MODELLING THE EFFECTS OF CLIMATE CHANGE ON WILDFIRE RISK FOR A REGION IN SOUTH EAST SPAIN

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This dissertation is submitted as an Independent Geographical Study as a part of a BSc degree in Geography at King's College London.

Abstract

A Geographical Information System (GIS) was used to selectively weight variables concerned with the ignition of wildfire to produce a simple risk model. This model structure was used to gauge the effects of climate changes predicted by three General Circulation Models on wildfire risk for a small area of south east Spain. The results illustrate that predicted changes would increase wildfire risk. Further, heterogeneity of wildfire risk is not shown to increase but warmer, drier areas are found to be most sensitive to climate change, changing at a rate faster than surrounding areas. The methodology used is justified, though there are many areas for improvement and extension. In this sense, the model is merely a first step in producing an integrated climate change impact assessment model for wildfire risk.

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INTRODUCTION

1.1 Wildfire as a Hazard

During 1994, 17,156 fires in Spain, a country particularly susceptible to wildfire, burnt over 405,000 hectares of forest, woodland and grazing land, damaged farm and holiday buildings, and caused the deaths of 22 people (Vélez 1995). Though an extreme year, this case illustrates the importance of understanding the risk that wildfire hazard imposes. As with many other natural hazards, scientists attempt to reduce risk to human welfare by forecasting the probability that such events will occur at a given time in a given location. Further, the effects of fire as an ecological disturbance are of interest to environmental managers. Risk evaluation is used to manage the environment in question to reduce threat.

Evaluation of the danger wildfire causes partly demands the consideration of factors involved in the ignition of a fire in the natural environment. These factors include the vegetation (fuel) available to burn, topography, human activities, and climatic conditions (Yool *et al.* 1985, Whelan 1995, Chuvieco and Salas 1996, Camia *et al.* 1999, Chuvieco *et al.* 1999). In particular, climatic conditions are important for determining both fuel conditions and the global distribution of regions particularly susceptible to wildfire occurrence. For example, Smith (1992) notes that regions with a mediterranean, semi-arid climate exhibit conditions that make them most susceptible to wildfire. Extreme weather conditions are attributed as being the predominant driving force behind the severe 1994 fire season in Spain mentioned above.

The recent debate on the possibility of climatic change due to anthropogenic factors, fuelled by research and publications such as the Intergovernmental Panel on Climate Change (IPPC) Third Assessment Report (TAR) (IPCC 2001), has major implications for regions highly susceptible to wildfire. Deviation from current climatic conditions may mean changes in the probability of wildfire occurrence and the spatial distribution of this risk. As transitional climate regions, mediterranean regions may experience the most pronounced effects of climate change (Lavorel *et al.* 1998).

1.2 Objective and Aims

The specific objective of this study is to model wildfire risk for a small area of south east (SE) Spain, analysing the sensitivity of wildfire risk to climatic variables and relating this to current climate model predictions of future climate. The objective will be reached by completion of two aims:

1. To build a wildfire risk model using a Geographic Information System (GIS) predicting wildfire risk for the Rambla de Nogalte river catchment in SE Spain (Figure 1),
2. To use this model to analyse the sensitivity of wildfire risk to changes in climatic variables, in line with current General Circulation Models' (GCMs) predictions of future climate.

Thus, it will be possible to illustrate how wildfire risk in SE Spain may be affected by changes in climate. The hypothesis explored here is that predicted changes in future climate, i.e. increases in temperature alongside decreases, or at best no change, in rainfall (Handmer *et al.* 1999), will cause a general increase in wildfire risk. Further, changes in the spatial pattern of wildfire risk will be examined, including its heterogeneity and variance from current conditions. Finally, this study will explore the potential of the model produced for future analysis, highlighting improvements and developments for more rigorous assessment.

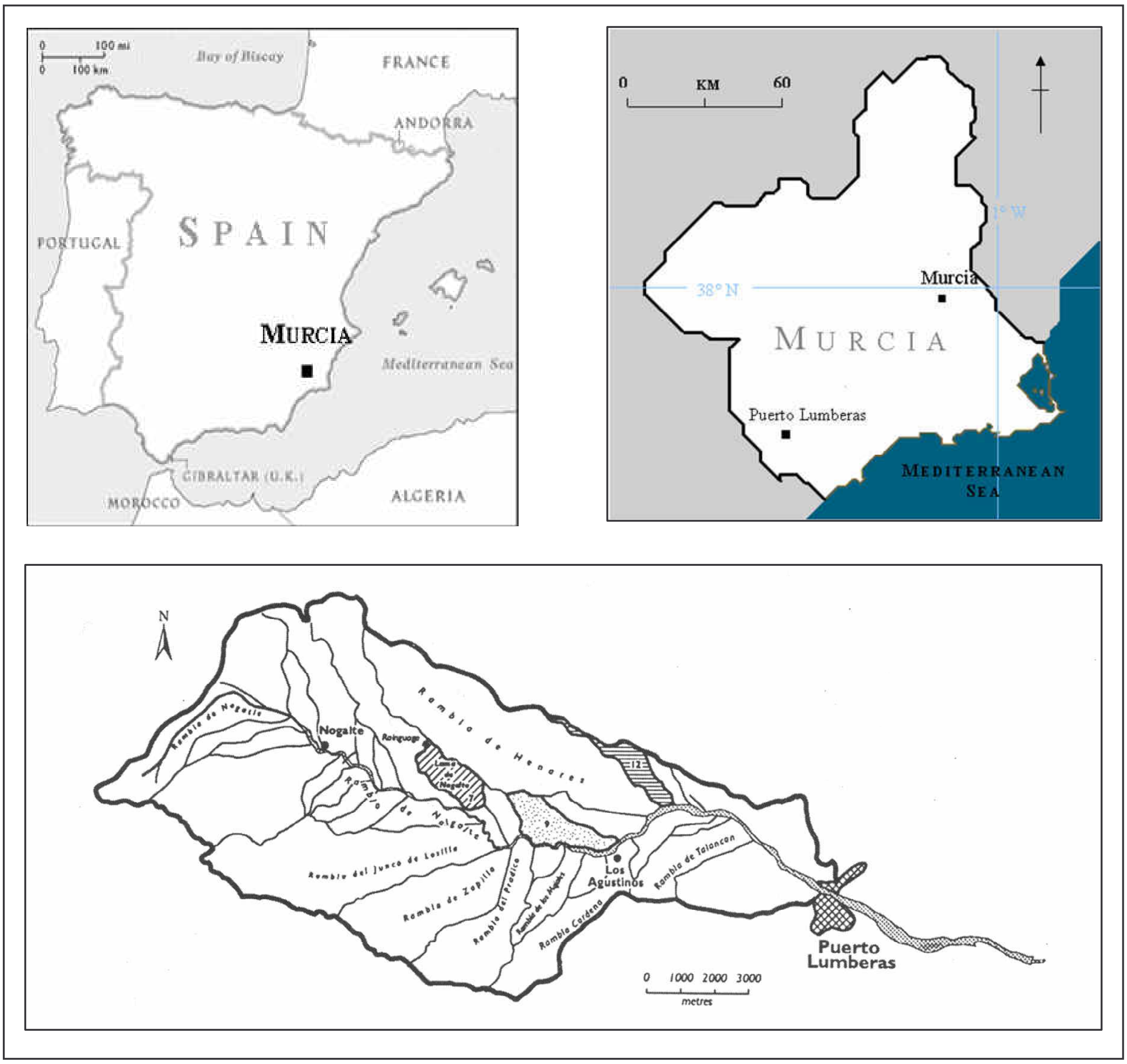


Figure 1. Location of the study area. These maps, of various scale, depict the location of the study area in the province of Murcia, SE Spain.

Sources: Región de Murcia (1999), Thornes *et al.* (2000), National Geographic (2001)

1.3 The Study Area

The study area for this wildfire risk study is the Rambla de Nogalte river catchment in SE Spain. In the province of Murcia, the town of Puerto Lumberas lies on its border (Figure 1). The elevation of the predominantly phyllite catchment ranges from 450 m to above 1200 m, and has an area of 171 km^2 (Thornes *et al.* 2000). Landuse is mostly tree crops, olives and almonds, with other areas of mattoral, less dense scrub, wheat, oak trees or bare ground (Bull *et al.,* In press).

1.4 Defining Wildfire Risk

It is important to note that a distinction must be made between wildfire hazard, risk and danger. Though poor usage of such terms has been recognised (see Bachmann and Allgöwer 1998, Allard 1999) there is still no universally recognised terminology. Table I compares some published definitions of the terms *'risk'* and *'hazard'*, throughout which there is agreement that '*risk'* concerns the probability or likelihood of an event, i.e. a wildfire, occurring. This element will be kept throughout this study, ignoring impacts upon humans. The definition of risk used here is thus:

> *The likelihood of a wildfire occurring, due to factors governing its ignition.*

Table I. Definitions of the terms *'risk'* and *'hazard'*. This table has been split into specific wildfire definitions (above) and generic natural hazard definitions (below).

Author	*Definition of 'risk'*	*Definition of 'hazard'*
FAO (1986) from Bachmann and Allgöwer (1998)	"The chance of fire starting, as affected by the nature and incidence of causative agencies." (p. 2179)	"A measure of that part of the fire danger contributed by the fuels available for burning." (p. 2179)
Chuvieco and Congalton (1989)	None.	A measure of the fuel sources available for burning. (p. 148)
Bachmann and Allgöwer (1998)	"The probability of a wildfire to occur at a specified location and under given circumstances, and its expected damage on endangered objects." (p.2179)	None.
Chatto (1998)	"The probability that a fire will start. This should take into account the probability of both natural and unnatural causes." (p. 2248)	"Hazard is the potential for fire behaviour." (p. 2249)
Allen (1992) from Bachmann and Allgöwer (1998)	"The likelihood of specific undesired events occurring within a specified period or in specified circumstances arising from the realization of a specified hazard." (p. 2179)	"A physical situation with a potential for human injury, damage to property, damage to the environment or some combination of these." (p. 2179)
Smith (1992)	"The probability of hazard occurrence." (p. 6)	"A potential threat to humans and their welfare." (p. 6)

2

LITERATURE REVIEW

2.1 Impacts of Climate Change on Wildfire

In 1992, Torn and Fried highlighted that up until that point there had been "virtually no analysis of how climate warming would affect fire danger" (p. 257). It has only been in the last decade of the twentieth century that the global fire and climate research communities have undertaken the work of analysing if, and how, any changes in climate will affect the occurrence and frequency of wildfire.

Much research in this field has focused on boreal forest ecosystems, in particular in Canada. Stocks *et al.* (1998) compare the outputs of four GCMs, all of which indicate that there may be increases in fire severity and fire season length. With much finer spatial resolution, Regional Climate Models (RCMs) have also been used for study of wildfire in boreal forest. For example, Wotton *et al.* (1998) use an RCM to present similar findings to Stocks *et al.* (1998) and note that developments in RCMs will improve predictive capabilities in the future, as the effects of smaller scale landscape features, such as lakes, can be included.

However, Bergeron and Flannigan (1995) and Flannigan *et al.* (1998a) caution that while these increases in Canadian wildfire activity are probable, they will not be uniform and some areas may even experience decreases. This is compounded by Flannigan *et al.* (1998b) who conclude that fire frequency may be reduced for large regions of the northern hemisphere. By the definition used here, reduced frequency will mean reduced wildfire risk. However, it does not necessarily mean reduced wildfire danger, as the few fires that do occur will probably be larger and more intense due to the greater build up of fuel.

None of this research has specifically considered the impacts of climate change on wildfire risk in the mediterranean climate and vegetation of SE Spain. Studies of wildfire in the Mediterranean basin are numerous and detailed (Salas and Chuvieco 1994, Alcázar *et al.* 1998, Bovio and Camia 1998, Jiménez *et al.* 1998, Núñez-Regueira *et al.* 2000) but their consideration of the effects of climate change has been limited. Those that have considered the wildfire/climate change relationship have used observed data to draw empirical conclusions for the past (Vázquez and Moreno 1993, De Luís *et al.* 2001).

Vázquez and Moreno (1993), show that changes in climatic variables are related to increases in wildfire occurrence frequency and area burned, but that they are not the sole factor. Piñol *et al.* (1998) agree with this, attributing increases in wildfire hazard indices and area burned of a region in north east Spain to changes in temperature and relative humidity. However, other studies suggest human influence has caused changes in wildfire activity, not climatic influence (Moreno 1996). De Luís *et al.* (2001) use observed rainfall data for 1961 – 1990 to conclude that climatic conditions, particularly annual rainfall averages, may have become more favourable for wildfire and that this may continue in the future. They suggest that increases in burned area for this period across the region of Valencia, SE Spain, are driven by a combination of climate and land-use change. Thus, change in wildfire activity recently has been influenced by both climatic and human factors.

The majority, and most recent, of these studies have shown that changes in weather conditions, notably warming and drying (Piñol *et al.* 1998), have led to increases in wildfire activity in the Mediterranean. Wildfire risk evaluation for future climate has yet to be conducted for the Mediterranean in the same way it has for boreal forests. This study aims to begin to fill this gap in current research by building on recent wildfire risk models, and applying them to explore impacts of climate change.

2.2 Recent Wildfire Risk Modelling in the Mediterranean

On a large-scale, the Megafires project (Chuvieco 1997, UAH 1999) took into account five European countries particularly susceptible to wildfire. At a provincial resolution, the project predicted fire occurrence between 1991 and 1995 (Chuvieco *et al.* 1998). However, large scale studies, such as those in Boreal forest above, are less common because of the Mediterranean's more densely populated and intensively used landscape. Therefore, local-scale risk mapping at much smaller spatial resolutions (see Table II) has been more common, and is reviewed in more detail here.

Table II. Spatial scales of previous wildfire risk evaluation studies. These spatial resolutions are all comparable to the 50 m resolution of the wildfire risk model created here.

Study	*Spatial Resolution*
Chuvieco and Congalton 1989	50 m
Salas and Chuvieco 1994	50 m
Chuvieco and Salas 1996	30 m
Castro and Chuvieco 1998	50 m

The temporal scale also needs to be considered when mapping wildfire risk: do we want to analyse long- or short-term changes in risk? (Chuvieco *et al.* 1999)

Inherently this study considers long-term risk, i.e. over decades, as the impacts of climate change cannot be evaluated at the short-term (e.g. daily) basis.

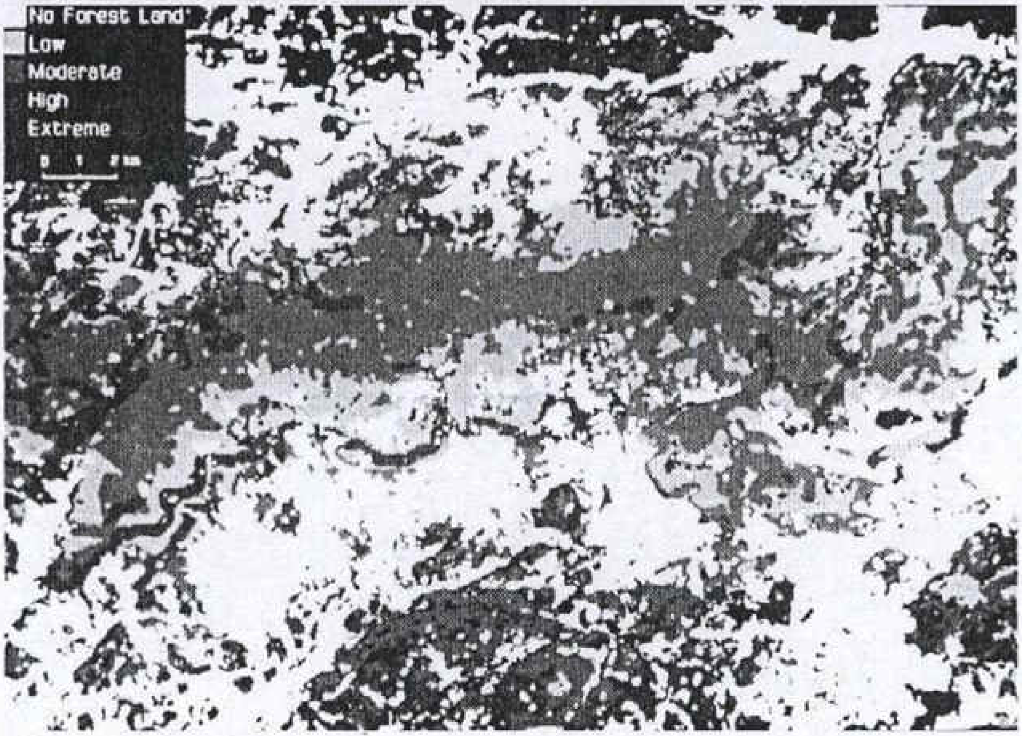


Figure 5. Final Fire risk map: (1) Low, (2) Moderate, (3) High and (4) Extreme risk

Figure 2. Example output of a wildfire risk map created using a GIS. This type of output, produced by Chuvieco and Salas (1996), will be produced for various climatic conditions here.

All wildfire risk mapping studies in the Mediterranean reviewed here (Table III) use Geographic Information Systems (GIS) to integrate several layers of spatial, wildfire-related data to derive maps of risk for their study areas (for example see Figure 2). This approach has been the most frequent use of GIS in wildfire modelling studies (Perry 1998) and stems from their utility to represent, analyse, and manipulate spatial data. Further, these studies have predominantly used a qualitative-objective method, using variables concerning the condition of vegetation (fuel) available to burn and the presence of human activity. This method assesses risk by assigning specific values to combinations of risk-related variables according to their importance (Chuvieco *et al.* 1999).

Table III. Spatial data used by various studies using GIS to evaluate wildfire risk. 'Y' indicates data was used, 'N' that it was not.

	Yool et al. (1985)	*Chuvieco and Congalton (1989)*	*Salas and Chuvieco (1994)*	*Chuvieco and Salas (1996)*	*Castro and Chuvieco (1998)*
Vegetation (Fuel)	Y	Y	Y	Y	Y
Elevation	N	Y	Y	N	N
Aspect	Y	Y	Y	Y	Y
Slope Angle	Y	Y	N	Y	Y
Wildfire History	Y	N	N	N	N
Temperature	N	N	N	Y	Y
Air Humidity	N	N	N	Y	N
Rainfall	Y	N	N	N	N
Human Activity	N	Y	Y	Y	Y

Table III is a useful aid to compare and contrast the studies using this methodology reviewed here. All four of the studies in which Chuvieco has partaken have been set in Spain and in each of these vegetation, human and aspect data have been assessed as necessary components of the model. Slope is considered in all except Chuvieco and Congalton (1989).

Salas and Chuvieco (1994), claim clear evidence for human influence is shown in their analysis of Spanish fire reports between 1968 and 1988. This shows most fires were started at weekends and during summer holidays, and near roads and trails. The summer holidays are the hottest and driest time of the year, with vegetation at its driest and most people using the landscape for recreation, and thus would expect to experience most fires. Similar analyses by Chuvieco and Salas (1996) and Vázquez and Moreno (1998) also found that most fires were started near roads and trails, though both used shorter data sets.

Climatic variables are less prominent in these studies, though Yool *et al.* (1985), Chuvieco and Salas (1996), and Castro and Chuvieco (1998) do integrate some into their risk indexes. Vázquez and Moreno (1993) give two good reasons for this. First, while fire is undoubtedly affected by weather, meteorological variables have not been shown to be strongly correlated to wildfire occurrence and thus other variables take greater priority. Second, "the most relevant weather variables for this purpose are generally not available from observatories"(p. 129). However, they go on to show that basic, widely available climate variables such as mean temperature and total precipitation *do* predict wildfire occurrence well and can be used to model wildfire risk for future changes in climate. This suggests a component of this type of modelling that has not been explored in full.

2.3 Climate Change and the Mediterranean

The Earth has a natural mechanism for maintaining atmospheric temperature, often referred to as the 'greenhouse effect'. Changes in climate, due to enhancement of this mechanism, are largely believed attributable to the emission of gases produced by human activity causing changes in the composition of the atmosphere (Kessel 2000). Potential changes in the climate can be examined by looking for trends in observed variables or by attempting to forecast changes using models.

Piñol *et al.* (1998) found temperature to have increased by 0.1 ºC per decade for the period 1910 – 1994 for north east Spain, and De Luís *et al.* (2001) found precipitation to have generally decreased between 1961 and 1990 for a region of SE Spain (Figure 3). De Luís *et al* do note, however, that their 30-year period of study does not necessarily show a trend in climate, but may instead be due to climate variability, a point not raised by Piñol *et al.* (1998). In a similar study, Palutikof *et al.* (1996a) show drying trends for the Mediterranean since the mid-twentieth century from empirical observation (Figure 3).

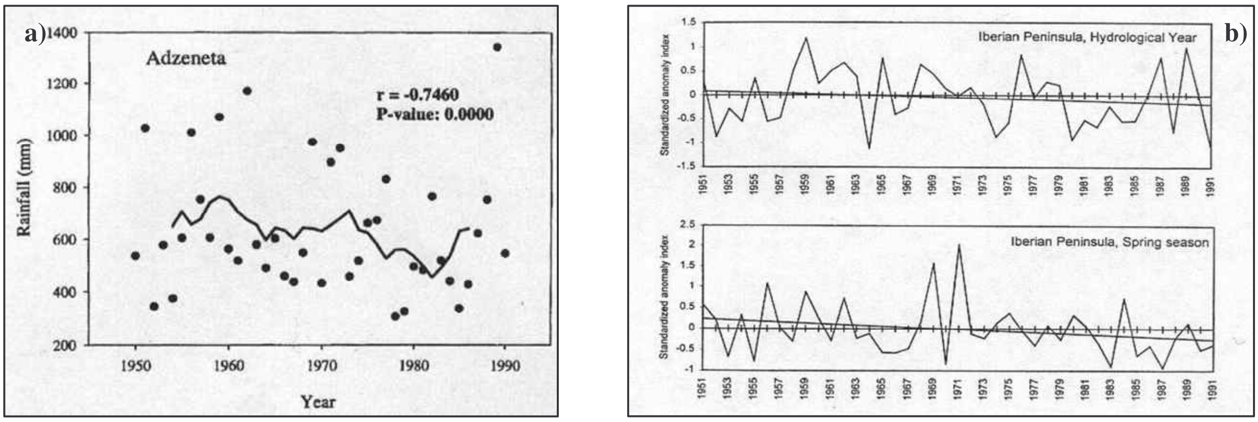


Figure 3. Recent drying trends in the Mediterranean. a) An example from De Luís *et al.* (2001) who found precipitation to have generally decreased for 1961 to 1990 in SE Spain. **b)** Palutikof *et al*. (1996a) found drying trends across the whole Mediterranean for a similar period.

General Circulation Models (GCMs) use atmospheric mechanics to aid understanding of the climate, and attempt to predict the consequences of changes in atmospheric composition (McGuffie and Henderson-Sellers 2001). Changes in atmospheric composition are described by emissions scenarios, such as the IPCC's SRES98 scenarios, which project changes for different economic, social and technological rates of development (Nakicenovic and Swart 2000). Many GCMs have been created and run by different agencies, for example the UK Meteorological Office's Hadley

Centre model HadCM2 (CRU 2000), which differ in their parameterisation and use of the four main equations of mass, energy, momentum and water vapour.

Palutikof *et al.* (1996b) used four GCMs to investigate possible future climates in the Mediterranean. They found that across the Mediterranean as a whole, warming will be experienced, in some places at a greater rate than the predicted global increase in temperature, and that this translates into increased rainfall in the north but decreased precipitation over the study area of this study, in the south, during winter and spring. However, Palutikof *et al* (1996b) caution that patterns of summer precipitation are not spatially coherent and so are difficult to predict.

McGuffie *et al.* (1999) showed that five GCMs all predict a decreased number of rain days per year, but more intense precipitation when it does fall. In addition, the IPCC Third Assessment Report (TAR) suggests that precipitation will decrease consistently across the year for the Mediterranean as a whole (Giorgi and Hewitson 2001). However, while GCMs consistently forecast increases in temperature, many still disagree on whether mean annual precipitation will increase or decrease for the Mediterranean (McGuffie *et al.* 1999). Precipitation will be influenced greater by seasonality than temperature, and may change in its frequency-intensity characteristics. GCM forecasts for the specific location of this study will be noted later.

It must be noted there are limitations to GCMs that reduce their usefulness. These limitations include a coarse spatial resolution (as shown by Figure 4) causing inaccuracies in local predictions (Osborn 1997), poor modelling of precipitation in terms of rain day frequency and intensity on those days (Osborn and Hulme 1999) causing a 'drizzle' effect, and poor seasonal prediction (Osborn and Hulme 1999). However, GCMs are seen as powerful tools for studying climate change (Palutikof *et al.* 1996b) and their consistency with physically based expectations and empirical observations means that their results can be taken seriously (Fowler and Hennessy 1995).

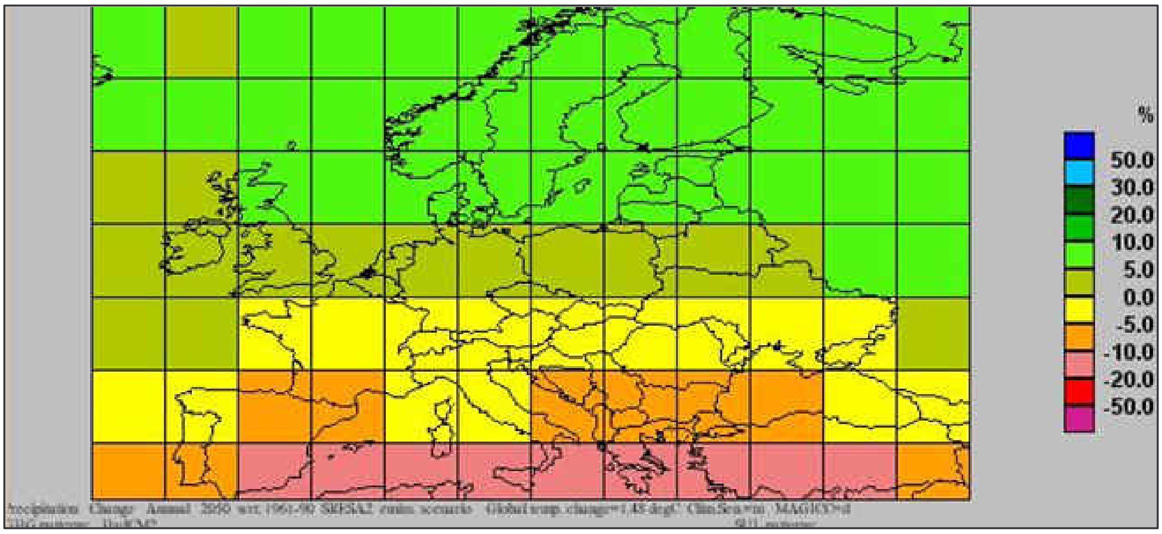


Figure 4. The coarse resolution of GCMs. With sections of only five cells to cover Spain, regional impacts assessments can be limited by the parameterisations this demands. Source: CRU (2000)

2.4 Literature Review Summary

The impacts of future climate change on wildfire have received little attention and have not been considered specifically in the Mediterranean to any great extent. Studies that have looked at changes in the Mediterranean have tended to show that climatic conditions are becoming more favourable for wildfire occurrence, increasing risk. Thus, there is need for an integrated approach to model the effects of changes in temperature and precipitation due to anthropogenically induced climate change on wildfire risk.

3

METHODOLOGY

Geographical Information Systems (GIS) can provide an accessible and realistic model of the world from which geographic questions can be asked (Martin 1996), and thus have been used extensively for wildfire risk evaluation. The GIS software *Arcview GIS (Version 3.2)* (ESRI 1999) was used in this study.

3.1 Data Used

Andrews and Queen (2001) note that when using a tool such as a GIS to create a wildfire model, to prevent misapplication and misinterpretation there should be a focus on the data, and not simply the users' needs. Based on earlier studies (Table II), and the spatial data available, the data chosen for this wildfire risk model were:

1. Vegetation (Fuel)
2. Aspect
3. Slope Angle
4. Proximity to Streams
5. Proximity to Roads
6. Temperature
7. Rainfall

Much of this data was not collected specifically for this study. Vegetation, Topographic, Meteorological and Drainage data of the study data has been used previously in Bull *et al.* (2000), Thornes *et al.* (2000) and Bull *et al.* (In press). Only the road network data was derived specifically for this model. The spatial resolution of the data, and thus of the end model, is 50m. This resolution has been shown by other studies to be adequate for local-scale wildfire risk evaluation (see Table II).

3.1.1 Landscape Data

The raw vegetation data was initially classified into vegetation type and density, with no regard for pyric properties (see Table IV). To better represent the wildfire risk the vegetation causes, the data was reclassed (Table IV and Figure 5), taking into account, qualitatively, physical characteristics such as size, bulk density, and loading of the vegetation

Table IV. Classification of vegetation data for use as wildfire fuel variable. The reclassification of the vegetation data combined some classes.

Original Classification	*New Classification*
Ploughed	Ploughed/Alluvial
Alluvial	Ploughed/Alluvial
Wheat	Wheat
Tree Crops	Tree Crops and Vines
Vines	Tree Crops and Vines
Scrub 10 – 29% Cover	Scrub 10 – 29% Cover
Scrub 30 – 49% Cover	Scrub 30 – 49% Cover
Sparse Oak	Oak
Dense Oak	Oak
Scrub 50 – 80% Cover	Scrub 50 – 80% Cover
Mattoral	Mattoral

A Digital Elevation Model (DEM) (Figure 6) was used to derive aspect (Figure 7) and slope angle (Figure 8), using functions in *Arcview.*

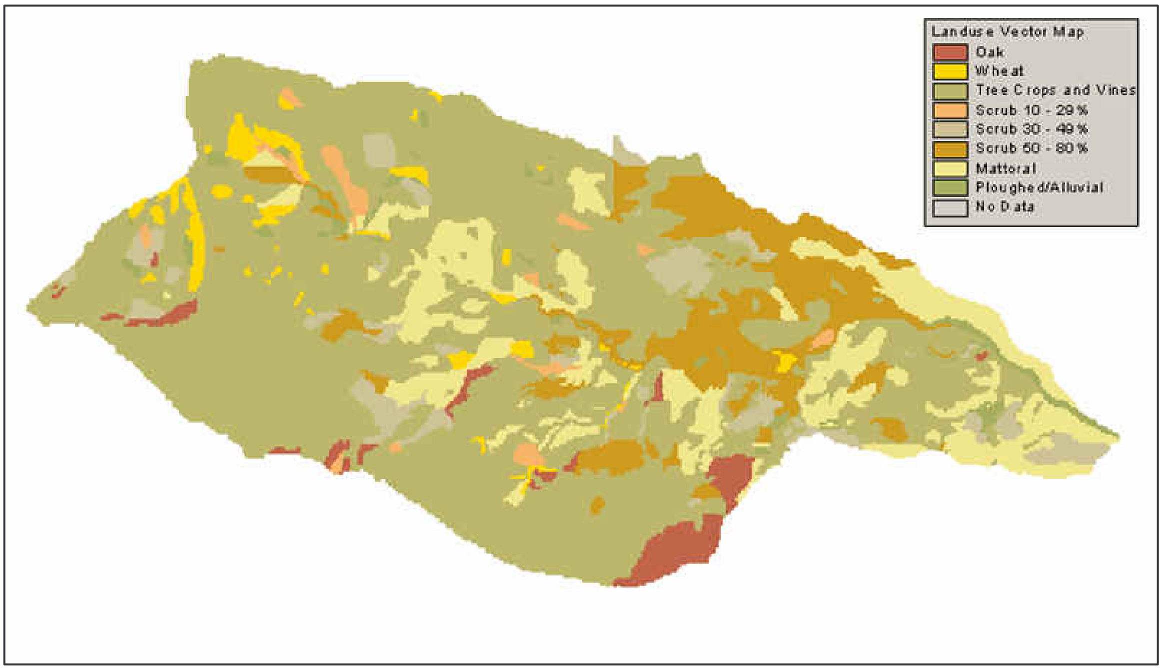


Figure 5. Reclassed vegetation map used in model. This reclassification, based on Table IV, was undertaken in order to more accurately represent wildfire ignition probabilities and characteristics of the vegetation.

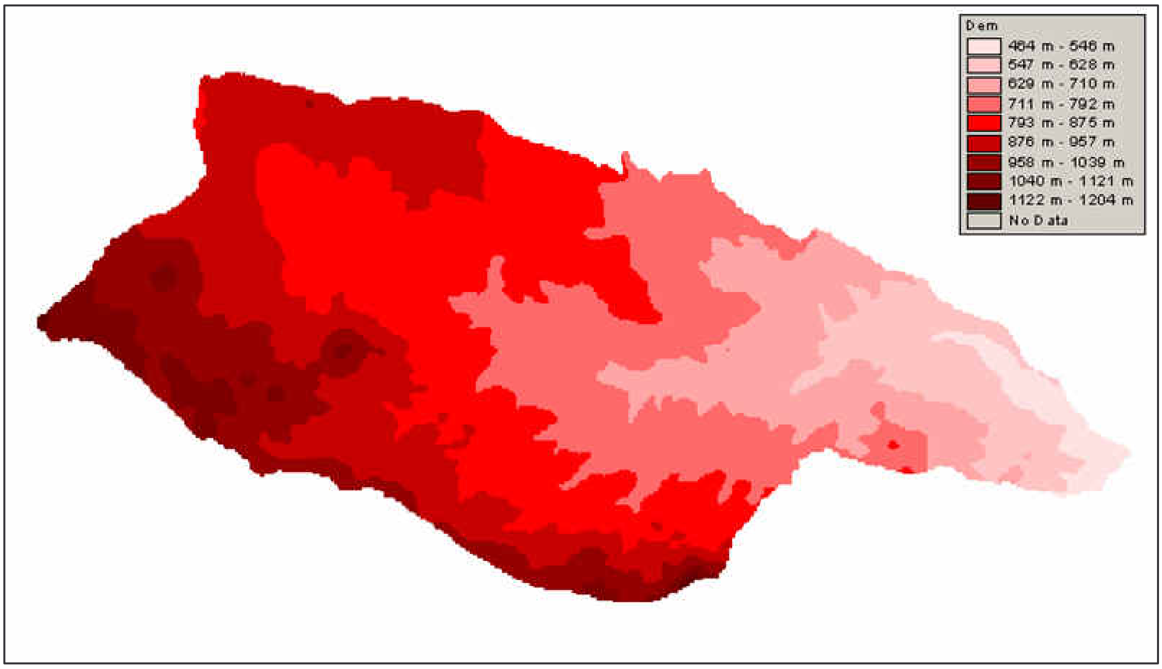


Figure 6. Digital Elevation Model. This was derived and used previously (Bull *et al.* 2000), and used here to derive aspect and slope data.

Aspect was classified into North, South, East, and West facing slopes and flat ground using the classification in Table V. Slope angle is measured and classified according to its gradient in percentage (Table V).

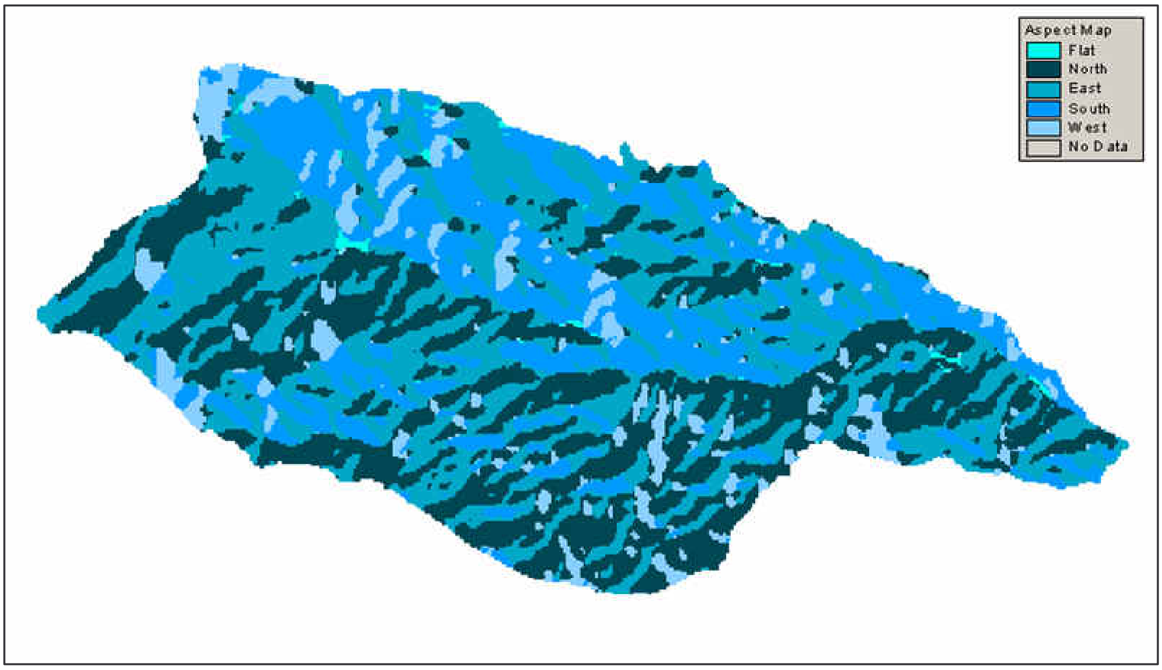


Figure 7. Aspect map. Aspect was derived from the DEM as classified in Table V.

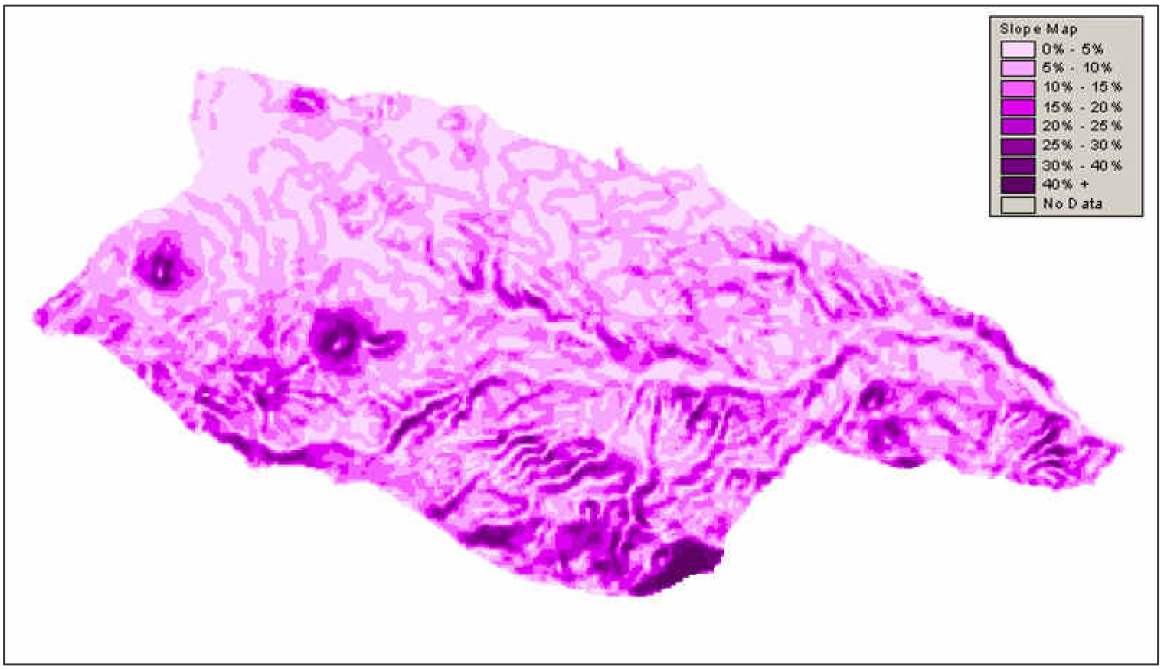


Figure 8. Slope map. Greater slope angles are shown here as darker purple and were derived from the DEM, classifed according to Table V.

The stream data (Figure 9) delineates the routes of waterways across the study area and has been used previously (Bull *et al.* 2000).

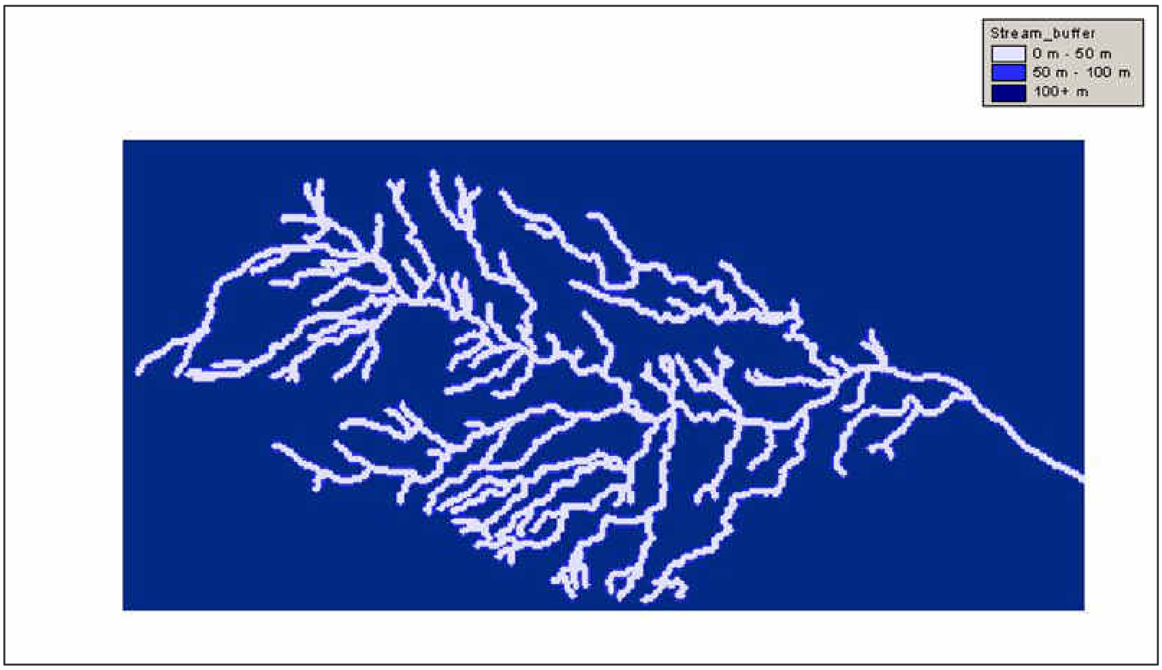
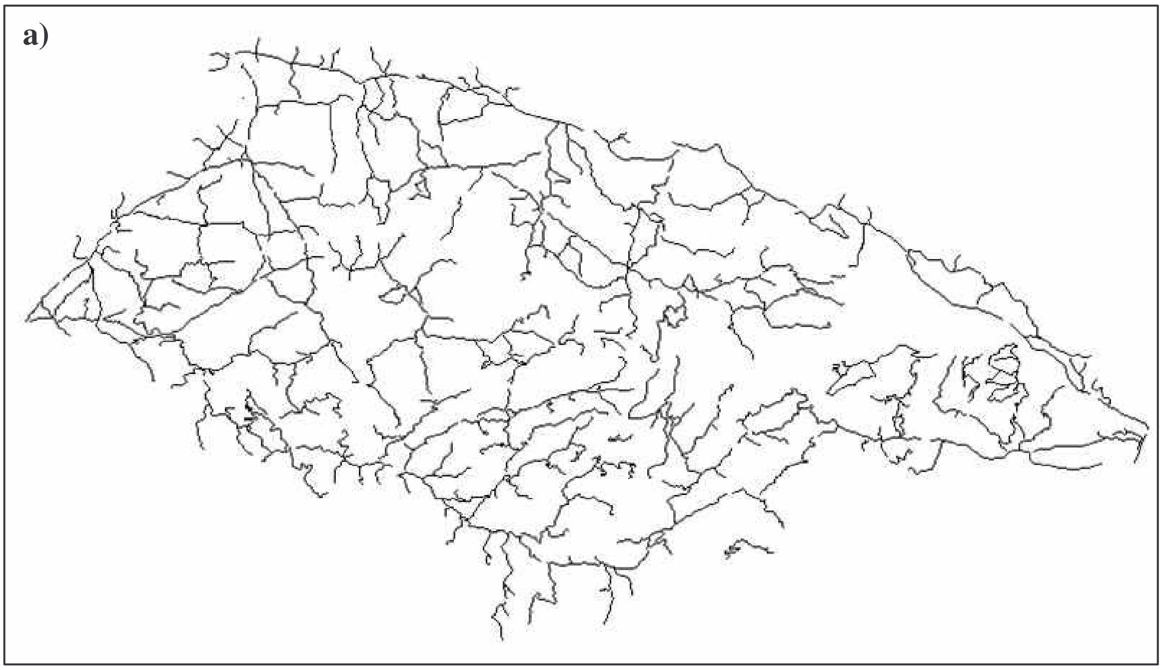


Figure 9. Stream buffer data. Buffers of 50 m were derived around the routed of waterways. The study area fits within the boundary of the blue background.

The locations and routes of roads were digitised from digital versions of 1:25,000 scale maps of the study area in *Arcview* (Figure 10a). Two proximity buffers of 50 m each were then created on both sides of all roads (see Figure 10b) to model the associated risk of ignition they cause found by Salas and Chuvieco (1994).

3.1.2 Climate Data

Basic climate variables, such as mean annual temperature and total precipitation, predict wildfire occurrence well and can be used to model wildfire risk for changes in climate (Vázquez and Moreno 1993). The data used for temperature and rainfall was taken from one temperature station and six rainfall gauges within the study area (Figures 13 and 14).



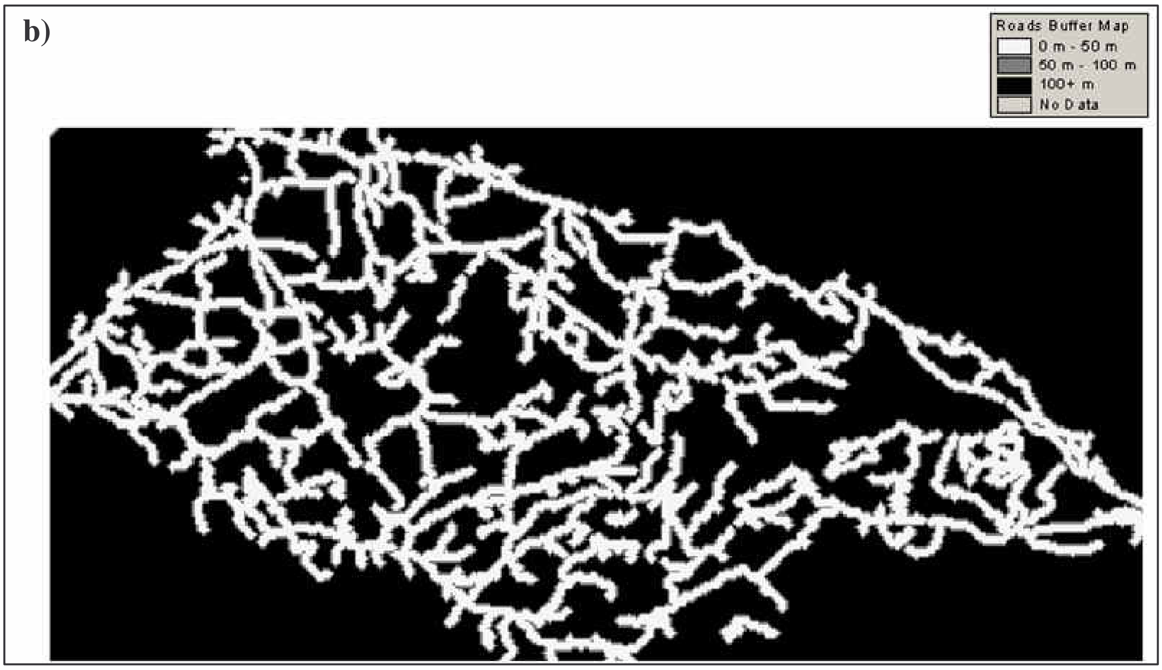


Figure 10. a) Digitised road data. This data was produced by digitising 1: 25,000 maps in A*rcView.* **b) Road buffer data.** This data was derived from **a)** and uses 50 m buffers. The study area fits within the boundary of the black background.

From these points, mean annual values, averaged over four years from 1997 to 2000, were calculated for each climate station. These values were later used to calculate the spatial distribution of the variables across the whole study area (Figures 13 and 14).

3.2 Model Structure

The combination of the data layers is crucial as it reflects the relative importance and level of effect of each variable (layer) on the final risk. It needs to be such as to realistically represent the actual processes involved in the ignition of a wildfire, but simple enough that changes in wildfire risk due to changes in climatic variables can be clearly seen. The method used here is one that selectively weights the variables, creating a quantitative formula. The structure also needs to allow quick and easy manipulation of model variables, in this case the climatic variables. Therefore, to create the final Wildfire Risk Index (WRI) these layers were combined into two sub risk indices, the Basic Risk Index (BRI) and the Climate Index (CI) (Figure 11).

The BRI is a product of the static risk variables, i.e. those risk variables that will remain constant throughout the investigation. Values of temperature and precipitation, the dynamic risk variables, will vary, causing the CI to vary. With the BRI remaining constant and the CI changing according to the values of the climatic variables, the WRI will vary according to the latter. Thus, changes in wildfire risk due to changes in climate will be observed in the model output.

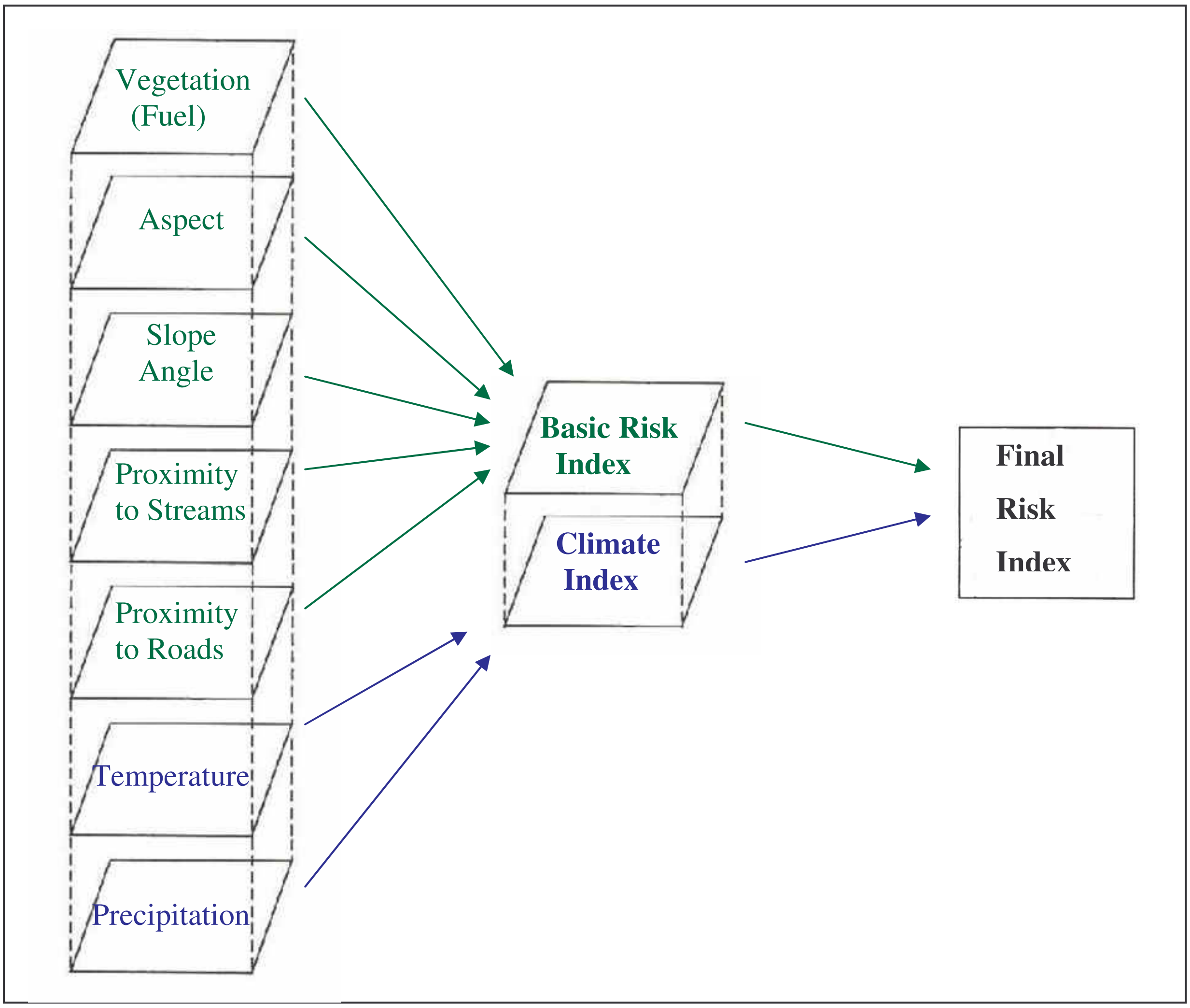


Figure 11. Basic structure of the wildfire risk model. The seven data layers are divided into static risk and dynamic risk variables, i.e. the Basic Risk Index and the Climate Index. These indices are combined to create the final Wildfire Risk Index, which can be examined for changes in the climatic variables.

3.2.1 The Basic Risk Index

The BRI is composed of the vegetation, aspect, slope angle, proximity to streams, and proximity to roads data (Figure 11). That these layers remain constant throughout the study implies that while changes may occur to climate, they will not occur to these variables. This is not the case, as landscapes are in a state of perpetual change. However, the assumption is justified for the use of this study. The decadal time scale considered is relatively short compared to the erosional, tectonic, social and technological processes causing changes to these variables, and emphasis is deliberately on the effects of climate change to ensure clear results.

Classes (and thus pixels) within each data layer (e.g. North, South, East and West of the aspect layer) were classified according to their influence on wildfire risk by assigning relative values, greater values corresponding to greater wildfire risk (Table V). These relative values were consistent for all layers, greatest risk receiving a score of ten and lowest risk one.

The manipulation of data to compose the BRI layer was kept to a minimum, again to ensure emphasis on climatic parameters and clear results. Thus, data layers are overlain according to relative, qualitative principles of the mechanisms of wildfire ignition.

The reclassification and scoring of vegetation types was completed on a qualitative assessment of the physical characteristics of the vegetation, based on previous research (Anderson 1982, Burgan and Rothermel 1984, Congalton and Chuvieco 1989, Sandberg *et al.* 2001)

Aspect layer values reflect the difference in microclimate for slopes of differing aspect. South facing slopes receive greater insolation than other aspects, causing increased air temperatures and decreased soil moisture (Briggs *et al.* 1998). This in turn reduces vegetation moisture, increasing wildfire risk (Núñez-Regueira *et al.* 2000).

Table V. Classification and risk values of BRI variables. The 'Risk Value' column shows the value used when calculating the BRI.

Classification	*Risk Value*
Vegetation Layer (weight 30)	
Ploughed/Alluvial	1
Wheat	3
Tree Crops and Vines	4
Scrub 10 – 29% Cover	4
Scrub 30 – 49% Cover	6
Oak	7
Scrub 50 – 80% Cover	8
Mattoral	10
Aspect Layer (weight 20)	
Flat	1
North (315° to 45°)	3
East (45° to 135°)	7
West (135° to 225°)	7
South (225° to 315°)	10
Slope Angle Layer (weight 5)	
0-5 %	1
5-10 %	3
10-15 %	4
15-20 %	7
20-25 %	7
25-30 %	8
30-40 %	8
40+ %	10
Proximity to Streams (weight 15)	
0 – 50 m	1
50 – 100 m	5
100+ m	10
Proximity to Roads (weight 30)	
100+ m	1
50 – 100 m	5
0 – 50 m	10

Slope angle is included in the model because of its influence on vegetation moisture content. Hortonian overland flow is dominant in semi-arid environments, with steep slopes being key runoff-producing areas (Bull *et al*. In press). Thus, soil moisture recharge occurs more readily on flatter ground, meaning vegetation here will be damper, reducing its effects on wildfire risk. A soil moisture model may have been more suitable, though to maintain simplicity consistent with other layers one was not used here.

Riparian vegetation, by definition, has greater moisture content than other vegetation in the landscape (Hancock *et al.*1996). Further, the moisture content gradient away from streams causes vegetation moisture content to decrease with distance from the stream (Jones 1997). As fire risk is dependent upon vegetation moisture content (Whelan 1995), buffers of 50 m were placed around the stream courses to model this behaviour.

Sets of 50 m buffers were again utilised around roads to model the risk associated with humans in the landscape. The buffers are given greater risk than the surrounding areas. The findings of Salas and Chuvieco (1994), described in the literature review, illustrate that this method, which has been used previously though with varying sized buffers (Chuvieco and Congalton 1989, Salas and Chuvieco 1994, Chuvieco and Salas 1996, Castro and Chuvieco 1998), is valid.

Finally, these classifications and relative risk values were combined using a simple weighted overlay in *Arcview* to reflect the importance of that variable (i.e. vegetation, aspect etc.) on wildfire risk. The combination of these layers is represented by equation (1),

$$\text{BRI} = 30v + 30r + 20a + 15st + 5sl \qquad (1)$$

where v is vegetation layer, r is roads layer, a is aspect layer, st is streams layer and sl is slope angle layer. Thus, vegetation and proximity to roads are six times more influential than slope angle on wildfire risk, and twice as influential than proximity to streams.

The vegetation (fuel) layer is one of the most important in wildfire risk modelling (Chuvieco and Congalton 1989, Viegas *et al.* 1998, Keane *et al*. 2001), with many fuel maps and classifications constructed, classifying vegetation according to its propensity to burn (Dimitrakopoulos and Mateeva 1998, Núñez-Regueira *et al.* 2000, Dimitrakopoulos and Panov 2001, Sandberg *et al.* 2001). As previously noted in the literature review and Table III, human activity is another important wildfire risk variable in Spain. Thus, these variables are given most weight.

Of the remaining variables, which consider the moisture state of the vegetation, aspect has been used most in the literature and is given most weight accordingly (Table III). Proximity to streams is given a slightly lesser weighting as, though less used, it is still deemed here to have a significant effect on vegetation moisture. Lastly, slope angle has least influence on wildfire risk and is weighted accordingly.

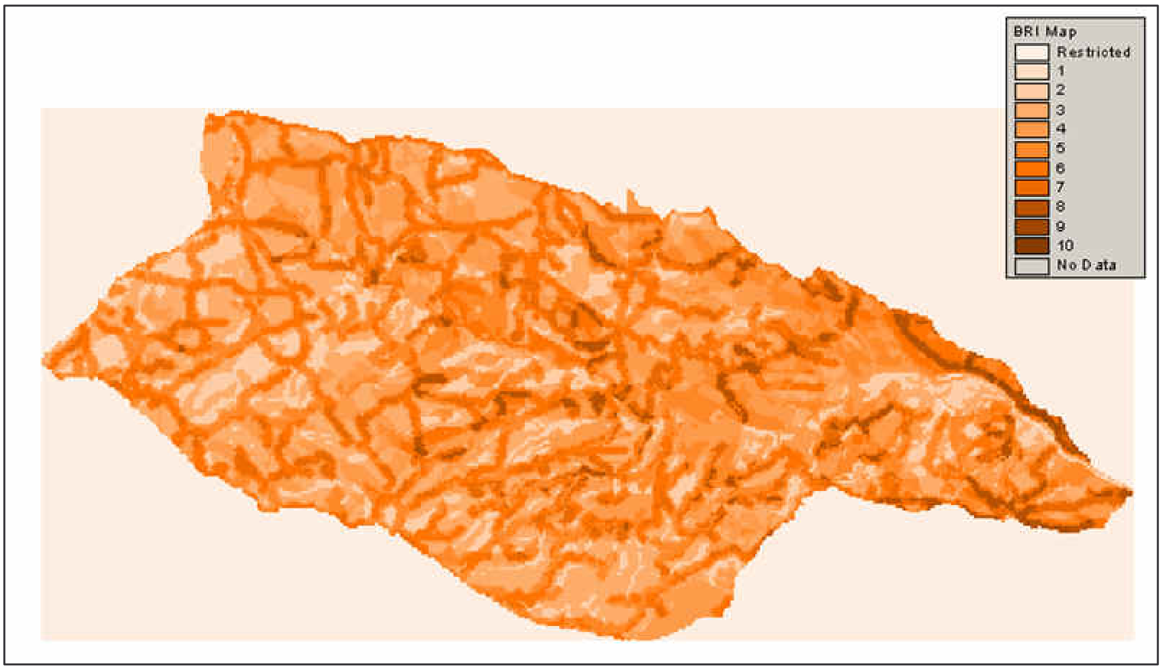


Figure 12. The BRI map. This map was created from the data layers described above and used in equation (1). Greater wildfire risk is shown as darker orange/brown, lesser risk as lighter orange.

This structure thus creates the control BRI (Figure 12). The predominant pattern observable is that of bands of darker colour following the route of roads. The greatest risk is found at the eastern of the northern boundary of the study area, due to the combined risk of Mattoral vegetation and close proximity to a road. These two patterns would be expected to be most prominent as they coincide with both variables of greatest weight (vegetation and roads) and the highest scoring aspects of those variables (Mattoral and within 50 m of a road). Generally, this map appears to explain well the risk provided by the variables considered.

3.2.2 The Climate Index

Temperature and precipitation were combined to form a Climate Index (CI). The CI was initially created for current climatic conditions as a control index, which could later be varied according to predictions of future climate. The distribution of these variables will not be uniform over the whole study area however, and thus spatial distributions across the study area were interpolated from the data points.

To represent the spatial distribution of temperature across their study area, Chuvieco and Salas (1996) derived a formula by regressing data from 27 weather stations both inside and outside the study area. This volume of data was unfortunately not available here and a more basic method was needed. In the troposphere, the layer of the atmosphere nearest the surface, air temperature cools at the environmental lapse rate, given by textbooks as between 0.6 and 0.65 ºC per 100 m of elevation globally (Neiburger *et al.* 1973, Riehl 1978, Nazarra 1979, Barry 1992, Briggs *et al.* 1998). However, there is regional and seasonal variation in the environmental lapse rate, as shown by Lautensach and Bögel (1956). They found the lapse rate to be above and below 0.5 ºC per 100 m for winter and summer respectively in mediterranean climates. Using the DEM, temperature was scaled by a rate of 0.5 ºC per 100 m, creating the temperature map shown in Figure 13. Castro and Chuvieco (1998) also used this method but with the rather faster rate of 1 ºC per 100 m.

The ideal method to estimate the spatial distribution of precipitation from point data is interpolation, the estimation of intermediate values in a series to form gradients between them (Robinson *et al.* 1995). However, with only six data points, interpolation mapping was not viable. Further, rainfall in semi-arid environments has a very irregular distribution (Alonso-Sarria and Lopez-Bermudez 1994), produced by small convective cells. This leads to a 'spotty nature' (Sharon 1972), which is difficult to represent as an annual mean.

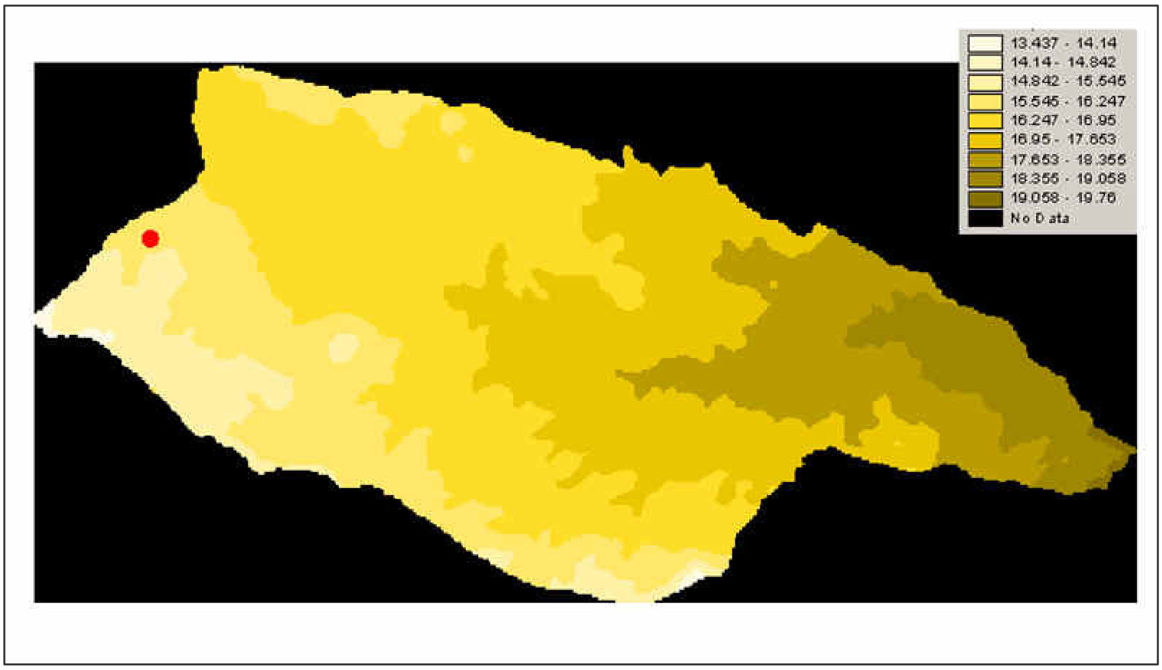


Figure 13. Temperature map. The temperature map was created by using elevation from the DEM (Figure 6) as a template to interpolate the single point temperature gauge (shown) across the study area. Warmer areas are darker yellow.

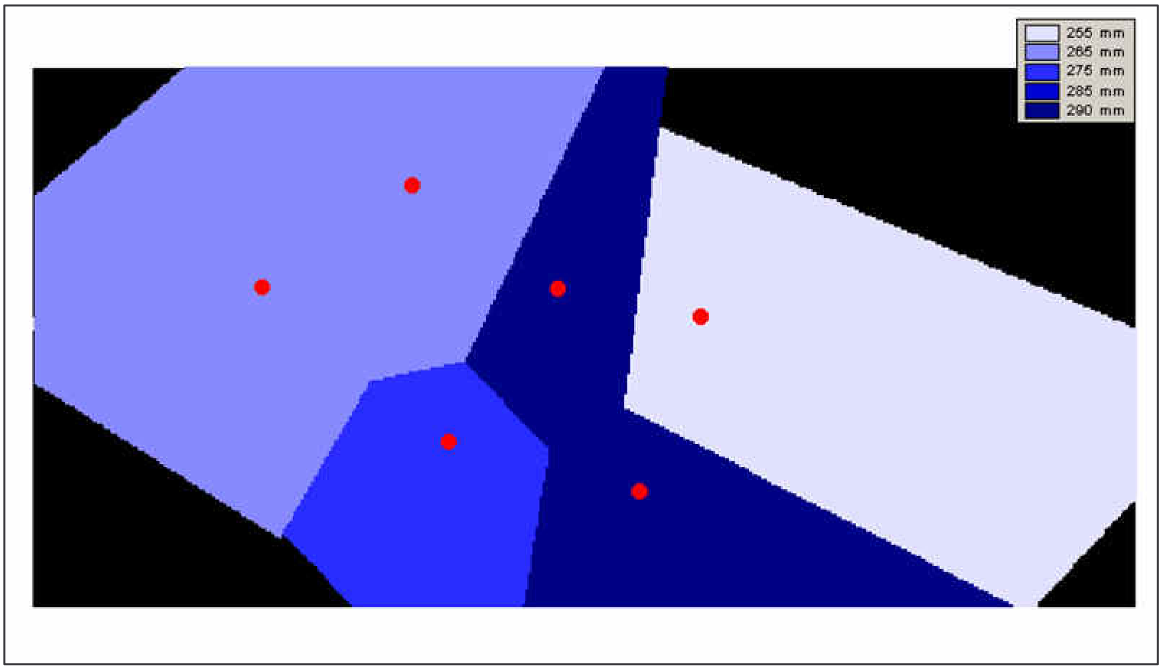


Figure 14. Rainfall map. Thiessen polygons were created, using data from the rain gauges (shown), to divide the study area in to regions of (theoretically) homogenous rainfall. The study area fits within the boundary of the black background.

Therefore, thiessen polygons were used (Chuvieco *et al.* 1999). This method simply divides the catchment area into polygons by lines that are equidistant between pairs of adjacent stations. Each polygon then represents the areal rainfall for that area, calculated from the rain gauge. This is not an ideal method, but because of the limited data and nature of mediterranean rainfall was the best possible. The map was produced (Figure 14) in the GIS *Idrisi (Version 2.0)* (Clark University 1997) and imported into *Arcview*.

Increased temperature can result in increased wildfire risk; conversely increased rainfall causes decreased wildfire risk. Thus, a simple formula was derived for the CI:

$$\mathrm{CI} = 10T - P \qquad (2)$$

where T is temperature layer and P is precipitation layer. As precipitation values are an order of magnitude greater than temperature (see Appendix II), the temperature layer is corrected by a coefficient of ten, to ensure that both variables are given equal weight. This maintains a realistic representation of their influence on the processes of wildfire ignition.

3.2.3 The Wildfire Risk Index

Overlaying the BRI and CI coverages created, the Wildfire Risk Index (WRI) is given by:

$$\mathrm{WRI} = \mathrm{BRI} + \mathrm{CI} \qquad (3)$$

The indices are summed and given equal weight. An alternative method would be to multiply layers. However, Bull *et al.* (In press) note that multiplying layers increases the range of values in the final index, reducing clarity. While this study is concerned with finding qualitative changes in behaviour and may benefit from a large range, as small changes in CI will be amplified allowing easier detection of potential changes in WRI, the *relative* risk of individual pixels can differ depending upon whether multiplication or addition is used. As variables have been summed throughout, addition is used here to maintain consistency, simplicity and clarity.

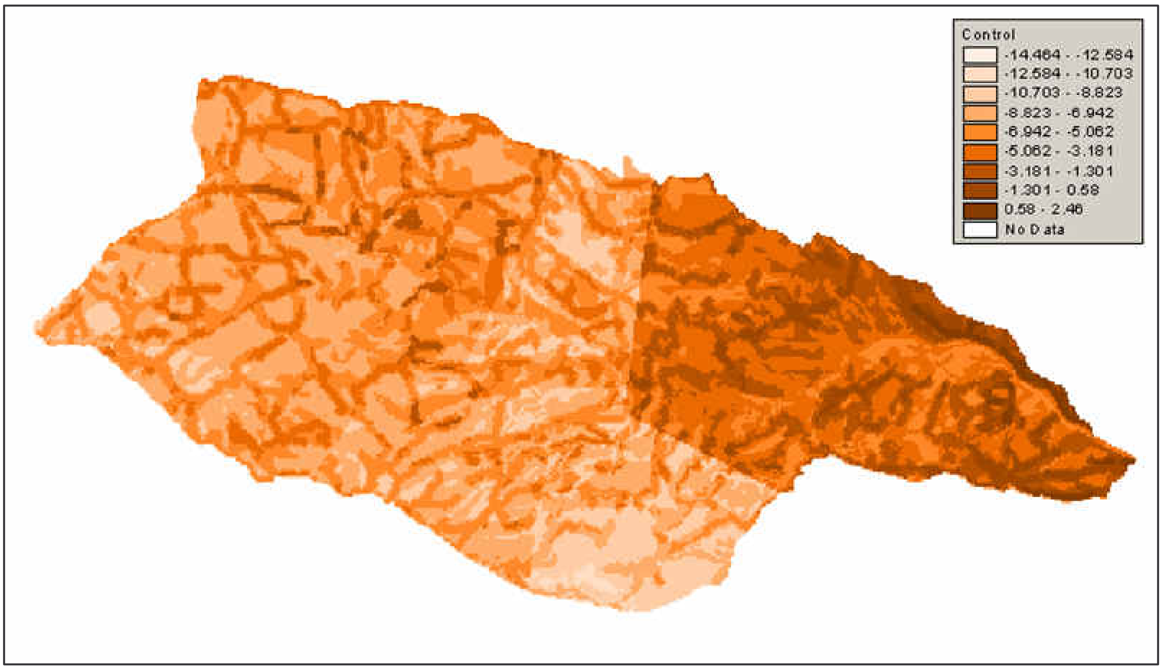


Figure 15. Control WRI. This risk map was created using equation (3) and will be used later to assess changes in risk by analysing deviation from its. Darker orange/brown denotes greater risk.

The control WRI (Figure 15) shows greater risk as darker orange/brown. As with the BRI map, the artefacts produced by the road buffering are observable in the control WRI map, but are not the most obvious pattern present. A sharp division between an area of greatest risk in the east of the study area and an area of lesser risk in the central part of the area is prominent. This sharp division is seemingly due to the influence of the precipitation layer, which lays areas of high and low mean annual precipitation alongside one another. This stark contrast would probably not be present in nature and is due to the use of thiessen polygons. Undesirable as it is because of its juxtaposition, it is an artefact of the observed precipitation data and thus an unavoidable component of the model.

3.3 Sensitivity Analysis of Wildfire Risk to Climate Change

To analyse changes in wildfire risk resulting from changes in climatic variables a sensitivity analysis was undertaken. This allowed climatic variables to be controlled, while the dependent behaviour of wildfire risk was observed.

The pattern of changes in temperature and precipitation predicted by three GCMs for SE Spain was taken from the CD-ROM *MAGICC/SCENGEN* (CRU 2000). The predicted changes for four of the IPCC's SRES98 scenarios (A1, B1, A2 and B2) from the UK Meteorological Office's HadCM2, the German Max Planck Institute's ECHAM3, and the Australian CSIRO3 models were used. These GCMs were chosen as their precipitation pattern correlation values, a method of GCM evaluation, ranked highest against a number of other models (Wigley 1999). These are not the most recent GCMs developed, with models HadCM3 and ECHAM4 now available, but, instead, those whose data was currently most accessible.

Using pairs of values reflecting all possible combinations of temperature and precipitation given by the GCMs for SE Spain (Figure 16 and Appendix I), 30 sets of climatic conditions were produced (Appendix II). Temperature values were varied equally by 0.5ºC, and precipitation by 4%, as these gave an adequate number of combinations for analysis whilst also matching the ranges of predicted changes. These 'conditions' were used in the CI, producing varying values of the WRI.

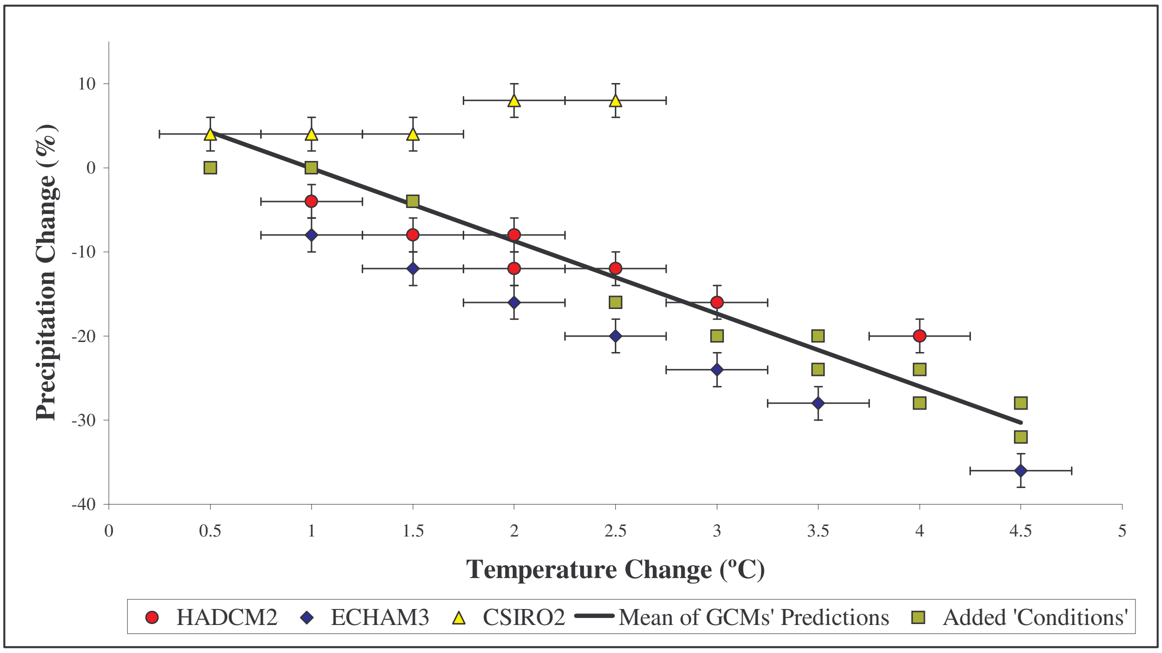


Figure 16. Possible future climatic 'conditions' predicted by the HADCM2, ECHAM3 and CSIRO2 GCMs for SE Spain. Predicted 'conditions' (combinations of precipitation and temperature) were binned into changes of 4% for precipitation and 0.5 °C for temperature. To better represent the range of predictions, and to provide an adequate number for analysis, further 'conditions' were added consistent with the mean of the GCMs' predictions shown.

For these values, the CI will give a range of pixel values for the WRI between -14.2 and +17.1. Using this range, five risk classes of equal interval were created, as shown in Table VI. The risk class 'Average' is denoted as such, as this class contains the mean pixel values for the whole study area for the control WRI. Deviation from this control class is used to illustrate changes in wildfire risk due to changes in climatic variables.

Table VI. Classification of risk according to pixel values. Pixels' risks are classified according to their WRI value. Deviation from the control, 'Average', class of study area mean and modal values will illustrate impacts of climate change.

Risk Class	*Pixel Value*
Low	-15 to -7.5
Average	-7.5 to 0
Above Average	0 to 7.5
High	7.5 to 15
Extreme	15 >

4

RESULTS AND ANALYSIS

Once the model had been created, several spatial aspects of wildfire risk were analysed. These were average landscape risk for different climatic conditions, potential changes in wildfire risk heterogeneity across the landscape due to changes in climatic conditions, and variance in risk from current levels for different climatic conditions.

4.1 Sensitivity Analysis

The average risk across the study area was calculated for each climatic condition and plotted against CI (Figure 17). Thus, WRI increases as the climate becomes drier and warmer, showing a very strong linear relationship. The r^2 value of 0.98 for WRI versus CI means that 98% percent of the variance in the WRI values for the area are explained by the climatic conditions. This is significant at the 0.01 (99%) level. Mean pixel values move from –6.1, average wildfire risk, through to 9.8, high risk. This highest risk is experienced in conditions very similar to those predicted by the ECHAM3 GCM for the year 2080 with a model sensitivity of 2.5ºC under the IPCC SRES98 scenario ‘A2’. Predicted changes in climate are shown by the model produced here to cause increases in wildfire ignition risk.

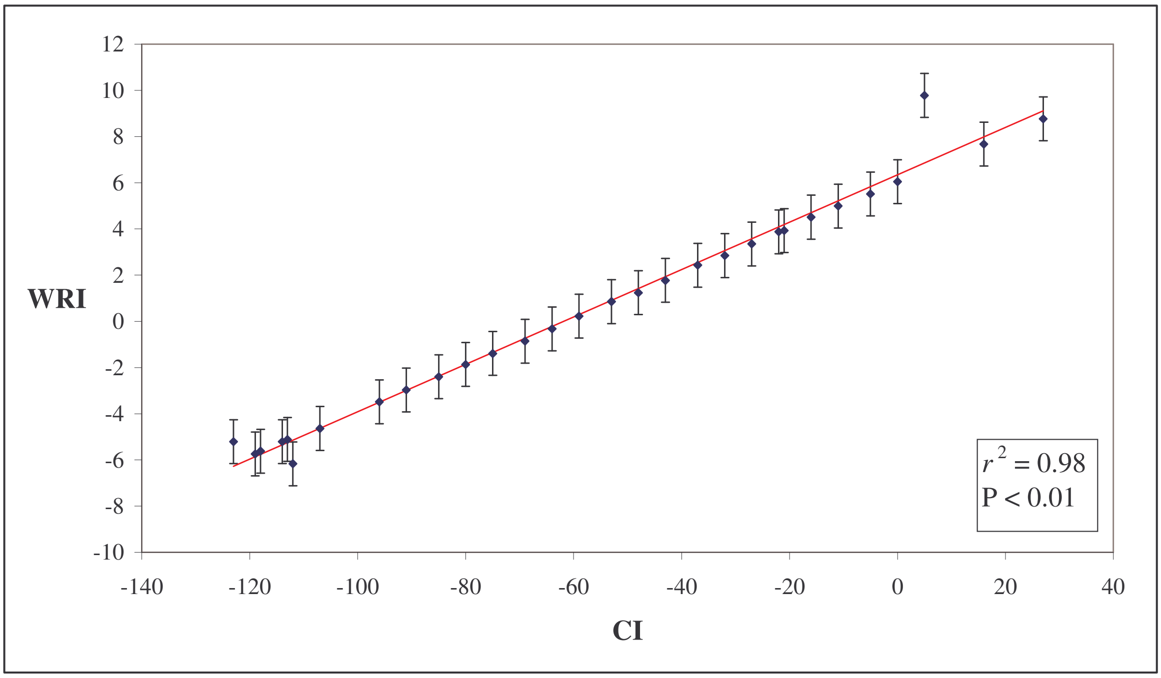


Figure 17. Mean pixel WRI value for study area vs. CI. The relationship between CI and WRI is indicates that as climates become warmer and drier mean wildfire risk across the study area increases. Error bars are ± 0.95 on the WRI scale.

4.2 Wildfire Risk Heterogenity

Heterogeneity is the predominant pattern in any landscape and the phenomena connected with this spatial heterogeneity, or patchiness, have become the main focus of landscape ecology (Farina 2000). Mediterranean landscapes in particular are heterogeneous in their structure (Makhzoumi and Pungetti 1999). Disturbances in a landscape (e.g. fire) are, among others, one control on this patchiness (Farina 2000), and can themselves be considered a part of landscape heterogeneity. Any changes to the disturbance regime (i.e. the average behaviour in terms of frequency, size, distribution etc. of the disturbance) will have implications for the rest of the landscape and its management (Spies and Turner 1999).

To examine any changes in the heterogeneity or patchiness of wildfire risk due to changes in climate, the Shannon-Wiener index of diversity (Appendix III) may be used to measure the order of a system (Krebs 1989). This index has been used in ecology to estimate changes in species diversity (Roberts and Zhu 2002, Gilliam 2002) and to measure changes in landscape mosaics due to large wildfires (Chuvieco 1999). Here, it is used to characterise the number of individual pixels of each risk class in the study area to detect whether wildfire risk across the landscape becomes more or less heterogeneous as climate changes.

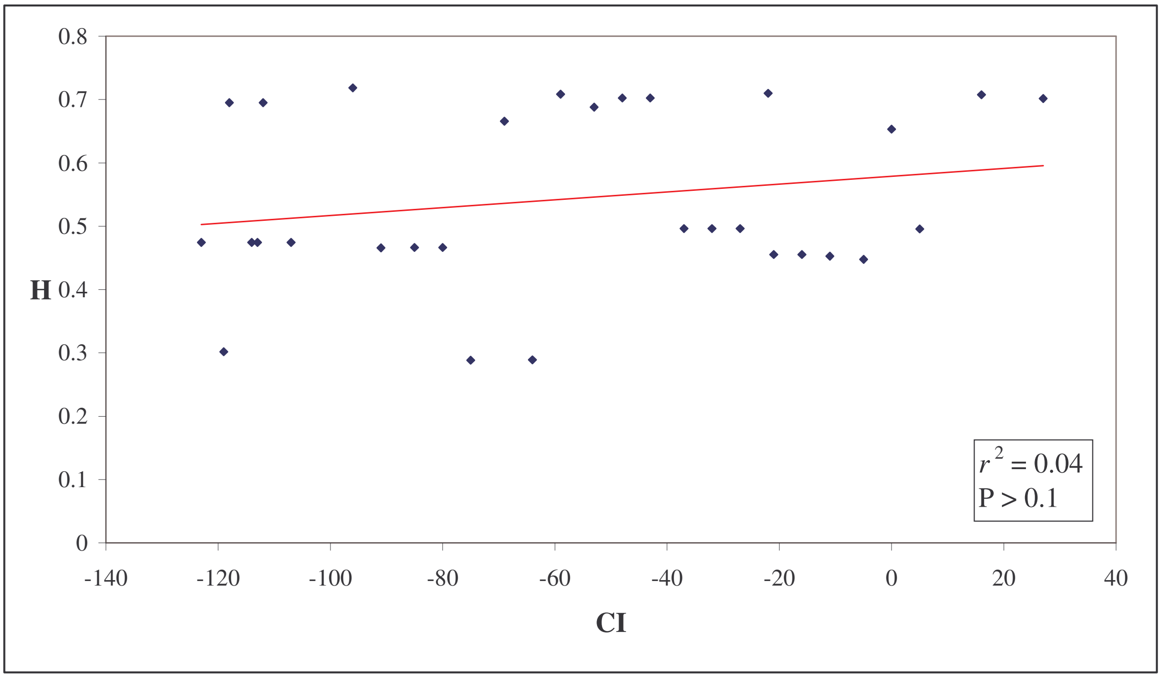


Figure 18. Shannon-Wiener index of diversity (H) vs. CI for each condition. This plot reveals that there is no significant trend between heterogeneity (Shannon-Wiener index) and climate change (CI) and thus fire risk is not becoming patchier.

There is no relationship between the Shannon-Wiener index (H) and CI value (Figure 18). The r^2 value of 0.04 is insignificant at any useful level of confidence. If the study area were becoming more heterogeneous in its wildfire risk (i.e. becoming patchier) the index would increase with CI. Therefore it seems climate change would not have an impact on the patchiness of wildfire risk at this resolution. However, there are important feedback links between fire and vegetation (Forman and Godron 1986), the pattern of one affecting the processes of another and vice versa. Thus, as the impacts of climate on the spatial distribution and pattern of vegetation have not been considered, trends in changes of wildfire risk across a dynamic vegetation mosaic, as opposed to the static one here, may not have become apparent. This is an area for future research, although here climate alone has not been found to influence landscape wildfire risk heterogeneity.

4.3 Wildfire Risk Variance

Though it has been shown that wildfire risk is not becoming patchier, this does not mean that risk is increasing at the same rate in all areas. If rates of increase of risk vary in different areas, environmental managers may need to account for this. An analysis of the spatial variation across the study area of deviation in risk from the control WRI was undertaken by subtracting the value of the control WRI from each condition for each pixel. From an initial, qualitative analysis of the output it was noted that the majority of the conditions exhibited greatest change in the driest areas (in the north-south band through the middle of the study area), lesser change in the warmer but wetter areas (at the eastern end of the study area), and least change in the coolest, wettest areas (in the western end of the study area) (Figure 19 and Appendix IV).

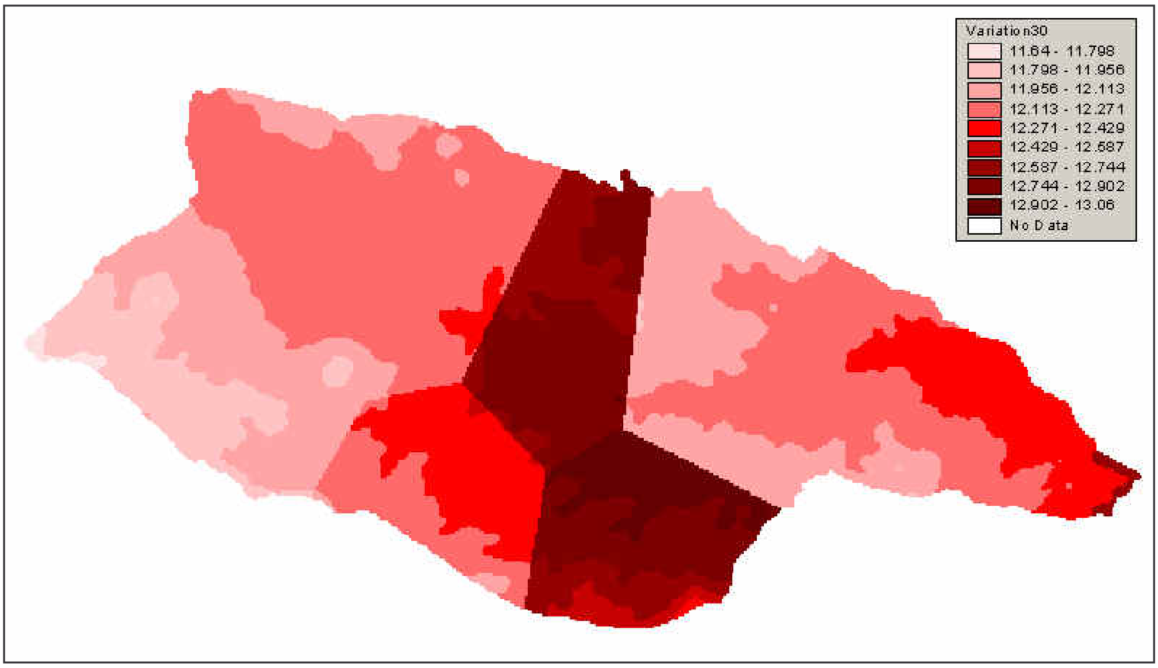


Figure 19. An example of the spatial distribution in deviation of risk from the control WRI. This example (for climatic condition 30, see Appendix II) was used in the qualitative analysis of spatial distribution of deviation from the control WRI of each condition and illustrates that the greatest deviation is in the driest, warmest section through the centre of the study area.

Plotting the magnitude of the greatest and smallest changes versus CI illustrates that there is a divergence in the rate of change between greatest and least risk, leading to a greater variance in risk across the study area (Figure 20). This does not account for risk spatially itself. However, by assuming that the qualitative observations made above are valid, it would seem that the drier areas are more sensitive to changes, and that wildfire risk is increasing quickest here. Less sensitive are the warmer but wetter areas, and least sensitive are the coolest, wettest areas. Thus, it would seem that as climate changes according to the climate predictions used here, areas already most at risk from wildfire ignition might experience greater increases in risk proportional to the surrounding landscape. Potentially, it is these areas that will need the greatest attention of environmental managers.

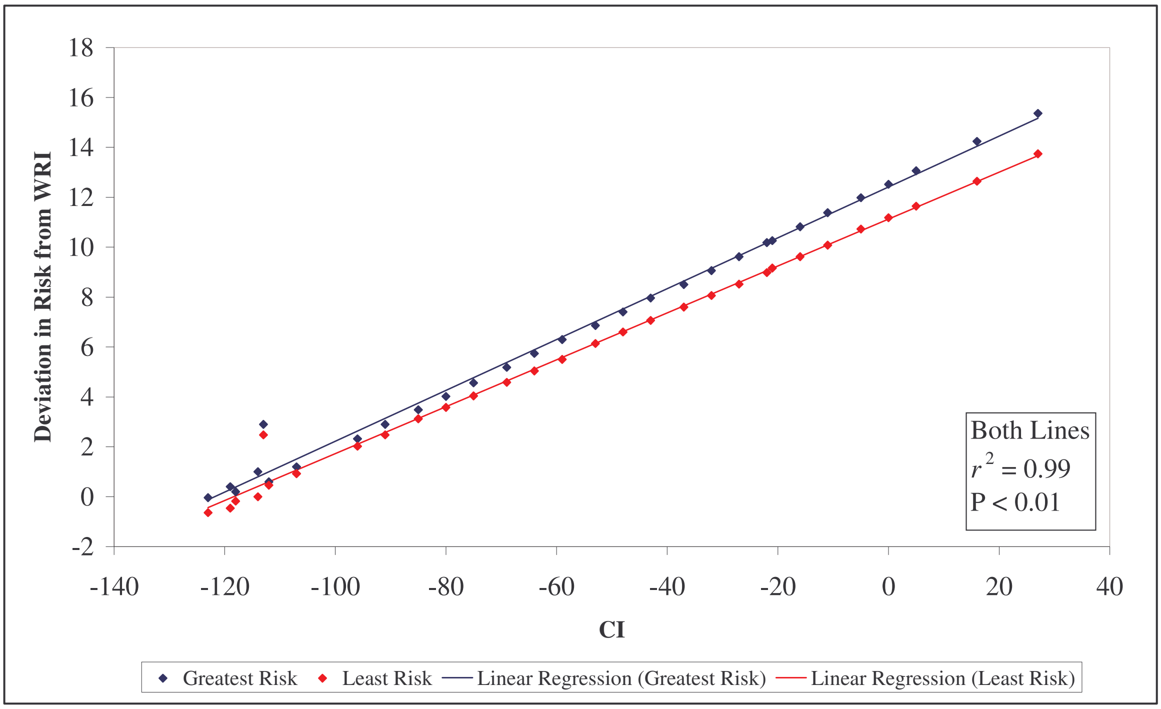


Figure 20. Greatest and least risk for each condition vs. CI. This plot clearly illustrates the divergence in deviation of risk from the control WRI for change in climate, i.e. the rate of change of risk with change in climate.

5

DISCUSSION

5.1 Environmental Modelling

As environmental scientists often do not have laboratories in which to experiment parallel to the real global environment and an empirically experimental approach is logistically impossible, they create models as a “surrogate laboratory” (Trenberth 1997 p.40). Llimitations are inevitable in models of the vastly complex natural environment, as no model will be able to consider every variable, interaction or process, and parameterisation is very often needed. This discussion focuses on the limitations of the model in this study and the potential improvement upon it that future study might make.

5.2 Limitations and Potential for Future Studies

5.2.1 Weaknesses in Spatial Data Used

The vegetation layer of this model is weak, as its creation was not specifically designed for a wildfire model. Gollberg *et al*. (2001 p.263) note that wildfire models should “be grounded in ecological research and principles”. The classification here takes into account simple aspects of the vegetation, such as species and fuel loading, but does not consider specific pyric properties, of which research into mediterranean species has recently occurred (Dimitrakopoulos and Mateeva 1998**,** Dimitrakopoulos and Panov 2001). Further, the ease of integration of remotely sensed (RS) data into GIS provides a potential data source for the construction of an improved fuel layer.

RS data is currently a central part of fuel mapping exercises, though improvements in technology are still needed (Keane *et al.* 2001).

The stream layer does not take into account the fact that streams in semi-arid environments are ephemeral (Thornes *et al.* 2000). Thus, the effects of this layer will vary through the year according to the volume of runoff and precipitation conditions. This is a factor concerned with seasonality, discussed below. As this model is based on annual data, this is not such a large problem as it might be. Further, the layer does not take into account the size of the stream, and differential buffering could be employed for streams of varying order.

5.2.2 Risk of Ignition

The risk of ignition is dependent upon the presence of an ignition source (Whelan 1995). This model only considers one – humans. While humans are the predominant ignition source of wildfires in mediterranean environments (Chuvieco and Salas 1996), others have not been included. These include, lightning, sparks caused by rocks in landslides, and volcanic activity (Whelan 1995). Of these, lightning has the greatest significance, causing 8 of the largest 21 fires between 1974 and 1994 in Spain (Vázquez and Moreno 1998). Research into the wildfire risk associated with different aspects of the landscape has been undertaken (Fowler and Asleson 1984) and is a potential layer to be incorporated into such a model as this.

The layer relating to human ignition sources could itself be improved. The inclusion of footpaths and recreation areas within the study area could have been made, as was done by Salas and Chuvieco (1994) and Chuvieco and Salas (1996). Mapping of wildfire risk due to arson is complex as it does not have a clearly defined spatial pattern (Chuvieco and Salas 1996), and has not been included in a wildfire risk model to date. There is potential for further research into this area of wildfire risk.

5.2.3 Climate Data Used

The use of GCMs for regional climate impacts assessments is restricted by the poor spatial resolution of their output (Hostetler 1994, Wilby and Wigley 1997, 2000). Further, changes in local scale convective rainfall, as found in semi-arid environments, are poorly predicted by GCMs (Osborn 1997). Developments in techniques to improve regional climate prediction detail have improved greatly in the last few years and include Regional Climate Models (RCMs) nested within GCMs (Giorgi and Hewitson 2001), and statistical downscaling of GCM outputs (Wilby and Wigley 1997). Using climate data produced specifically for regional scale studies, such as the data derived from these techniques, would greatly improve the accuracy of the CI here and should be used in the future if available. Further study may also explore the use of climatic variables other than simply temperature and precipitation, for example humidity.

5.2.4 Seasonality of Mediterranean Climates

Mediterranean environments, defined by the Koppen classification as receiving greater than three times as much winter rainfall as summer rainfall, are controlled to great degree by the seasonality of their climate (Briggs *et al.*1998). Hot, dry conditions through the summer are followed sharply by the rainy season from mid-October until the end of April (Palutikof *et al.* 1996b). This gives rise to the ideal conditions for wildfire, as a wet season, allowing vegetation growth and biomass build up, is followed by a long and hot dry season (Smith 1992). This seasonality is predicted to become more intense, temperatures increasing all year round but more so in the summer, alongside slight increases in winter rainfall but decreases of up to 15% in the summer (Palutikof 1996b). Further, increases in dry spells for the region are predicted by GCMs, with the mean number of rainfall days per year also decreasing (McGuffie *et al.* 1999). Intensification of seasonality will have greater effect on wildfire risk than the simple changes in annual mean conditions examined here. To more accurately represent the effects of climate change on wildfire risk in this region these seasonal changes should be incorporated into the model.

5.2.5 Natural Climate Variability

The regional scale and resolution used by previous wildfire risk studies for the SE Spain (Chuvieco and Congalton 1989, Salas and Chuvieco 1994, and Chuvieco and Salas 1996) was emulated here, and is much smaller than those used in the studies of Boreal forest by Bergeron and Flannigan 1995 and Stocks *et al.* 1998. Larger scale study has been suggested as more appropriate for climate change impact research as the current ability to detect spatial patterns of climate change and variability limits the ability to accurately detect the impact of climate change at small, regional scales (Hulme *et al.* 1999). With improvements in climate change models and prediction, this will become less of a problem. The main findings and argument of Hulme *et al.* (1999), however, are that natural multi-decadal climate variability may have as great, if not greater, impact on natural resources and systems than anthropogenic climate change, and should therefore be considered in future climate impact studies.

5.3 Results

Though simple, the methodology for the construction of the model used here has been justified on basic scientific principles of wildfire ignition, giving validity to the results. However, rigorous testing of the model, through a process of model evaluation or validation using empirical data to effectively 'hindcast' already observed events and monitor how accurate the model's prediction is (McGuffie and Henderson-Sellers 2001), would be desirable. This method has been used previously in wildfire risk modelling (Chuvieco and Congalton 1989, Flannigan *et al.* 1998a) though a lack of fire history for the study area prevents this here.

Finally, two points must be remembered when considering this study's results. First, there are weaknesses in the model, which has not been rigorously tested, and that there are numerous potential improvements. Second, these results are based on the output of three GCMs and the best estimate of the model is dependent upon the climate data used.

6

CONCLUSION

Research into the impacts of future climate change on wildfire has received little attention in the Mediterranean. However, those studies that have addressed it suggest that climatic conditions are becoming more favourable for wildfire occurrence, increasing risk. This study has used a Geographical Information System (GIS) to selectively weight variables concerned with the ignition of wildfire to produce a simple risk model for predicted future changes to climate. The majority of recent wildfire risk mapping exercises in the Mediterranean have used this methodology, but a lack of full consideration of climatic variables in earlier studies is evident. Therefore, the model structure produced was used to estimate the effects of climate changes predicted by GCMs, using simple climate variables.

The results of this study illustrate that predicted changes to climate would increase wildfire risk. The mean Wildfire Risk Index (WRI) value for the study area increases as the climate becomes drier and warmer, from being currently classed as 'average', to a class of 'high' for a climate predicted for 2080. Also, it has been shown that for predicted changes in climate, wildfire risk across the study area will not increase in its heterogeneity at a 50 m resolution. Finally, analysis of the model suggests that warmer, drier areas are more sensitive to the effects of climate change and that areas already most at risk from ignition of wildfire may experience greater increases in that risk proportional to surrounding areas.

Though the methodology of this study has been justified, it has been shown that there are many areas for improvement and extension of this study. These include weaknesses in the vegetation, stream and roads data; the potential inclusion of lightning data; the use of a more spatially resolute climate model; and the effects of seasonality and natural climate variability. In the context of the many improvements possible, this model is merely a first step in producing an integrated model to accurately estimate the effects of climate change on wildfire risk. However, it has illustrated the likelihood of increased wildfire risk in the Mediterranean under predicted future climates, and some potential spatial variations in it.

7

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APPENDIX I.

	Temperature Change (°C)			*Precipitation Change (%)*		
YEAR	2020	2050	2080	2020	2050	2080
A1						
HadCM2	1	2.1	2.9	-5.6	-11.4	-15.4
ECHAM3	1.3	2.6	3.5	-10.2	-20.9	-28.4
CSIRO2	0.7	1.4	1.9	2.5	5.1	6.9
Mean	1.0	2.0	2.8	-4.4	-9.1	-12.3
A2						
HadCM2	1	2.1	3.8	-5.2	-11.5	-20.7
ECHAM3	1.2	2.6	4.7	-9.6	-21.1	-38
CSIRO2	0.7	1.4	2.3	2.3	5.1	8.1
Mean	1	2	3.6	-4.2	-9.2	-16.9
B1						
HadCM2	0.9	1.6	2.2	-4.8	-8.6	-12.1
ECHAM3	1.1	1.9	2.7	-8.8	-15.7	-22.2
CSIRO2	0.6	1.1	1.5	2.1	3.8	5.4
Mean	0.9	1.5	2.1	-3.8	-6.8	-9.6
B2						
HadCM2	0.9	1.8	2.4	-5.1	-9.5	-13.1
ECHAM3	1.1	2.1	3	-9.3	-17.4	-24.1
CSIRO2	0.6	1.2	1.6	2.3	4.2	5.9
Mean	0.9	1.7	2.3	-4	-7.6	-10.5

APPENDIX II.

Climatic ‘conditions’ used to investigate possible changes in wildfire risk.

Condition Number	*Temperature (ºC)*	*Precipitation (mm/yr)*
Control	15.8	275
1	16.3	275
2	16.3	286
3	16.8	253
4	16.8	264
5	16.8	275
6	16.8	286
7	17.3	242
8	17.3	253
9	17.3	264
10	17.3	286
11	17.8	231
12	17.8	242
13	17.8	253
14	17.8	297
15	18.3	220
16	18.3	231
17	18.3	242
18	18.3	297
19	18.8	209
20	18.8	220
21	18.8	231
22	19.3	198
23	19.3	209
24	19.3	220
25	19.8	198
26	19.8	209
27	19.8	220
28	20.3	176
29	20.3	187
30	20.3	198

APPENDIX III.

The Shannon-Wiener index of diversity.

$$H = \sum_{i=1}^{s} (p_i)(\ln p_i)$$

where H = Shannon-Wiener Index

s = number of species (risk classes)

p_i = proportion of total sample belonging to ith species (number of pixels in ith risk class)

Source: Krebs (1989)

APPENDIX IV

Examples of maps used for qualitative analysis of wildfire risk variance in section 4.3. These maps are for variation from the control WRI of climatic conditions 10, 15, 20 and 25 (Appendix II). The map for climatic condition 30 is shown in the text.