecological disturbances relies on a Poisson process for extreme values (e.g. Dayananda, 1977). For example, Davison and Smith (1990) and Katz *et al.* (2005) appeal to a Pareto distribution of extreme outcomes to model infrequent but unusual events. Yet, the fires studied here are frequent events, occurring over a dozen times a year, rather than once every thirty years. Extreme event studies consider observable distributions (e.g. Gaines and Denny, 1993). It is not possible to observe the underlying probability of fires. We can only record fires that do occur. In these circumstances, a stochastic binary model, such as probit, is appropriate.

4.4.1 Probit

Probit analysis offers a convenient functional form for estimating a probability model with an observed dependent variable, y , of either zero (“no fire”) or one (“fire or fires occurs”), where y_i is the outcome of a binomial process over time. (See, for example Johnston and DiNardo, 1997). We can define 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 is a vector of observable explanatory variables; ε_i is an unobservable aleatoric element, which we assume is normally distributed with a standard deviation of σ ; y_i^* is normally distributed, conditional on X and can be estimated using maximum likelihood estimation. Therefore,

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

4.4.2 Capturing Seasonality

Seasonality can take a number of forms in time-series models (e.g. Franses, 1996). Stochastic seasonality is ruled out by the fact that the data are stationary. We assume seasonal fluctuations in daily fires can be represented deterministically using seasonal dummy variables. These dummy variables include the month of the year, the day of the week, the presence of a bank holiday and school holidays. These dummy variables are intended to capture a shift in the mean probability of a fire for those days over and above other factors at work. Deterministic seasonality is a special case of a broader group of seasonal models (Albertson and Ayles, 1996). Alternative specifications are not readily handled with daily data. Nor is there reason to suppose seasonal effects, such as weekend peaks in visitors, vary from year to year. However, we do find periodic seasonality in the relationship between maximum and minimum temperature over the course of a year.

4.4.3 Variable Specification

Temperature is specified in terms of both maximum daily air temperature and minimum temperature, which usually occurs at night. Precipitation is accumulated rainfall or snowfall in the past 24 hours measured in mm of moisture at 0900 GMT.

High temperatures and low precipitation have a cumulative effect on fire risk. Moisture evaporates and is transpired from plants. The water table drops in peat bogs, leaving a baked and cracked surface where the peat is exposed. A soil moisture deficit builds up and vegetation can dry out, becoming more flammable. So we are concerned to capture two related concepts: the cumulative effect of weather on local conditions and the idea of a “dry spell”, or “hot spell”.

The cumulative effect of precipitation and temperature is expressed through rainfall and temperature temporal shadows – the lagged effect of recent weather. To calculate rainfall temporal shadow, for example, for the past week, the procedure is as follows: Firstly, we take seven day moving averages across the whole sample period and calculate the typical moving average for each date in the year (excluding 29th February). This captures the idea of “typical weather” for the time of year. Then daily rainfall temporal shadow is the actual moving average precipitation ending on that day, minus the typical moving average for those dates across all years in the sample. This gives an indicator of departures from usual weather over the past week. Fourteen, twenty-one and fifty-six day rainfall and temperatures are calculated in a corresponding way. Longer rainfall shadows encompass shorter shadows in order to capture the cumulative effect of dry weather. This creates potential multicollinearity, which implies caution when interpreting coefficients, but is less

of a problem when using the model for its intended purpose of forecasting. Rainfall and temperature temporal shadows are eliminated hierarchically by testing restrictions on the longest shadows first.

The distribution of daily rainfall both for the Peak District and the British Isles resembles a gamma distribution (Coe and Stern, 1982; Stern and Coe, 1984; Chandler and Wheeler, 1998; Spanos, 1999, ch.3). On a typical day, precipitation is less than 1 mm. Median rainfall at Buxton is only 0.7 mm. But, average rainfall is much higher at 3.6 mm as the mean is pulled upward by extreme events - torrential downpours that occur from time to time.

Bearing this in mind, dry spells are defined in terms of the deciles and median of the rainfall distribution. If the rainfall in the past seven days is in the bottom decile for that time of year, an indicator variable for a dry period is set at 1. Once classified as unity, the indicator dummy remains dry until there is a seven-day period of above median rainfall⁶. The same approach is adopted to categorise a “hot spell” (temperature is easier to handle statistically). Surprisingly, 26% of days fall into “dry spell” clusters as defined here. The frequency of dry spells reflects the episodic nature of rainfall. Indeed, we can go so far as to say that the problem of moorland wild-fires would barely exist if rainfall was evenly distributed over time.

There is an added complication in so far as intense storms may run off quickly and barely reduce vulnerability to fire (CCVE, 2005). The surface of dry peat becomes hydrophobic⁷, so prolonged, gradual rainfall is required to soak vegetation and soil. Precipitation levels do not capture the duration of daily rainfall.

The dummy variables “fireweek” and “multifire” reflect the persistence of fires in the past seven days. These can be interpreted as the difficulty of fully dousing a fire that has set into peat sub-soil; the persistence of circumstances favouring a fire over time; or a symptom of *spatial* autocorrelation in our data as fires flare up near previous incidents. Spatial autocorrelation may manifest itself as time-series autocorrelation if adjacent fires are sparked on successive days.

The moors are occasionally closed to public access due to high fire risk. They were also shut due to the outbreak of foot and mouth disease from late February to late May 2001 – potentially a time of high fire risk. These closure days are accounted for by a dummy variable, although data on closure dates is incomplete. There is no guarantee that these emergency access restrictions are observed by the public. In any event, roads through the park remain open, which means the moors are still vulnerable to cigarettes discarded from cars.

Monthly dummies have two facets, as they capture both changes in plant phenology with the time of year and seasonal shifts in visitor behaviour. In contrast, dummy variables for days of the week, bank holidays and school holidays only relate to visitor activity.

⁶ Alternative specifications for these hot spell and dry spell clusters were tested and gave almost identical results, suggesting the model is robust with respect to these variables.

⁷ A hydrophobic surface is one inhibits water absorption.

4.5 Methodology and Estimation

All estimates were arrived at using a “general to specific” approach to model evaluation associated with David Hendry (Davidson *et al.*, 1978) and others (summarised by Gilbert, 1986). This involves estimation of a very general model for the occurrence of fires encompassing a wide range of weather and visitor-related explanatory variables, and testing successive restrictions on these variables using specification tests. The resulting model should be consistent with knowledge about physical processes and human behaviour and also account for the underlying statistical properties of the data set. The final model in tables 4.1 and 4.2 began with 33 variables. Successive tests of restrictions reduced this to a final set of 15 explanatory factors. Taking the instance of days of the week, only Friday, Saturday and Sunday turn out to be significantly different in terms of fire incidence from Wednesday, which was used as a base.

Models were estimated using daily data beginning 1st February 1978 to 1st August 2004. The second half of 1976 and the first half of 1977 was set aside for model validation. Multi-fire days were counted simply as fire days (i.e. $y_i = 1$). November, December and January were eliminated from the estimation period as there was only one fire during these winter months across the whole sample period. For some of the time, the moors would have been snow-covered and not susceptible to fire. In the forecast function, the probability of wildfires in these months was assumed to be negligible.

The use of "seasonal" dummy variables implies selection of a base date, with which other "seasons" (holidays, days and/or months in this case) may be compared. A Wednesday in October was selected as the base; it was neither a bank holiday nor a school holiday, there was no fire in the previous week and it was not a dry spell.

4.6 Forecasting Outbreaks of Fires

4.6.1 The probability of a “fire day”

Results of the probit model are given in Tables 4.1 and 4.2. The dependent variable being explained is “the probability of a fire occurring that day”. We report both the coefficients of the estimated model, which determine the probit “score” and the change in probability associated with a small change in the explanatory variable evaluated at the mean. In the case of dummy variables, coefficients represent the change in probability resulting from a switch in value at the mean.

It is apparent that some factors contribute more fire risk than others, especially the influx of visitors to the area as proxied by the day of the week and occurrence of bank holidays. It is human-impact, rather than meteorological pressure that emerges as the main villain of the piece. Daily precipitation, past rainfall (P21, P56) and temperature (T28) temporal shadows and the “dry spell” indicator function (Ip7) are significant - all of which point to the role of moisture in damping down fire risk. But these variables have relatively slight effect. A typical British bank holiday is almost five times more perilous than seven days of dry weather.

Variable	Coefficient	Standard error	z	Pr > z
Fire past week	0.463	0.107	4.31	0.000
Precipitation	-0.080	0.023	-3.47	0.001
Minimum temp	-0.082	0.016	-5.21	0.000
Maximum temp	0.108	0.013	8.51	0.000
Bank holiday	0.606	0.158	3.85	0.000
Friday	-0.300	0.142	-2.11	0.035
Saturday	0.250	0.104	2.42	0.016
Sunday	0.280	0.101	2.76	0.006
April	0.592	0.116	5.10	0.000
May	0.442	0.103	4.30	0.000
P21	-0.101	0.037	-2.74	0.006
P56	-0.111	0.046	-2.43	0.015
Ip7	0.237	0.092	2.57	0.010
T28	0.094	0.027	3.46	0.001
Constant	-3.51	0.164	-21.5	0.000

Notes:

Estimated in levels. Sample period 1st February 1978 to 1st August 2004. Daily observations from February to October. Estimated using maximum likelihood
No. of Observation = 7287; Log likelihood = -614.1;
Likelihood Ratio $\chi^2(14) = 525.4$; Prob > $\chi^2 = 0.0000$;
Pseudo R² = 0.2996
Base month October, base day Wednesday

Table 4.1: Final Probit model of the Likelihood of Moorland Wild Fire Day

Higher maximum temperatures are clearly associated with greater fire risk, reflecting the dangers of hot, sunny days in sparking fires. Conversely *higher* minimum temperatures are associated with a *lower* fire risk. Minimum temperature at night is a proxy for the onset of spring (Watt, 1954). Warmer days and the absence of night frost trigger plant growth: greener vegetation is less prone to fire than old, dry, shrivelled plants that survive winter by withdrawing moisture from their stems. Spring growth of new green vegetation is one reason why April is 1.6 times riskier than May, holding everything else equal.

Bank holidays are risky, with the added chance of 1.7 in a 100 of a fire at the mean, over and above the underlying level of risk for that day. School holidays were included as a potential explanatory variable because arson by children was thought to be a cause of wildfires (CCVE, 2005). There is no statistical evidence to support this view. Either the observation is apocryphal; junior arsonists are persistent truants, or the activities of juveniles are restricted to localities outside the Peak District. Moor closure made no significant difference to the prevalence of fires, probably due to shortcomings in the data; some closure dates are unrecorded. There is no evidence on compliance and roads were still open: one fire occurred while the moors were officially closed. So we cannot draw conclusions about the effectiveness of closure as a policy to reduce fire risk.

Variable	$\frac{\partial y}{\partial x}$	Mean value	Proportion of days
Fireweek	0.010*	<i>dummy variable</i>	4.8%
Precipitation	-0.001	3.3mm	
Minimum temp	-0.001	6.1 °C	
Maximum temp	0.001	13.0 °C	
Bank holiday	0.017*	<i>dummy variable</i>	2.6%
Friday	-0.003*	<i>dummy variable</i>	14.3%
Saturday	0.004*	<i>dummy variable</i>	14.3%
Sunday	0.005*	<i>dummy variable</i>	14.3%
April	0.014*	<i>dummy variable</i>	11.1%
May	0.009*	<i>dummy variable</i>	11.5%
P21	-0.001	-0.002	
P56	-0.001	-0.007	
Ip7	0.004*	<i>dummy variable</i>	26.3%
T28	0.001	-0.006	

* is for discrete change of dummy variable from 0 to 1
Observed P = 0.0259; Predicted P = 0.0042 at mean

Table 4.2: Probit model Evaluated at the Mean of the Likelihood of Moorland Wild Fire Day

Inclusion of a dummy, taking the value 1 if there was one or more fire in the previous week, suggests either circumstances conducive to a fire, or possibly time-series or spatial autocorrelation between local fire incidents. “Hot spells” were not significant, although dry spells remain in the final model. Inspection of the data suggests that hot spells are characterised by occasional thunderstorms and torrential rain.

4.6.2 The risk of fire

The potential impact of global warming is illustrated by a spring bank holiday in May (Figure 4.3)⁸. This is a high-risk day, used to illustrate the workings of the model. In 1978, there were seven fires on spring bank holiday with a temperature of 22.5°C – the hottest such day in the sample. The data suggest, under current climate conditions, that the risk of a fire (or fires) on this particular day is about 8%. The probit function for the average climate on such a day was evaluated. The maximum temperature was varied from a low of 8°C to an extreme of 25°C and the likelihood of a fire (or fires) being reported was considered. Allowance was made for the corresponding rise in minimum temperature, which has both a deterministic and a periodic relationship with maximum temperature across the year.

⁸ The cumulative normal density function is difficult to evaluate (see Burington, 1973, table 18, pp.424-7). Excel subroutine NORMSDIST calculates the area under a cumulative normal standardised distribution, converting a probit z score into a probability that a dependent variable is less than a given value.

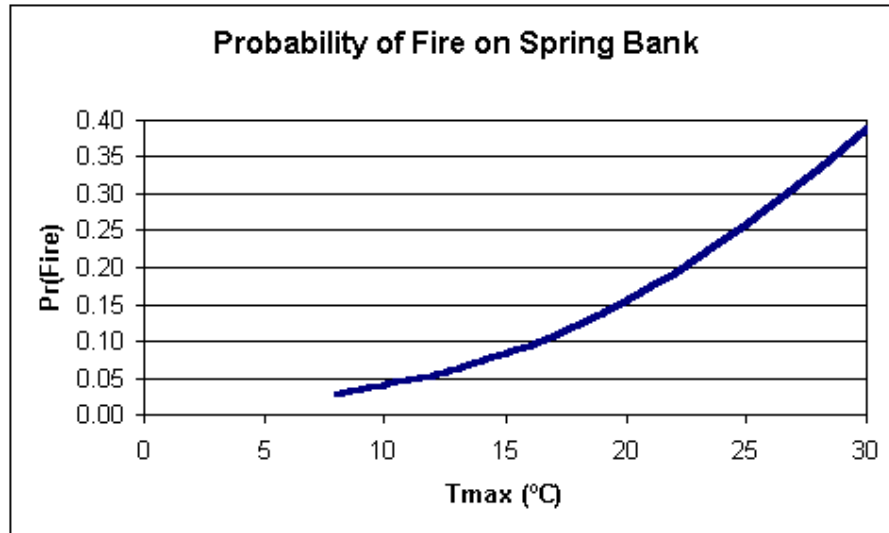


Figure 4.3: Probability of a fire on a spring bank holiday: Variation with temperature

The average maximum temperature for spring bank holidays is 14.87°C. The *ex-post* risk of a fire that particular day is $2/26 = 0.077$. The model predicts a 0.069 chance of a fire at the average temperatures prevailing on spring bank holiday. The probability of a fire rises non-linearly from daily odds of 3% at 8°C to a 26% chance at 25°C.

The outcome of the model can be re-expressed using a contingency table, applying the probit model to 26 years of data, including the winter months where we predict no fires (there was one in 27 years) (Table 4.3). Since the probit model forecasts probability of a fire, a threshold level was chosen for declaring a fire risk. Here, we take a 5% chance of a fire that day as a serious risk. A higher threshold means fewer false alarms, but more fires missed.

Naturally, it is easy to predict “no fire days” since they are prevalent. Instead we focus on “fire days”. We forecast 86% false alarms at the 5% threshold. We predict an outbreak of fire correctly one in seven times (i.e. 14%). This is a function of the cautious threshold chosen for alerts. Expressed in annual terms, we correctly predict five fires out of seven in a year. If fire crews were on standby for 36 days a year, we would anticipate nearly three-quarters of the fires. Evidently there is a trade-off between risk and the cost of keeping crews on standby.

Probit Forecast "Fit"

		PF	PNF				
F		14%	1%	F	71%	29%	100%
		86%	99%		NF	9%	91%
		100%	100%				

Note:

25th November 1977 through 1st August 2004

Based on $n = 9747$ days, 190 of which are "fire days"

PF refers to a day on which a fire is predicted, where the probit function indicates there is a "significant" (5% threshold) probability of a fire.

F refers to a day on which there is a fire: Similarly PNF and NF refer to days on which no fire is predicted, and when there is no fire respectively. Thus, for example, the *ex-post* proportion of incorrect predictions of "No Fire", is 1%.

Table 4.3: Contingency Table for Moorland Wild Fires

4.6.3 Fitting the model out-of-sample

A key test of the specification of the probit model is its ability to predict a separate data set. The model estimated between 1978 and 2004 outlined in table 1 was used to predict fire days for the second half of 1976 and the first half of 1977 (temperature data is missing for Buxton from 1st June to 29th August 1977). This is a tough but appropriate test as the hot summer of 1976 was a bad time for fires. The model must forecast satisfactorily out-of-sample in these circumstances, as it is to be applied to a hotter climate in future. The year 1976 is an appropriate analogy for climate change as many of the fires occurred later in the summer, as we might expect if the climate shifts towards wetter winters, earlier springs, but hotter and drier summers.

		PF	PNF			PF	PNF	
F		45%	5%	F		63%	38%	100%
NF		55%	95%	NF		9%	91%	100%
		100%	100%					

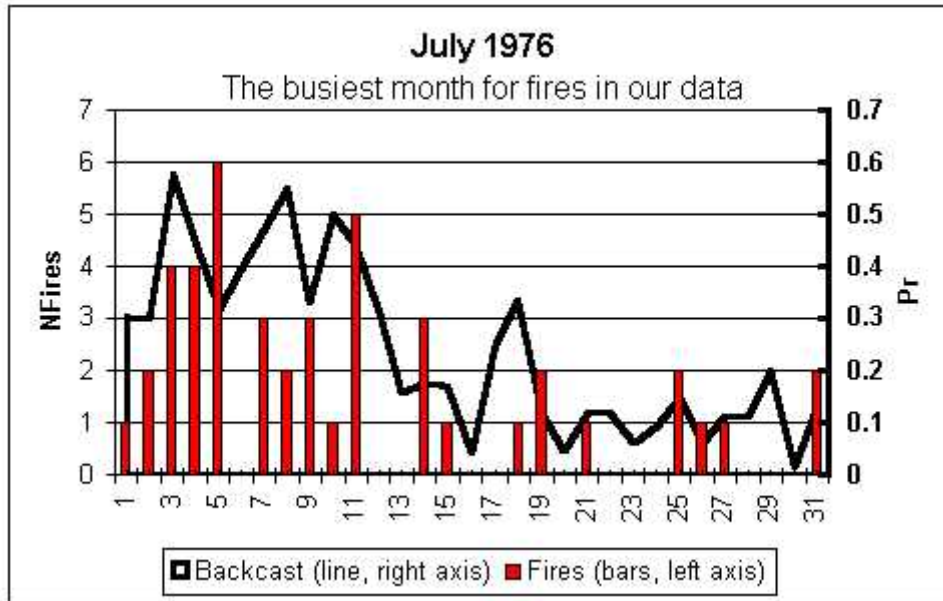
		PF	PNF			PF	PNF	
F		20%	11%	F		5%	95%	100%
NF		80%	89%	NF		2%	98%	100%
		100%	100%					

Note:

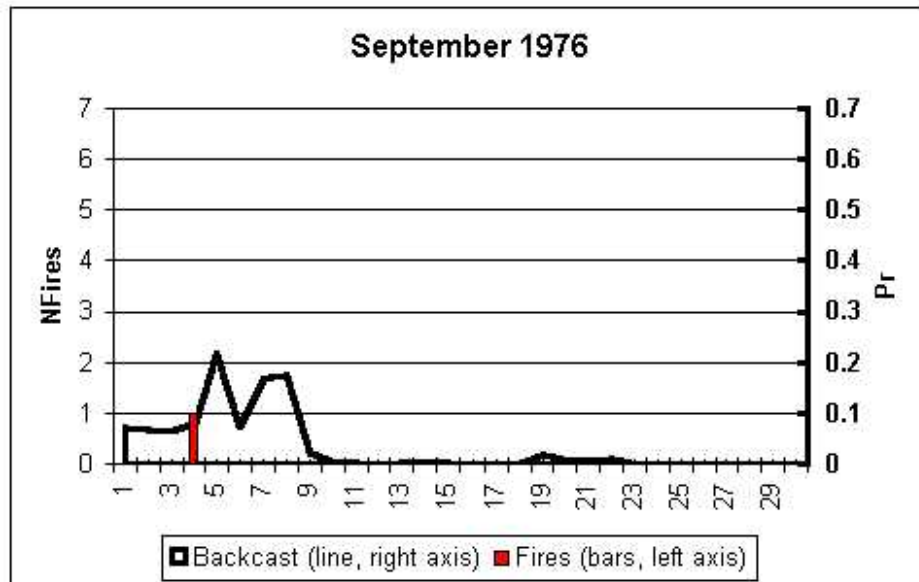
Based on $n = 365$ days, 40 of which are "fire days"
 1st June 1976 through 31st May 1977
 Refer to Table 3.3 for key.

Table 4.4: Backcasts of Wild Fires

A backcast on the holdout sample using the probit model shows we predict the precise timing of fire days 63% of the time (Table 4.4). The total number of fire days was over predicted at the five per cent threshold, anticipating 55 fire days when there were only 40 actual fire days. This is to be expected as visitors to the moors are specifically encouraged to be more careful in their behaviour at times of extreme fire risk such as 1976. It is said, but we cannot substantiate, that an emergency order was issued to close the moors on safety grounds that year. Visual inspection of the predictions shows the probit model is very good at anticipating high risk periods but the precise timing of the forecast fire day is often out by just a day or two (Figure 4.4). High probability fire days are usually associated with multiple fires.



(a)



(b)

Figure 4.4: Backcast of the probability of a fire compared with actual number of fires: (a) for July 1976; (b) for September 1976

In order to assess goodness of fit of the forecasts, the backcast predictions were also compared with a naïve seasonal model of the ex-ante probability of a fire in any given month (Table 4.4). Consider the ex-post probability of a fire in month m , p_m . A fire is “forecast” by the naïve model on day t if $U_t < p_m$ where $U_t \sim U[0,1]$. Thus, fires are “forecast” at random in such a way that the proportion of “forecast” fires in a month is determined by the ex-post proportion of actual fire-days.

Considering days when fires occurred in the hold-out sample, five per cent were correctly forecast by the naïve model compared to 63 per cent correctly forecast by the probit model. Conversely, if the probit model predicts “no fire”, it is 95 per cent accurate, while a naïve prediction of no fire is only 89 per cent accurate.

4.7 Simulating the Effect of Climate Change

The effects of climate change were simulated using BETWIXT daily predictions for future climate (CCVE, 2005) with the preferred model. The potential impact of climate change on the probability of wildfires is complex: There are immediate effects caused by rises in peak temperatures and reductions in summer precipitation. There is also an indirect effect due to the cumulative impact of lower precipitation and higher temperatures on soil moisture and evapotranspiration from moorland vegetation.

This data on future weather are derived from a stochastic weather generator, which simulates site-specific weather for Manchester. There is controversy over the best approach to weather generation (e.g. Wilks and Wilby, 1999; IPCC, 2005). In this case, daily weather was used, simulated by a first-order Markov chain model of the type developed by Jones and Salmon (1995) outlined in Watts *et al.* (2004). Indicator variables, such as dry spells, were calculated relative to weather that prevailed in the base period used for estimation. There were no leap years in the prediction. There is a potential bias in favour of fire days due to a minimum precipitation cut-off of 1 mm imposed by the BETWIXT generator. No change in visitor numbers was assumed, in accordance with the findings of Albertson *et al.* (2005).

We are awaiting data from Betwixt simulated daily climate data for Buxton. Preliminary analysis using Betwixt data for Manchester Ringway suggests a greater number of fires, and that the spring period is still very important for wildfire outbreaks.

There is potential feedback between climate change, vegetation and fire risk. (CCVE, 2005). Climate change is likely to alter species composition. Some changes will increase fire risk, such as a reduction in cotton grass bog in favour of dwarf shrub communities like bilberry and crowberry, but not managed heather (section 3.7). A decrease in managed heather coverage or a reduction in grazing pressure would increase fire risk (Bruce, 2000). Indirect changes in species composition and fire risk may also occur due to climate-induced or legislation-induced changes in land-use.

4.8 Further developments

The Probit model developed here has wider application in forecasting similar spatially distributed hazards such as forest fires, where there is a need to manage prescribed burning and alert recreation visitors and local residents to the dangers posed by wildfires (Morehouse, 2001). A local forecasting system based on expert judgement of the sort outlined by Abramson *et al.* (1996) could be used to predict extreme weather conditions likely to induce fires. The PDNP has already led the way in fire risk management by subscribing to the weekly MORECS index (Met Office Rainfall and Evaporation Calculation System) to predict fire risk, and has recently transferred to the new national Fire Severity Index (section 5.2.1). The Probit model is an locally-based additional tool.

More than one fire occurred on some days. The maximum number of daily fires reported during the estimation period is seven. Ordered probit could be used to predict the number of fires, assuming the occurrence of fires on any given day is independent, e.g. an arsonist does not light more than one fire on the same day.

The area of a fire is a proxy for its severity and damage caused. The potential size of fires could be forecast using Tobit analysis, taking account of additional factors such as wind strength and direction (though data is incomplete). This would help deployment of fire-fighting resources such as back-up fire tenders, or static reservoirs or hydrants. There are statistical difficulties associated with censored regression models of this sort (e.g. Maddala, 1983). Modelling size of fires is subject to sample selection bias. Very small fires are likely to be omitted from the data. The area of very large fires may be under-recorded as it is difficult to estimate the coverage of a severe blaze without GPS. There is considerable variation in the precision of estimated areas and fire records do not always include estimates of the size and location of fires. The tapered Pareto distribution is preferred for modelling wildfire size in California (Schoenberg *et al.*, 2003), so assumptions of normality underlying the Tobit model may not be valid with regard to area, as opposed to frequency.

Other possible refinements could include combining results from the spatial and temporal analysis by developing spatially-constrained Probit models; for instance, separate models for high risk and low habitats. Temporally-constrained models might also be explored; for instance, before and after the introduction the FAP and FOG fire management initiatives in the late 1990's, or summer and spring fires. All would require a larger fire database using fire records from additional sources.

4.9 Conclusions

A non-linear probit model was used to forecast the likelihood of wildfires in the Peak District at different times of the year, days of the week and under various weather conditions. Current and past rainfall was found to damp fire risk. The danger of fire increases with daily maximum temperature. Dry spells or recent fire activity also signal extra fire hazard. Certain days of the week are more fire prone due to human activity and some months of the year are more risky reflecting the changing flammability of moorland vegetation. The model backcasts the extreme events of 1976/7 successfully.

Climate change is likely to bring wetter winters, but hotter and drier summers. The simulations suggest that it is changes in climate variability and weather extremes that matter more than slight changes in average temperatures or rainfall. The non-linear relationship between the risk of wildfires and key weather variables, such as dry spells, means that a slight increase in the frequency of isolated periods of hot dry weather can have disastrous impact. Yet a gentle rise in mean temperature over a long time period may have negligible effect on fire danger.

These results point to a variety of management solutions to reduce the outbreak of fires, to fight fires more effectively and to restore land damaged by wildfire outbreaks. Continued education of footpath users is a priority, and patrolling on critical fire days. The probability model demonstrates global warming will have a damaging effect on a sensitive landscape if adaptation strategies are not pursued.

4.10 Notes on Data Sources

The sample of fires is drawn from record books on the incidence of fires maintained by rangers for the Peak District National Park Authority and compiled by Moors for the Future. The data omits local grass fires on the urban periphery outside the Park boundary. Daily data on the occurrence, number and size of fires runs from June 1976 to July 2004. The period February 1978 to July 2004 was used for estimation. We retained the data for 1976 and 1977 for out-of-sample forecasting to validate the model. Weather data is for Buxton (NGR SK 058734; latitude 53.257, longitude -1.913), from the UK Meteorological Office Land Surface Observation Stations database, kindly provided through the British Atmospheric Data Centre (<http://badc.nerc.ac.uk>). A full series of data is not available for the preferred moorland weather station, Holme Moss.

School holiday dates are for a primary school in the City of Salford, one of many in the visitor catchment area. Data was analysed using *SPSS* version 11.0 and *Stata* release 8.2.

5. Implications for management

5.1 Climate change, fire risk and moorland implications for management

5.1.1 Increased probability of wildfire incidence

Climate change scenarios suggest that the maximum temperature in the Peak District is likely to increase by 3°C to 5.5°C during the summer, and that the area is likely to receive 23%-45% less rainfall in summer by the 2080s (section 2.4). This will have significant consequences for wildfire risk. Temporal modelling of fires found that the risk of wildfire outbreaks increased with maximum temperature. Dry spells and recent fire activity also signalled extra fire hazard. Additionally, current and past rainfall damps fire risk. Weekends and bank holidays days are more fire prone due to human activity and April, May, July and August are more risky, reflecting the combination of increased visitor use and changing flammability of moorland vegetation.

Climate change impacts are complex: immediate effects in the alteration of fire vulnerability are likely due to rises in peak temperatures and reductions in summer precipitation. There is also an indirect effect due to the cumulative impact of lower precipitation and higher temperatures on soil moisture and evapotranspiration from moorland vegetation. Therefore, climate change is likely to increase the probability of wildfire incidence, and increase the number of multiple fire days. The severity of fires may also increase, and this may cause the burnt area to extend.

Climate change is also likely to change the habitat and distribution of vegetation types, thus affecting the fire hazard. For example, increases in mean annual temperature around 3°C may result in a reduction of 25% in the current extent of blanket bog (Bardgett *et al.*, 1995). Reduced soil moisture, and aeration, and increased oxidation of peat soils are likely to result in a change in vegetation type from blanket bog to dry heath and acid grassland. Dry heath dominated by heather is not as at risk to fire as other habitat types, but this is largely due to prescribed managed burning. If the expanse of heather increased, this would require more management, and the number of escaped fires may be likely to increase. Additionally, changes are likely in the amount of fuel accumulated in woody biomass. Other types of dry heath, especially that dominated by bilberry, had more reported fires than cotton grass blanket bog, but grassland had fewer. These changes in vegetation composition, therefore, will have complex effects on fire risk.

5.1.2 Implications for moorland management

Fire risk differs in different parts of the PDNP, varying with land cover. Spatial analysis (section 3.7) showed that more fires occurred on bare blanket peat and eroding moorland than any other habitat. These habitats are most severely affected by fire because they are least likely to recover, and fires are likely to reoccur there. Bilberry, heather and crowberry are flammable and have a relatively high fire risk, (which is reduced by managed burns in the case of heather moor), but are generally more able to recover (CCVE, 2005). This has implications for moorland management; it suggests that continuation of burning practises on heather moor will reduce wildfire risk. Additionally, it suggests that some habitats are

more vulnerable to wildfires, and it is here that careful management needs to occur, particularly with regards to reducing the fire risk. The reseeded of bare peat and gully-blocking activities designed to revegetate bare peat will be doubly beneficial in that they should also reduce fire risk (Figures 5.1 and 5.2). Such restoration work should be concentrated on bare peat areas close to the Pennine Way and other lines of access.



Figure 5.1: Restoration of vegetation on Bleaklow by re-seeding and use of geojute to stabilise slopes. Revegetation of bare peat should reduce fire risk (Photograph © Jonathan Aylen).



Figure 5.2: Gully-blocking on Bleaklow to raise the water table, trap peat sediment and encourage colonisation by cotton grass and other blanket bog species. Such activities should reduce fire risk (Photograph ©Julia McMorrow).

Increased probability of wildfire incidence will have significant and direct effects on the management of the Peak District National Park, and particularly the reaction to fires (section 5.2.1). More resources will be required to extinguish fires. Greater costs will be incurred by landowners to extinguish fires, particularly if helicopters are required more frequently. Speed of response of the fire service will become more important in limiting the fire spread, since the burn area is likely to increase with more intensive fires, and will result in further destruction of the landscape. Additionally, managed fires on heather will require more effort to avoid getting out of control.

Burn scars caused by wildfires in spring and summer are likely to experience greater erosion due to increases in winter rainfall, causing the vegetation to be more vulnerable to wildfire the following spring.

Whilst the future level of visitor demand is difficult to predict, the PDNP can influence the pattern of visitor access, for example through car parks and modification to the road network. Spatial modelling found that there was a relationship between the number of fires and distance to roads, since most fires occurred within 300m of the road, but no pronounced relationship with distance to car parks. This may suggest that improving accessibility and physical capacity of the road network would lead to an increased fire risk, but may also mean that changing the locations of car parks (as a potential management option) would have relatively little affect on wildfire risk. However, increasing accessibility and car parking capacity would lead to deterioration of the visitor experience and perceptual capacity, since most visitors to the Peak District visit for the natural wilderness, landscapes and scenery. Fires were significantly more common on Access Land so that recent land opened as part of CRoW is thought likely to increase the fire risk. The spatial analysis found a relationship with distance from the Pennine Way and the number of fires, but, as with roads and Access Land, this may be due partly to increased fire reporting.

The spatial analysis so far conducted assumes that fire risk has not changed over time due to management initiatives. However, refinements could be made to model whether fire risk differs spatially before and after the setting up of the Fire Advisory Panel and Fire Operations Group and with the implementation of proposed fire risk management strategies, such as campaigns to raise public awareness or moor closure (section 3.19).

Any climate-induced or legislation-induced changes in land uses will be influential on habitat vulnerability and wildfire risk. This includes some important economic policy drivers of land use change, such as changes to the Common Agricultural Policy. A reduction in grazing, through agricultural or climate change drivers, would lead to increased biomass and changes in plant community composition, which are likely to lead to an increase in fire risk (CCVE, 2005). Other influential agricultural policies may include subsidies for diversification, for example, encouraging tourism through better provision of tourist facilities.

5.2 Wildfire Management

The main driver of current fire risk management is the need to minimise moorland fires for the numerous stakeholders and landowners. Concerns are high regarding the likely consequences of climate change on fire risk, and are associated with likely increased costs

of management, the likelihood of increasing damage, other associated impacts on environmental resources, and the impacts on the current users of the moors (CCVE, 2005).

It is important to note that burning remains an important management tool. Fire is a natural part of the moorland semi-natural ecosystem. Any increase in the amount of woody or brown biomass will generate more material to burn. Therefore, an increase in managed heather moor would reduce fire risk, as management is geared towards reducing wildfire risk by reducing fuel loads in order to maintain a mosaic of different-aged heather for grouse (CCVE, 2005). The caveat is that managed fires would need even more careful control to prevent them from escaping.

5.2.1 Current fire management options and strategies in use

Moorland areas are currently exempt from fire and workplace safety legislation, and there is no legal requirement to extinguish moorland fires. However the ‘do nothing’ option would be in direct conflict with the objective of a national park i.e. it is established to protect and enhance the natural environment. Therefore, fire management strategies are essential to reduce the number of fires and/or the scale of fire impacts.

There are two elements of fire management: managing the direct and the indirect consequences of the fire itself. These require different strategies. Fire management undergoes three phases of decisions; prevention, preparation and reaction (Figure 5.3).



Figure 5.3: Phases of fire management

- *Prevention*

Managing the fire risk, or fire prevention, involves reducing the likelihood of fire hazard, coupled with reducing the vulnerability of the moorland environment (CCVE, 2005).

Since the majority of fires are started by human negligence, *raising awareness* is very important. Current public awareness campaigns in the Peak District include the Fire Awareness Week (the last one taking place on April 16th-24th 2005). This tour around the main Peak District towns and key visitor areas is led by organisations in the Fire Operations Group, including fire fighters from all six fire services operating in the area, as well as National Park Rangers, Moors for the Future, National Trust, United Utilities, Severn Trent Water and moorland keepers, to give demonstrations, information and answers questions (MFF, 2005b). Fire awareness sessions are also given in schools in the surrounding areas by local fire brigades, and moorland awareness workshops are run by Moors for the Future. Additionally, they also publish leaflets (MFF, 2005c) and visit burn scars during weekends to raise awareness on site. These public awareness activities will need to be increased, especially at times of high risk.

Moor closure is also a preventative option at times of high fire risk. Closure of moors affects landowners and visitors, restricting access to public rights of way. However, moor closure does not mean that the public are completely excluded, since footpaths remain (open access to public rights of way are not restricted, however, access to moorland can be restricted). Baynes and Bostock (2003) suggest that where there is doubt in instigating moor closure, the Sandford Principle must apply, favouring the nature conservation interest over the desire for public access. Closure adversely affects the visitor economy. Importantly, visitors can also provide a fire watch, and therefore closure of moors may be counter-productive, since there are then fewer people to spot fires and report them, so increasing the risk of the fire spreading.

Preventative measures such as moor closure and installation of fire ponds are largely covered by the *Fire Advisory Panel (FAP)*. The FAP is a forum of stakeholders, including local land managers, who fulfil a strategic rather than tactical function. They advise on decisions such as moor closure (MFF, 2005d). It has not yet specifically considered the implications of climate change on future management, but recognises that this is an increasingly important issue (CCVE, 2005).

- *Preparation*

Preparation is coordinated by the Peak District *Fire Operations Group (FOG)*, which has established operational Fire Plans and a spatial database to ensure that appropriate equipment is available (FireGIS, discussed below). It is the tactical counterpart to the FAP, which has played a strategic role.

Preparation is also carried out by *local fire services*, responsible for fighting moorland fires. Special training and equipment is needed to fight moorland wildfires, which includes helicopters (BBC News, 2003). The Fire Service does not currently consider moorland in its costed risk assessments or budgets. Fire Service representatives at the Climate Change and the Visitor Economy workshop (2005) expressed concern at the

budget implications of fighting more moorland fires. It would put additional pressure on the service, and they may have to start costing this in, and considering impacts of climate change.

Technical decision-making tools to aid preparation and reaction include the *FireGIS* spatial database for the Peak District National Park. It differs from the fire risk spatial model developed in section 3 in that it is a tactical rather than a strategic tool. It is used to assist the logistics of fire fighting by assisting fire-fighters to locate the resources they need to extinguish fires and gain access to the fire. It is widely distributed and contains information on access points, water sources and key contact persons (CCVE, 2005).

Recently the *Fire Risk Index* has replaced the *MORECS* index. *MORECS* was based on a 40 km grid square (Hough and Jones, 1997), and was, thus, found to be unreliable, most notably in the Spring 2003 fires, where it produced only a 'high' not 'extreme' risk rating for the PDNP (Baynes and Bostock, 2003). The Fire Severity Index is produced by the Met Office on a 10km grid and uses a similar approach to the widely-used Canadian daily severity rating model (Met Office, 2005; Natural Resources Canada, 2005). It differs from the statistical method used in section 4 in that it is based on physical models. It has been produced as a result of the necessity for landowners, managers and the public to be aware of the fire risk, and archive data and forecasts for the next five days are freely available via the Countryside Agency website (Opengov 2005).

- *Reaction*

Wildfires traditionally used to be put out by large numbers of people using *fire beaters*. From the 1980s, this was aided by *helicopters* using dipper buckets. However, there are increasing problems of resources in terms of manpower and helicopter use due to financial pressures. Helicopters are expensive and helicopter companies have started to take long-term contracts, making helicopters more difficult to hire to fight fires at short notice (Bruce, 2002).

Landowners must cover the cost of helicopters at the moment. Estimated costs used by United Utilities (UU) during the 1997-8 fires were £70K. A risk sharing strategy is used by insuring against fire fighting costs, but this is expensive. For example, the National Trust (NT) has £5,000-£10,000 worth of insurance cover for their High Peak Estate alone. There is currently lobbying of Defra for additional funding to help with management costs, such as helicopters.

The Climate Change and the Visitor Economy Risk Workshop, attended by stakeholders, identified the existing and additional options to manage fire risk (CCVE, 2005):

- *Fire watch* – a fire watch is a possible fire prevention strategy. This could involve landowners and managers as well as organisations such as Moors for the Future and PDNPA. Wardening is already carried out, but this analysis could inform of the highest risk areas and days that would need more frequent patrolling. Visitors also act as a fire watch.
- *Gully-blocking* is currently being carried out which primarily acts to control and stop gully erosion, to reduce water discharge and to prevent sediment loss from

peatlands. This also acts to reduce fire hazard by retaining water and moisture in the vegetation.

- **Raising public awareness** through signing, leafleting and posters. This is a no regret option.
- **Smoking bans** on access land. This was considered as a possibility, since cigarette pouches have been given out recently.
- **Raising government awareness and lobbying** for central funding. This is another no regret option. Central funding would be extremely valuable to fire management, particularly for fire fighting resources such as helicopters and specialist equipment.
- **Recycling water** would be a preventative measure in extreme risk areas.
- **New water storage** possibilities, e.g. ponding. This will become increasingly important since as the climate warms, there will be more evapotranspiration and less water storage in existing ponds during high fire risk months. Ponds have to be a certain size and depth to be used by helicopters, and
- **Moor closure** was considered an.
- **Dousing moors with water**. Wetting vegetation in particularly dry periods to aim to prevent fire ignition and spread.
- **Management of visitors**. Moor closure is one extreme and controversial management option that has been necessary in the past. In addition, other access restrictions, including access to car parks, could be imposed during high risk periods.

Changes post CRow

It should be stressed that the Peak District has led the way in managing moorland fire risk. FAP and FOG, like MFF, exemplify the partnership approach needed to tackle the implications of climate change in the rural uplands.

Despite this, the future of FAP is uncertain, and, with it, the role of local control over management responses to fire risk. Under the CRow act, local land managers will no longer be able have an input into moor closures decisions; they will be taken nationally, triggered automatically when the Fire Secerity Index reaches a critical threshold. Given that MORECS failed to signal the need for moor closures in April 2003, the Countryside Alliance and the Moorland Association have expressed concern about sole reliance on the new index to signal fire risk (Baynes and Bostock, 2003).

5.3 Policy recommendations

Climate change is likely to bring hotter, drier summers, affecting the soil moisture and evapotranspiration from moorland vegetation. This is likely to increase the probability of wildfires, as well as the severity of fires and the area burnt. The number of multiple fire days is also likely to increase. Management of fires will be increasingly difficult, and it will be particularly difficult to control managed fires. Implications for management have already been discussed. Policy recommendations are summarised below.

- The continuation of rotational burning practises on heather moor is important, as it reduces fuel load and therefore fire risk, but even more careful control of the fire will be required as escapes will be more likely.
- Moorland restoration works, such as the reseeded and gully-blocking being undertaken by Moors for the Future, should be continued because they are likely to reduce fire risk by creating less vulnerable habitats and raising the water table. Bare peat areas close to paths, roads and car parks on Access Land should be prioritised. Monitoring will be required to gauge the response of restored areas to climate change, especially for species at their limit of their range. The accumulation of (ungrazed) brown biomass on vegetated patches within reseeded areas should be monitored and the policy of sheep exclusion reviewed if required.
- The combination of increased access under CRoW and climate change will increase fire risk which will require moor closure and other access restrictions, but needs to be accompanied by additional fire watches so that fires do not go un-reported.
- Preventative measures, such as wetting and fire watch monitoring, and fire fighting (equipment, fire ponds) should be located close to paths and roads.
- Fires boundaries should be mapped by rangers using GPS-mapped (to allow centroid and area to be calculated) and the inferred ignition point located. Fires since June 2004 in the ranger's fire log should be compiled into a digital data base to complement the one used here. It should include: the centroid (centre point) of the burned area; its area; the inferred fire ignition point and confidence in this data; inferred cause and confidence.
- Metadata for spatial data layers for the PDNP is patchy. Work being undertaken by MFF to build a complete metadata database should be actively encouraged so that thematic and geometric accuracy of derived map products such as the fire risk map is known.
- The probit model is tailored to local conditions so should be used to supplement the Met Office Fire Severity Index in identifying high fire risk days. Dry, hot spring bank holidays are particularly critical.
- The methods of spatial and temporal modelling developed here justify further work, as detailed below. The fire risk map should then be used to identify other high risk areas where prevention measures and fire-fighting equipment can be located, and the spatial model can be used predict the impact on proposed measures fire risk.
- The Peak District National Park has pioneered a partnership approach to management, as exemplified by MFF and FAP. It is an effective way of managing increased fire risk and the other implications of climate change and should be continued. The participation of a wide range of stakeholders and the incorporation of local knowledge will lead to more effective fire risk management.
- The cost of fighting moorland fires should be reviewed, for instance, inclusion of moorland fires in Fire Service annual budgets and whether landowners should meet the full cost of helicopter hire.

5.3.1 Further Research

There is great potential for further research on moorland wildfires in the Peak District National Park. Some research areas include:

- Use of recorded fire data from other sources. It would be particularly valuable to use fire data from the fire stations surrounding the Peak District National Park, since some fires close to roads may be attended by the fire services and not PDNPA rangers.
- Examination of additional data in the original fire database may be of interest, such as looking at the relationships between the size of the fire and weather/location. This was omitted from the current work as not all fires had information on fire size. Additionally, the spatial modelling was only carried out for the Dark Peak ESA, due to habitat data. This could be extended and an analysis carried out for the South-West Peak ESA.
- Use of additional weather and climate data would benefit the temporal analysis. This could include the use of wind speed (omitted from this study due to incomplete records). Wind speed data may correlate well with fire area, since it is believed to influence spread of fire. Additionally, weather data from other location such as Holme Moss could be used for the limited dates available (again, Holme Moss was omitted from this study due to incomplete records, as the weather station closed in 1995). Further, the analysis would benefit from climate change data from Buxton (by running the weather generator for Buxton), as unfortunately this was not available in the timescale).
- Spatially-distributed climate data could possibly be added to the spatial database by interpolating between available rainfall gauges or by using hydrological models based on digital elevation data.
- Work on selection, scoring and weighting spatial layers would improve the model. Involving stakeholders in these decisions would allow perceptual models of fire risk to be compared.
- A pilot study using archive and new satellite remote sensing could be carried out to compare detection of active fires against reported fire in the ranger's fire log.
- A model could be created that combined results from the spatial and temporal analysis, by creating separate models for high and low risk habitats or spring and summer fires.

5.4 Acknowledgements

The work is part of the Climate Change and the Visitor Economy in the Northwest (CCVE) project, carried out by CURE and Sustainability Northwest, and funded by Defra and the Northwest Development Agency. We wish to thank:

- The Peak District National Park (PDNP) and Moors for the Future (MFF) for access to the rangers' fire log
- MFF, Defra and other stakeholders for access to digitised maps
- Participants of CCVE Fire Risk workshop January 2005 for advice on fire risk and management in the PDNP
- The University of Manchester for Richard Karooni's postgraduate part-bursary for the MSc in Environmental Monitoring, Modelling and Reconstruction. Much of the work was originally carried out for RK's dissertation.

6. References

- Abramson, B., Brown, J., Edwards, W. Murphy, A. & Winkler R.L. (1996). Hailfinder: A Bayesian system for forecasting severe weather. *International Journal of Forecasting*, 12, 1, 57-71.
- Agnew, M.D. (1997). Tourism. In: J.P. Palutikof, S. Subak & M.D. Agnew (Eds.). *Economic Impacts of the Hot Summer and Unusually Warm Year of 1995*, 157-162, London: Department of the Environment.
- Aguado, I., Chuvieco, E., Martin, P., Salas, J. (2003). Assessment of forest fire danger conditions in southern Spain from NOAA images and meteorological indices. *International Journal of Remote Sensing*. 24, 1653 – 1668.
- Albertson, K. & Ayles, J. (1996). Modelling the Great Lakes Freeze: forecasting and seasonality in the market for ferrous scrap. *International Journal of Forecasting*, 12, 3, 345-359.
- Albertson, K., Ayles, J & Cavan, G. (2005). Visitor Attraction figures in relation to climate: The potential impact of global climate change on zoos, 5th *International Zoo and Aquarium Marketing Conference, Allwetterzoo, Münster, Germany, 1st- 4th June* (forthcoming, Conference Proceedings).
- Allgower, B *et al.* (2002) *Methods for Wildland Fuel Description and Modelling: a state of the art*. EUFIRELAB: Euro-Mediterranean Wildland Fire Laboratory, a ‘wall-less laboratory for wildland fire sciences and technologies in the Euro-Mediterranean region. Deliverable D-02-01. Available online [accessed 2 Oct 2005] http://www.eufirelab.org/prive/directory/units_section_2/D-02-01/D-02-01.pdf
- Anderson, P. (1986). *Accidental Moorland Fires in the Peak District: A Study of their Incidence and Ecological Implications*, Buxton: Peak District Moorland Restoration Project.
- Anderson, P.A., Tallis, J.H. and Yalden, D.W. (1997). *Restoring Moorlands: The Moorland Management Project Phase 3 Report*, Bakewell: Peak Park Joint Planning Board, 153pp.
- Anderson, P. (1990). *Moorland Recreation and Wildlife in the Peak District*. Report for the Peak Park Joint Planning Board.
- Auslander, M., Nevo, E., Inbar, M. (2003). The effects of slope orientation on plant growth, developmental instability and susceptibility to herbivores. *Journal of Arid Environments*. 55, 405 – 416.
- Bardgett, R.D. Marsden, J.H. Howard, D.C. and Hossell, J.E. (1995). The extent and condition of heather in moorland and the potential impact of climate change. In: D.B.A. Thompson, A.J. Hester, and M.B. Usher. (eds), *Heathland and Moorland, Cultural Landscapes*, Scottish Natural Heritage, HMSO Edinburgh.

Baynes, T. P. and Bostock, S. N. (2003). Burning Issues. Presented at the Wildfire event held in Otterburn, August 2003. Available from:
<http://www.moorlandassociation.org/burn.doc> (last accessed 26/09/05).

BBC News (2003) Wildlife fears as Peak fire rages: helicopters are being used to drop water on a large fire on moorland in the Peak District
http://newswww.bbc.net.uk/2/hi/uk_news/england/derbyshire/2956771.stm [available online, last accessed 30 Dec 2005].

Beven, K. (1997) TOPMODEL: a critique. *Hydrological Processes*, 15: 1069-1085.

Brookes N. (2003) *Vulnerability, risk and adaptation: A Conceptual framework*, Tyndall Centre, University of East Anglia, 16pp.

Brenner, J. Green, K, Coen, J and McLellan S (2001). Assessing Fire Risk in Florida Using Integrated GIS and Remote Sensing Applications. *ESRI 2001 International User Conference*. [available online, accessed Sept 2005]
<http://gis.esri.com/library/userconf/proc01/professional/papers/pap826/p826.htm>

Bruce, M. (2000) 'Embracing fire – an overseas example: forest and moorland fire in Scotland' People Ecosystems and Wildland Fires - working in harmony, 2000, *Interior West Fire Council (IWFC) annual meeting and workshop. 3-5 Oct 2000, Edmonton, Alberta* [available online, last accessed 19 Aug 2005]
<https://secure.modwest.com/interiorwestfirecouncil.org/Proceedings/IWFC2000.pdf>

Bruce, M. (2002). *United Kingdom: Country Report for the United Kingdom*. Available from: http://www.fire.uni-freiburg.de/iffn/country/gb/gb_2.htm (last accessed Sep 2005).

Burington, R.S. (1973). *Handbook of Mathematical Tables and Formulas, 5th Edition*, New York: McGrawHill

Carver, S., Evans. E & Kingston, K. (2002) *Exploring environmental decision making using Internet GIS, Public participation in locating a nuclear waste disposal site*. University of Leeds [available online, last accessed 2 Oct 2005]
<http://www.ccg.leeds.ac.uk/teaching/nuclearwaste/>

Centre of Ecology and Hydrology, CEH. Land Cover Map, [available online, last accessed 2 Oct 2005] http://www.ceh.ac.uk/sections/seo/lcm2000_home.html

Climate Change and the Visitor Economy, CCVE (2005) *Risk Workshop: Moorland Wildfires in the Peak District*. Technical Report, Manchester, UK, 28th January 2005. Manchester, Centre for Urban and Regional Ecology, 2005.

Chuvieco, E., Congalton, R. G., (1989) Application of Remote Sensing and Geographic Information Systems to Forest Fire Hazard Mapping. *Remote Sensing of the Environment*. 29, 147 – 159.

Chuvieco, E., Salas, J. (1996). Mapping the spatial distribution of forest fire danger using GIS. *Geographical Information Systems*. 10, 333 – 345.

Chuvieco, E., Cocero, D., Riaño, D., Maryin, P., Martinez-Vega, J., del la Riva, J. and Pérez, F. (2004) Combining NDVI and surface temperature for the estimation of live

fuel moisture content in forest fire danger rating. *Remote Sensing of Environment*, 92: 322-331.

CURE, Centre for Urban and Regional Ecology (2004). *Climate Change and the Visitor Economy: Inception Report*. Manchester: CURE, University of Manchester, February (available online, last accessed 9 June 2005).

<http://www.art.man.ac.uk/PLANNING/cure/PDF/inception.pdf>

Chandler, R.E. and Wheater, H.S. (1998). *Climate Change Detection using Generalized Linear Models for Rainfall – a case study from the West of Ireland, II. Modelling of Rainfall Amounts on Wet Days*. London: University College London, Department of Statistical Science, Research Report no. 195, June, [available online, last accessed, 20 June 2005] <http://www.ucl.ac.uk/Stats/research/Resrprts/abs98.html>

Coe, R. and Stern, R.D. (1982). Fitting models to daily rainfall data. *Journal of Applied Meteorology*, 21, 1024-31

CRU (2005). Daily time-series output and figures from the CRU weather generator, [available online, last accessed 21 July 2005]

<http://www.cru.uea.ac.uk/projects/betwixt/cruwg-daily/>

Davidson, J.E.H., Hendry, D.F., Srba, F. and Yeo, S. (1978). Econometric modelling of the aggregate time-series relationship between consumers' expenditure and income in the United Kingdom. *Economic Journal*, 88, 352, 661-692

Davies, M. (2003). Fire behaviour and characteristics on heather moorland. [available online, last accessed 14 Sept 2005]

<http://homepages.ed.ac.uk/ebfr89/firebeat/home.htm>).

Davison, A.C. & Smith, R.L. (1990). Models for exceedances over high thresholds. *Journal of the Royal Statistical Society, Series B*, 52, 3, 393-442

Dayananda, P.W.A. (1977). Stochastic models for forest fires. *Ecological Modelling*, 3, 4, 309-313

Department of Environment, Food and Rural Affairs (formerly Ministry of Agriculture, Fisheries and Food). (1996). *The Heather and Grass Burning Code*. London: MAFF Publications, PB 1029. <http://www.defra.gov.uk/rds/hgbc.pdf> last downloaded 9th June 2005.

Defra, Department of Environment, Food and Rural Affairs (1999). *Appraisal of Options on Access to the Open Countryside of England and Wales*. Available [available online, last accessed last accessed 4 Oct 2005]. <http://www.defra.gov.uk/wildlife-countryside/access/appraise/index.htm>

DTI (2003). *Energy White Paper - our energy future: creating a low carbon economy*. Department of Trade & Industry, London.

Evans, A.J. Kingston, R. and Carver, S. (2004). Democratic input into the waste disposal problem. *Journal of Geographical Systems*, 6: 117-132.

Galicia, L., López – Blanco, J., Zarco – Arista, A. E., Filips, V., García – Oliva, F. (1999). The relationship between solar radiation interception and soil water content in a tropical deciduous forest in Mexico. *Catena*. 36, 153 – 164.

Franses, P.H. (1996). *Periodicity and Stochastic Trends in Economic Time-series*, Oxford University Press

Gaines, S.D. & Denny, M.W. (1993). The largest, smallest, highest, lowest, longest, and shortest: extremes in ecology. *Ecology*, 74, 6, 1677-1692

Gilbert, C.L. (1986). Professor Hendry's econometric methodology. *Oxford Bulletin of Economics and Statistics*, 48, 3, 283-307

Giles, A.R. and Perry, A.H. (1998). The use of a temporal analogue to investigate the possible impact of projected global warming on the UK tourist industry, *Tourism Management*, 19, 1, 75-80

Gimingham, C. (1972). *Ecology of Heathlands*. Chapman and Hall.

Hough, M. N. and Jones, R. J. A. (1997). The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0 – an overview. *Hydrology and Earth System Sciences*, 1(2), 227-239.

Hudson, P. (2000). Impact of public access on grouse management. [available online, last accessed 4 Oct 2005].

http://www.countryside.gov.uk/LAR/Recreation/NCAF/NCAF6_2.asp

Hulme, M. Jenkins, G.J. Lu, X. Turnpenny, J.R. Mitchell, T.D. Jones, R.G. Lowe, J. Murphy, J.M. Hassell, D. Boorman, P. McDonald, R. and Hill, S. (2002). *Climate change scenarios for the United Kingdom: the UKCIP02 scientific report*. Oxford: United Kingdom Climate Impacts Programme, April.

IPCC, Intergovernmental Panel on Climate Change (2005). About stochastic weather generators at http://ipcc-ddc.cru.uea.ac.uk/ddc_weather_generators.html accessed 14th July 2005.

Jaiswal, R. K., Mukherjee, S., Raju, K. D., Saxena, R. (2002). Forest fire risk zone mapping from satellite imagery and GIS *International Journal of Applied Earth Observation and Geoinformation*. 4, 1 – 10.

Johnston, J. & DiNardo, J. (1997). *Econometric Methods*, New York: McGraw-Hill, fourth edition.

Jones and Salmon (1995). Development and Integration of a Stochastic Weather Generator into a Crop Growth Model for European Agriculture. Final report to Institute of Remote Sensing Applications, Agricultural Information Systems, MARS Project under contract NO. 5631-93-12 ED ISP GB.

Katz, R.W., Brush, G.S. & Parlange, M.B. (2005). Statistics of extremes: modelling ecological disturbances, *Ecology*, 86, 5, 1124-1134.

Liddle, M.J. (1975). A theoretical relationship between the primary productivity of vegetation and its ability to tolerate trampling. *Biological Conservation* 103: 3-14.

Lindley, S. J. (2001). Virtual tools for complex problems – an overview of the AtlasNW regional interactive sustainability atlas for planning for sustainable development *Impact Assessment and Project Appraisal*, 19 (2): 141-151.

Mackay A.W and Tallis J.H (1996). Summit-type blanket mire erosion in the forest of Bowland, Lancashire, UK: predisposing factors and implications for conservation, *Biological Conservation*, 76,1, 31-44.

Maddala, G.S. (1983). *Limited-Dependent and Qualitative Variables in Econometrics*, Cambridge U.P.

Mayes, J. (1996). Spatial and temporal fluctuations of monthly rainfall in the British Isles and variations in the mid-latitude westerly circulation. *International Journal of Climatology*, 16, 5, 585-596.

Met Office. MORECS, *Met Office Rainfall and Evaporation Calculation System*, [available online, last accessed 2 Oct 2005], <http://www.metoffice.com/environment/morecs.html>

Met Office (2005) The Met Office Fire Severity Index for England and Wales. [available online, last accessed 30 Dec 2005] http://www.openaccess.gov.uk/lwwcm/resources/file/ebc7ac43784c72a/Index_Report_final_version3.0.doc

Milne, J.A. and Hartley, S.E. (2001). Upland Plant Communities: Sensitivity to Change. *Catena* 42: 333-343.

McEvoy, D. Lindley, S. Handley, J. McMorrow, J. and Cavan, G. (2005). Changes to climate and visitor behaviour: implications for vulnerable landscapes in the North West region of England. Submitted to *Sustainable Tourism*.

McMorrow, J.M. and Worman, C. (2002). Dark Peak Fieldwork website [available online, accessed 4 Oct 2005] <http://www.art.man.ac.uk/Geog/fieldwork/>

Morehouse, B.J. (2001). Climate, forest fires, and recreation: insights from the U.S. Southwest, *Proceedings of the First International Workshop on Climate, Tourism and Recreation*, A. Matzarakis and C.R. de Freitas (Eds.), 41-50, Porto Carras, Halkidiki, Greece. International Society of Biometeorology, [available online, last accessed 25th May 2005] <http://www.mif.uni-freiburg.de/isb/ws/report.htm>

Moors for the Future Partnership, MFF (2005a). *Moors for the Future Maps (September 2005)*, Castleton: MFF.

Moors for the Future Partnership, MFF (2005b). Fire protection. [available online, last accessed 30 Dec 2005] <http://www.moorsforthefuture.org.uk/mftf/information/fire.htm>

Moors for the Future Partnership, MFF (2005c). Fire Kills. Moor care leaflet. [available online, last accessed 30 Dec 2005] <http://www.moorsforthefuture.org.uk/mftf/downloads/moor%20care/Fire%20Kills%20Leaflet.pdf>

Moors for the Future Partnership, MFF (2005d). Information on Peak District National Park Fire Advisory Panel (FAP) and Fire Operations Group (FOG), [available online, last accessed 30- Dec 2005] <http://www.moorsforthefuture.org.uk/mftf/downloads/FAP%20&%20FOG%20objectives.doc>

Morgan, P. Hardy, C.C., Swetnam, T.W. Rollins, M.G. and Long, D.G. (2001). Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. *International Journal of Wildland Fire* 10: 329-342.

Natural Resources Canada. *Canadian Wildland Fire Information System, Fighting Wildland Fire with Technology* [available online, accessed 2 Oct 2005] http://cwfis.cfs.nrcan.gc.ca/en/publications/fighting_fire_tech_e.php

Open.gov (2005). *Met Office Fire severity index* [available online, last accessed 30 Dec 2005] http://www.openaccess.gov.uk/wps/portal/lut/p.cmd/cs.ce/7_0_A/s/7_0_G3/s.7_0_A/7_0_G3

Osborn, T.J., Hulme, H., Jones, P.D. & Basnett, T.A. (2000). Observed trends in the daily intensity of United Kingdom precipitation, *International Journal of Climatology*, 20, 4, 347-364.

Osborn, T.J. & Hulme, H. (2002). Evidence for trends in heavy rainfall events over the UK, *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 360, 1796, 1313-1325.

Palutikof, J.P. (1997). Fire. In: J.P. Palutikof, S. Subak & M.D. Agnew (Eds.). *Economic Impacts of the Hot Summer and Unusually Warm Year of 1995*, 157-162, London: Department of the Environment

Peak District National Park Authority (2001). Peak District Fact Sheets. [available online, last accessed 14 Sep 2005]: <http://www.peakdistrict.org/>

Peak District National Park Authority (20??). Peak District National Park Management Plan 2000-2005. available online, last accessed 25 Sep 2005] <http://www.peakdistrict.org/pubs/manplan.pdf>

Peak District National Park Authority (20??). State of the Park Report 2000.

Radley, J. (1965). Significance of major moorland fires, *Nature*, 215, March 27, 1254-1259.

Ryan, K.C. (1991). Vegetation and Wildland Fire: Implications of Global Climate Change. *Environment International* **17**: 169-178.

Schoenberg, F.P., Peng, R. & Woods, J. (2003). On the distribution of wildfire sizes, *Environmetrics*, *14*, 6,583-592.

Shackley, S, Wood, R., Hornung, M., Hulme, M., Handley, J., Darier, R., and Walsh, M. (1998). *Everybody Has An Impact: Changing By Degrees: The Impact of Climate Change in the North West of England*. Manchester: Sustainability North West.

Shaw, S. C., Wheeler, B. D., Kirby, P., Phillipson, P. & Edmunds, R. (1996). *Literature Review of the Historical Effects of Burning and Grazing of Blanket Bog and Upland Wet Heath*. English Nature Research Reports, Number 172. Peterborough: English Nature and Countryside Council for England and Wales.

Spanos, A. (1999). *Probability Theory and Statistical Inference: Econometric Modelling with Observational Data*, Cambridge U.P.

Stern, R.D. & Coe, R. (1984). A model fitting analysis of rainfall data, *Journal of the Royal Statistical Society, Series A*, *147*, 1, 1-34.

Setiawan, I., Mahmud, A.R., Mansor, S., Mohamed Shariff, A.R., Nuruddin, A.A. (2004) 'GIS – grid – based and multi – criteria analysis for identifying and mapping peat swamp forest fire hazard in Pahang, Malaysia' *Disaster Prevention and Management*. *13*, 379 – 386.

Telltale and Countryside Training Partnership (2004). Celebrating the Peak District Landscapes: Landscape Interpretation Plans for the Peak District. Pp 82. [available online, last accessed 25 Sep 2005]

<http://www.moorsforthefuture.org.uk/MFF/downloads/moor%20care/LANDIPS%20Final%20report%2012%20Dec%20LE.pdf>

Thompson, R. (1999). A time-series analysis of the changing seasonality of precipitation in the British Isles and neighbouring areas. *Journal of Hydrology*, *224*, 169-183.

Trotter, S. (2003). Burning up; the causes and impacts of moorland wildfires. [available online, last accessed 30 Dec 2005]

http://www.thebmc.co.uk/safety/advice/articles/31_fires.pdf

Vakalis, D., Sarimveis, H., Kiranoudis, C., Alexandris, A., Bafas, G. (2004) A GIS based operational system for wildland fire crisis management. I. Mathematical modelling and simulation. *Applied Mathematical Modelling*. *28*, 389 – 410.

Ward, L.K (1993). Fires and the hot dry summers 1989 and 1990, *Impacts of the Mild Winters and Hot Summers in the United Kingdom in 1988-1990*, M.G. R. Cannell and C.E.R. Pitcairn (Eds.), 113-114, London: HMSO for the Department of the Environment.

Watt (1954). Frost and the advance and retreat of bracken, *New Phytologist*, 53, 117-130.

Watts, M., Goodess, C.M. & Jones, P.D. (2004). The CRU daily weather generator, *BETWIXT Technical Briefing Note 1, version 2*, February, Norwich: Climatic Research Unit, University of East Anglia [available online, last accessed 21 July 2005] http://www.cru.uea.ac.uk/projects/betwixt/cruwg_daily/

Wilks, D.S. & Wilby, R.L. (1999). The weather generation game: a review of stochastic weather models. *Progress in Physical Geography*, 23, 3, 329-357.

Wotton, B. M. Flannigan, M. D. (1993). Length of the fire season in a changing climate, *The Forestry Chronicle*, 69, 2, 187-192.